Improvements of link performance and capacity in DSA systems

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Improvements of Link Performance and Capacity in DSA Systems.

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T H È S E

"To my wife and family"

Acknowledgments

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I would like to thank you all without mentioning any names. I am certain that you know who you are.

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Chapter 1

Résumé en Français

1.1 Introduction

Actuellement, les réseaux sans fil sont réglementés par une politique d'assignation des fréquences fixes (FSA). Dans ce modèle, le spectre radio disponible est divisé en blocs des fréquences fixes séparées par des bandes de garde. Ces blocs sont attribues à des technologies spécifiques, à des titulaires des licences ou à des services pendant des longues périodes. Cependant, cette approche fait obstacle au développement des nouvelles technologies sans fil et des équipes de communication car chaque nouvelle technologie radio à besoin de sa propre bande de fréquence pour fonctionner et ils restent très peu des bandes de fréquences à attribuer. En plus, des mesures d'occupation du spectre prouvent que l'attribution fixe de fréquences également se traduit par une faible efficacité dans l'utilisation du spectre de frequence, car une grande partie du spectre reste sous-utilisé. Ces observations ont motivé les organismes de réglementation pour rechercher des méthodes d'accès différentes pour résoudre les problèmes présentés ci-dessus. En conséquence, l'utilisation de la radio cognitive (CR) et de la technologie d'Accès Dynamique au Spectre (DSA) sont apparue comme des possibles solutions pour résoudre le manque d'efficacité dans l'utilisation du spectre en permettant le partage des bandes de frequence. Dans une telle approche, les utilisateurs secondaires (SUs) sont autorisés à accéder dynamiquement au spectre non-utilisé dans les bandes des utilisateurs primaires (PUs). Ces bandes non-utilisés sont communément appelées trous du spectre ou "*Spectrum Holes*". L'objectif de DSA est de maximiser l'utilisation du spectre sous licence par l'accès secondaire et, en même temps, promouvoir la mise en place rapide des nouvelles technologies et des services sans fil sans avoir besoin de mettre une toute nouvelle fréquence à cet effet. Tout ce processus est basé sur l'agilité de fréquence et l'intelligence offertes par la technologie de la CR.

Au cours de nos travaux de recherche, différents scénarios de DSA ont été étudiés. Ces scénarios diffèrent dans l'architecture du réseau (c.-à-d. distribuée ou centralisée) et dans l'orientation du réseau (c.-à-d. Ad-hoc ou cellulaire). Nous avons également analysé deux techniques différentes pour l'utilisation secondaire du spectre dans le contexte de la radio cognitive. Une des techniques est dans la forme de recouvrement ou "*Overlay*", qui est l'utilisation opportuniste des bandes non-utilisées dans le spectre des PUs par les SUs équipés de la CR. L'autre technique est sous la forme de sous-couche ou "*Underlay*", ce qui impose des restrictions sévères sur les niveaux de puissance de transmission des SUs. Notre objectif est de fournir des solutions pour améliorer la performance et la capacité des systèmes de DSA en utilisant la technologie de la CR, tout cela sans changements majeurs dans les courants architectures sans fil.

1.2 Contexte et Motivations

La CR à été intensivement proposée comme la technologie qui permettra le DSA. Les systèmes de DSA utilisent des techniques novatrices de gestion du spectre, qui permettent à différents systèmes de partager la même bande de fréquence et d'utiliser le spectre radio de manière efficace. La technologie de la CR permet le développement d'un système intelligent et adaptatif de communication sans fil qui est en mesure de travailler dans un environnement de façon consciente. Les réseaux de DSA qui utilisent la technologie de la CR sont censés d'apporter une amélioration significative du débit de transmission et une extension de la couverture des systèmes sans fil de prochaine génération.

La CR idéal doit être conscient de son environnement, elle peut planifier à l'avance et négocier la meilleure partie du spectre pour fonctionner. Elle peut utiliser la meilleure puissance de transmission et le meilleur schème de modulation. En plus, la CR idéal peut gérer tous ces ressources en temps réel pour satisfaire la qualité de service et les demandes des utilisateurs. Néanmoins, la CR idéal est actuellement dans les premières étapes de recherche, avec la plupart des travaux qui se déroulent dans les universités. Il existe également un important effort de l'industrie vers la normalisation et la commercialisation de la technologie de la CR. Importants acteurs de l'industrie qui font des efforts de R&D dans la technologie CR sont notamment : Alcatel-Lucent, Ericsson et Motorola de l'industrie de l'équipement mobile ; BT et Orange des opérateurs de réseaux ; Philips et Samsung de l'industrie électronique ; HP et Dell de l'industrie informatique et finalement Microsoft et Google et de l'industrie du logiciel Internet.

La principale caractéristique des appareils avec des fonctionnalités cognitives est leur capacité de modifier dynamiquement leur fréquence de fonctionnement pour accéder au meilleur spectre de fréquence sans interférer avec les réseaux primaires. Cela peut se produire soit sur instruction d'une station de base ou de manière autonome par les appareils eux-mêmes en fonction de l'utilisateur et des exigences du réseau. Ces exigences peuvent dépendre du contexte des applications et peuvent inclure des prix, de la qualité de service et des économies d'énergie.

Grâce à la technologie de la CR, les systèmes de DSA peuvent permettre, à des réseaux sans fil de prochaine génération, de briser les barrières rigides d'accès au spectre imposées par le modèle actuel de FSA. Dans ce contexte, le DSA peut avoir lieu de plusieurs façons :

- Entre un réseau primaire avec licence et un réseau secondaire (par exemple l'accès secondaire au spectre des chaînes de télévision ou aux bandes cellulaires ou au spectre militaire).
- Dans le même système primaire (par exemple le partage du spectre 3G en femtocells).
- Entre deux systèmes primaires (par exemple la location en temps réel et le commerce du spectre entre deux technologies sans fil ou entre deux opérateurs de téléphonie mobile).

Dans un futur proche, il est prévu que le DSA basé sur la technologie de la CR ira bien au-delà que de l'accès secondaire au spectre. Comme résultat des tendances actuelles dans la libéralisation du spectre y compris la disponibilité du spectre sous licence pour les transactions en temps réel, les dispositifs cognitifs peuvent être en mesure d'accéder à différents types de fréquences. Ces types de fréquences peuvent inclure : un spectre sous licence (par exemple les bandes cellulaires, les bandes TV), sans licence spectre (c.-à-d.

bandes ISM), ainsi que le spectre qui est acquis en temps réel, soit en crédit-bail ou à titre secondaire.

La motivation principale de notre recherche se situe sur les questions ci-dessus et vise à la proposition des solutions différentes afin de maintenir des communications fiables entre les utilisateurs secondaires préservant intacte à tout moment l'activité de réseaux primaires.

1.3 Organisation de la Thèse

Cette thèse porte sur l'amélioration des performances de la liaison et de la capacité dans les systèmes de DSA utilisant la technologie de la CR et elle fournit différentes solutions dans ce sujet. La structure de cette thèse est organisée comme suit :

- Le chapitre 3 fournit une introduction générale aux réseaux DSA et présente les enjeux et les défis de tels environnements. D'ailleurs, nous présentons également les technologies d'accès sans fil existantes qui pourraient être les principaux acteurs comme PUs ou SUs (si ces technologies sont équipées de la CR) dans les réseaux sans fil de prochaine génération. En outre, nous énonçons les différences entre les deux principales techniques de partage des fréquences dans les réseaux de DSA. Ces techniques sont connus sous le nom de *Overlay* et *Underlay*. En plus, nous présentons les possibles architectures et les différents composants qui pourraient rendre possible cet accès dynamique. Finalement, dans ce chapitre, nous présentons les différents travaux de normalisation spécifiques concernant CR et DSA.

- Le chapitre 4 est consacré à notre première contribution. Dans ce chapitre nous présentons un panorama des différents protocoles multicanaux MAC permettant le DSA. Ces protocoles sont principalement basés sur le mécanisme d'accès de la norme IEEE 802.11. Nous faisons une comparaison des principales caractéristiques de chaque protocole en fonction du nombre d'émetteurs-récepteurs, de la nécessité de synchronisation, de la nécessité d'un canal de contrôle commun et des différentes manières de faire rendez-vous. Une description détaillée de leurs mécanismes d'accès est également fournie. Le but de ce chapitre est de montrer comment chaque protocole MAC multi-canal confronte les nombreux problèmes qui surgissent dans le DSA et ainsi pouvoir identifier les avantages et les inconvénients de chaque protocole afin d'être mis en application correctement dans les réseaux de radio cognitive.

- Dans le chapitre 5, une autre contribution importante de notre travail de recherche est également présenté, la transmission d'un canal de contrôle cognitif ou *Cognitive Beacon Channel* (CBC). Dans ce chapitre, nous présentons notre proposition pour l'utilisation des canaux logiques du GSM (RACH, AGCH et TCH) et de la signalisation de l'UMTS (MIB et SIBs) du canal de diffusion pour transmettre la signalisation aux SUs dans les réseaux hétérogènes (par exemple 3GPP, Wi-Fi, WiMAX et futurs systèmes cognitifs). Nous présentons une évaluation de notre CBC concernant : le délai total pour récupérer le canal cognitif, la densité totale des SUs, la portée du canal cognitive et le débit binaire net requis. Le but de ce chapitre est de démontrer que les technologies 3GPP existantes peuvent être mises en application pour transmettre la signalisation avec un débit acceptable dans les futurs réseaux de DSA.

- Le chapitre 6 contient les dernières contributions de cette thèse. Ce chapitre propose l'utilisation du processus de point de Poisson comme une nouvelle méthode d'analyse à appliquer dans l'approche de la température d'interférence. Dans ce chapitre, nous développons premièrement un modèle pour l'environnement de radio fréquence. Après, par l'utilisation du processus de point de Poisson, nous déterminons les éléments essentiels pour le calcul de la capacité par-lien et la capacité totale d'un réseau secondaire suivant les modèles de la température d'interférence dans les cas idéal et généralisé. Après de finir cette analyse mathématique, nous démontrons l'application de notre modèle par un exemple numérique dans lequel, nous considérons comme PUs un réseau UMTS et comme SUs un réseau UWB. Finalement, par l'utilisation des inégalités de concentration, nous déterminons une limite supérieure de la probabilité de coupure (*Outage*) du réseau primaire lorsque les SUs transmettent.

- Enfin, le chapitre 7 conclut cette thèse et donne un aperçu des perspectives et les travaux futurs dans ce domaine de recherche. La liste de nos publications et la bibliographie complète se trouve à la fin du document.

1.4 Contributions

Les réseaux DSA imposent plusieurs défis de recherche en raison de la large gamme de fréquences disponibles ainsi que les diverses exigences de qualité de service des applications. Par conséquence, au cours de nos travaux de recherche nous avons étudié les différentes architectures de ce nouveau paradigme en matière de communication sans fil. Dans la littérature existent plusieurs approches proposées pour le partage du spectre. Ces approches vont des architectures entièrement autonomes et distribués aux architectures entièrement centralisées dans lesquelles l'accès dynamique au spectre est géré de manière centralisée. Dans cette thèse, nous présentons notre vision dans ce domaine et nous établons des différentes propositions permettant le DSA. En plus, nous avons analysé et identifié les problèmes et les défis de notre recherche. Enfin, nous avons évalué nos propositions dans cette matière.

Dans cette thèse, nous présentons différentes solutions pour améliorer les performances du lien et de la capacité des utilisateurs mobiles dans un contexte secondaire, tout en accordant l'activité indemne des réseaux primaires. Nos propositions diffèrent dans l'architecture du réseau, dans l'orientation du réseau et dans la technique d'accès pour le partage du spectre (c.-à-d. *Overlay* ou *Underlay*). Cependant elles ont toutes comme objectif l'établissement de communications fiables entre les utilisateurs secondaires.

En identifiant, en étudiant, et en analysant les enjeux et défis des réseaux DSA, nous avons apporté les contributions suivantes :

- Nous avons fait une analyse approfondie des protocoles MAC multicanaux existants proposés pour augmenter le débit du réseau, pour améliorer l'utilisation du spectre et pour réduire l'interférence causée par l'utilisation secondaire du spectre dans une manière opportuniste (c.-à-d. *Overlay*). Dans cette analyse, nous avons décrit les mécanismes d'accès de chaque protocole et nous avons fait une comparaison des protocoles en fonction de leurs principales caractéristiques de fonctionnement. Finalement, nous avons indiqué les différentes manières de donner rendez-vous pour la transmission des données de chaque un des protocoles.

- Nous avons proposé l'utilisation des canaux logiques du GSM et de l'UMTS pour permettre la transmission d'une voie balise cognitive nommée *Cognitive Beacon Chan-*

nel. Ce canal de contrôle cognitif contribue à améliorer la conscience du spectre de fréquence par le transport de signalisation aux utilisateurs mobiles dans un environnement de technologie d'accès de radio multiple. Nous avons comparé la performance de nos propositions et nous avons prouvé que nos approches obtiennent des meilleures performances que d'autres propositions.

- Nous avons démontré que les technologies 3GPP existantes possèdent les capacités requises pour transmettre la signalisation avec un débit acceptable; en utilisant une architecture centralisée ou une architecture coordonnée dans les réseaux de DSA hétérogènes.

- Nous avons également proposé l'utilisation d'une nouvelle méthode analytique à appliquer dans le modèle de la température d'interférence. Cette approche est une technique *Underlay* dans laquelle les SUs essaient de coexister avec PUs au lieu d'éviter les signaux des réseaux primaires. Notre méthode se fonde sur le processus de point de Poisson.

- En utilisant le processus de point de Poisson, nous avons développé un nouveau modèle pour évaluer la capacité atteint d'un réseau secondaire, l'interférence causée à un réseau primaire et la puissance de transmission autorisée des utilisateurs secondaires afin de garantir que l'activité des utilisateurs primaires ne soit pas affectée par transmissions des utilisateurs secondaires.

- Finalement, par l'utilisation des inégalités de concentration, nous avons déterminé une limite supérieure sur la probabilité de coupure (*Outage*) du réseau primaire quand les SUs transmettent en utilisant le modèles Idéal et généralisé de la température d'interférence.

1.5 Conclusions et Perspectives

Cette thèse a abordé la question de l'amélioration de la qualité de la liaison et de la capacité dans les réseaux de DSA. L'objectif de notre recherche était de fournir des solutions différentes afin de maintenir des communications fiables entre les utilisateurs secondaires en préservant intacts à tout le moment l'activité des réseaux primaires. Dans cette thèse, ont été présentés et analysés différentes propositions pour atteindre cet objectif. Ces propositions ont différé dans l'architecture du réseau, dans l'orientation du réseau et dans la technique d'accès utilisée pour le partage du spectre.

Après d'avoir fourni une introduction générale aux réseaux de DSA et avoir présenté les enjeux et les défis dans tels environnements. Nous avons présenté les technologies d'accès sans fil existantes qui pourraient être les principaux acteurs, comme PUs ou SUs, dans les réseaux sans fil de prochaine génération. Comme nous avons énoncé dans cette thèse, pour rendre possible un accès dynamique efficace, un équilibre approprié entre la technologie, la régulation et les modèles économiques doit régner. À cette fin, organismes de normalisation tels que l'IEEE, l'UIT-R et l'ETSI, entre autres, ont continué à travailler sur les normes spécifiquement liés au DSA à la CR.

Dans le chapitre 4, nous avons présenté un panorama des différents protocoles MAC multicanaux permettant le DSA dans les réseaux ad hoc distribués. Ces protocoles sont principalement basés sur le mécanisme d'accès de la norme IEEE 802.11. Nous avons fait une comparaison des principales caractéristiques de chaque protocole en fonction du nombre d'émetteurs-récepteurs (TRx), de la nécessité de synchronisation, de la nécessité d'un canal de contrôle commun et des différentes manières de donner rendez-vous. Dans notre analyse, nous avons montré que la plupart des protocoles MAC cognitifs sont basées ou inspirées sur les protocoles MAC multicanaux proposés pour les réseaux non cognitifs. Ainsi, ils héritent leurs caractéristiques de fonctionnement et naturellement leurs mérites et démérites. En ingénierie, toute amélioration est livré avec un compromis et dans le cas des protocoles MAC multicanaux pour le DSA, cette condition demeure. Quelques exemples des compromisses décrites par notre l'analyse sont :

La mise en oeuvre des protocoles qui utilisent un seul TRx est plus facile comparée à la mise en oeuvre des protocoles qui utilisent multiples TRx. Néanmoins, dans les protocoles d'un seul TRx le problème de terminal caché surgisse ainsi que le problème du retard de commutation de canal. En général, les protocoles qui utilisent multiples TRx obtiennent des meilleures performances, en comparaison avec les protocoles qui utilisent un seul TRx, sous un éventail de situations. Cela est dû au fait qu'ils peuvent atteindre des débits plus élevés et ils peuvent facilement éviter le problème des stations cachés dans les environnements multicanaux. Cependant, ces protocoles sont plus complexes et plus coûteux que les protocoles qui utilisent un seul TRx. Dans le cas des protocoles qui utilisent un canal de contrôle dédié, ils peuvent être affectés par le la possibilité de goulot d'étranglement dans certaines conditions de fonctionnement. Dans ce cas, les rendez-vous multiples peuvent alléger le problème de la congestion, mais ils posent le défi d'assurer que l'émetteur et le récepteur visitent le même canal de rendez-vous. Finalement, les protocoles de division de phase ou *Split Phase* et ceux de canal contrôle dédié, séparent explicitement les paquets de contrôle et les paquets de données. Cependant, cela ne signifie pas nécessairement une amélioration des performances car le fait de générer plus des rendez-vous est inutile lorsque les canaux de données sont déjà saturés, et vice versa. Plus précisément, la performance des protocoles de division de phase dépend fortement sur le choix de la durée des phases de contrôle et de données.

En raison de la grande quantité des protocoles MAC multicanaux proposés dans la littérature pour améliorer l'utilisation du spectre, nous considérons que montrant comment chaque protocole confronte les nombreux problèmes qui surgissent dans le DSA et indiquant les compromis de chaque protocole, nous avons facilité la sélection précise du protocole approprié à mettre en application dans les futures réseaux de DSA distribués. Néanmoins, comme nous avons décrit dans cette thèse, pour obtenir les paramètres nécessaires pour l'accès au spectre dans les réseaux ad-hoc distribués, une station mobile doit balayer le spectre entier à la recherche des informations sur occupation du spectre. Ce processus peut exiger beaucoup de temps et peut augmenter considérablement la consommation de la batterie des appareils mobiles. Pour surmonter ce problème, en chapitre 5, nous avons proposé l'utilisation d'un canal de control cognitif ou CBC en tant qu'assistant pour les stations mobiles, pour sélectionner le réseau approprié selon les besoins des utilisateurs (par exemple la technologie d'accès radio (RAT), la bande de fréquence, l'utilisation secondaire du spectre, etc.). Pour mettre en application le CBC, nous avons proposé l'utilisation des canaux logiques de GSM (RACH, AGCH et TCH) et la signalisation du BCH (MIB et SIBs) de l'UMTS. Nous avons comparé les performances (c.-à-d. le délai pour récupérer le canal cognitif, la densité totale des utilisateurs, la portée du canal cognitif et le débit net requis) de nos propositions avec le les implémentations de "*Broadcast*" et "*On-demand*" CPC du projet E2R II. Comme nous l'avons montré, notre implémentation utilisant les canaux de GSM surpasse légèrement la proposition de *On-demand* dans le projet E2R II. Cependant, notre proposition utilisant la signalisation de l'UMTS surpasse clairement l'approche de *Broadcast* CPC du projet E2R II. Ce dernier résultat est dû au fait que les stations mobiles savent exactement quand décoder leur information. Cette caractéristique conduit à une réduction de la consommation d'énergie dans les appareils mobiles et, par conséquent, les utilisateurs mobiles peuvent augmenter le temps utile de leur équipement, ce qui est l'une des caractéristiques les plus désirables des dispositifs mobiles de prochaine génération. D'ailleurs, notre proposition en utilisant la signalisation de l'UMTS n'est ni sensible au nombre de mailles couvertes par le CBC ni au nombre de requêtes envoyées par les utilisateurs.

En Adaptant l'utilisation des canaux logiques de GSM et de l'UMTS pour transporter le CBC, nous avons profité de deux technologies existantes, qui on été avérés efficaces et acceptées dans le monde entier. D'ailleurs, nous avons démontré que les deux technologies de 3GPP possèdent également les capacités nécessaires pour transmettre la signalisation avec un débit acceptable dans un environnement de technologie d'accès multi-Radio (multi-RAT). En outre, en utilisant l'information véhiculée par le CBC dans les réseaux GSM ou UMTS, le DSA pourrait se faire sans que les stations mobiles aillent besoin de balayer le spectre entier afin de trouver des informations sur son utilisation. En plus, si une détection appropriée des trous du spectre dans les bandes des utilisateurs primaires est effectuée par les propriétaires du spectre (c.-à-d. Operateurs), ils pourraient promouvoir la libération des bandes de fréquences et tirer bénéfice de l'utilisation secondaire de leur spectre si des procédures de location sont effectués.

Les propositions pour l'accès dynamique au spectre présentés en chapitre 4 et chapitre 5 diffèrent dans l'architecture du réseau et dans l'orientation du réseau. Tandis que le chapitre 4 a présenté plusieurs approches pour le DSA dans les réseaux ad-hoc distribués, le chapitre 5 a présenté notre proposition de l'accès dynamique utilisant une architecture de réseau cellulaire centralisée. Néanmoins, la caractéristique commune de ces propositions est l'utilisation d'une technique d'accès opportuniste pour le partage du spectre (c.-à-d. *Overlay*). Cette technique est basée sur l'action d'éviter les PUs par l'utilisation des trous du spectre pour la transmission de données.

L'autre technique d'accès de spectre, proposée comme possible solution au problème d'accès/attribution dynamique au spectre est connue comme *Underlay*. Dans cette technique, la communication entre les SU est autorisée dans les bandes des PUs si la puissance d'émission des SUs est assez faible qu'elle ne nuit pas les PUs. Comme nous avons énoncé dans cette thèse, l'approche d'*Underlay* impose des restrictions sévères aux niveaux de puissance transmise et ainsi elle exige l'opération dans des largeurs de bande ultra grandes (UWB). La caractéristique principale de cet approche est le fait que les SUs tentaient de coexister avec PUs au lieu d'essayer d'éviter des signaux de PUs. Dans ce contexte, en chapitre 6 nous avons proposé l'utilisation du processus de point de Poisson comme nouvelle méthode analytique à appliquer dans le modèle de la température d'interférence (IT). Ce modèle est une approche d'*Underlay* proposée par la FCC comme un autre moyen d'accéder de façon dynamique au spectre de fréquence.

Le processus de point de Poisson est un outil mathématique qui nous a permis d'évaluer, de façon simple : la capacité réalisable par un réseau secondaire, l'interférence causée au réseau primaire et la probabilité de coupure (*Outage*) du réseau primaire. À cette fin, nous avons premièrement développé les expressions nécessaires pour estimer l'interférence de base moyenne, l'interférence moyenne causée par d'autres SUs et l'interférence moyenne causée par les PUs actifs. En utilisant ces résultats, nous avons estimé la puissance de transmission autorisée des SUs pour garantir que l'activité des PUs ne soit pas affectée par la transmission des SUs. Cette analyse a été effectuée pour les cas idéal et généralisé du modèle d'IT. Ensuite, en utilisant le théorème de Shannon-Hartley, nous avons dérivé les expressions de la capacité moyenne par lien des SUs et la capacité totale du réseau secondaire. Finalement, par l'utilisation des inégalités de concentration, nous avons déterminé une limite supérieure sur la probabilité de coupure du réseau primaire lorsque le réseau secondaire transmet.

Afin d'obtenir des résultats numériques utilisant nos expressions dans un scénario réaliste, nous avons examiné la capacité réalisable d'un système d'UWB, WiMedia, comme réseau secondaire et le réseau UMTS comme réseau primaire. Nos résultats prouvent que pour ce scénario, le réseau secondaire obtient une performance limitée en termes de capacité, comparée aux vraies possibilités d'une norme d'UWB (par exemple IEEE 802.15.3a) dans un contexte d'utilisateurs non-primaire/secondaire. Cependant, ces performances peuvent facilement être améliorées si le réseau secondaire opère avec une bande passante plus large, ce qui est l'une des caractéristiques de la couche MAC de WiMedia. En outre, en chapitre 6, nous avons démontré que la communication des SUs est possible causant des dommages mineurs aux utilisateurs primaires suivant le cas idéal et généralisé du modèle d'IT. D'ailleurs, par l'utilisation des inégalités de concentration, nous avons établi que, afin de garantir que seulement 1% des PUs soit affectée par la transmission des SU, il coûtera environ 25% de la puissance moyenne de transmission des SUs et 20% de la puissance pour une probabilité de coupure des PUs en-dessous de 5%. En plus nous avons démontré que, pour un scénario avec un grand nombre des SUs, la restriction de la puissance d'émission des utilisateurs secondaires n'entraîne pas une réduction significative de la capacité par lien du réseau secondaire. Il est à noter que les résultats de la capacité de SUs et leurs leurs dégâts sur les PUs présentés par notre analyse, sont améliorables si l'intensité des SUs et la bande passante du réseau secondaire sont augmentées, ce qui est une tendance des réseaux sans fil de prochaine génération.

En conclusion, les résultats obtenus à partir de notre travail de recherche ont indiqué que un DSA efficace est réalisable et peut se faire avec les technologies sans fil actuelles qui existent sur le marché. Nous avons également confirmé que la communication fiable entre les utilisateurs secondaires, en préservant intact à tout moment l'activité de réseaux primaires, est possible en utilisant différentes techniques et différentes architectures de DSA pour le partage du spectre. Ainsi, à partir de nos résultats, nous pouvons affirmer qu'en mettant en application les techniques proposées pour l'utilisation secondaire du spectre, nous pouvons améliorer la performance de la liaison et de la capacité dans les futurs systèmes de DSA.

1.5.1 Perspectives

Nous considérons que l'amélioration des performances de la liaison et de la capacité dans les systèmes de DSA n'est pas une tâche triviale. Par conséquent, pour obtenir un accès dynamique efficace nous devons compter sur des techniques robustes de partage du spectre pour éviter toute interférence. Dans le cas de l'accès opportuniste au spectre (c.-à-d. *Overlay*), les attributs de base pour réaliser le DSA sont: la détection précise des trous du spectre, des protocoles efficaces de gestion de mobilité et une prise de décision optimale pour la reconfiguration de la CR. Dans le cas des techniques d'*Underlay*, l'estimation précise des interférences existantes et le bon contrôle de la puissance de transmission sont des actions cruciales pour éviter l'augmentation de la limite de température. En plus d'atténuer l'interférence, les nouvelles radios devront réaliser une estimation plus précise du canal de communication, non seulement en fréquence, mais aussi en temps et en espace. Ceci implique une génération des signaux plus compliqué et aussi un récepteur plus évolué capable de traiter l'énergie reçue. Par conséquent, toutes les améliorations des issues mentionnées ci-dessus représenteront un perfectionnement global de ce nouveau paradigme de DSA.

Tout au long de notre travail de recherche et pendant la phase de conception de nos propositions de DSA, nous avons identifié certaines questions qui ont attiré notre attention et nous sommes convaincus qui seraient des domaines de recherche intéressants. Cette thèse a présenté des approches permettant le DSA et ces propositions diffèrent dans l'architecture du réseau, dans l'orientation du réseau et dans la technique d'accès pour le partage du spectre. Les travaux futurs impliquent une analyse plus détaillée de la QoS sur les transmissions des SUs dans les approches proposées. Mesures de qualité telles que le retard et la perte de paquets seront analysés afin d'étendre les capacités de nos architectures pour l'utilisation secondaire du spectre. En plus, bien que notre recherche ne se concentre pas sur les questions liées à la commercialisation du spectre dans le processus de DSA. Nous considérons que ce sujet devrait être abordé afin d'éviter l'hésitation des propriétaires du spectre et d'améliorer la transparence et l'efficacité de ce processus.

Se concentrant sur la mise en oeuvre de notre canal de contrôle cognitif (CBC), une analyse détaillée des la capacité du canal de diffusion (MIB et SIB) de l'UMTS est recommandé afin d'avoir une estimation précise de combien SIBs peuvent être consacrés à la transmission d'information sur l'occupation du spectre. Le but de cette analyse est double : d'abord pour estimer la quantité maximale, en termes des SUs, que le réseau peut prendre en charge et puis pour déterminer la quantité maximale d'information, en termes de bits, que le CBC peut transmettre. Dans le cas de notre implémentation du CBC utilisant le réseau GSM, cette analyse n'est pas nécessaire car il est supposé qu'un canal trafic (TCH) est attribué à chaque SU.

Dans le cadre d'un travail futur, nous allons étendre notre analyse de l'utilisation du processus de point de Poisson dans les réseaux de la CR pour d'autres environnements réseau. En utilisant les approches idéal et généralisé du modèle d'IT, nous évaluerons : l'interférence causée au réseau primaire, la puissance d'émission autorisée des SUs afin de garantir que les activités des PUs ne seront pas affectées par la transmission des SUs et la capacité du réseau secondaire. L'analyse ci-dessus sera réalisée en tenant compte des différentes technologies d'accès sans fil (par exemple, WLAN, WiMAX, LTE, Zigbee, etc). L'objectif de cette analyse sera de comparer les performances des différents réseaux sans fil dans un contexte des utilisateurs primaires/secondaires.

Notre recherche s'est concentrée principalement sur les aspects techniques de DSA, cependant, nous sommes conscients que ces futurs réseaux ne diffèrent pas des réseaux actuels seulement dans l'utilisation de la technologie de la CR mais également dans les modèles économiques et les stratégies de gestion ; particulièrement dans le cas de l'utilisation secondaire du spectre dans les bandes sous licence. Dans cette perspective, nous avons identifié deux domaines de recherche qui pourraient améliorer le DSA dans les bandes sous licence : des nouveaux modèles économiques pour l'accès secondaire et des mécanismes efficaces de facturation.

- Des nouveaux modèles économiques pour l'accès secondaire : Les propriétaires du spectre des bandes sous licence sont des éléments importants de notre architecture car ils sont censés à partager leurs ressources pour offrir l'utilisation secondaire aux utilisateurs mobiles. Par conséquent, le fait de fournir incitations intelligentes et efficaces qui motivent les propriétaires du spectre pour autoriser l'accès secondaire est primordial. Des nouveaux modèles économiques peuvent donner des solutions sur la manière de commercialiser l'utilisation secondaire du spectre. Pour cette raison, il est nécessaire de trouver des de nouveaux modèles qui offrent une stratégie commerciale claire pour permettre à tous les participants de ces nouvelles architectures d'être économiquement récompensés.

- Des mécanismes efficaces de facturation : La question de la tarification est primordiale quand l'utilisation secondaire s'offre sur les bandes sous licence. Les opérateurs cellulaires ne déploieront aucune architecture secondaire s'il n'y a aucun moyen de facturer les utilisateurs secondaires. Ainsi, nous estimons que des nouveaux mécanismes de facturation visant à fournir une plateforme distribuée efficace de tarification motiveraient les operateurs réseaux ou fournisseurs de services à participer au paradigme de DSA.

Nous sommes certains qu'en s'attaquant aux problématiques techniques et économiques mentionnées ci-dessus, la performance de nos propositions pour le DSA s'améliorera et pourrait être considérée pour un futur déploiement.

Abstract

Recently, several studies initiated mainly by the Federal Communications Commission (FCC), which is charged with regulating communications by radio, television, wire, satellite and cable in US, have shown that the frequency spectrum is inefficiently exploited: some bands are highly crowded at some day hours or in certain dense urban areas while others remain poorly utilized. These problems, together with the rapid evolution of Cognitive Radio (CR) technology have pointed to the implementation of Dynamic Spectrum Access (DSA) in next generation wireless networks. The key promise of these systems is the possibility of highly flexible and efficient management and reuse of spectrum across all its dimensions.

DSA systems use innovative spectrum management techniques, which allow different systems to share the same frequency band to utilize the radio spectrum in an efficient way. CR technology enables the development of intelligent and adaptive wireless communication systems that are able to work in an environment aware manner. DSA networks using CR technology are expected to provide significant throughput improvement and coverage extension for next generation wireless systems.

During our research work, we propose different approaches to solve the dynamic spectrum access/allocation problem for future CR systems and we present some of the key research challenges associated with this new paradigm. For that purpose, we study Ad-hoc as well as cellular orientations allowing dynamic access to spectrum. Moreover, we investigate different network architectures for DSA, ranging from fully autonomous and distributed to fully centralized architectures in which dynamic access to spectrum is centrally managed. In addition, we also study two different techniques for spectrum sharing: Overlay and Underlay. Even if our proposals differ in the network orientation, in the network architecture and in the spectrum access technique for spectrum sharing, all of them have as goal the improvement of the link performance and the capacity of secondary networks while granting the activity of primary users (PUs).

In this thesis, we firstly develop an extensive analysis of existing multi-channel MAC protocols for Ad-hoc networks. These protocols were proposed to increase network throughput, to improve spectrum utilization and to reduce interference caused by secondary use of the spectrum in an opportunistic (i.e. Overlay) manner. In our analysis we make a comparison of the key features of each protocol according to the number of transceivers, the need for synchronization, the need for a common control channel and the different ways to make rendezvous. By pinpointing the advantages, disadvantages and hardware requirements of each protocol, we facilitate the accurately selection of the appropriate solution to be implemented in future distributed DSA networks. Nevertheless, to obtain the necessary parameters for spectrum access in distributed Ad-hoc networks, a mobile station has to scan the entire spectrum looking for occupancy information. This scanning process may require a lot of time and can greatly impact the battery consumption in mobile devices. To overcome this problem, in this thesis we propose the use of a Cognitive Beacon Channel (CBC). This cognitive control channel helps to improve spectrum awareness by conveying signalization to mobile users in a multi-radio access technology environment and allows DSA using a centralized or a coordinated architecture. The main advantage of our proposal is the fact that our CBC re-use existing 3GPP technologies, proved to be efficient and accepted worldwide.

The Interference Temperature model used for spectrum sharing is our last research axis. This approach is an Underlay technique in which secondary users (SUs) attempt to coexist with PUs instead of avoiding primary networks. Using the Poisson point process, we develop a new model to evaluate the achieved capacity of a secondary network, the interference caused to a primary network and the allowed transmission power of SUs to guarantee that activity of the PUs won't be affected by their transmissions. Afterwards, by the use of Concentration Inequalities, we determine an upper bound on the outage probability of the primary network when the SUs transmit following the Ideal and the Generalized Interference Temperature models.

The results obtained from our research work indicate that efficient DSA is feasible and can be done with the current wireless technologies in the market. We also confirmed that reliable communication between SUs, preserving undisturbed at all time the activity of primary networks is possible following different DSA techniques and different DSA architectures for spectrum sharing. Thus, from our results we can state that by implementing the proposed techniques for the secondary use of the spectrum, we can improve the link performance and the capacity in future DSA systems.

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Acronyms

AAS	Adaptive Antenna Systems
AC	ATIM ACK
AES	Advanced Encryption Standard
AGCH	Access Grant Channel
AICPC	Acquisition Indicator CPC
AR	Ad hoc Traffic Indication Message Request
AS-MAC	Ad hoc SEC Medium Access Control
ATIM	Ad hoc Traffic Indication Message
ATM	Asynchronous Transfer Mode
A-CTS	ATIM CTS
A-RE	ATIM Reservation
A-RTS	ATIM RTS
BCH	Broadcast Channel
BPSK	Binary Phase Shift Keying
BRAN	Broadband Radio Access Networks
BS	Base Station
BT	British Telecom
CAP	Cognitive Access Point
CBC	Cognitive Beacon Channel
CCCH	Common Control Channel
CCR	Common Control Radio
CCK	Complementary Code Keying
CDMA	Code Division Multiple Access

CD-MMAC Cooperative Diversity Multi-Channel MAC Protocol

CEPT European Conference of Postal and Telecommunications

CHREQ Channel Status Request

CHRPT Channel Report slots

CMS Cognitive Mobile Stations

CN Core Network

CPC Cognitive Pilot Channel

CPE Consumer Premise Equipment

CR Cognitive radio

CREAM-MAC Cognitive Radio-EnAbled Multi-Channel MAC

CS Circuit-Switched

CSMA/CA Carrier Sense Multiple Access/Collision Avoidance

CSR Channel-State-Receiver

CSCC Common Spectrum Coordination Channel

CST Channel-State-Transmitter

CTS Clear to Send

DBCPC Downlink Broadcast CPC

DBPSK Differential Binary Phase Shift Keying

DC Data Channel

DCF Distributed Coordination Function

DES Data Encryption Standard

DFS Dynamic Frequency Selection

DIFS Distributed Inter-frame Space

DODCPC Downlink On-Demand CPC

DQPSK Differential Quadrature Phase Shift Keying

DSA Dynamic Spectrum Access

DSL Digital Subscriber Line

DSSS Direct Sequence Spread Spectrum

DSU Delegate Secondary User

DySPAN	Dynamic Spectrum Access Networks
EDCA	Enhanced Distributed Channel Access
EDGE	Enhanced Data rates for GSM of Evolution
EIR	Equipment Identity Register
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
EV-DO	Evolution-Data Optimized
E2R II	End-to-End Reconfiguration Project part II
E3	End-to-End Efficiency Project
E-UTRAN	Evolved UMTS Terrestrial Access Network
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hoping Spread Spectrum
FSA	Fixed Spectrum Assignment
GCC	Group Control Channel
GERAN	Generic Radio Access Network
GGSN	Gateway GPRS Support Node
GLR	Gateway Location Register
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HCCA	Hybrid Coordination Controlled Channel Access
HCF	Hybrid Coordination Function
HC-MAC	Hardware-Constrained MAC
HLR	Home Location Register
HN	Home Network
HiperLAN	High Performance Local Area Network

HiperMAN	High Performance Radio Metropolitan Area Network
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IP	Internet Protocol
IR	Infrared
ISDN	Integrated Services Digital Network
ISM band	Industrial, Scientific and Medical band
ISP	Internet Service Provider
IT	Interference Temperature
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union-Radiocommunication
LAN	Local Area Network
LTE	Long Term Evolution
MAC	Media Access Control
MBWA	Mobile Broadband Wireless Access
MCHTP	Multi-Channel Hidden Terminal Problem
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MMAC	Multi-Channel MAC Protocol
MMAC-CR	Multi-Channel MAC Protocol for Cognitive Radio
MME	Mobility Management Entity
MS	Mobile Station
MSC	Mobile Switching Center
MT	Mesh Traffic

NAV	Network Allocation Vector
NRM	Network Reconfiguration Management
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSMAC	Opportunistic Spectrum Media Access Control
OSP	Opportunistic Spectrum Period
PCF	Point Coordinating Function
PCL	Preferred Channel List
PCAM	Primary Channel Assignment Based MAC
PPP	Poisson Point Process
PRM	Protocol Referenced Model
PS	Packet-Switched
PSM	Power Saving Mechanism
PSTN	Public Switched Telephone Network
PU	Primary User
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RAC	Resource Awareness Channel
RACH	Random Access Channel
RACPC	Random Access CPC
RAN	Radio Access Network
RAT	Radio Access Technology
RE	Radio Enabler
RF	Radio frequency
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RRC	Radio Resource Control
RRS	Reconfigurable Radio Systems

RTS	Request to Send
RTSu	Request to Send update
Rx	Receiver
SAP	Service Access Point
SCC41	Standards Coordinating Committee 41
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDR	Software Defined Radio
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SCL	Secondary users Channel Load
SDM	Spatial Division Multiplexing
SFN	System Frame Number
SIB	System Information Block
SIFS	Short Inter Frame Space
SIP	Spectral Image of Primary users
SM	Spectrum Manager
SRAC	Single-Radio Adaptive Channel
SRP	Scan Request Period
SSCH	Slotted Seeded Channel Hopping
SSF	Spectrum Sensing Function
SU	Secondary User
SUG	Secondary User Group
TCH	Traffic Channel
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TL	Temperature Limit
TPC	Transmit Power Control
TRM	Terminal Reconfiguration Management
TRx	Transceiver

TTI	Transmission Time Interval
TVBD	TV Band Device
TVWS	TV White Space
Tx	Transmitter
UCC	Universal Control Channel
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UNII	Unlicensed National Information Infrastructure
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra Wide Band
VLR	Visitor Location Register
VoIP	Voice over IP
WEP	Wired Equivalent Privacy
WG	Working Group
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPA	Wireless Protected Access
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WRC	World Radiocommunication Conference
WWAN	Wireless Wide Area Network
W-CDMA	Wideband Code Division Multiple Access
3G	Third Generation
3GPP	The 3G Partnership Project
3GPP2	The 3G Partnership Project 2
4G	Fourth Generation

Chapter 2

Introduction

Nowadays, wireless networks are regulated by a Fixed Spectrum Assignment (FSA) policy. As we can see in Figure 2.1, in this model the available radio spectrum is divided into fixed and non-overlapping blocks of spectrum separated by guard bands. These blocks are assigned to specific technologies, license holders or services for long periods. However, this approach obstructs the development of new wireless technologies and communication devices because each new radio technology need its own frequency band to operate and there are few spectrum bands to be allocated [41]. Moreover, spectrum occupancy measurements [51] evidence that fixed spectrum allocations also result in low efficiency in spectrum utilization because a large portion of the spectrum remains underutilized [22]. These observations have motivated the regulatory bodies to investigate different access methods to overcome the above mentioned problems. As result, the use of Cognitive Radio (CR) technology and Dynamic Spectrum Access (DSA) has emerged as a possible solution to solve the low efficiency in spectrum utilization by allowing spectrum sharing. In such an approach, Secondary Users (SUs) are allowed to dynamically access the unused spectrum in Primary Users (PUs) bands, commonly referred as "spectrum holes". The aim of DSA is to maximize the usage of licensed spectrum through secondary access and, at the same time, to promote rapid introduction of new wireless technologies and services without the need for setting aside any new spectrum for this purpose. All this process is based on the frequency agility and intelligence offered by CR technology.

During our research work, different scenarios for DSA have been studied. These scenar-

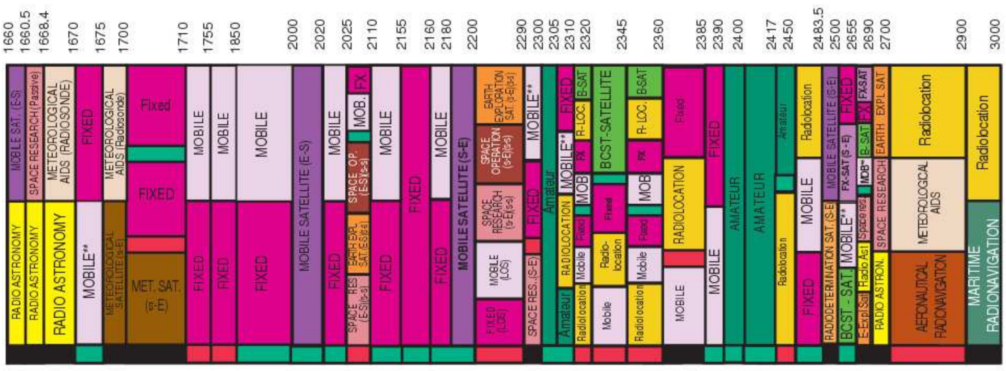

Figure 2.1: Fixed Spectrum Assignment chart

ios differ in the network architecture (i.e. distributed or centralized) and in the network orientation (i.e. Ad-hoc or cellular). We also analyzed two different techniques of secondary use of spectrum in cognitive radio context. One is in the form of Overlay, which is the opportunistic usage of idle bands in the PU spectrum by cognitive radios and the other in the form of Underlay, which imposes severe restrictions on transmitted power levels of SUs. Our objective is to provide solutions improving the link performance and the capacity in DSA systems using CR technology, all this without major changes in current wireless architectures.

The outline of this chapter is as follows: section 2.1 presents the background and motivation of our research. Section 2.2 explains the main contributions of our research to this domain. Finally, section 2.3 provides the thesis overview.

2.1 Background and Motivation

Cognitive Radio [53] is being intensively researched as the enabling technology for DSA. The concept of CR was first described by Mitola and Maguire in [55] as the fact of:

"Transforming radio nodes from blind executors of pre-defined protocols to radio-domain aware intelligent agents that search out ways to deliver the services that the user wants even if that user does not know how to obtain them".

The Ideal CR must be aware of its surrounding environment, it can plan ahead and negotiate for the best part of the spectrum to operate in and at the best power, modulation scheme etc, and manage these resources in real time to satisfy the service and user demands. Nevertheless, the Ideal CR is currently at the early proof-of-concept stage research, with most of the work taking place in universities. There is also significant industry effort towards prototyping, standardization and commercialization of the CR technology. Important industry players with active R&D efforts in CR technology include Alcatel-Lucent, Ericsson and Motorola from the mobile equipment industry, BT and Orange from network operators, Philips and Samsung from the consumer electronics industry, HP and Dell from the computer industry, and Microsoft and Google from the Internet/software industry [58].

The principal characteristic of devices with cognitive functionality is their ability to dynamically change their frequency of operation, by accessing the best available spectrum without interfering with primary networks. This may happen either upon instruction from a base station or autonomously by devices themselves depending on the user and network requirements. These requirements may depend on context, application and location and can include price, QoS, and energy saving.

Using CR technology, DSA systems can enable next generation wireless networks to break the rigid spectrum access barriers imposed by the current FSA model. In this context, DSA may take place in several ways:

- Between a licensed primary network and a secondary network (e.g. secondary spectrum access to TV channels, 3G cellular bands or military spectrum).
- Within the same primary system (e.g. micro-macro sharing of 3G spectrum in femtocells).
- Among two primary systems (e.g. real-time leasing and trading of spectrum between two wireless technologies or between two different cellular operators).

In a future, it is expected that DSA based on CR technology will go far beyond secondary spectrum access only [58]. As a result of current trends in spectrum liberalization, including the availability of licensed spectrum for real-time trading, cognitive devices may be able to access different types of spectrum for their connectivity. These types of spectrum may include: licensed spectrum (e.g. cellular bands, TV bands), unlicensed spectrum (i.e. ISM bands), as well as spectrum that is acquired in real-time, either through leasing or on a secondary basis.

The main motivation of our research lies on the above issues and aims at the provisioning of different solutions in order to maintain reliable communications between SUs preserving undisturbed at all time the activity of primary networks.

2.2 Thesis Contributions

DSA networks impose several research challenges due to the broad range of available spectrum as well as diverse QoS requirements of applications. Therefore, during our research work, we studied different architectures of this emerging paradigm in wireless communication and networking. In literature, the proposed approaches for spectrum sharing range from fully autonomous and distributed to fully centralized architectures in which dynamic access to spectrum is centrally managed. In this thesis, we present our vision in this area, and we establish different proposals enabling DSA. Furthermore, we analyzed and identified the issues and challenges of our research. Finally, we evaluated our proposals in this subject matter.

In this thesis, we present different solutions to improve the link performance and the capacity of mobile users in a secondary context while granting the unharmed activity of primary networks. Our proposals differ in the network architecture, in the network orientation and in the spectrum access technique for spectrum sharing (i.e. Overlay or Underlay). However all of them have as goal the establishment of reliable communications between SUs.

By identifying, studying, and analyzing the issues and challenges of DSA networks, we made the following contributions:

- We made an extensive analysis of existing multi-channel MAC protocols proposed to increase network throughput, to improve spectrum utilization and to reduce interference caused by secondary use of the spectrum in an opportunistic (i.e. Overlay) manner. Through this analysis, we described their access mechanisms, we made a comparison of key features of each protocol according to their principal characteristics of operation and we stated the different ways to make rendezvous for data transmission of each protocol.

- We proposed the utilization of the logical channels of GSM and UMTS to allow the transmission of a Cognitive Beacon Channel. This cognitive control channel helps to improve spectrum awareness by conveying signalization to mobile users in a multi-radio access technology environment. We compared the performance of our propositions and we showed that our approaches overcome other implementations.

- We demonstrated that existing 3GPP technologies possess the required capabilities to convey signalization with an acceptable throughput; following a centralized or a coordinated architecture in heterogeneous DSA networks.

- We also proposed the utilization of a new analytical method to be applied in the Interference Temperature model. This approach is an Underlay technique in which SUs attempt to coexist with PUs instead of avoiding primary networks' signals. Our method relies on the Poisson point process.
- Using the Poisson point process, we developed a new model to evaluate the achieved capacity of a secondary network, the interference caused to a primary network and the allowed transmission power of SUs to guarantee that activity of the PUs is not affected by their transmissions.
- Finally, by the use of Concentration Inequalities, we determined an upper bound on the outage probability of the primary network when the SUs transmit following the Ideal and the Generalized Interference Temperature models.

2.3 Thesis Overview

This thesis focuses on the improvements of link performance and capacity in DSA systems using CR technology and provides different solutions in this subject matter. The structure of this thesis is organized as follows:

- Chapter 3 provides a general introduction to DSA networks and presents the issues and challenges in such environments. Moreover, we also present existing wireless access technologies which could be the principal actors as PUs or SUs (if they are equipped with CR technology) in next generation wireless networks. Furthermore, we state the differences between the two principal techniques for spectrum sharing in DSA networks known as Overlay and Underlay. In addition, we present the possible architectures and different components that could make possible this dynamic access. Finally, in this chapter, we present specific standardization work concerning CR and DSA.
- Chapter 4 is dedicated to our first contribution. We present an overview of different multi-channel MAC protocols allowing DSA. These protocols are principally based on the IEEE 802.11 MAC mechanism. We make a comparison of key features of each protocol according to the number of transceivers, the need for synchronization, the need for a Common Control Channel (CCCH) and the different ways to make rendezvous. A detailed description of their access mechanisms is also provided. The aim of this chapter is to show how each multi-channel MAC protocol confronts the numerous problems that arise in DSA and to pinpoint the advantages and disadvantages of each protocol in order to be accurately implemented in cognitive radio networks.
- In chapter 5 an important contribution of our research work is also presented, the Cognitive Beacon Channel (CBC). In this chapter we present our proposal for the utilization of GSM logical channels (RACH, AGCH and TCH) and UMTS signaling (MIB and SIBs) of the Broadcast Channel to convey signalization to SUs in heterogeneous networks (e.g. 3GPP, Wi-Fi, WiMAX and future cognitive radio systems). We present an evaluation of our proposed CBC with regard to: the total delay to retrieve the cognitive channel, the total SUs density, the cognitive channel range and the required net bit rate. The purpose of this chapter is to demonstrate that existing

3GPP technologies can be implemented to convey signalization with an acceptable throughput in future DSA networks.

- Chapter 6 contains the last contributions of this thesis. This chapter proposes the utilization of the Poisson point process as a new analytical method to be applied in the Interference Temperature (IT) approach. In this chapter, we firstly develop a model for the RF environment. Afterwards, by the use of the Poisson point process, we determine essential elements for the calculation of the achievable per-link capacity and the total capacity of a secondary network following the Ideal and the Generalized IT models. After concluding this mathematical analysis, we demonstrate the application of our model by a numerical example in which, we consider the PUs as a UMTS network and the SUs as an UWB network. Finally, by the use of Concentration Inequalities we determine an upper bound on the outage probability of the primary network when the SUs transmit.

- Finally, chapter 7 concludes this thesis and provides an overview of the perspectives and future work in this research area.

Our list of publications and the complete bibliography are listed at the end of the document.

Chapter 3

DSA in Next Generation Wireless Networks

The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the existing users. Nevertheless, DSA networks impose several research challenges due to the broad range of available spectrum as well as diverse Quality-of-Service (QoS) requirements of applications. In this respect, we have identified a research area to contribute to the enhancement of the link performance and capacity in DSA systems using CR technology. Using CR technology, DSA techniques can allow mobile stations (MSs) to determine which portions of the spectrum are available and detect the presence of PUs when a SU operates in a licensed band. Moreover, these techniques also can be used to select the best available channel for communication.

Currently, the literature provides interesting approaches concerning DSA and CR technology in next generation wireless networks. In this chapter, we present the different architectures and components that could make possible this dynamic access. Furthermore, we also state the differences between the Overlay and the Underlay techniques for spectrum sharing. In addition, we present specific standardization work concerning CR and DSA.

The outline of this chapter is organized as follows: Section 3.1 provides an introduction to DSA in next generation wireless networks and explains the two principal approaches for the secondary use of the spectrum. Section 3.2 provides a set of standards allowing DSA inside and outside the IEEE. Finally, Section 3.3 concludes this chapter.

3.1 Dynamic Spectrum Access Networks

A goal of DSA is enabling next generation wireless networks to break the rigid spectrum access barriers imposed by the current FSA model. Moreover, it can dramatically increase the amount of spectrum accessible to the network increasing network capacity in comparison to current approaches. In addition, DSA can be designed to leave existing networks operating using the current policies of licensed spectrum unchanged, thus protecting and augmenting current infrastructure and investments [8].

The use of CR technology is the key characteristic of DSA networks. This technology provides the capability to use the spectrum in an opportunistic manner. DSA techniques and CR technology allow SUs to determine which portions of the spectrum is available and sharing the spectrum without harmful interference to PUs when SUs operate in a licensed band. Furthermore, DSA and CR technology enable SUs to select the best available channel to meet user communication requirements and coordinate access to this channel with other users. Moreover, DSA and CR technology also allow SUs to vacate the channel when a PU is detected maintaining seamless communication requirements during the transition to other spectrum band. In addition, DSA and CR technology also can provide fair spectrum scheduling methods among secondary networks presents in the same spectrum band. These are some functionalities of DSA networks that enable spectrum-aware communication protocols [3].

In this section, we present the possible architectures and components of DSA networks and we describe their basic elements. Furthermore, we present the two principal approaches of DSA: Overlay and Underlay.

3.1.1 Architectures of Dynamic Spectrum Access Networks

A number of architectures has been proposed recently for future DSA systems, ranging from fully autonomous and distributed to fully centralized architectures in which dynamic access to spectrum is managed centrally. A classification of these architectures can be described as follows:

- Distributed and autonomous DSA: These types of architectures are mainly proposed for cases where the construction of an infrastructure is not preferable. Here, each MS is responsible for the spectrum allocation and access. In this approach, a MS first senses the spectrum it wishes to use and characterizes the presence, if any, of PUs. Based on that information, and regulatory policies applicable to that spectrum, the MS identifies spectrum opportunities and transmits in a manner that avoids interfering with PUs.

- Centralized DSA: In this approach, a centralized entity controls the spectrum allocation and access procedures. With aid to these procedures, generally, a distributed sensing procedure is proposed such that each MS in the DSA network sense the spectrum it wishes to use and forward their measurements about the spectrum allocation to the central entity and this entity constructs a spectrum allocation map. Finally, the central entity indicates which portions of the spectrum can be utilized.

- Coordinated DSA: This approach is the less ambitious form of DSA. Nevertheless, as currently wireless networks are still regulated by the FSA model, this solution represents a more realistic approach to be implemented in near future. Here, dynamic access to spectrum takes place exclusively within spectrum portions reserved by regulatory authorities or spectrum owners for secondary use [45]. The access to this piece of spectrum is then managed via a central entity which permanently owns the spectrum and only grants a timebound lease to the requesters. Within the spectrum available to the central entity, certain fixed frequencies are for spectrum information channels. These channels can be used to receive request for spectrum usage and to transmit instructions on available channels.

3.1.2 Architecture Components of Dynamic Spectrum Access Networks

The architecture components of DSA networks can be classified into two groups as the primary system and the secondary system. The basic elements of these two systems are defined as follows:

The primary system or primary network can be a primary system in licensed band or a primary system in unlicensed band according to their band of operation.

The primary system in licensed band is an existing network (e.g. 3G/LTE cellular, digital TV broadcast, WiMAX, etc) that has an exclusive right to use a certain spectrum band. Therefore, unlicensed networks can neither interfere with the primary network in an intolerable way nor occupy the license band. The components of the primary system in licensed bands are as follows [3]:

- The Primary base-station or licensed base-station is a fixed infrastructure network component which has a spectrum license such as base-station transceiver system (BTS) in a cellular system. In principle, the primary base-station does not have any capability for sharing spectrum with SUs. Nevertheless, in future next generation networks the primary base-station may have both legacy and secondary protocols for the access of SUs in primary networks.

- The PU or licensed user has a license to operate in a certain spectrum band. This access can only be controlled by the primary base-station and should not be affected by the operations of any other unlicensed users. Primary users do not need any modification or additional functions for coexistence with secondary base-stations and SUs.

The primary system in unlicensed bands is a primary system operating in open or free access bands (e.g. ISM band). In this type of networks, various primary systems should use the band compatibly. Specifically, primary systems operating in the same unlicensed band shall coexist with each other while considering the interference to each other (e.g. WiFi, Bluetooth, Zigbee, etc). These primary systems may have different levels of priorities which may depend on some regulations [11].

The secondary system or secondary network doesn't have a fixed operating frequency band and it neither has privilege to access licensed nor unlicensed bands. Therefore, the spectrum access is allowed only if PUs is not affected by SUs transmissions. Hence, the secondary access could be only via DSA (i.e. using Overlay or Underlay approaches) as will be explained in the section 3.1.3. A special case appears if SUs have the same right to access the spectrum that PUs; this event could occur only in unlicensed bands. Since there are no license holders, all network entities can access the spectrum bands. In that case, users should compete with each other for the same unlicensed band. Thus, sophisticated spectrum sharing methods among users are required in this special case. Moreover, if multiple secondary network operators reside in the same unlicensed band, fair spectrum sharing among these networks is also required. In [70], we have presented an overview of several protocols, which have been proposed in literature, to overcome the aforementioned problems.

Secondary systems can be deployed both as an infrastructure network and an Ad hoc network as shown in Figure 3.1. The components of a secondary network and a brief description of each component are as follows [3]:

- The SU is the mobile user without spectrum license to operate in a certain spectrum band. Hence, additional functionalities following the Overlay or the Underlay approach are required to share the licensed spectrum band.

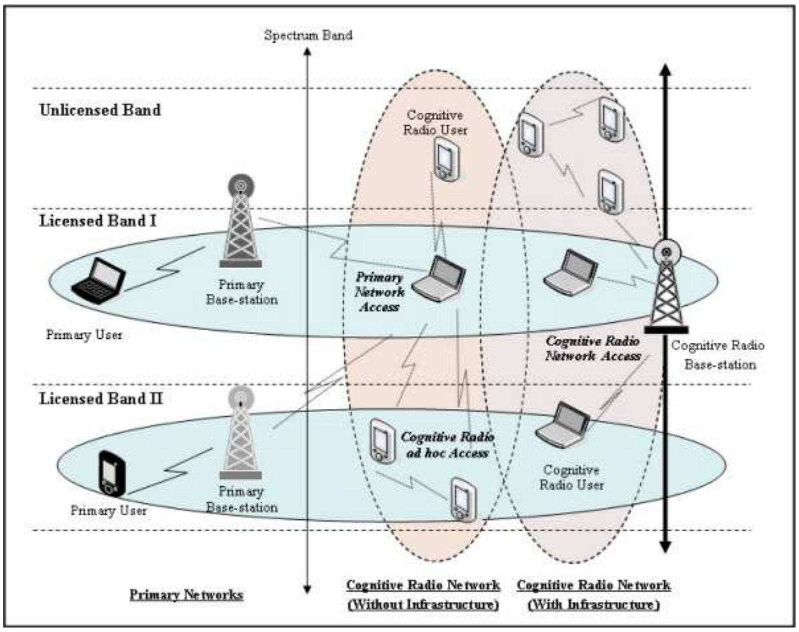

Figure 3.1: Architecture of Next Generation Wireless Networks [3]

- The Secondary base-station is a fixed infrastructure component with DSA capabilities. It provides single hop connection to SUs without spectrum access license. Through this connection, SUs can access other networks.
- The Spectrum broker or scheduling server is a central network entity that plays a role in sharing the spectrum resources among different secondary networks. The spectrum broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple secondary networks.

3.1.3 DSA Techniques in Next Generation Wireless Networks

In literature, there exist two different approaches of secondary use of spectrum in cognitive radio context. One is in the form of Overlay, which is the opportunistic usage of idle bands in the PU spectrum by cognitive radios and another in the form of Underlay, on which a MS begins transmission such that its transmit power, at a certain portion of the spectrum, is regarded as noise by PUs so avoiding interference. To achieve this, the Underlay approach imposes severe restrictions on transmitted power levels. Therefore, it requires operating over ultra wide bandwidths to achieve good performances in terms of throughput. In this section, we present the principal characteristics of these two approaches.

3.1.3.1 Overlay

The Overlay approach is an aggressive solution to increase spectrum utilization promoted by the thesis of J. Mitola in 2000 [54] and in the Spectrum Policy Task Force report of the FCC in 2002 [22]. The rules in secondary use of frequency spectrum in the Overlay approach specify that licensed users, known as PUs, have the rights to transmit and to receive without interference from other users in certain spectrum bands. Nevertheless, when these bands are free from the presence of PUs, they can be used by SUs. But as

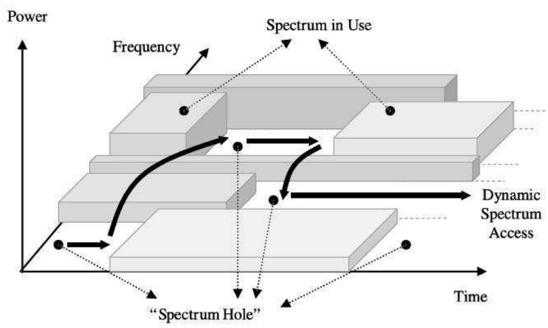

Figure 3.2: DSA using spectrum holes [3]

soon as a PU starts the activity in its channel, the SU has to leave that channel to avoid interference [75].

To achieve efficient DSA, SUs equipped with CR technology must firstly identify frequency bands currently available for transmission. This requires spectrum sensing over time, frequency and space. Therefore, the ability of the radio technology to capture or sense the information from its radio environment is the main function of cognitive radios. Once unused spectrum has been identified, SUs can access the spectrum and begin data transmissions. However, since the radio environment changes over time and space, SUs must also be capable to detect these changes and adjust its transmission parameters so that interference margin to any active PU in the vicinity is not exceeded. Any environmental change during the SU's transmission such as user movement or traffic variation can trigger this adjustment. This latter capability of adjusting operating parameters for the transmission, not only at the beginning of a transmission but also during the transmission, without any modifications on the hardware components of cognitive radios is known as *Reconfigurability* [3]. There exist several parameters that can be reconfigured in cognitive radios according to the characteristics of the available spectrum. The principal of these parameters is the frequency of operation. This characteristic allows the CR to use the most suitable frequency band to communicate and if a PU starts activity on that band, it can select another one to continue communications avoiding interference with the PU. This particular attribute in cognitive radios of being able to change the frequency of operation is known as spectrum mobility. Other examples of the reconfigurable parameters are: modulation, transmission power and communication technology.

Thus, the most important challenge for SUs in the Overlay approach is to use the spectrum portions assigned to PUs that are not being utilized at specific time and location without interfering with PUs as illustrated in Figure 3.2. These unused portions of the spectrum are known as spectrum holes or white spaces. For that reason, the Overlay approach is also known as an opportunistic approach.

3.1.3.2 Underlay

The Underlay approach is a simpler and conservative way to allow spectrum sharing compared with the Overlay approach. Underlay transmission relies on the fact that if the bandwidth is increased, reliable data transmission can occur even at power levels so low that primary radios in the same spectral bands are not affected. For this purpose a new model, which is intended to quantify and manage the sources of interference in a

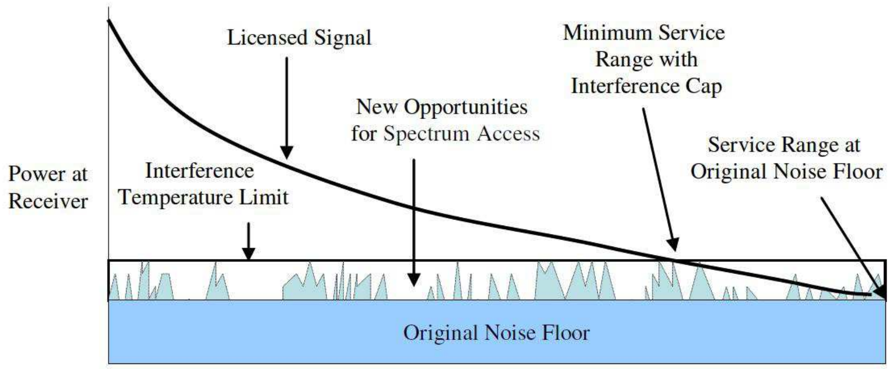

Figure 3.3: Interference Temperature model [23].

radio environment, has been introduced by the FCC [23]. This model is referred to as Interference Temperature (IT) model and is shown in Figure 3.3.

In the IT model the signal of a radio station is designed to operate in a range at which the received power approaches the level of the noise floor. However, it is possible for the noise floor to rise due to the appearance of new sources of interference, thereby causing a progressive degradation of the signal coverage at various points within the service area. This phenomenon is indicated by the peaks above the original noise floor in Figure 3.3.

Unlike the traditional transmitter-centric approach, the interference temperature model manages interference at the receiver through the interference temperature limit. This limit provides a “worst case” characterization of the RF environment in a particular frequency band and at a particular geographic location, where the receiver could be expected to operate satisfactorily [29]. As long as the SUs do not exceed this limit by their transmissions, they can use this spectrum band.

The difficulty of this receiver detection model lies in effectively measuring the interference temperature. A SU is naturally aware of its transmit power level and its precise location with the help of a positioning system. With this ability, however, its transmission could cause significant interference at a neighboring receiver on the same frequency. Thus, the most important challenge to ensure the success of this DSA technique is to find the way for a SU equipped with a CR to measure or estimate the interference temperature at nearby primary receivers. For this purpose, in [69], we have proposed the utilization of the Poisson point process as a new analytical method to be applied in the Interference Temperature model. This proposition is presented in detail in chapter 6.

Finally, is worth mentioning that while the large bandwidth required for the Underlay approach suggests high throughput, the low transmit power drastically limits transmit distances for high-rate communication, making this approach suitable only for short range applications such as WPAN or for short to medium range applications but at a lower rate (i.e., sensor networks). Figure 3.4 illustrates the Underlay and the Overlay spectrum sharing approaches that we have presented trough this section.

3.2 Standards allowing Dynamic Spectrum Access

In recent years, as showed in Figure 3.5, the increase in computational abilities of electronic devices and developments in computer science and artificial intelligence have permitted re-

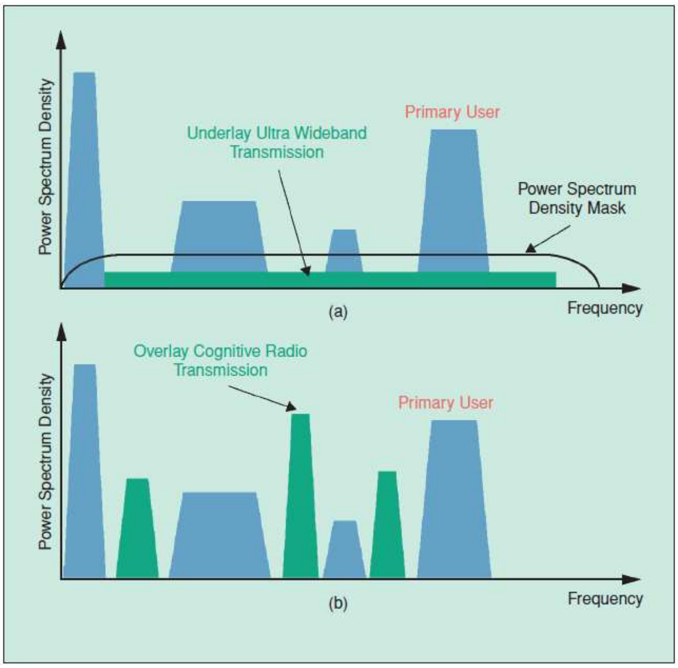

Figure 3.4: (a) Underlay and (b) Overlay spectrum sharing approaches [9].

searchers to start thinking about introducing cognitive functionalities in wireless networks and devices. These functionalities allow wireless systems to become more flexible. They also enable appropriate actions by adapting the internal parameters, after inferring from the environment, to best fulfill the needs of the user. It is expected that these cognitive enabled wireless systems will be the dominating force in combating observed scarcity of the radio spectrum. For these reasons, DSA and CR concepts are gaining momentum in academia, industry and standardization bodies. Companies like Vanu, Inc. and Shared Spectrum Company, projects like the DARPA XG, the EU E2R and now E3, the Dutch Adaptive Ad Hoc Free Band Wireless Communications (AAF) project, and research groups in numerous universities are focusing on DSA and CR [62]. Growing interest in CR was also demonstrated by the start in 2005 of the IEEE Communications Society Technical Committee on Cognitive Networks [40]. Therefore, due to the importance of DSA and CR, standardization bodies such as the IEEE, the ITU-R and the ETSI among others, have continued working on standards related specifically to Dynamic Spectrum Access, cognitive and opportunist radio. The common objective of these standards is in all cases to improve the use of spectrum.

3.2.1 DSA and Cognitive Radio Standardization inside the IEEE

In this section we provide an overview of the goals, structure, and roadmap of the IEEE standards based on CR technologies allowing DSA.

3.2.1.1 IEEE SCC41 formerly (IEEE P1900)

In 2004, the IEEE initiated a set of standardization projects related to CR called IEEE P1900. The IEEE P1900 Standards Committee was established in the first quarter 2005 jointly by the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic

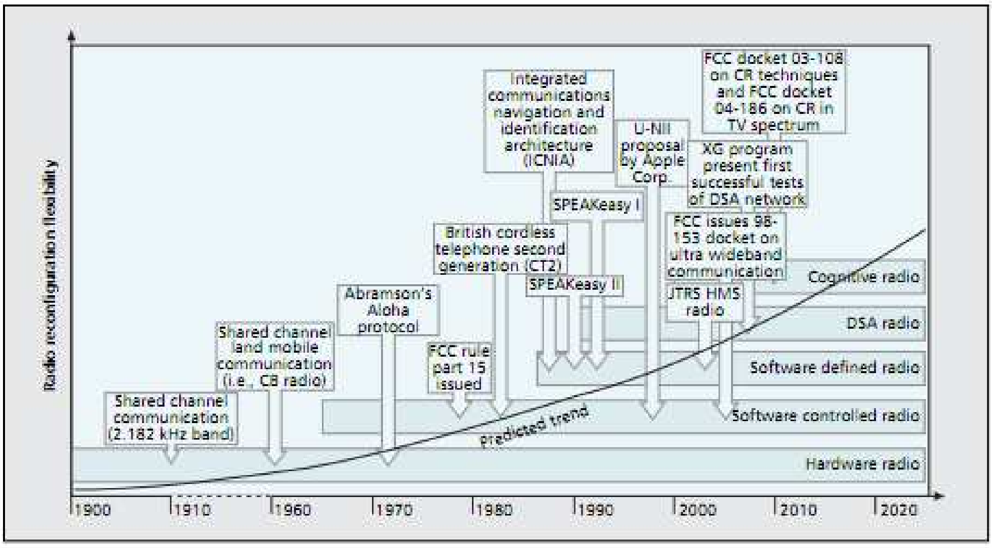

Figure 3.5: History of CR-like systems, with a view of the future [62].

Compatibility (EMC) Society. The IEEE P1900 evolved in 2006 into IEEE Standards Coordinating Committee 41 (IEEE SCC41), Dynamic Spectrum Access Networks (DySPAN). The work of the IEEE P1900.x Working Groups continues under IEEE SCC41 [39].

The objective of the IEEE SCC41 is to develop supporting standards related to cognitive and opportunist radio, and more precisely on dynamic spectrum access networks. Their focus is on improved use of spectrum, control the interference level, and optimize the coordination of different wireless technologies including network management and information sharing [27]. Now the IEEE SCC41 has become the premier forum for standardizing concepts related to CR.

IEEE SCC41 is divided into six working groups (WGs), each responsible for evolving standardization processes for different aspects of CR and DSA. The WGs are identified as IEEE 1900.x, where .x represents one of the WGs [39]:

IEEE 1900.1 “Working Group on Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management”.

The 1900.1 WG is responsible for providing definitions of important terms and concepts of CR and related technologies for dynamic spectrum access. It further describes how these technologies relate to each other and create new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms. The key idea is to standardize and explain technically precise definitions related to CR and DSA.

IEEE 1900.2 “Working Group on Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence between Radio Systems”.

The mandate of the IEEE 1900.2 WG is to provide technical guidelines for the interference analysis criteria and establish a framework for measuring and analyzing the interference between radio systems. This WG intends to establish a common standard platform for coexistence or in contrast interference between radio systems operating in the same frequency band or between different frequency bands.

IEEE 1900.3 “Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules".

The aim of the IEEE 1900.3 is to define a set of recommendations by using formal mathematical concepts and methods that help in assuring the coexistence and compliance of the software modules of CR devices before proceeding toward validation and certification of the final devices. According to [39], the IEEE 1900.3 WG was dismantled in 2008.

IEEE 1900.4 "Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks"

From April 2009, 1900.4 Working Group works on two projects [39]:

- IEEE 1900.4a: Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks - Amendment: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands.
- IEEE 1900.4.1: Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks

The IEEE 1900.4 WG is responsible for defining the overall system architecture, splitting the functionality between terminals and the network and also the information exchange between coordinating entities. Its main goal is to increase the overall system utilization of reconfigurable terminals while increasing the perceived QoS.

All IEEE 1900.4 enabled devices should operate in an opportunistic and dynamic manner such that they will not degrade the performance of primary radio access devices. The study of heterogeneity in wireless access technologies and multi-homing of the devices (with CR capability) differentiates this WG from other WGs of SCC41. The first task of the IEEE 1900.4 WG is to focus into the architectural and functional definitions. Three use cases are addressed by the IEEE 1900.4-2009 architecture:

- Dynamic Spectrum Assignment: frequencies are dynamically assigned to Radio Access Networks (RAN).
- Dynamic Spectrum Sharing: frequency bands assigned to RANs are fixed but a given band is potentially shared between several RANs.
- Dynamic Radio Resource Usage Optimization: terminals choose, in a distributed manner, which radio access technology/technologies (RATs) to connect to.

An example of the important work that is ongoing within the SCC41 is illustrated in Figure 3.6. This figure shows the SCC41 concept of operations that enable spectrum management between cognitive and non-cognitive RANs. The network reconfiguration management (NRM) functions communicate with the terminal reconfiguration management (TRM) function to provide interoperability between different wireless network environments. The radio enabler part simply provides the link between the NRM and TRMs. The dynamic spectrum access and management of these environments include distributed decision-making via policies for each network [67].

IEEE 1900.5 "Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications".

Started in August 2008, the purpose of the IEEE 1900.5 WG is to define a set of policy languages and their relation to policy architectures for managing the features of

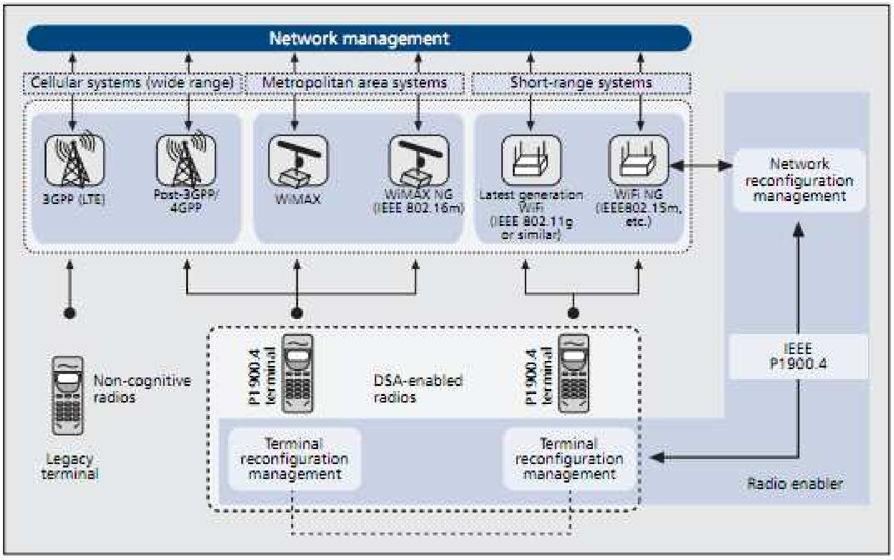

Figure 3.6: The P1900.4 concept of operations where terminals use CR techniques to operate across a variety of existing network infrastructures and maintain seamless connectivity [67].

CR for DSA applications. The initial work will concentrate on standardizing the features necessary for a policy language to be bound to one or more policy architectures to specify and orchestrate the functionality and behavior of cognitive radio features for dynamic spectrum access applications; future additional tasks will build on this foundation to standardize how this is done in greater detail, paying special attention to interoperability concerns.

IEEE 1900.6 "Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems". This WG, also started in August 2008 will define the information exchange between spectrum sensors and their clients in radio communication systems. This group develops a standard that defines the interfaces and data structures required for exchange of sensing related information. The resulting standard will provide a formal definition of data structures and interfaces for exchange of sensing related information.

3.2.1.2 IEEE 802.22

The IEEE 802.22 WG was formed in 2004. This standard specifies the air interface including the MAC and physical layer of point-to-multipoint wireless regional area networks (WRAN) based on CR technology. The IEEE 802.22 WG intended to enable the deployment of a CR-based WRAN for use by unlicensed devices or SUs, in the spectrum that is currently allocated to the TV service. It uses unoccupied TV channels in the VHF/UHF broadcast bands, these known as TV White-spaces, between 54 MHz and 862 MHz depending on the region of operation [38].

There is a large market for broadband wireless access in rural and other non-served/ underserved areas where wired infrastructure cannot be economically deployed. Products based on the IEEE 802.22 standard will be able to serve those markets and increase the efficiency of spectrum utilization in spectrum currently allocated to, but unused by, the

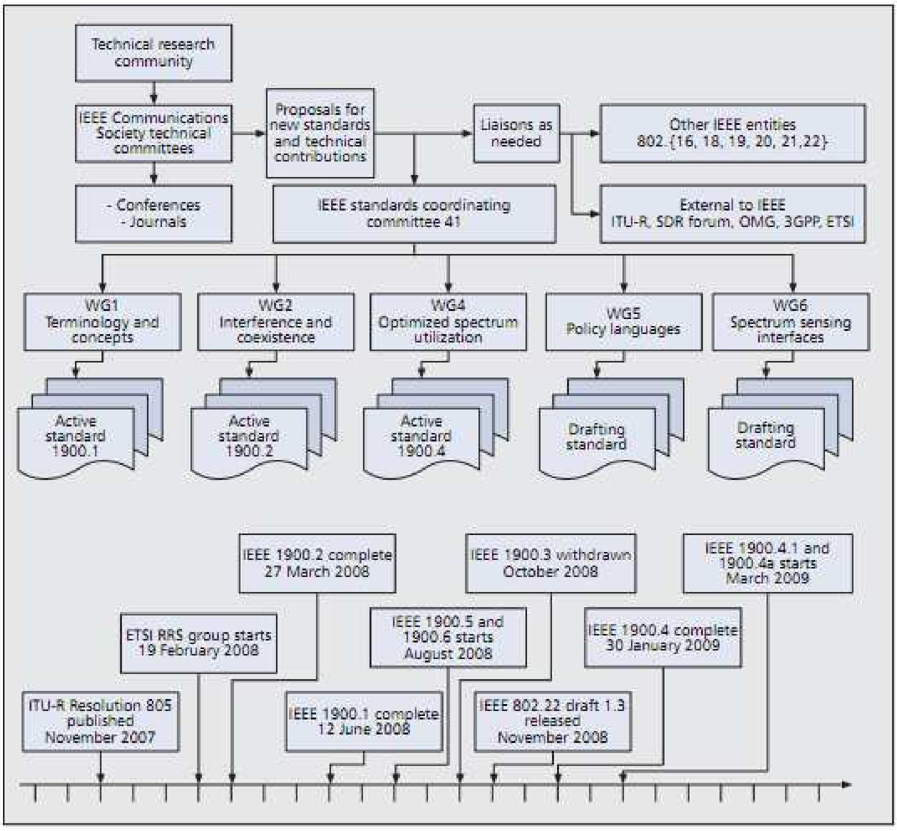

Figure 3.7: CR standardization: (top) IEEE SCC41 organization structure and its relationship with other standardization entities; (bottom) time line of important standardization projects related to CR [27].

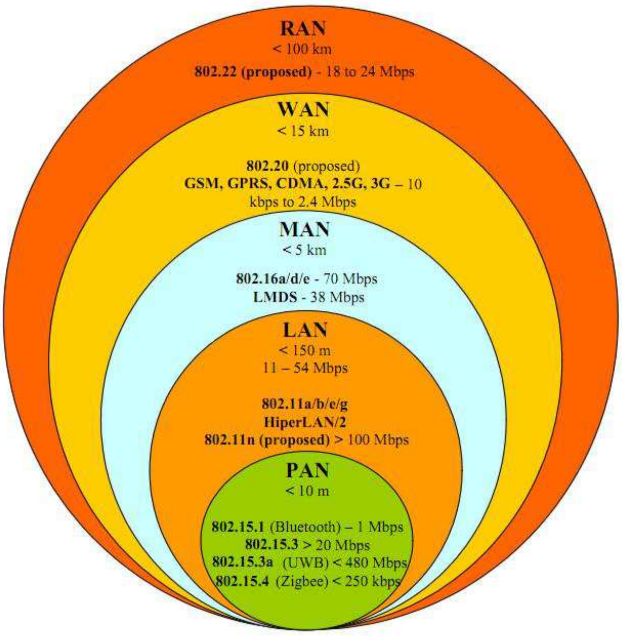

Figure 3.8: IEEE 802.22 wireless RAN classification as compared to other popular wireless standards [15].

TV broadcast service. Based on these facts, the TV band Notice of Proposed Rule Making (NPRM) [24] was the natural next step taken by the FCC. This NPRM, released in May of 2004, proposes to allow SUs to operate in the TV broadcast bands provided no harmful interference is caused to licensed or primary users PUs, in this case TV receivers [15].

The goal of IEEE 802.22 is to define an international standard that may operate in any regulatory regime. Therefore, the current IEEE 802.22 project shall accommodate the various international TV channel bandwidths of 6, 7, and 8 MHz. Nevertheless, at the present time, the major push towards the commercial deployment of CRs is coming mostly from the US.

IEEE 802.22 devices are composed of base stations (BSs) and consumer premise equipments (CPEs). The operations of BS/CPEs can be divided into two major categories: sensing and transmitting/receiving data. Sensing and avoiding PUs transmission is the prioritized task of all IEEE 802.22 enabled devices. If any of the channels used by IEEE 802.22 network is occupied by PUs, IEEE 802.22 devices must vacate the channels and switch to some other unused channel. Therefore, in addition to the traditional role of the BSs, IEEE 802.22 BSs also are in charge of performing distributed sensing to detect the presence of PUs and their used channels. In this standard, the BSs, instruct the various CPEs to perform distributed measurement on different TV channels. Based on the feedback received, the BS decides which of the channels are free to be used [38].

The IEEE 802.22 system specifies spectral efficiencies in the range of 0.5 bps/Hz up to 5 bps/Hz. If an average of 3 bps/Hz is considered, this would correspond to a total PHY data rate of 18 Mbps in a 6 MHz TV channel. The minimum data rate of the system is 1.5 Mb/s in the DL and 384 kbps in UL, which is comparable to DSL services. It is expected that a BS supports up to 255 CPEs. With regard to the BS coverage range, this is another distinctive feature of 802.22 WRAN as compared to existing IEEE 802 standards, which can go up to 100 Km if power is not an issue (current specified coverage range is 33 Km at 4 Watts CPE EIRP). WRANs have a much larger coverage range than today's wireless networks, due to its higher power and the favorable propagation characteristics of TV frequency bands [15].

The physical layer of IEEE 802.22 is close to IEEE 802.16e and based on OFDMA scheme in TDD mode. However, FDD mode is expected to be supported in the future. The digital modulation types used in this standard are QPSK, 16-QAM, and 64-QAM.

The MAC layer will be based in DSA using CR technology [38]. This is because the spectrum access needs to be highly dynamic in order to respond quickly to changes in the operating environment.

In IEEE 802.22, there is a dependency on a centralized BS. Therefore, network entry is a straightforward process in existing MAC protocols. Nevertheless, this is not the case for DSA networks, since there is no predetermined channel that a CPE may use to look for a BS. The current IEEE 802.22 standard addresses this problem by having a CPE scan all frequency channels when it starts up and then sending their occupancy information (i.e. whether PUs have been detected or not). However, the above described operation of IEEE 802.22 is incapable of preventing the hidden terminal problem, which arises when there is a PU near the CPE but outside the sensing region of the BS, operating in the same frequency as the broadcasting frequency of the BS. As the BS continues its transmission, it interferes with the PU and the CPE cannot inform the BS of the existence of the PU due to the interference generated by the PU over the CPE (i.e. CPE may even become unable to decode the broadcasting frequency of the BS). Moreover, the CPE is not allowed choose any other channel to connect to the BS, unless the BS provides the permission. In this case, the CPE might think that there is no BS transmitting at that time and might switch off, and the BS might also think that there is no CPE and stop broadcasting after some time, which results in low spectrum utilization [26]. To alleviate this problem several Multi-channel MAC protocols for DSA have been proposed in literature [70].

Figure 3.9 shows the proposed protocol referenced model (PRM) for a CR node that is likely to be adopted by the IEEE 802.22 WG. Definition of an appropriate PRM is important because it defines the system architecture, functionalities of various blocks, and their mutual interactions. The proposed PRM separates the system into the cognitive, data/control, and management planes. The data/control and management planes (non-cognitive components) look similar to other standards within the IEEE. The spectrum-sensing function (SSF) and geolocation function that interface with the RF stage of the device provide information to the spectrum manager (SM) on the presence of incumbent signals, as well as its current location. The SM function makes decisions on transmission of the information-bearing signals. The SM at the subscriber location is called the spectrum automaton (SA), because it is assumed that almost all of the intelligence and the decision-making capability will reside at the SM of the base station. The PHY, MAC, and convergence layers are essentially the same as in 802.16. Security sub-layers are added between service access points (SAPs) to provide enhanced protection [67].

3.2.1.3 Other IEEE 802 standards with CR capabilities

Although IEEE SCC 41 and IEEE 802.22 are the primary cognitive standards efforts today, many completed IEEE 802 standards already include CR/DSA-like capabilities or related building blocks [67].

The IEEE 802.15 group of WPAN working in the license exempt bands (2.4 GHz) was

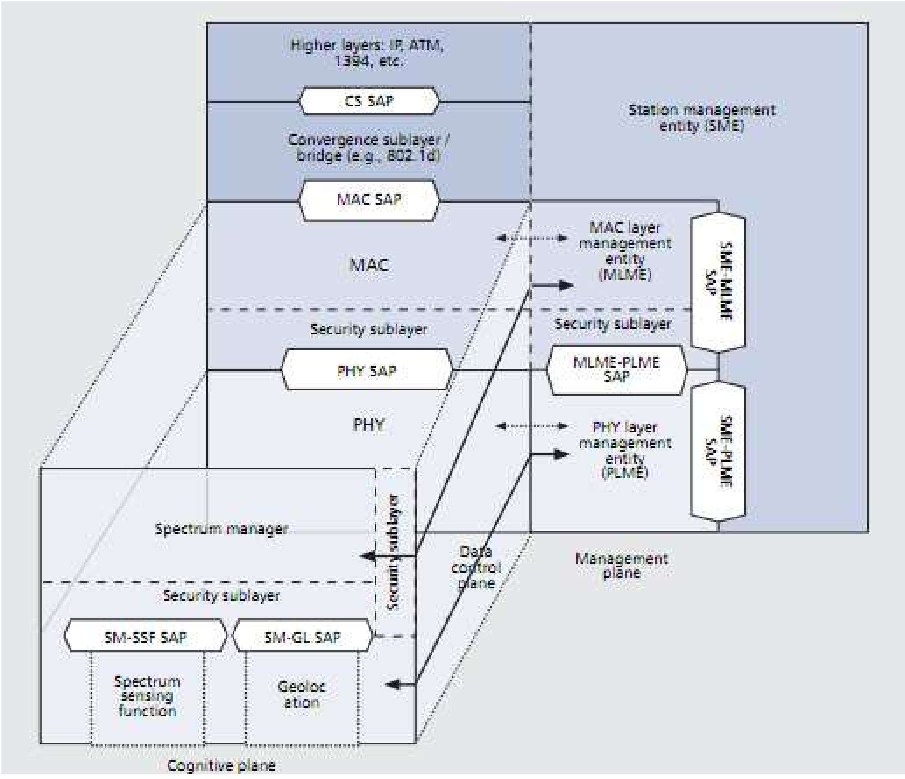

Figure 3.9: A cognitive radio interface diagram for the IEEE 802.22 standard [67].

one of the first standards to confront coexistence issues. These include IEEE 802.15.2-2003, which describes general coexistence guidelines and IEEE 802.15.4-2003, which describes dynamic channel selection mechanisms [27]. Many of the IEEE 802.15 protocols were required to share the same unlicensed band utilized by the IEEE 802.11 standard. Systems implementing the IEEE 802.15 protocols generally are unable to communicate with systems implementing IEEE 802.11 protocols. Rather, they simply interfere with each other.

Specifically, the IEEE 802.15.2-2003 Task Group provides recommended practices for coexistence of IEEE 802.15 WPAN with other selected wireless devices operating in unlicensed frequency bands. IEEE 802.15.2-2003 also contains a collection of collaborative and non-collaborative techniques for the IEEE 802.11-1999 edition devices to facilitate coexistence with IEEE 802.15 devices operating in unlicensed frequency bands, and suggests modifications to other IEEE 802.15 standards to enhance coexistence with other selected wireless devices operating in unlicensed frequency bands.

On the other hand, the IEEE 802.15.4-2003 Task Group defines the protocol and interconnection of devices via radio communication in a personal area network. The standard uses carrier sense multiple access with a collision avoidance medium access mechanism and supports star as well as peer-to-peer topologies. It includes dynamic channel selection (DCS) and operates at low power, among other techniques, to support coexistence with other wireless devices [67].

Coexistence mechanisms are also included in IEEE 802.11 standards: IEEE 802.11-2007 and IEEE 802.11y-2008.

The IEEE 802.11-2007 provides mechanisms for dynamic frequency selection (DFS)

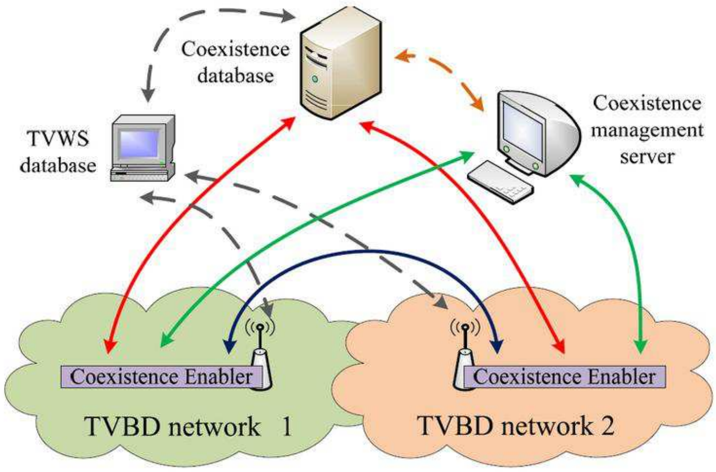

Figure 3.10: Proposed IEEE 802.19 architecture to enable coexistence [64].

and transmit power control (TPC) that may be used to satisfy regulatory requirements for coexistence between systems. These features deal with the fact that other systems (such as military radars) may operate in the unlicensed national information infrastructure (UNII) bands (5GHz) and require protection. The DFS features developed for IEEE 802.11 allow for the detection of military radar and the relocation of a potentially interfering IEEE 802.11 basic service set (BSS) to another frequency. The techniques were developed initially for IEEE 802.11h [27].

The IEEE 802.11y-2008 is an extension of IEEE 802.11 to the 3650-3700 MHz frequency range, which is shared with satellite Earth stations in the U.S. It standardizes the mechanisms required to allow shared 802.11 operations with other users. Likely required mechanisms include: specification of new regulatory classes (extending 802.11j), sensing of other transmitters (extending 802.11a), transmit power control (extending 802.11h), dynamic frequency selection (extending 802.11h) [67].

The IEEE 802.19 is the Wireless Coexistence Working Group within IEEE 802. The IEEE 802.19 was created, based on the successes of 802.15.2. This standard specifies radio technology independent methods for coexistence among dissimilar or independently operated TV Band Device (TVBD) networks and dissimilar TV Band Devices [37]. When completed, these methods will be useful for cognitive systems, especially the ones which are going to operate in the TV White Spaces. Various deployment options to facilitate coexistence are being considered, where a separate TV White Space (TVWS) database would be maintained in each case, which communicates with the Coexistence Enabler for each TVBD network. In one of the deployment option considered, a separate coexistence database and a coexistence management server (or simply the coexistence manager) is also introduced, which aid the coexistence enablers and TVWS database to decide which white space to allot to which TVBD network. This system architecture supports both centralized and distributed decision making [64]. Currently, the IEEE 802.19 technical advisory group is evaluating coexistence between IEEE 802.11y and IEEE 802.16h [27].

The IEEE 802.16 group has its own set of standards that support CR-like functionalities. The IEEE 802.16a-2003, as an amendment to IEEE 802.16-2001 described the operation of the wireless MAN interface of broadband wireless access (BWA) networks in unlicensed bands. It also discussed interference analysis and coexistence issues for BWA networks in these bands. The IEEE 802.16.2-2004, which superseded the IEEE 802.16.2-2001, describes engineering practices to mitigate interference in BWA systems. This document explained methods of efficient coexistence of multiple BWA systems. Also in 2004, the IEEE 802.16h was started to consider improved coexistence mechanisms (as policies and medium access control enhancements) to enable coexistence among license-exempt systems based on IEEE standard 802.16 and to facilitate the coexistence of such systems with primary users The resulting standard likely will include cognitive capabilities and mechanisms that can be broadly applicable in many systems. Finally, the IEEE 802.16m provides an advanced air interface for operation in licensed bands. It will meet the cellular layer requirements of IMT-advanced next-generation mobile networks while providing continuing support for legacy Wireless MAN-OFDMA equipment. It is possible cognitive technology may be introduced in this amendment [67].

3.2.2 DSA and Cognitive Radio Standardization outside the IEEE

Even if the IEEE is the most important standardization body, it is also important to look at other standardization efforts outside the IEEE. Therefore this section provides a brief description of such standards.

3.2.2.1 ITU-R Activities Related to CR

Standardization bodies outside of IEEE are also working on their own sets of standards related to CR, and ITU-R is particularly active. Studies on SDR and CR Systems were initiated at the World Radiocommunication Conference held in 2007 (WRC-07) through Resolution 956: "Regulatory measures and their relevance to enable the introduction of software-defined radio and cognitive radio systems. In the CR implementation domain, in 2007 ITU-R published ITU-R Report M.2117, "Software Defined Radio in the Land Mobile, Amateur, and Amateur Satellite Services". In Resolution 951: "Enhancing the International Spectrum Regulatory Framework", ITU-R concluded "that evolving and emerging radio communication technologies may enable sharing possibilities and may lead to more frequency-agile and interference tolerant equipment and consequently to more flexible use of spectrum". After then Study Group 1, Working Part 1B "Spectrum management methodologies and economic strategies" has been assigned to be the lead organizational entity within ITU-R in WRC-11. ITU-R works on a longer timescales than many other bodies, thus the studies initiated at the WRC-07 typically ends in results presented at the next WRC in 2012 [64].

ITU-R Study Group 5 (Mobile, Radio Determination, Amateur, and Related Satellite Services) Working Party 5A is developing a draft new ITU-R report on "Cognitive radio systems in the land mobile service" is being developed including descriptions of applications of cognitive radio systems and possible deployment scenarios. The latest version dates from December 2009. The draft report is a comprehensive document and seems to address all possible aspects from CR techniques to co-existence issues. The work on CR in Study Group 5 is also involving WP 5D "IMT Systems" where the work on another draft new ITU-R report on "Cognitive Radio Systems Specific to IMT Systems" has just started. The first version dates from March 2010. The scope of this work is to consider the inclusion of CR systems into the IMT family of technologies [27].

3.2.2.2 ETSI Standards Related to CR

In February 2008 ETSI started a new technical committee on reconfigurable radio systems (RRS), with liaison with IEEE SCC41 and SDR Forum. The RRS has the responsibility for standardization activities related to Reconfigurable Radio Systems encompassing system solutions related SDR and CR, to collect and define the related Reconfigurable Radio Systems requirements from relevant stakeholders and to identify gaps, where existing ETSI standards do not fulfil the requirements, and suggest further standardization activities to fill those gaps [21].

RRS has four groups: WG1 (System Aspects), WG2 (Radio Equipment Architecture), WG3 (Functional Architecture for Cognitive Pilot Channel), and WG4 (Public Safety). WG1 issued two drafts related to technical recommendations: DTR/RRS-01002, “Cognitive Radio System Concept”, and DTR/RRS-01003, “Spectrum Aspects of Cognitive Radio and Software Defined Radio Systems”. WG2 issued three documents: one complete technical recommendation, TR 102 680, “SDR Reference Architecture for Mobile Device”, and two draft recommendations, DTR/RRS-02003, “Radio Base Station Software Defined Radio Status, Implementations and Costs Aspects, Including Future Possibilities”, and DTR/RRS-02004, “Multiradio Interface for Software Defined Radio Mobile Device Architecture and Services”. WG3 published two draft recommendations, DTR/RRS-03004, “Functional Architecture”, and DTR/RRS-03007, “Cognitive Pilot Channel Design”. Finally, WG4 issued two draft recommendations: DTR/RRS- 04005, “System Aspects for Public Safety”, and DTR/RRS-04006, “User Requirements for Public Safety” [27].

In the beginning of 2010, ETSI RRS created several interesting work items such as: “Operation in White Space Frequency Bands”, “Coexistence Architecture for Cognitive Radio Networks on White Space Frequency Bands” and “Use Cases for RRS operating in licensed spectrum”. As a next step after having progressed with the work on use cases and architecture, ETSI RRS plans to create new work items on Cognitive Management and Control mechanism, e.g. to work on communication mechanisms for coordination of network elements. Such a work may be based on earlier work on the Cognitive Pilot Channel (CPC) and the Cognitive Control Radio (CCR) and may include mechanisms to exchange spectrum sensing information [64]. With regard to the CPC, in [71] another implementation of a cognitive control channel named, Cognitive Beacon Channel (CBC) is presented. Using the CBC, the network can take advantage of existing 3GPP technologies to assist MSs in the process of DSA and in reconfiguration procedures. This proposition is presented in detail in chapter 5.

3.2.2.3 Software Defined Radio Forum Activities

The SDR Forum is also involved in several activities related to CRs, CNs, and DSA. The operation plan from January 2009 described the following activities [27]:

- The CR WG is initiating preparation of a literature survey to identify and present quantifiable metrics that objectively measure the benefits of CR technology. Initial work on this report was expected to conclude in 2009.

- The group Test Guidelines and Requirements for Secondary Spectrum Access of Unused TV Spectrum will aim at use cases and test requirements for the use of CR techniques to allow unlicensed secondary spectrum access for unused TV bands.

- A "Test and Measurement of Unique Features for Software-Defined/Cognitive Radios" report is being prepared by the Test and Measurement Task Group to identify the unique test challenges created by systems with SDR/CR features and propose solutions in such a framework.
- The CR Market Study will represent a market study focused on CR and white space communications.

Apart from this, in the course of 2009 and 2010, the SDR Forum will aim at projects related to different topics such as certification of CR technologies, CR architecture recommendations, design processes and tools, and a hardware abstraction layer for CR.

3.2.2.4 3GPP Activities Related to CR

3GPP is also interested in standardizing CR-like features in its future releases. In particular, 3GPP plans to enhance LTE standard in Release 10 with CR functionalities. For example the idea of a cognitive reference signal is proposed through which each radio access network can broadcast the interference level, frequency bands, and radio access technologies of other networks, and other information that can help newly joined user equipment to choose the best radio access network [27].

3.2.2.5 Object Management Group Activities Related to CR

The Object Management Group (OMG) is an international, open membership, not-for-profit computer industry consortium. The OMG is also involved in activities related to next generation radio systems, with the Software Radio Special Interest Group and Software Based Communication (SBC) Domain Task Force (DTF). The mission of the SBC DTF is the development of specifications supporting the development, deployment, operation, and maintenance of software technology targeted to software defined communication devices. Some of the goals of the SBC DTF are related to the use of Unified Modeling Language (UML) and model drives development technology for SDR, interoperability and exchangeability of software defined components, and, in general, attempts to broaden the scope to new related technologies such as: CR, smart antennae, streaming components, digital IF, spectrum management [59].

3.3 Conclusions

In this chapter we explored the new paradigm of dynamic spectrum access, a technology which is expected to have a profound impact on the architecture of next generation wireless systems. DSA networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the secondary use of the spectrum. Along this chapter, we have introduced proposed methods, properties and current research challenges of future DSA networks using CR technology. Nevertheless, the Overlay and Underlay sharing strategies, which have been discussed here, represent only the first steps towards implementing such systems. Moreover, in this chapter were introduced the efforts and the operational domain of standardization working groups inside and outside the IEEE that are focused on DSA and CR. As noted in [27], standardization on DSA and CR should support a proper balance among technology, policy and business. However, to support this balance, standardization bodies need to work together in order to facilitate the interaction between the standards development process and the research community on DSA and CR technology.

DSA networks raise several technical, business, and network-related challenges. Many researchers are currently engaged in developing the communication technologies and protocols required for the implementation of these CR networks. However, to ensure efficient spectrum-aware communication, more research is needed along the lines introduced in this chapter.

Our research considers different approaches of DSA using CR technologies as a path towards a world where next generation wireless networks are capable of interacting and providing uninterrupted services to mobile users in a secondary user context. Thus, combining existing wireless technologies and interesting concepts such as spectrum sensing, spectrum management, spectrum mobility and spectrum access, we consider that reliable communications between secondary users are possible without interfering with primary networks.

Chapter 4

DSA via Multi-Channel MAC Protocols

Multi-channel MAC protocols have been proposed to improve spectrum utilization and to increase network throughput by allowing multiple transmissions in a set of frequency channels. The purpose of these multi-channel MAC protocols is to enhance the overall performance of Wi-Fi like protocols (using IEEE 802.11 based mechanisms) with DCF as MAC technique. However, this technique was not designed to work in a multi-channel environment.

In this chapter, we present an overview of different multi-channel MAC protocols; we describe their access mechanisms and we make a comparison of key features of each protocol according to the number of transceivers (TRx), the need for synchronization, the need for a CCCH (Common Control Channel) and the different ways to make rendezvous. The aim of this chapter is to show how each multi-channel MAC protocol confronts the numerous problems that arise in DSA.

The outline of this chapter is organized as follows: Section 4.1 provides an introduction of some issues of dynamic access that appear in distributed Ad-hoc networks. In section 4.2 we present an extensive analysis of different multi-channel MAC protocols allowing DSA in an opportunistic (i.e. Overlay) manner. Section 4.3 summarizes the different key features of the presented multi-channel MAC protocols. Finally, Section 4.4 concludes this chapter.

4.1 DSA Issues in Distributed Ad-hoc Networks

In distributed Ad-hoc networks, to obtain the necessary parameters for spectrum access, a MS has to scan the entire spectrum looking for occupancy information. Many researchers have proposed different multi-channel MAC protocols to increase network throughput, to improve spectrum utilization and to reduce interference caused by secondary use of the spectrum. Many of these studies consider Wi-Fi like protocols (or IEEE 802.11 based mechanism).

The physical layer of IEEE 802.11b is divided into 11 channels for the FCC or North American domain and 13 channels for the ETSI or European domain; these channels are located 5 MHz apart in frequency and each one has an overall channel bandwidth of 22 MHz [13] [36]. To be non-overlapping (or orthogonal), these channels must be located 25 MHz apart. Thus channels 1, 6 and 11 can be used simultaneously without interference

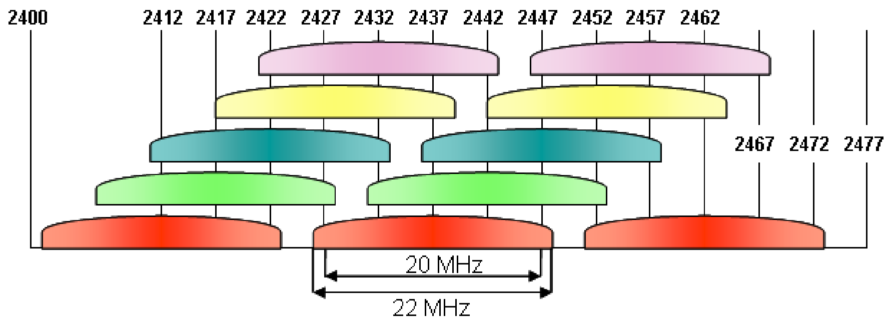

Figure 4.1: IEEE 802.11b channelization scheme (figure inspired from [13])

[68].

As we stated before, a CR is an intelligent communication device, capable of adapting its transmission parameters (i.e. frequency channel, modulation and power) based on the interaction with its environment. Nevertheless, common MAC protocols do not provide, in general, mechanisms for channel switching. The IEEE 802.11 standard uses a DCF as medium access technique. However, the DCF, which employs carrier sense multiple access with collision avoidance, was not designed to work in a multi-channel environment [68]. Therefore, when there are multiple independent channels that can be used simultaneously, the need for enhanced multi-channel MAC protocols that allow DSA becomes paramount.

4.1.1 Rendezvous in Multi-Channel Protocols

In multi-channel MAC protocols, MSs exchange control information to concur on the channel for data transmission in the user plane. This process is known as "*Rendezvous*". Proposed protocols vary in how MSs negotiate the channels to be used for data transmission and the way to solve medium contention. These protocols can be divided into two groups according to their principle of operation, these groups are: single rendezvous and multiple rendezvous protocols.

In single rendezvous protocols, the rendezvous between a sender and its receiver can take place on at most one channel at any time. On the other hand, in multiple rendezvous protocols several rendezvous can take place in different channels simultaneously, thereby mitigating the control channel congestion.

4.1.2 Hidden Terminal Problem

One of the principal problems in wireless networking is the Hidden Terminal Problem. Hidden nodes in a wireless network refer to nodes that are out of range of other nodes or a collection of nodes. In this section, we describe this problem in a single and in a multiple channel environment.

4.1.2.1 Hidden Terminal Problem in a Single Channel Environment

In a single channel environment, the hidden terminal problem occurs when MSs cannot detect signal from other MSs by carrier sensing because they do not have a physical connection to each other. Figure 4.2 illustrates this problem: MS "A" sends a message to MS "B"; "C" cannot detect the signal from "A" since "C" is out of range of "A". So for

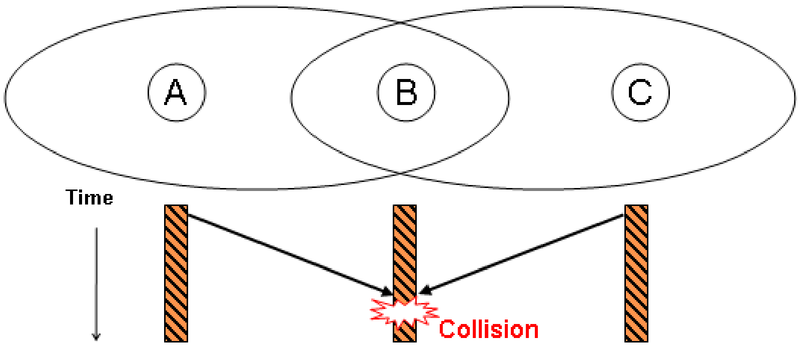

Figure 4.2: Single-Channel Hidden Terminal Problem.

station “C”, the channel is idle. When MS “C” sends a message to “B”, this message will collide at “B” with the message sent from “A”. In this scenario “C” is the hidden node to “A”.

4.1.2.2 Virtual Carrier Sensing using RTS/CTS Exchange

To deal with the above problem, the IEEE 802.11 MAC layer uses the DCF mechanism, which employs virtual carrier sensing to solve the hidden terminal problem by using the RTS/CTS exchanging mechanism. In this procedure, when a mobile station wants to initiate communication, it first sends a RTS (Request-To-Send) message and the receiver replies by sending a CTS (Clear-To-Send). The RTS and the CTS contains the NAV (Network Allocation Vector), which is the expected duration of time that other MSs around the communication pair must refrain from sending data to avoid collisions.

This procedure can solve the hidden terminal problem in a single channel environment, under the assumption that all MSs have the same transmission range. However, as we'll see in the next section, the DCF mechanism cannot work well in a multi-channel environment.

4.1.2.3 Multi-Channel Hidden Terminal Problem

In multi-channel environments, the Multi-Channel Hidden Terminal Problem (MCHTP) occurs when MSs in the network listen to different channels and so miss the RTS/CTS procedure of neighbors. The MCHTP is illustrated in Figure 4.3 inspired from [68]. Initially, MS “A” wants to communicate with “B”, so “A” sends an ATIM RTS (A-RTS) which includes the data channel selection to “B” on the CCCH (Channel 0). After receiving the A-RTS, MS “B” selects the Channel 3 to communicate with “A” and sends back an A-CTS, notifying their neighbors that the data channel number 3 has been selected. In a single channel environment the RTS/CTS exchange avoids collisions in the transmission ranges of “A” and “B”. However, in a multi-channel environment other MSs could be involved in communication on different channels while the A-RTS/A-CTS procedure is taking place. That is the case of MSs “C” and “D”, as they are communicating in channel 2 they do not hear the A-CTS sent by “B”. When they finish their communication on Channel 2, MSs “C” and “D” switch to Channel 0 and now they select Channel 3 to reinitiate communication. When MS “C” sends the first message to “D”, this message will cause collision to MS “B” on Channel 3.

One possible solution would be a unique channel or moment to which every MS in the

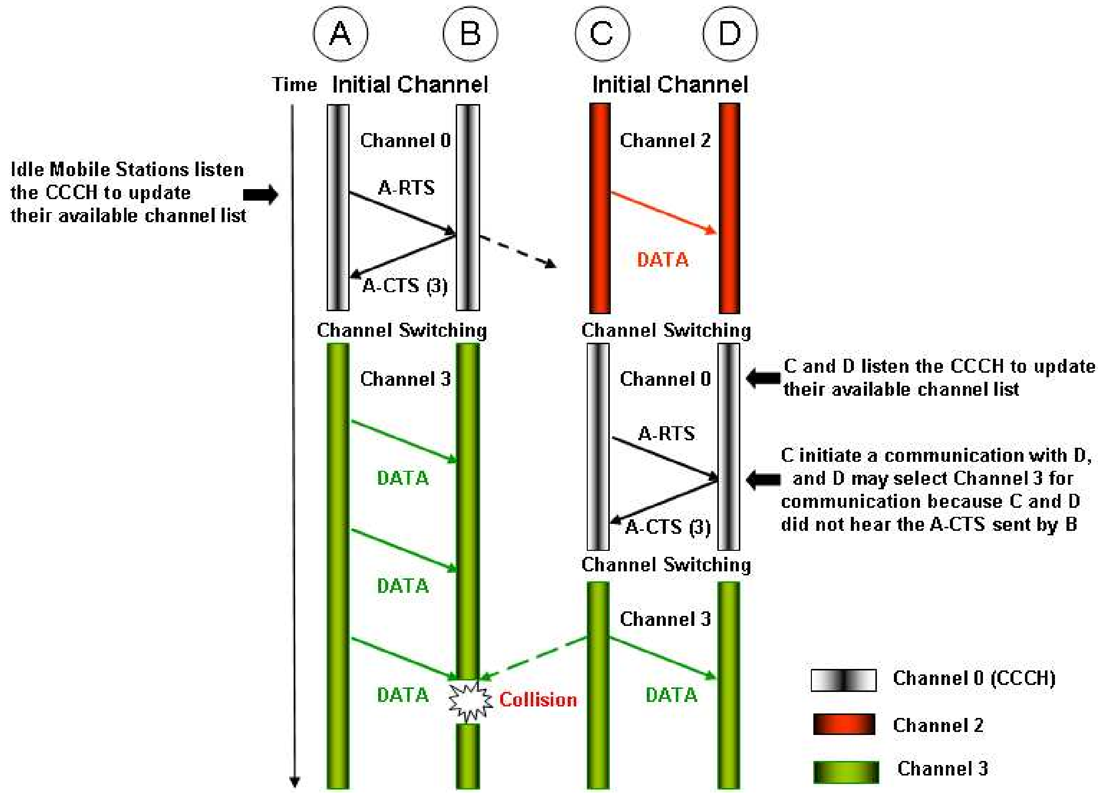

Figure 4.3: Multi-Channel Hidden Terminal Problem.

network listens. This ensures that the A-RTS/A-CTS procedure can be heard by all MSs and avoids the Multi-Channel Hidden Terminal Problem [68].

4.2 An Overview of DSA via Multi-Channel MAC Protocols

In this section, we present an overview of different multi-channel MAC protocols proposed to increase network throughput, to improve spectrum utilization and to reduce interference caused by secondary use of the spectrum. We analyze these protocols describing their access mechanisms and we present a comparison of key features of each protocol according to the number of half-duplex transceivers, the need for synchronization, the need for a CCCH and the different ways to make "rendezvous" for data transmission.

In [56], multi-channel MAC protocols have been classified into four categories according to their principles of operation:

1. Dedicated Control Channel: This type of protocol uses at least two TRx per MS, one is used for control information exchange and the other is able to switch between channels for data transmission. As plotted in Figure 4.4, in this approach, there is no need for global synchronization to make rendezvous because the control channel is always tuned by all the MSs in the network and therefore, the MCHTP is easily avoided. However, this protocol presents two principal problems, the need for two TRx and the possibility of control channel bottleneck.

2. Common Hopping: This type of protocol uses one TRx per MS. This TRx is able to

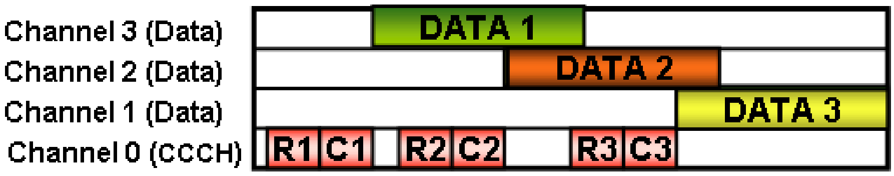

Figure 4.4: Dedicated Control Channel approach (inspired from [56]).

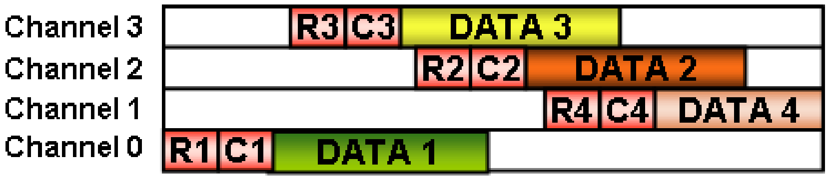

Figure 4.5: Common Hopping approach (inspired from [56]).

switch between channels for control information exchange and data transmission. As depicted in Figure 4.5, to make rendezvous, MSs hop together synchronously over all channels and pause their hopping sequence when the agreement between sender and receiver is made. The merit of this protocol is the use of all channels for data transmission. However, the synchronization among MSs is crucial.

3. Split Phase: This type of protocol uses one TRx per MS. As we can see in Figure 4.6, time is divided into Control phase and Data phase, this division has the objective to ensure that all MSs listen to the control phase, thus avoiding the MCHTP. Two important disadvantages of this approach are the need for global synchronization and the wasted data channels during the control phase. However, with only one TRx, this protocol solves the MCHTP and it can be used as an energy-efficient MAC protocol (Power Saving Mode of IEEE 802.11 standard).

4. Multiple Rendezvous: This type of protocol uses one TRx per MS. This TRx is able to switch between channels for control information exchange and data transmission. Each MS follows a hopping pattern generated in a pseudo-random way using a seed. If a MS wants to establish communication, it must firstly determine the hopping sequence of the intended receiver and re-align their hopping sequence to that of the receiver. If the receiver is idle, the sender begins data transmission. In this approach time is divided into slots; therefore, synchronization is required. The principal advantage of this type of protocols is that multiple rendezvous can be made in different channels at the same time, thus improving the network throughput and

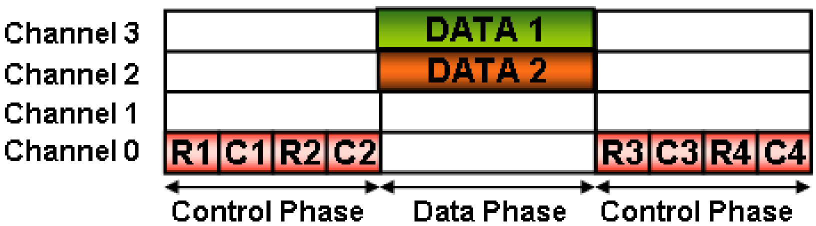

Figure 4.6: Split Phase approach (inspired from [56]).

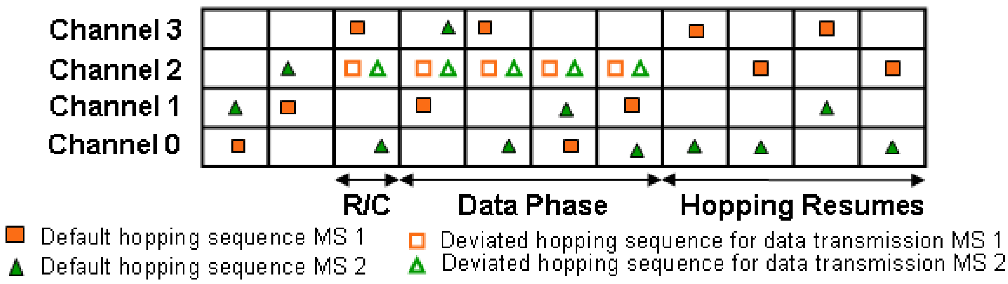

Figure 4.7: McMAC protocol (inspired from [56]).

avoiding the CCCH bottleneck. However, coordination between MSs is essential.

After this classification, which is essential to compare the existing multi-channel MAC protocols, we now present our analysis of several protocols allowing DSA in an opportunistic (i.e. Overlay) manner in distributed Ad-hoc networks. The purpose of this work is to describe how each multi-channel MAC protocol faces and resolves the various complications that arise in DSA and pinpoint the advantages and disadvantages of each protocol in order to be accurately implemented in cognitive radio networks.

4.2.1 "McMAC: A Parallel Rendezvous Multi-Channel MAC Protocol"

McMAC is a multiple rendezvous protocol and so each MS has only one TRx [30]. In the beginning, a sender selects a seed to generate its default hopping pattern (e.g. its MAC address). To allow neighbor discovery and synchronization, all MSs must beacon at every channel for a certain period; therefore, neighbors eventually learn its hopping sequence because the seed is included in all the sender's packets. To make rendezvous, a MS can deviate from its default hopping sequence and hops to the receiver's channel. If the receiver is idle, both MSs stop hopping and begin data transmission. As depicted in Figure 4.7, when data transmission ends, the communication pair resumes its default hopping sequence. The disadvantages of this protocol are the need for coordination and synchronization between communication pairs. However, multiples rendezvous can be made simultaneously on different channels.

4.2.2 "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver"

In MMAC protocol, each MS is equipped with one TRx [68]. As plotted in Figure 4.8, time is divided into an alternating periods of control and data phases (split phase). An Ad Hoc Traffic Indication Message (AR), at the start of each control interval, is used to indicate traffic and negotiate channels for utilization during the data interval. A similar approach is used in IEEE 802.11's power saving mode (PSM). This scheme uses two new packets which are not used in IEEE 802.11 PSM: the ATIM ACK (AC) and the ATIM-RES (A-RE). These packets inform neighboring MSs of the Sender (S) and Destination (D) of which channels are going to be used during the data exchange. During the control period, named ATIM window, all MSs have to attend the default channel and contend for the available channels. Once reservation is successful, the MSs switch to the reserved channel. With only one TRx this protocol solves the Multi-Channel Hidden Terminal Problem. A Preferred Channel List (PCL) is used to select the best channel based on

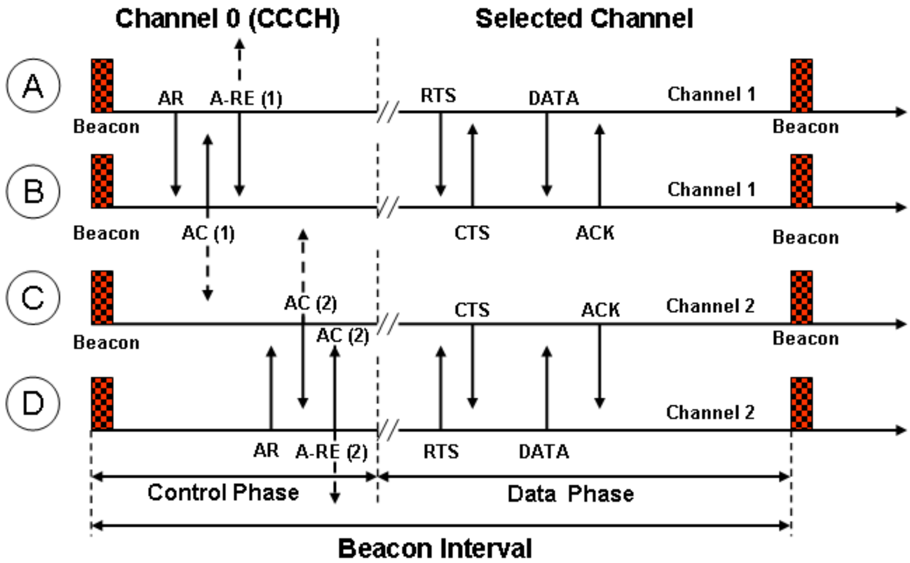

Figure 4.8: MMAC protocol (inspired from [68]).

traffic conditions. In this list all the channels are classified by the status: HIGH, MID, and LOW.

The principal disadvantages in this protocol are the need for synchronization, which might be difficult to implement in Ad Hoc networks and the wasted data channels during the control phase or ATIM window. However, with only one TRx this protocol solves the MCHTP.

4.2.3 "A Distributed Multichannel MAC Protocol for Cognitive Radio Networks with Primary User Recognition"

In MMAC-CR protocol, time is split into alternating periods of control and data phase and each user is equipped with one TRx [75]. A similar approach is used in IEEE 802.11 PSM. This protocol has two data structures: the Spectral Image of Primary users (SIP), which contains the channels used by PUs, and the Secondary users Channel Load (SCL), which is used to select the communication channel in terms of traffic.

The proposed protocol is divided into four phases: during phase I, the MSs contend to transmit a beacon (which is needed to establish and maintain communications in an orderly fashion) and perform a fast scan; this scanning process is used to update the SIP value of the scanned channel. Phase II is used to determine the spectral opportunities by listening to C mini-slots (there is one mini-slot for each data channel). Each MS informs the others of the presence of PUs by transmitting a busy signal in the corresponding mini-slot. In Phase III, using ATIM packets (AR and AC), the channels are negotiated. Phase IV is used for data transmission or fine sensing for idle MSs.

MMAC-CR with only one TRx solves the MCHTP. Alternating periods of control and data phases, this protocol avoids the possibility of control channel bottleneck. However, the synchronization and coordination between MSs are essential to make rendezvous which might be difficult to implement in Ad hoc networks. The overall protocol is plotted in Figure 4.9.

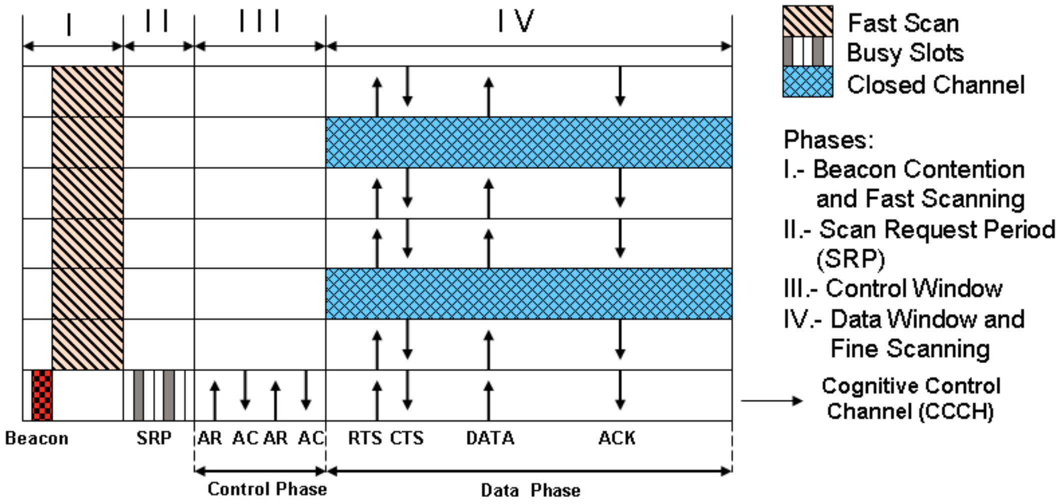

Figure 4.9: MMAC-CR protocol (inspired from [75]).

4.2.4 "Hardware-constrained Multi-Channel Cognitive MAC"

In HC-MAC, each MS is equipped with one TRx [41]. In this protocol, there is no need for global synchronization. As we can see in Figure 4.10, to make rendezvous, HC-MAC protocol exchanges control packets using a CCCH. In this protocol, there are three phases: Contention phase, Sensing phase and Transmission phase and each phase has a RTS/CTS exchange:

- C-RTS/C-CTS: using the RTS/CTS mechanism of IEEE 802.11 DCF mode, a pair of MSs reserves all the channels (CCCH and data channels) for the following two phases (sensing and transmission).
- After sensing the different data channels, the pair exchanges a S-RTS/S-CTS on the CCCH to inform each other about channel availability. A set of channels (only one in single TRx case) is then selected.
- After data transmission on the different selected channels, the communication pair indicates the end of transmission by a T-RTS/T-CTS exchange. This allows neighboring MSs to begin the contention phase with a random back off.

Authors outline two constraints for cognitive radios, sensing and transmission, the former used to optimize the stopping of spectrum sensing and the latter used to optimize the spectrum utilized in transmission by SUs.

The major drawback of this scheme could be that after one communication pair wins the CCCH, using the C-RTS/C-CTS exchange; other MSs must defer their sensing and transmission. Then, for a certain time, only one pair uses all available channels and other users must wait for the T-RTS/T-CTS notification to contend again in the control channel.

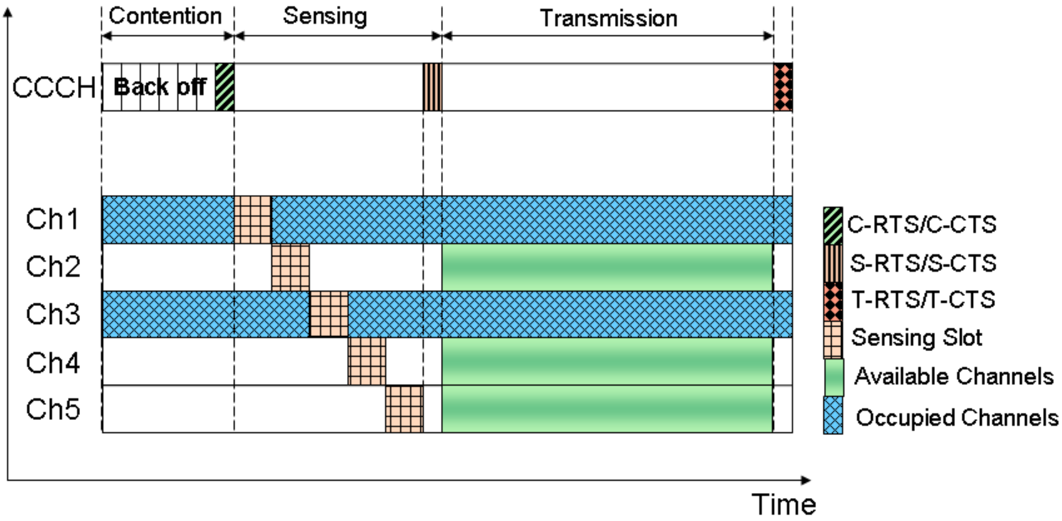

Figure 4.10: HC-MAC protocol (inspired from [41]).

4.2.5 "Distributed Coordinated Spectrum Sharing MAC Protocol for Cognitive Radio"

This protocol uses two TRx per MS, one is used for control information exchange and the other is able to switch channels for data transmission [57]. There is no need for synchronization to make rendezvous because the control channel is always tuned by the MSs. In this protocol, SUs employ a time slot mechanism for cooperative detection of PUs around the communication pair by using the CHRPT (channel report slots). Each MS informs the others about the presence of PUs, on the sender and on the receiver side, by transmitting a busy signal in the corresponding mini-slot (there is one mini-slot for each data channel).

The source sends to destination the RTS which includes its available channel list. Neighbor MSs, which hear the RTS, compare the sender list with their own. If they detect a PU occupation in a channel, they reply with a pulse in the specified time slot during CHRPT (signaling occupied channels seen by the neighbors). If necessary, the source updates its RTS sending a RTSu. The same mechanism occurs on the destination side. After the RTS reception the destination waits to get the possible RTSu for a certain time named UIFS. If the RTSu does not arrive, the destination will handle the RTS. After the RTS reception, the destination sends to its neighbors the Channel Status Request (CHREQ), which includes the destination's available channel list among the listed channels of the source. At the end of channel verification by the destination neighbors, the receiver sends the CTS with the chosen channel.

The major drawbacks of this scheme are the time wasted in channel verification by the neighbors and the need for two TRx. However, this procedure ensures the absence of PUs in the vicinity of the communication pair and with the use of two TRx this protocol solves the MCHTP. The overall protocol is plotted in Figure 4.11.

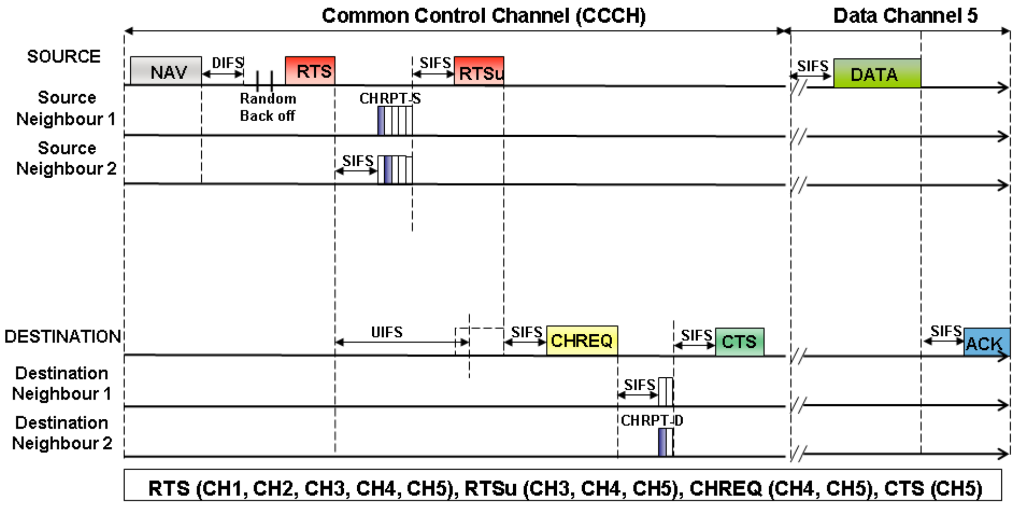

Figure 4.11: Procedure of the proposed protocol (inspired from [57]).

4.2.6 "Os-MAC: An Efficient MAC Protocol for Spectrum-Agile Wireless Networks"

In Os-MAC protocol, each SU is equipped with one TRx; this protocol uses the IEEE 802.11 DCF mode [28]. This approach seeks to exploit the available spectrum opportunities using MSs coordination. One entity per channel is a "delegate", the delegates are chosen among all MSs and they make reports about channel quality. The notion of a Secondary User Group (SUG) is used to designate a group in which a set of users want to communicate with each other. In each SUG, at any time, only one member can transmit and the others must receive.

As plotted in Figure 4.12, OS-MAC divides time into periods and each period is named Opportunistic Spectrum Period (OSP). In each OSP, there exist three consecutive phases: Select, Delegate, and Update Phase. In the first phase, each SUG selects the "best" Data Channel (DC) based on traffic conditions and uses it for communication during the totality of the OSP period. During the second phase, a Delegate Secondary User (DSU) is chosen to represent the DC during the Update Phase, in which all DSUs switch to the CCCH to update each other about their channel conditions. Meanwhile, all non-DSUs continue transmitting on their DCs.

An important aspect of this protocol is the notion of groups and the delegate for each DC. This mechanism can improve the channel classification, essential for defining the best channel based on traffic conditions, which could be used for data transmission.

4.2.7 "Performance Evaluation of a Medium Access Control Protocol for IEEE 802.11s Mesh Networks"

CCC protocol uses multiples TRx per MS; one is used for control information exchange and the others tune the available channels for data transmission [7]. There is no need for global synchronization to make rendezvous because the control channel is always tuned by the MSs. As plotted in Figure 4.13, the CCC protocol defines a CCCH over which MSs exchange control and management frames. The rest of the channels, called Mesh Traffic (MT) channels, are used to carry the data traffic. Reservations of the various MT channels

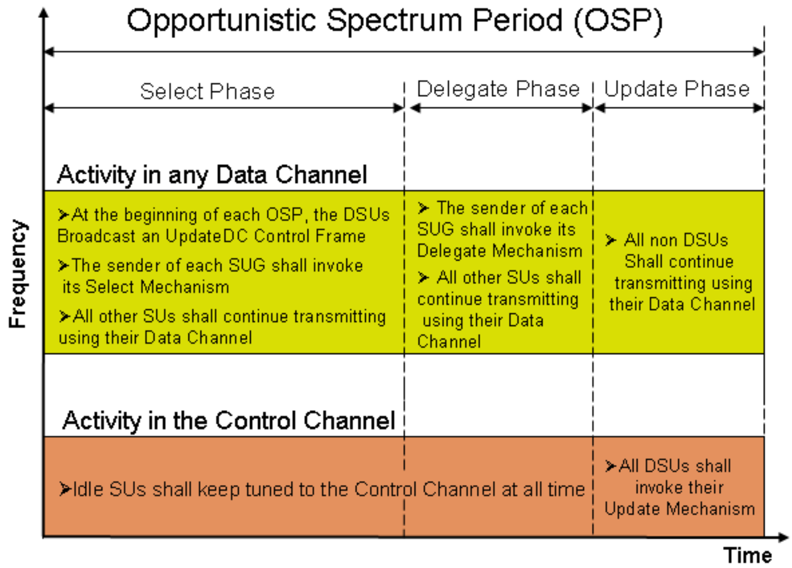

Figure 4.12: OSP in Os-MAC protocol (inspired from [28]).

are made by exchanging control frames on the CCCH.

This protocol has the same advantages and disadvantages presented of the dedicated control channel approach: there is no need for synchronization to make rendezvous and with the use of multiple TRx this protocol solves the MCHTP. However, this protocol requires several TRx (one for each MT channel) and the possibility of control channel bottleneck exists.

4.2.8 "TMMAC: An Energy Efficient Multi-Channel MAC Protocol for Ad Hoc Networks"

In TMMAC, each user is equipped with one TRx; time is divided into control phase (ATIM window) and data phase [80]. The ATIM window size is not fixed and can be adapted based on traffic conditions. The data phase is slotted, only a single data packet can be transmitted or received during each time-slot. The purpose of the control window is twofold, the channel negotiation and the slot negotiation. In the data phase, each MS switches to the negotiated channel and uses its respective time slot for packet transmission or reception.

This protocol has the same advantages and disadvantages presented in split phase protocols: the need for global synchronization and the wasted data channels during the control phase. However, with only one TRx, this protocol solves the MCHTP.

4.2.9 "Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks"

In the Single-Radio Adaptive Channel (SRAC) algorithm, each SU is equipped with one TRx [49]. This algorithm proposes an adaptive channelization, where a radio combines multiple fixed channels with minimum bandwidth, named "atomic channels", based on its needs to form a new channel with more bandwidth, thus forming a "Composite channel". In this algorithm there is no need for global synchronization. SRAC also proposes "Cross-

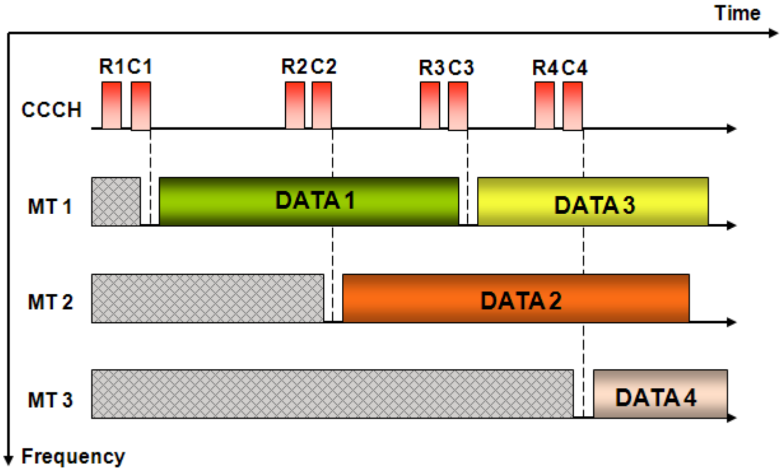

Figure 4.13: CCC MAC protocol (inspired from [7]).

Channel Communication", utilized to enable transmission and reception when there are multiple jamming sources and there is no common idle spectrum between the transmitter and the receiver. A MS has a stable channel for reception, which is used by its neighbors to reach that MS. This channel can be modified but this modification must follow strict rules to enable future communications. In the case of a modification in their receive channel, MSs must immediately communicate their new receive channel to all of their neighbors by sending a "notification frame".

The merits of this algorithm are the adaptive channelization and the fact that it requires neither a CCCH nor synchronization because the MSs have a pre-assigned channel for reception.

4.2.10 "A Full Duplex Multi channel MAC Protocol for Multi-hop Cognitive Radio Networks"

In this protocol, each SU is equipped with three TRx named: "Receiver, Transmitter and Controller". To communicate, the "Transmitter" of the sending MS and the "Receiver" of the receiving MS must be tuned to the same channel.

In [12], there is no need for synchronization because the CCCH is always tuned by the MSs using the "Controller". A MS selects an unused frequency band as its home channel (HCh); it tunes the "Receiver" to its HCh and informs the others about the selected channel by broadcast in the CCCH. This protocol uses the CSMA/CA scheme of IEEE 802.11 DCF mode. With the use of three TRx, MSs can reduce communication delay by transmitting packets while they are receiving and this protocol easily avoid the MCHTP. However, the need for three TRx will increase the overall cost.

4.2.11 "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks"

SSCH protocol uses one TRx per MS [6]. In this protocol, each sender chooses one of the possible hopping patterns generated in a pseudo-random way, there is one hopping pattern for each available channel. To make a rendezvous, a sender must wait until its current hopping pattern intersects with that of the receiver before it can send data. The principal

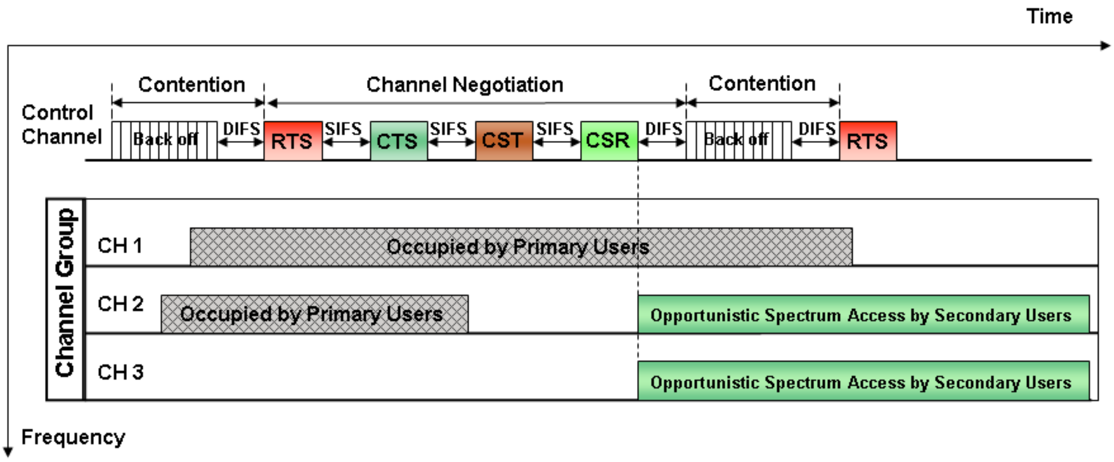

Figure 4.14: CREAM-MAC protocol (inspired from [73]).

disadvantage of this protocol is the time wasted waiting to coincide with the receiver. However, multiples rendezvous can be made at the same time in different channels and the control channel bottleneck is avoided.

4.2.12 "CREAM-MAC: An efficient Cognitive Radio-EnAbled Multi-Channel MAC Protocol for Wireless Networks"

In the Cognitive Radio-EnAbled Multi-channel MAC (CREAM-MAC) protocol, each SU is equipped with one TRx that can dynamically utilize one or multiple channels to communicate [73]. In this protocol, MSs also have multiple sensors (there is one sensor for each data channel) that can detect PUs activity, simultaneously, on different channels.

As we observe in Figure 4.14, the CREAM-MAC protocol employs a CCCH as the "rendezvous channel". This protocol does not require global synchronization. With one TRx, this protocol solves the Multi-Channel Hidden Terminal Problem employing a four-way handshake. These control packets are: RTS/CTS and CST/CSR. The RTS/CTS exchange prevents the collisions among the SUs by reserving the CCCH for channel negotiation. The CST/CSR exchange avoids collisions between SUs and the PUs by allowing SUs to share sensing information about PUs channel occupation.

The merits of the CREAM-MAC protocol are the fact that there is no need for global synchronization and with the use of only one TRx and multiple sensors, this protocol solves the MCHTP.

4.2.13 "Distributed Coordination in Dynamic Spectrum Allocation Networks"

In [81], the notion of groups with similar views of spectrum availability is addressed. Each SU is equipped with one TRx. This protocol employs a recursive distributed voting scheme for selection of a "Coordination Channel" (CCH) for a group and this "user group" is assembled based in similar spectrum channel availabilities. The CCH is used as the only means to connect SUs, thus, only members of the same group can directly communicate with each other. To maintain network connectivity "bridge" nodes, located on the edge of each group, must manage at least two different CCH to transfer data packets

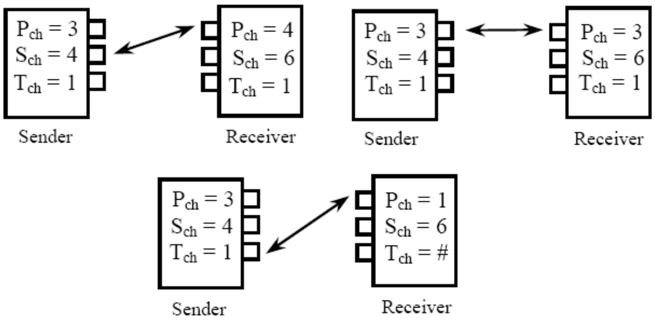

Figure 4.15: PCAM protocol (inspired from [73]).

between groups and connect users with different spectrum perspectives. The group setup, including the "bridge" nodes and the group maintenance are carried out by using specific algorithms. These algorithms are executed during network initialization and when the network conditions change (e.g. PU starts activity in a channel occupied by SUs).

The merit of this approach is its possible application in the case of secondary use of the spectrum by WLAN devices in TV white spaces, principally, because the interference condition with PUs is determined by distance.

4.2.14 "Primary Channel Assignment Based MAC (PCAM) A Multi-Channel MAC Protocol for Multi-Hop Wireless Networks"

In PCAM protocol, as depicted in Figure 4.15 each user is equipped with three TRx [60]. This scheme eliminates the need for a dedicated control channel that arise the possibility of control channel bottleneck when the traffic increases. In this protocol, a MS selects a frequency band as its primary channel (Pch) using one TRx, this will be used as a receiver channel and a secondary channel (Sch) is used as transmitter while the third TRx (Tch) is used only for transmission and reception of broadcast messages. PCAM protocol removes the constraints of time synchronization and control channel saturation because the channels are pre-assigned and with three TRx, this protocol can avoid the MCHTP. However, the need for three TRx will increase the overall cost.

4.2.15 "Performance of Multi Channel MAC Incorporating Opportunistic Cooperative Diversity"

In CD-MMAC, time is divided into fixed periods (split phase), each user is equipped with 1 TRx [1]. This protocol uses the same mechanism proposed by So et al. in MMAC [68]. The authors of this protocol add the notion of relays between source and destination. Time is divided into fixed-time intervals (control phase and data phase) using beacons. A small window, named ATIM, at the start of each interval is used to indicate traffic and negotiate channels to be used during the data phase. This protocol uses intermediate nodes as relays to increase the probability of transmission success.

This protocol solves the MCHTP with only one TRx. However, two drawbacks of CD-MMAC are the need for global synchronization and the wasted data channels during the control phase.

4.2.16 "A Multi channel MAC for Opportunistic Spectrum Sharing in Cognitive Networks"

In AS-MAC (Ad hoc SEC Medium Access Control) protocol [52], the primary network is a TDMA/FDMA (GSM) cellular system and the secondary network is an Ad hoc network that can decode the control information of GSM system. Sensing the vacant slots, a SU uses the resources left utilized by the PU, which could be a base station or a MS. To obtain all the parameters like synchronization, frequency correction and cell information, secondary users decode the beacon channel from the base station. To make rendezvous, this protocol employs RTS/CTS and Reservation (RES) mechanism.

4.2.17 "Adaptive MAC Protocol for Throughput Enhancement in Cognitive Radio Networks"

In this protocol, each user is equipped with 2 TRX, this protocol proposes two channels, the first one is a WLAN channel which is always available for data transmission, the second one, named "Cognitive channel", is available sporadically [48]. When traffic conditions restrain the use of the cognitive channel, this channel is used for frame errors recovery by transmitting the same information in both channels, known as frequency diversity in MIMO systems; otherwise, the cognitive channel can be used to increase the overall throughput by sending sequential frames using both channels.

The drawback of this scheme could be the need for two TRx. However, this procedure can enhance the overall throughput if the cognitive channel is available.

4.2.18 "Spectrum Sharing Radios"

This paper proposes a possible approach of spectrum sharing in an opportunistic way (i.e. Overlay) for data transmission and in Underlay way, using UWB technology, only for control messages exchange [9]. In this approach, authors propose two different types of control channels, the first one, is a low throughput and wide coverage channel, named "Universal Control Channel (UCC)", which is used as a CCCH allowing the co-existence of several Radio Access Technologies (RATs). The second type of channel, named Group Control Channel (GCC), works as "Group Coordination Channel", with high throughput and short coverage, this channel allows sensing information exchange, link maintenance and performs channel allocation.

The advantage of the use of UWB Control Channels is that we could have a realistic and reliable Cognitive Control Channel, always free of Primary users, to convey control information for the entire network, which is one of the principal assumptions in several propositions of Multi-Channel MAC protocols.

4.2.19 "Cognitive Radio System using IEEE 802.11a over UHF TVWS"

This paper presents a practical implementation of the IEEE 802.22 standard with PUs and SUs. The architecture consists of Cognitive Mobile Stations (CMS) and a Cognitive IEEE 802.11 Access Point (CAP), which performs band sensing and available channel determination [2]. The CAP has 1 TRx and 1 Rx for sensing, the CMS are equipped with 1 TRx. There is no CCCH, the CAP sends a broadcast message to inform all stations about the available channels list in TV bands and the time synchronization. A Geo-location module is used to guarantees that the cognitive radio units will never transmit

Protocol Name or Publication Title	Number of Transceivers	Principle of Operation
McMAC	One	Multiple Rendezvous
MMAC	One	Split Phase
MMAC-CR	One	Split Phase
HC-MAC	One	Split Phase
Distributed Coordinated Spectrum Sharing MAC Protocol for CR	Two	Dedicated Control Channel
Os-MAC	One	Split Phase
CCC	Multiple	Dedicated Control Channel
TMMAC	One	Split Phase
SRAC	One	MSs Select a Channel for Reception
SSCH	One	Multiple Rendezvous
A Full Duplex Multi channel MAC Protocol for Multi-hop Cognitive Radio Networks	Three	MSs Select a Channel for Reception
CREAM-MAC	One and Multiple Sensors	Dedicated Control Channel
Distributed Coordination in Dynamic Spectrum Allocation Networks	One	Common Control Channel for a Group
PCAM	Three	MSs Select a Channel for Reception
CD-MMAC	One	Split Phase

Table 4.1: Multi-Channel MAC Protocols: Number of Transceivers and Principle of Operation.

on a channel that is determined to be within a protected service contour of the licensed TV stations.

4.3 Comparison of Key Features

In Table 4.1 and Table 4.2, we summarize the different key features of the multi-channel MAC protocols that have been presented in this section.

4.4 Conclusions

CR technology offers the possibility for additional use of radio spectrum by SUs and multiple channel protocols allow DSA due to the fact that different rendezvous and data transmissions of SUs can be performed dynamically on different channels.

In this chapter several existing multi-channel MAC protocols have been introduced and analyzed. The advantages of these protocols have been discussed with regard to different

Protocol Name or Publication Title	Need for Synchronization	Primary and Secondary Context
McMAC	Yes	No
MMAC	Yes	No
MMAC-CR	Yes	Yes
HC-MAC	No	Yes
Distributed Coordinated Spectrum Sharing MAC Protocol for CR	No	Yes
Os-MAC	Yes	Yes
CCC	No	No
TMMAC	Yes	No
SRAC	No	Yes
SSCH	Yes	No
A Full Duplex Multi Channel MAC Protocol for Multi-hop Cognitive Radio Networks	No	Yes
CREAM-MAC	No	Yes
Distributed Coordination in Dynamic Spectrum Allocation Networks	No	Yes
PCAM	No	No
CD-MMAC	Yes	No

Table 4.2: Multi-Channel MAC Protocols: Need for Synchronization and Primary/Secondary Context.

factors: the number of transceivers, the need for synchronization, the need for a CCCH and the different ways to make rendezvous for data transmission. The presented multi-channel MAC protocols, which are based principally on the DCF medium access mechanism of the IEEE 802.11, have as common objectives improving the spectrum utilization and increasing the total network throughput.

Based on the fact that cognitive MAC protocols implementations are inspired on multi-channel MAC protocols proposed for non-cognitive networks, they inherit their operation characteristics and of course they merits and demerits. As we described in this analysis, the implementation of single TRx protocols are easier compared with multiple TRx protocols. Nevertheless, in single TRx protocols the hidden terminal problem arise together with the problem of channel switching delay. On the other hand, multiple TRx protocols can achieve higher throughputs and can easily avoid the MCHTP. However, these protocols are more complex and more expensive than single TRx protocols. In the case of the protocols employing a dedicated control channel, they can be affected by the possibility of bottleneck under some operating conditions. Multiple rendezvous channel can alleviate the congestion problem but raises the challenge of ensuring the idle transmitter and receiver visit the same rendezvous channel. Finally, Split Phase and Dedicated Control Channel protocols explicitly separate control packets from data packets. This division can lead to generate more successful rendezvous. Nevertheless, this process is useless to improve performance when there are few available data channels or when they are already congested.

As we have shown through this chapter, each multi-channel MAC protocol faces and resolves differently the various complications that arise in DSA. Therefore, the selected approach has to be chosen carefully based on the advantages, disadvantages and hardware requirements of each protocol in order to be accurately implemented in cognitive radio networks.

Chapter 5

DSA via Cognitive Control Channels

Reconfiguration, as described in chapter 3, is the major contributor towards DSA networks. This is the capability of cognitive radios to adjust their operating parameters not only at the beginning of a transmission but also during the transmission, without any modifications on the hardware components. It also implies the dynamic adaptation of MSs and network elements to the set of RATs, which are most appropriate for the conditions encountered in specific service areas and time of the day. Reconfiguration consists of changing the selected RATs, resource allocation, network parameters and software components of terminals in order to optimize the global utilization of the spectrum resources. Next generation wireless networks will be characterized by a multiplicity of networks and types of accesses. Nevertheless, the "classical" initial access to the network is not efficient because, when a MS is switched on, it has no information about the location of the RATs within the frequency range [35]. Therefore, as we describe in chapter 4, to obtain the necessary parameters for dynamic access, a MS has to scan the entire spectrum looking for occupancy information. However, the scanning process may require a lot of time and can greatly impact the battery consumption in mobile devices [32].

To overcome the above problems and to facilitate the connection to the network, the use of cognitive control channels have been proposed as assistants for MSs, to select an appropriate network according to user's requirements (e.g. RAT, frequency channel, secondary use of the spectrum, etc). This proposal has been studied mainly in the E2R II and E3 projects under the name of Cognitive Pilot Channel (CPC) and several papers have been published in this context.

In this chapter, we propose two different implementations of a cognitive control channel named Cognitive Beacon Channel (CBC). The first implementation uses three logical channels (RACH, AGCH and TCH) of GSM and the second one uses UMTS signaling (MIB and SIBs) of the Broadcast Channel (BCH). The purpose of the information conveyed by the CBC in the bands of GSM and UMTS, is the same as other cognitive control channels proposed in literature, which is providing assistance to MSs in the process of DSA and in reconfiguration procedures. Nevertheless, the main advantage of our proposal is the fact that our CBC re-uses existing 3GPP technologies, proved to be efficient and accepted worldwide, to convey this signaling information for DSA.

The outline of this chapter is organized as follows: Section 5.1 reviews some issues concerning the CPC approach in the E2R II project. Section 5.2 presents other proposals of cognitive control channels besides our CBC and the CPC of the E2R II project. Section 5.3 presents our proposition. In section 5.4 we present the evaluation model describing the parameters, expressions and default values considered for the performance analysis. In section 5.5, we compare our proposed CBC implementation using logical channels of GSM and UMTS signaling with the CPC implementation performed in the E2R II project. Finally, in section 5.6 we present our conclusions.

5.1 CPC Issues

5.1.1 Regulatory Issues

Spectrum bands are assigned via regulatory bodies [50]. The regulators negotiate with operators the amount and the utilization conditions of the spectrum bands to be assigned. Nevertheless, the approbation of a worldwide standardization and implementation of the CPC will require some modifications on the Radio Regulation (RR) of the International Telecommunications Union (ITU). These modifications also require an appropriate decision taken by a World Radio Conference (WRC) [19].

With regard to this worldwide CPC, in 2007 it was approved to add to the next WRC's agenda (conference to be held in 2011), a proposal of *"the possible need for a worldwide cognitive pilot channel"*. A contribution was filed from France Telecom which specifically introduced the CPC concept into the work of ITU-R 8A Working Party. This contribution stemmed from the EU research project E2R II and had the support of project partners such as Motorola, Nokia, Alcatel Lucent, Telefonica and Telecom Italia. As a consequence, the CPC was included as a related radio technology in the working document. In parallel with the ITU, in July 2007, the European Conference of Postal and Telecommunications Administrations (CEPT) submitted a proposal to put the CPC concept on the agenda for the 2011 edition of the WRC, and CEPT members promoted this agenda item in the discussions that took place at the WRC-07 (October-November 2007, Geneva). At the same time, a number of Arab States, via agenda item 1.10, introduced their own proposal with regard to cognitive radio studies, putting more emphasis on Software Defined Radio (SDR) aspects. As a result of the ensuing negotiations the approved agenda of the WRC-11 proposes *"to consider regulatory measures and their relevance to enable the introduction of software defined radio and cognitive radio systems based on the results of ITU-R studies"*, indicating with regard to the CPC that *"some studies indicate a possible need for a worldwide harmonized cognitive supporting pilot channel (...) whilst other studies indicate that the availability of a database could support access and connectivity, and therefore support the use of these systems"*. However, it needs to be noted that wired or wireless access to some form of database is also mentioned as a potential alternative to the CPC [19].

The standardization of the CPC within IEEE was initiated through the creation of the P1900.4 Working Group within the P1900 Standards Group, dealing with *New Generation Radio Standards*. As we state in chapter 3 on section 3.2.1 the IEEE P1900 was reorganized into the Standards Coordination Committee 41 (SCC41), Dynamic Spectrum Access Networks (DySPAN). All Working Groups under P1900.4 continued its work under this name.

As a reminder, three reference use cases of the P1900.4 system have been defined:

a) Dynamic Spectrum Assignment.

b) Dynamic Spectrum Access.
c) Distributed Radio Resource Usage Optimization.

The purpose of the use case c), is to perform an optimized use of spectrum by different RATs in a composite network by distributing decision-making intelligently between networks and terminals. On this basis, a number of system requirements were collected and three crucial system entities defined:

- The Network Reconfiguration Manager (NRM), managing the wireless network for optimization of spectrum usage.
- The Terminal Reconfiguration Manager (TRM), managing the terminal for optimization of spectrum usage within the framework defined by the NRM and in a manner consistent with user preferences and available context information.
- The Radio Enabler (RE) used as a logical communication channel between NRM and TRM.

It is this last component (i.e. RE), which may run over one or more existing (or dedicated) RATs, that constitutes the CPC [19].

As we will describe in the next section, if a worldwide standardization and implementation of a cognitive control channel is approved, it would represent an important tool for MSs to obtain knowledge about spectrum occupation facilitating the secondary use and the DSA.

5.1.2 Secondary Use and DSA via the CPC

The conventional CPC implementations consider an underlying grid consisting of uniform square meshes. A mesh is defined in [19] as: *"An area where certain radio-electrical commonalities can be identified (e.g. a certain frequency that is detected with a power above a certain level in all the points of the mesh)"*. The mesh is characterized by its geographic coordinates, and its size would depend on the minimum spatial resolution where the mentioned commonalities can be identified.

Via the CPC, the network transmit information blocks to provide detailed information about the available radio technologies present in each mesh. The information conveyed by the CPC for a given mesh is illustrated in Figure 5.1. The CPC includes the information indicating the geographic coordinates and location of each mesh. It also indicates the list of operators available in the mesh and for each operator, the CPC indicates the available RAT and the corresponding frequency bands per RAT.

In the case of the secondary use of the spectrum, the CPC also transmit relevant information for this dynamic access. This information is transmitted for each operator as if it was an additional RAT indicating the frequencies available for DSA. As depicted in Figure 5.1, the CPC transmit this information using a specific field named *Secondary Use*. With this information MSs can select the RAT and the available frequency bands to be used according to the users'requirements. Thus, using the information conveyed by the CPC, spectrum owners can control the access to their spectrum by signaling authorized spectrum bands (or spectrum holes) that can be used by SUs. As we stated in section 3.1.3, the spectrum holes represent spectrum portions assigned to primary users that are temporarily unutilized. Moreover, this control for spectrum access using the CPC, can

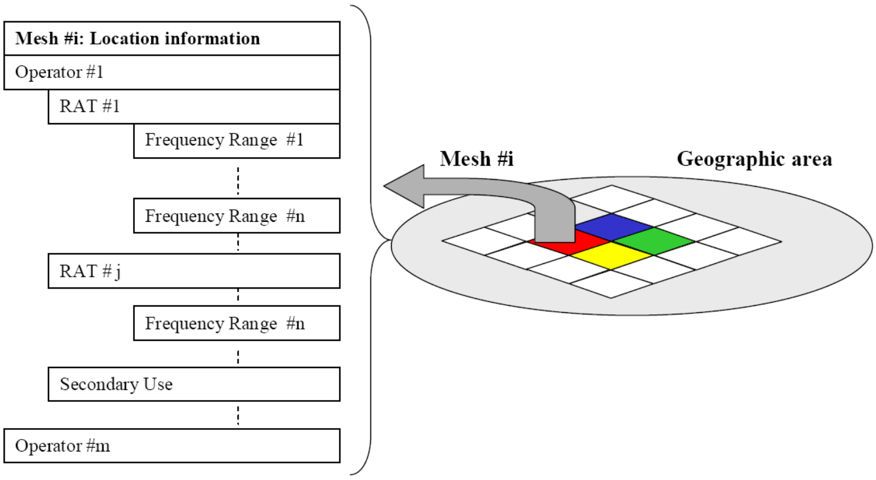

Figure 5.1: Information to be sent per mesh [61]

also be applied to solve one of the principal problems of DSA in a cognitive radio context: to avoid interference from SUs to PUs without spectrum sensing by MSs.

In distributed Ad-hoc networks, SUs equipped with cognitive radios autonomously decide the frequencies upon which they can transmit. This means that MSs perform a non-regulated secondary use of spectrum and hence, the spectrum owners (e.g. operators) do not get any financially benefit. Therefore, operators might be reluctant to allow their bands to be secondary-used. However, the use of cognitive channels provides a regulated framework for secondary usage, in the sense that owners of temporarily released frequency bands can be clearly identified by the spectrum regulator, such that the regulator can economically promote the release of frequency bands for the sake of improved spectrum usage. Furthermore, stringent controls on terminals accessing the CPC for secondary usage could be enforced, to avoid interference issues. Consequently, cellular operators could actually benefit from the secondary usage of their spectrum if renting procedures are carried out [33].

5.1.3 Proposed Architectures for the CPC

The dynamic access to the spectrum via the CPC can be viewed as a *Coordinated DSA* approach. This is because the access to the spectrum is managed via a central entity which permanently owns the spectrum and only grants a time-bound access to the requesters within the spectrum portions reserved for secondary usage. This architecture for DSA was previously presented in section 3.1.1. Nevertheless, the use of cognitive control channels can be also performed in fully centralized architectures for dynamic access to spectrum.

In [61], three different types of CPC implementations were proposed: the Out-band, the In-band and the Combined CPC.

The Out-band implementation is characterized by the utilization of a new frequency channel (universal if possible) to transport the CPC. The drawbacks of this approach are the need for a universally available frequency band and the need for a new infrastructure to transmit the CPC. This approach is depicted in Figure 5.2. The main advantage of this approach is that as the CPC is based on a new universal radio interface hence the Out-band architecture remains independent of the technologies supported by the MSs.

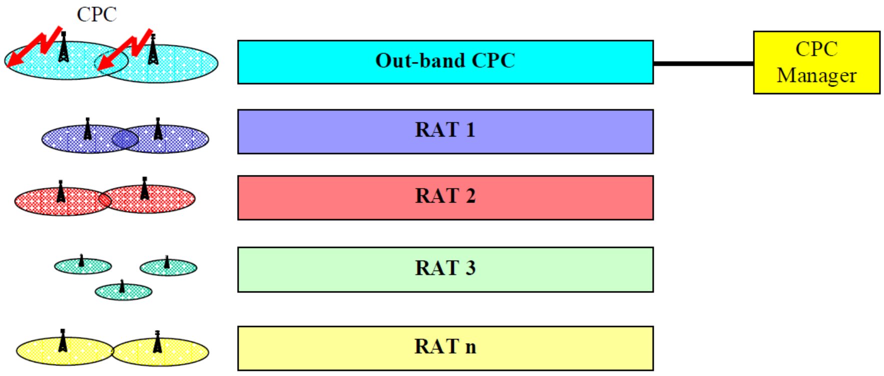

Figure 5.2: Out-band implementation [61]

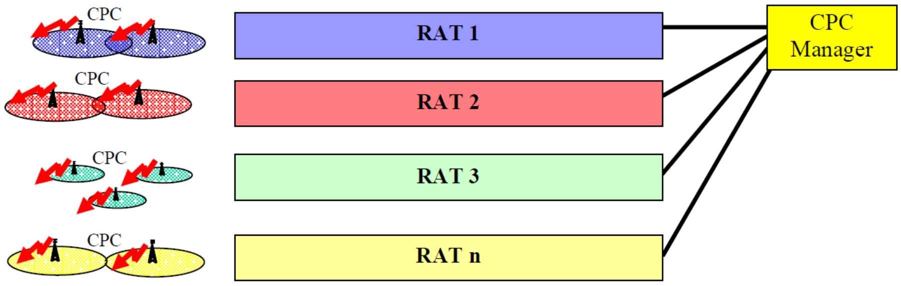

Figure 5.3: In-band implementation [61]

In the In-band approach, plotted in Figure 5.3, the CPC requires neither a new universal frequency band nor a new infrastructure because the CPC transmission is made using a frequency channel (physical or logical) of an already existing RAT. The principal disadvantages of this proposal are the need to scan the totality of the spectrum to find the RAT used to transmit the CPC and that MSs must support the utilization of this RAT.

As we observe in Figure 5.4, the third approach is a combination of the Out-band and the In-band CPC. The Combined CPC uses the Out-band approach only to transmit the location (RAT, frequency and operator) of the In-band CPC. The purpose of this process is to help the MSs to easily find where the CPC is transmitted (the main inconvenience of the In-band approach). After locating the CPC, using the Out-band approach, the In-band CPC conveys the detailed information about the spectrum utilization of the mesh where the MS is located. The drawbacks of this approach are the need for a universally available frequency to transmit the Out-band CPC. However, the process of scanning the whole spectrum after switching on is avoided.

5.1.4 CPC Capturing Procedure at the Terminal Side

The CPC operational procedure at the terminal side is described in Figure 5.5. Initially, during a phase named "start-up", MSs are switched on and determine their location using a positioning system (e.g. a GPS). Afterwards, MSs detect the CPC (it is supposed that the mobile knows the CPC technology and its frequency band) and determine their mesh. As mentioned in [61], the detection of the CPC will depend on the implementation used for

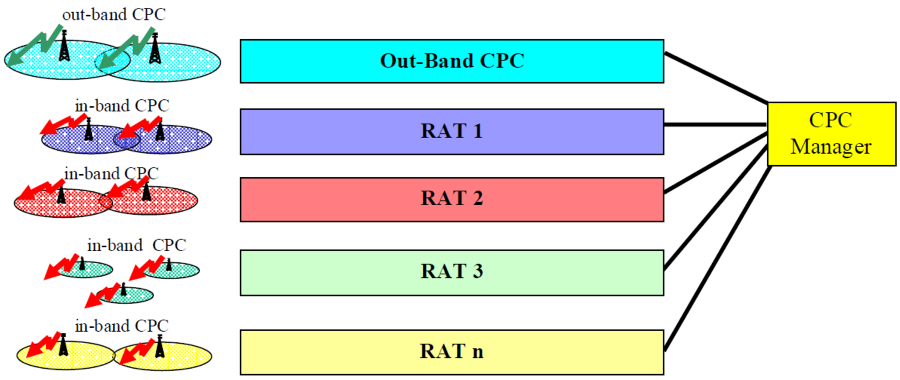

Figure 5.4: Combined implementation [61]

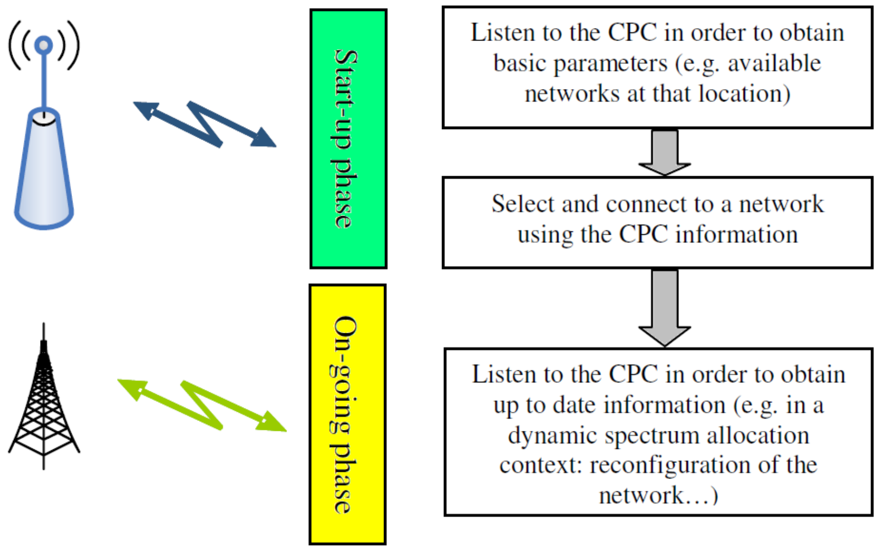

Figure 5.5: CPC capturing procedure (figure inspired from [50])

its transmission (i.e. Out-band, In-band or Combined CPC). After the CPC detection, the MSs decode the information about the available technologies (i.e. the operators deploying these RATs and the corresponding frequency bands) in the mesh where they are located. Once the MSs have selected a specific network, they leave the “start-up” phase and enter in the “on-going” phase. This phase is carried out to periodically determine the variations in the radio environment (e.g. network reconfigurations, network load, etc) [33].

5.1.5 CPC Delivery Strategies

Two different strategies to deliver the CPC were analyzed in [61]: the Broadcast and the On-demand CPC. The Broadcast approach uses a unique channel named Downlink Broadcast CPC (DBCPC). This channel is periodically transmitted by the network to convey the information corresponding to different meshes in the area covered by the CPC. In this strategy, when the MSs have detected the CPC they just have to wait for the information corresponding to their mesh. As plotted in Figure 5.6, the total time to

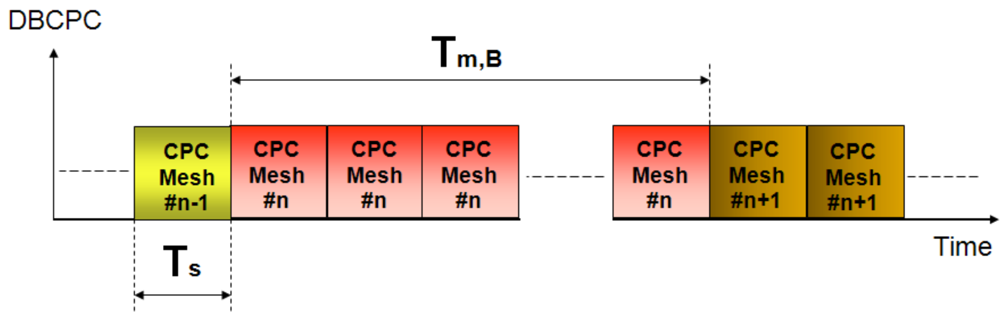

Figure 5.6: Broadcast CPC (figure inspired from [61])

transmit the information of one mesh depends on the bit rate of the DBCPC and is denoted as $T_{m,B}$. In order to simplify the synchronization of the terminals with the overall sequence of information transmitted in the channel, the DBCPC can be organized in different time slots of duration T_S.

On the other hand in the On-demand CPC, MSs do not have to wait to obtain the information of their corresponding mesh because the CPC information is transmitted when requested by the MSs. This approach requires the use of three logical channels. The first one, named Random Access CPC (RACPC), is an uplink slotted channel used by the MSs to send the requests to retrieve the CPC information. The second one, named Acquisition Indicator CPC (AICPC), is a downlink channel used by the network to indicate that the requests sent by the MSs have been successfully received. Finally the third one, named Downlink On-Demand CPC (DODCPC), is the channel used by the network to transmit the information of the mesh where the MS is located.

As we observe in the example depicted in Figure 5.7 from [61], the uplink and the downlink channels are organized into slots of duration T_S. The AICPC and the DODCPC are multiplexed on the same time slots by making use of different fields of a certain burst structure. In this example, the MS 1 sends a request in slot #1. This request contains the geographical coordinates of the terminal and a short random identifier. Since there is no collision in the transmission, the slot #2 in the AICPC indicates that the request of MS 1 has been successfully received. The AICPC is indicated by AI in Figure 5.7. Then, the transmission of the CPC information corresponding to the mesh where the MS 1 is located starts in the DODCPC. This transmission has a total duration of $T_{m,OD}$ and it depends on the bit rate of the downlink channel. It is assumed that the delay in getting the information from the CPC manager is negligible. Similarly, the MS 2 sends the request in the slot #2 of the RACPC and it receives the corresponding AICPC in the slot #3 of the downlink channel. However, since the DODCPC in this slot is transmitting the information corresponding to MS 1, MS 2 should wait until the slot #i to start receiving the information of its mesh. As we observe in this figure, in the slot #3 of the RACPC a collision occurs between MS 3 and MS 4, and therefore the AI in the subsequent slots indicate a *Null* value, reflecting that no request has been received. Then, the terminals will wait a random time before retransmission. In this example MS 3 retransmits the request in slot #i+1 and afterwards it receive the corresponding AICPC in the downlink channel.

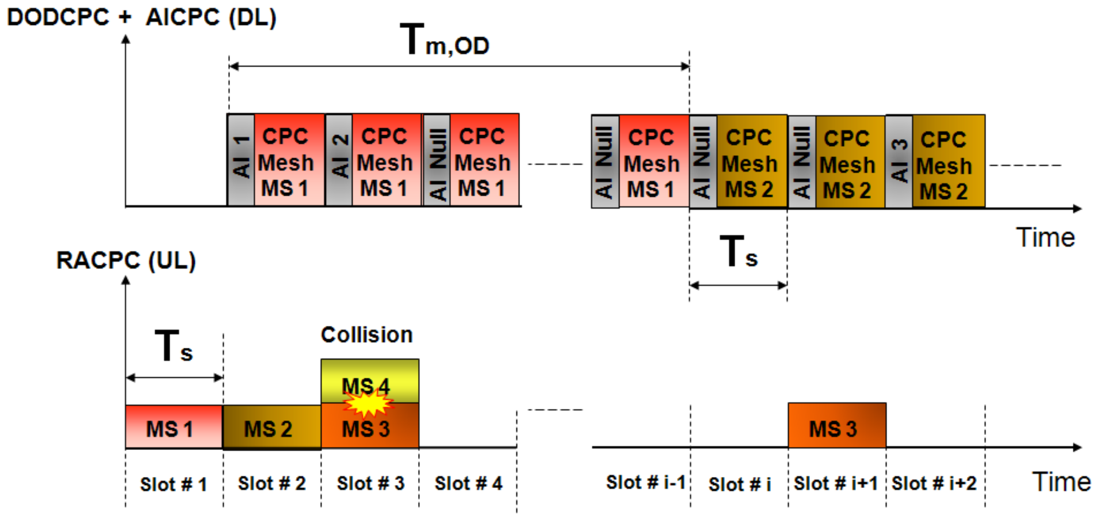

Figure 5.7: On-demand CPC (figure inspired from [61])

5.2 Other Cognitive Control Channels

There exist other approaches besides the CPC of the E2R II project and all of them have the same objective: to achieve network coordination for spectrum access using a specific channel only to convey control information to MSs. In [65], a Common Spectrum Coordination Channel (CSCC) has been proposed. In this approach, MSs use two half-duplex transceivers, one for control information exchange over the CSCC and the other is used for data transmission. MSs that want to use the spectrum or that are already transmitting; announce their radio parameters and spectrum usage information by broadcasting in the CSCC. The spectrum access is based on etiquette policies. Different spectrum access algorithms could be selected depending on network service conditions, for example: priority based methods, FCFS (First-Come-First-Served) or dynamic pricing auction [42].

In [31], another proposition using a dedicated channel for control information exchange is presented. The Resource Awareness Channel (RAC) uses a universally available frequency band to convey information about spectrum utilization of active MSs. As in [65], in this approach, active users periodically transmit on the RAC to inform other MSs about their spectrum occupation (i.e. the resources being used on their transmissions). The RAC is a random access channel; therefore, all users who want to transmit on the RAC first listen to the channel before initiating transmissions, following the multiple access method named Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). If the channel is busy, users postpone transmissions using a binary exponential back off. The purpose of this proposition is also to assist the MSs to modify their transmission parameters in an intelligent fashion, being aware of spectrum conditions to avoid interference between users.

5.3 Cognitive Beacon Channel via GSM and UMTS

This section presents our proposal for the utilization of GSM logical channels (RACH, AGCH and TCH) and UMTS signaling (MIB and SIBs) of the Broadcast Channel to transmit a Cognitive Beacon Channel (CBC). The CBC will help to improve spectrum awareness by conveying signaling to mobile users in a multi-Radio Access Technology (multi-RAT) environment (e.g. 3GPP, Wi-Fi, WiMAX and future cognitive radio systems). Taking advantage of this spectrum knowledge, the purpose of the CBC is to transmit the necessary information to allow DSA using a centralized architecture. The principal motivation of this proposition is to obtain benefit from existing 3GPP technologies proved to be efficient and accepted. The results of our analysis show that the CBC proposal, using logical channels of GSM and UMTS outperform, respectively, the On-demand and the Broadcast CPC implementations of the E2R II project.

In the case of the GSM standard, instead of the utilization of sparing bits from the BCCH as suggested in [66], we use the Random Access Channel (RACH), the Access Grant Channel (AGCH) and the Traffic Channel (TCH). We assume that the RACH is slightly modified to send the requests to retrieve the CBC information. Using the AGCH the network confirms the reception of the requests and the TCH is used to convey the information of the required mesh. The blocks used to transport the TCH have a maximum limit of 260 bits and the TCH has a block recurrence of 20 ms [47].

In the case of UMTS, we use a Master Information Block (MIB) and the System Information Blocks (SIBs) of the logical Broadcast Channel (BCH) to transmit the CBC information. The MIB conveys all the scheduling information needed to find the SIBs in the BCH. The MIB contains the number of segments, the System Frame Number (SFN) of the first segment and the SFN offset of the remaining segments for each of the SIBs [10]. The blocks used to transport the SIBs have a maximum limit of 246 bits and the UMTS Terrestrial Radio Access Network (UTRAN) transmits the SIBs every 20 ms and the MIBs every 80 ms [74].

Our proposal, using GSM and UMTS channels to transport the CBC, corresponds to an "In-band Transmission" in [61]. This is because GSM and UMTS are existing technologies; therefore, the CBC transmission will require neither new infrastructure nor new frequency channels. The purpose of the information conveyed by the CBC, in the bands of GSM and UMTS, is providing assistance to MSs in the DSA process and in reconfiguration procedures in heterogeneous networks.

5.4 Evaluation Model

In this section, we describe the expressions and default values considered to evaluate the performance of our proposed CBC implementation, using logical channels of GSM and UMTS, with the Broadcast and the On-demand CPC approaches in the E2R II project.

In order to fairly evaluate these approaches, we use the same model and parameters utilized in [61]. In this model, the total number of information bits to be transmitted for a single mesh is denoted by I_m. This value includes only useful information without synchronization or redundancy bits and is expressed as:

$$I_m = B_{GEO} + N_{OP}\left(B_{OP} + N_{RAT}\left(B_{RAT} + N_{FREQ}B_{FREQ}\right)\right),$$

where:

- B_{GEO} is the geographic information (latitude and longitude in minutes and in seconds) and is equal to 53 bits.

- B_{OP} is the operator information (country code and the mobile network code identifiers) and is equal to 20 bits.

- B_{RAT} is the information to identify the RAT (until 15 different RATs) and is equal to 4 bits.
- B_{FREQ} is the frequency information (from $F_{min} = 0$ to $F_{max} = 10$ GHz with a raster of $\Delta f = 200$ kHz, thus having a total of 50000 frequencies) and is equal to 16 bits per frequency.
- N_{OP} is the number of operators presents in the mesh.
- N_{RAT} is the number of RATs corresponding to each operator.
- N_{FREQ} is the number of frequency ranges (i.e. channels of 200 kHz) per RAT.

For this analysis the value of I_m was set to 4253 bits/mesh. This value correspond to one mesh with the following characteristics: 5 operators, 5 RATs per operator and 10 frequency ranges per RAT.

In the next section we summarize and describe the complete parameters, expressions and default values considered for the performance analysis of the Broadcast and On-demand CPC of E2R II and our GSM and UMTS proposals.

5.4.1 Analysis Broadcast Approaches

In the Broadcast approaches (E2R II and UMTS), after switching on, MSs determine their location and their mesh during the start-up phase. After this phase MSs, in the Broadcast implementation in the E2R II project, are always synchronized with the DBCPC and when mobile users need to obtain the complete information of their mesh, they just have to wait.

As explained in section 5.1.5 the DBCPC of the E2R II is a downlink slotted channel. Therefore, the number of slots to transmit the information of one mesh, denoted by $N_{S,B}$ can be expressed as:

$$N_{S,B} = \left\lceil \frac{I_m}{R_b T_S} \right\rceil,$$

where R_b is the net bit rate and T_S is the time slot duration. In the implementation proposed in the E2R II project these values are equal to 10 kbps and 10 ms respectively.

The total transmission time of one mesh in the Broadcast CPC is given by:

$$T_{m,B} = N_{S,B} T_S.$$

Then, assuming that one CPC transmitter sends the information of N_m meshes, the total CPC broadcast period is $T = T_{m,B} N_m$. Authors in [61] also assume that users are always synchronized with the CPC channel and that a user requires getting the CPC information randomly with equal probability in any time between 0 and T and the arrival can correspond to any mesh with equal probability. Therefore, the average delay to obtain the information of the Broadcast approach in the E2R II project is expressed as:

$$D_{BCPC} = T_{m,B} \left(\frac{N_m}{2} + 1 \right).$$

For the evaluation of the Broadcast CBC using UMTS signaling (MIB and SIBs), we assume that MSs only decode the BCH when the information of their corresponding mesh is transmitted. To achieve this, MSs first decode the MIB to exactly locate the SIB or SIBs where the information of their mesh is conveyed (i.e. users are not always synchronized with the CBC channel). Therefore, the time that MSs need to decode the CBC to obtain the relevant information of their mesh using UMTS can be computed as:

$$D_{BCBC} = MIB_{Periodicity} + MIB_{Duration} + T_{m,BCBC},$$

where the $MIB_{Periodicity}$ is equal to 80 ms and the $MIB_{Duration}$ is equal to 20 ms [74]. $T_{m,BCBC}$ is the total transmission time of one mesh in broadcast using UMTS and is given by:

$$T_{m,BCBC} = N_S T_{TI},$$

where T_{TI} is the Transmission Time Interval of the SIBs and is equal to 20 ms. N_S are the number of SIBs to transmit the information of one mesh in broadcast and is expressed by:

$$N_S = \left\lceil \frac{I_m}{R_b T_{TI}} \right\rceil,$$

where R_b is the net bit rate of the BCH of UMTS and is equal to 12.3 kbps [74].

Finally, it is worth mentioning that for comparison purposes, the total delay estimated in the Broadcast methods (E2R II and UMTS) was the average time that MSs need to decode the cognitive channel (CBC or CPC) to get the information of the mesh were they are located.

5.4.2 Analysis On-demand Approaches

In the On-demand approaches (E2R II and GSM), the total delay to obtain the information of the desired mesh is the sum of two delays: the uplink access phase and the time to send the information of the mesh where the MS is located. Thus, the total delay in the On-demand approaches can be expressed as:

$$D_{OD} = D_{RA} + D_S,$$

where D_{RA} is the delay of the uplink access phase and D_S is the service time.

Similarly to the E2R II protect, for the random access phase a simple S-ALOHA model is considered with slots of duration T_S. It is assumed that terminals know at the beginning of one slot if a collision has occurred in the previous slot. Then, after a collision, a geometric back-off is used for retransmissions, meaning that retransmissions are carried out in the next slot with probability q. Taking this into account, the delay of the random access part is computed as in [79] as:

$$D_{RA} = T_S \left(\frac{1+q}{q p_s} + \frac{1}{2} - \frac{1}{q} \right),$$

where q is the retransmission probability (i.e. collision has occurred in the previous slot) and p_s is the success access probability (i.e. no collision in one slot) given by:

$$p_s = e^{-\lambda_T T_S}. \tag{5.1}$$

In Eq. 5.1, λ_T is the total access rate including retransmissions and it can be related with the arrival rate λ as:

$$\lambda = \lambda_T e^{-\lambda_T T_S}. \tag{5.2}$$

From Eq. 5.2 it is possible to derive the value of λ_T as:

$$\lambda_T = -\frac{W_0(-\lambda T_S)}{T_S},$$

where $W(x)$ is the Lambert W-function. If x is real, then for -1/$e \leq x < 0$ there are two possible real values of $W(x)$. The principal branch of W is analytic at 0. This follows from the Lagrange inversion theorem, which gives the series expansion below for W_0 [16]:

$$W_0(x) = \sum_{n=1}^{\infty} \left(\frac{(-n)^{n-1}}{n!} \right) x^n.$$

As in [61], after successfully receive the requests, the system is modeled as a M/D/1 queue with arrival rate λ and service time $T_{m,OD}$, corresponding to the transmission time of the information of one mesh. The bit rate of the channel that conveys the information of the cognitive channel (DOCPC or TCH) is Rb. These channels are organized in slots of duration T_S and in each slot a number of I_{AI} bits should be transmitted for the AICPC or the AGCH. Therefore, the number of slots to transmit the information of one mesh is denoted by $N_{S,OD}$ is expressed as:

$$N_{S,OD} = \left\lceil \frac{I_m}{R_b T_S - I_{AI}} \right\rceil,$$

where I_{AI} is a random identifier of the MS used for the AICPC and AGCH. The value of I_{AI} was equal to 5 bits. R_b and T_S was set to 10 kbps and 10ms respectively in the implementation proposed in the E2R II.

In the case of the On demand CBC approach, using GSM logical channels (RACH, AGCH and TCH), the evaluation parameters that change in relation to the implementation proposed in the E2R II project were: the net bit rate R_b and the block recurrence T_S of the traffic channel (TCH) of the GSM standard. These parameters were equal to 13 kbps and 20 ms respectively [47].

Similarly to the Broadcast approach, the total transmission time of one mesh in On-demand mode denoted by $T_{m,OD}$ is computed as:

$$T_{m,OD} = N_{S,OD} T_S.$$

The total amount of request per second in the area is denoted by λ and is expressed as:

$$\lambda = \eta \lambda_u \pi R^2,$$

where η is the user density expressed in (users/km^2). λ_u is the number of requests of each user to access the CPC which was set to 0.0003 request per second. This represents approximately 1 request per hour. Finally R is the Radius in km of the cognitive channel (CPC or CBC).

So, the time D_S to send the information of the mesh where the MS is located can be computed as:

$$D_S = T_{m,OD} + \left(\frac{\lambda T_{m,OD}^2}{2(1 - \lambda T_{m,OD})} \right).$$

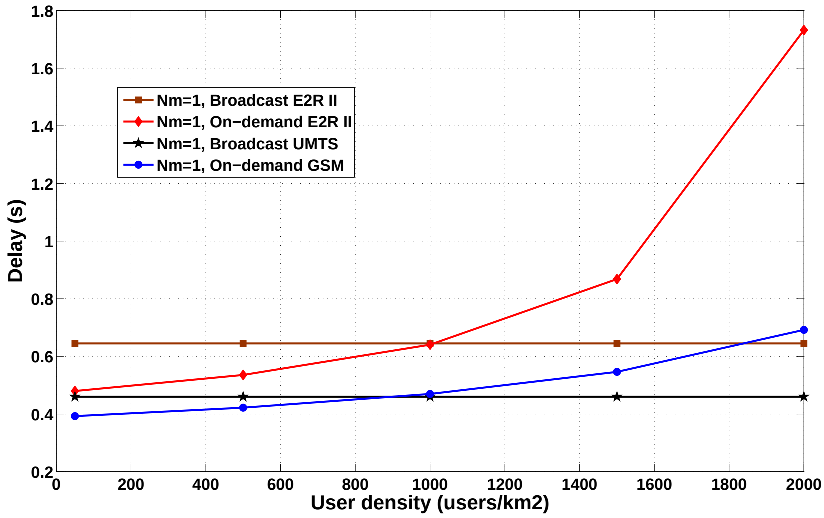

Figure 5.8: Total delay as a function of the user density with the number of meshes (N_m) equal to 1.

Finally, we recall that the bit rate used for this analysis in all systems (Broadcast and On-demand approaches in the E2R II project and our proposed GSM and UMTS) is equal to the net bit rate of information bits (i.e. without including synchronization or redundancy bits). For more details on these parameters or the evaluation model please refer to [61].

5.5 Analysis Results: Broadcast and On-demand CPC, GSM and UMTS Proposals

This section presents the evaluation performance of the Broadcast and the On-demand CPC approaches of the E2R II project and our CBC implementation using 3GPP technologies.

In Figure 5.8 and Figure 5.9, the total delay to obtain the information of the desired mesh as a function of the total user density for a fixed number of meshes (N_m) was analyzed.

Figure 5.8 shows the performance of Broadcast and On-demand CPC of the E2R II project and our UMTS and GSM proposals. The transmitter range of the CPC or CBC was set to 1 km, the number of meshes was equal to 1 and the corresponding mesh area was around 1700m x 1700m. In Figure 5.8, we notice that contrary to the On-demand proposals, the delay to obtain the information of the desired mesh of the Broadcast approaches is insensitive to the user density. The delay to receive the information is longer in the On-demand E2R II approach than in the GSM proposal and the difference, in terms of time decoding the cognitive channel, between the Broadcast implementation in the E2R II project and our UMTS proposal is equal to 185 ms.

In Figure 5.9, the number of meshes was increased to 30. The range of the cognitive channel (CBC or CPC) was 1 km; in consequence, the corresponding mesh area was around 320m x 320m.

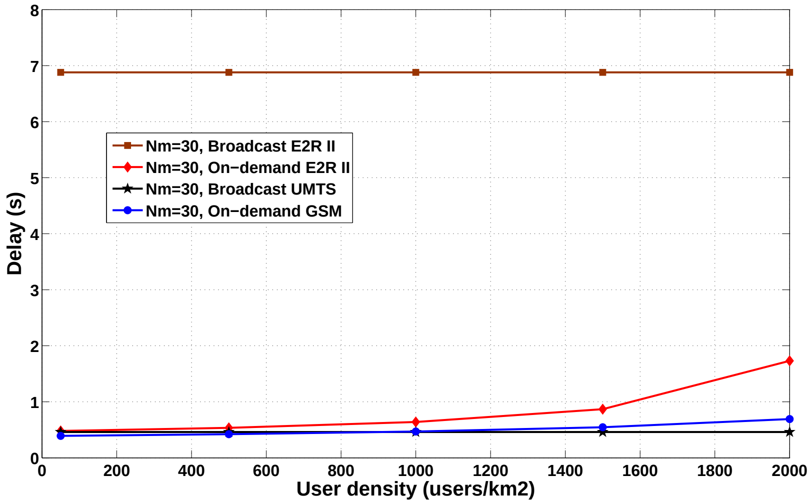

Figure 5.9: Total delay as a function of the user density with the number of meshes (N_m) equal to 30.

As we can see in Figure 5.9, with the increase in the number of meshes, the time that MSs need to decode the cognitive channel in the Broadcast approach of the E2R II project becomes longer (i.e. users have to listen the DBCPC for a long time until they retrieve the information of their mesh) [61]. However, in the case of UMTS, this phenomenon does not occur because mobile users only have to decode their corresponding SIB or SIBs instead of decoding all the DBCPC.

In Figure 5.8 and Figure 5.9, we observe that when the number of meshes is increased, the performance in terms of delay to retrieve the CPC or CBC information using the On-demand approaches (E2R II and GSM) is not affected.

In Figure 5.10, the total delay to obtain the information of the desired mesh as a function of the transmitter range of the cognitive channel (CBC or CPC) was compared. The user density was set to 2000 users/km^2 and the mesh size was fixed to 100m x 100m. Therefore, with the increase of the transmitter range, the number of meshes covered by the cognitive channel (CPC or CBC) and the total amount of requests also increase.

As we observed previously in Figure 5.8 and Figure 5.9, the On-demand proposals are sensitive to the user density and as noted in [61], there is a fixed limit in terms of load (request per second) given by the M/D/1 queue system of the On-demand approach in the E2R II project. This is the cause of instability when the CPC range exceeds the barrier of 1.05 km in Figure 5.10. In the case of GSM, this instability does not occur at the same range because the bit rates (R_b) and the block recurrences (T_S) are different in both implementations. In Figure 5.10, we observe again that our propositions using GSM and UMTS obtain the shortest delay.

Finally, the last comparison to show the performance of the E2R II implementations and our propositions is plotted in Figure 5.11. This figure analyzes the required down link bit rate as a function of the transmitter range of the cognitive channel (CBC or CPC). The maximum delay in retrieving the CBC and the CPC was set to 5 seconds and the same parameters of mesh size and user density considered in Figure 5.10 were used to plot Figure 5.11.

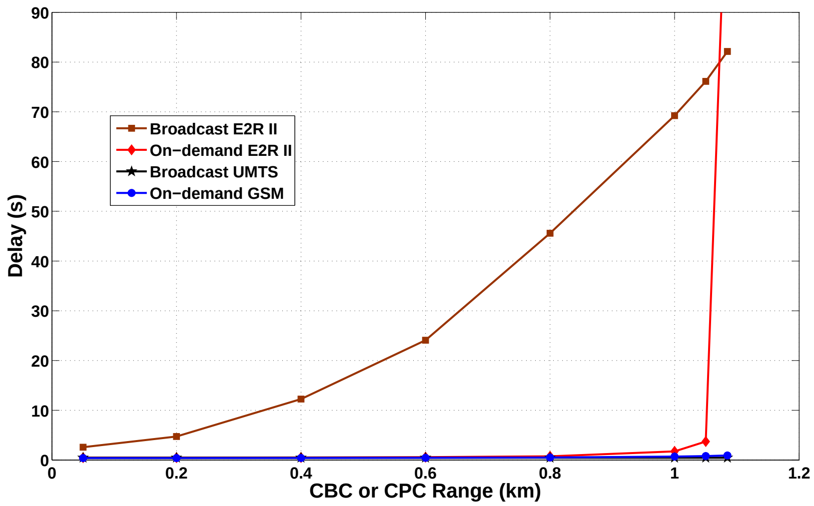

Figure 5.10: Total delay as a function of the range of the cognitive channel (CBC or CPC) for a mesh size of 100m x 100m.

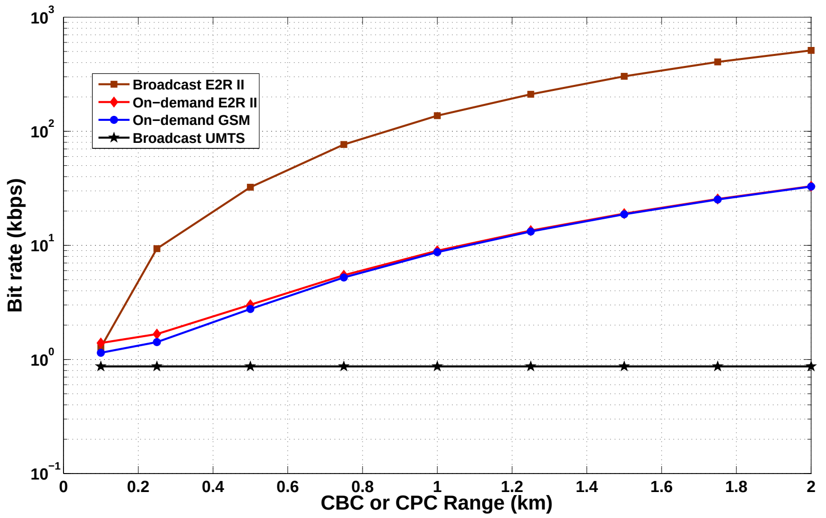

Figure 5.11: Required net bit rate as a function of the cognitive channel (CBC or CPC) range to guarantee a maximum delay of 5s for a mesh size of 100m x 100m.

As we can see in Figure 5.11, the required bit rate using UMTS signaling is the lowest and is always constant. This is because this approach is neither sensitive to the number of meshes (unlike the Broadcast approach in the E2R II project) nor the number of requests sent by the users (unlike the On-demand proposal in the E2R II project and in our GSM approach).

5.6 Conclusions

This chapter has proposed the utilization of GSM logical channels (RACH, AGCH and TCH) and UMTS signaling (MIB and SIBs) of the Broadcast Channel to transmit a Cognitive Beacon Channel. The CBC can help to improve spectrum awareness and to facilitate the connection to the network by conveying signaling to mobile users in a multi-RAT environment (e.g. 3GPP, Wi-Fi, WiMAX and future cognitive radio systems). Taking advantage of this spectrum knowledge, the purpose of the CBC is to transmit the necessary information to allow DSA using a centralized architecture. The results of our analysis show that our proposals, using logical channels of GSM and UMTS outperform, respectively, the On-demand and the Broadcast CPC implementations of the E2R II project.

The principal motivation of this proposition is to obtain benefit from existing 3GPP technologies proved to be efficient and accepted worldwide. As we described in this chapter, using the information conveyed by the CBC, spectrum owners can control the access to their spectrum by signaling authorized spectrum bands (or spectrum holes) that can be used by SUs. In that sense, owners of temporarily released frequency bands can economically promote the release of frequency bands for the sake of improved spectrum usage. Consequently, cellular operators could actually benefit from the secondary usage of their spectrum if renting procedures are carried out.

Chapter 6

Poisson Point Process and Interference Temperature Model in Cognitive Radio Networks

As we have presented in this thesis, DSA and CR technology have emerged as new mechanisms capable to improve the spectrum efficiency and performance by allowing flexible usage of the radio spectrum. In the last years, two different strategies of spectrum sharing have been identified. One is through opportunistic spectrum access, known as Overlay and the other is through the use of low power spread-spectrum, known as Underlay [9]. The Overlay approach is based on avoidance of PUs through the use of spectrum sensing and adaptive allocation. On the other hand in the Underlay approach, which is of interest in this chapter, the transmission of SUs is allowed in PUs bands, if the transmission power is low enough that it does not harm the PUs. As this approach imposes severe restrictions on transmitted power levels, it requires operating over ultra wide bandwidths to achieve good performances in terms of throughput. Under this framework, in November 2003, the concept of Interference Temperature (IT) was proposed by the FCC, as another way to dynamically manage and allocate spectrum resources [23]. The principal characteristic of the IT model, as an Underlay approach, is the fact that in this model SUs attempt to coexist with PUs meanwhile, in other proposals for DSA (i.e. Overlay approaches), SUs try to avoid PUs signals [14].

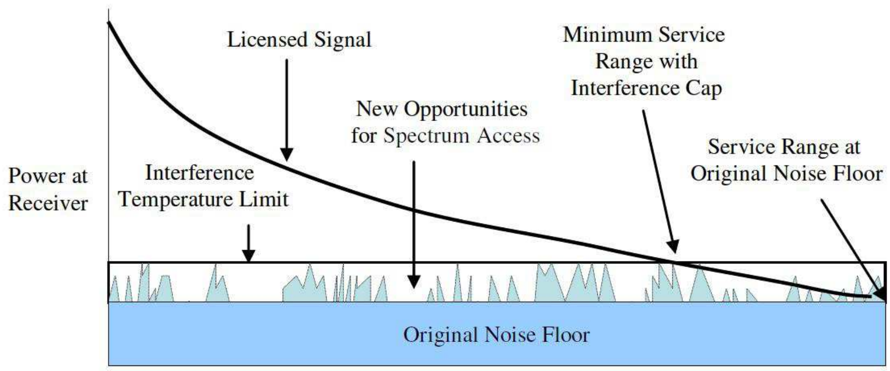

Figure 6.1: Interference Temperature model [23].

This section proposes the utilization of the Poisson point process as a new analytical method to be applied in the IT approach. For this purpose, we firstly develop a model for the RF environment. Afterwards, by the use of the the Poisson point process, we determine essential elements for the calculation of the achievable per-link capacity and the total capacity of a secondary network following the Ideal and the Generalized IT models. After concluding this mathematical analysis, we demonstrate the application of our model by a numerical example where, we consider the PU as a UMTS network and the SU as an UWB network. In addition, by the use of Concentration Inequalities we determine an upper bound on the outage probability of the primary network when the SUs transmit. Finally, we demonstrate the feasibility of our model by the analysis of the reference distance in the UMTS and WiMedia frequency bands.

The rest of the chapter is organized as follows. Section 6.1 describes the Ideal and the Generalized interference temperature models and details the physical features of the system. This section also provides a review on Poisson point process theory and Concentration Inequalities. In section 6.2, we present our model for the calculation of the SUs mean capacity and we develop a numerical analysis in a realistic scenario. Bounds of the outage probability of PUs using Concentration Inequalities are found in section 6.3. Section 6.4 presents an analysis of the mean interference, the allowed SUs transmission power and the mean capacity of SUs taking into account the reference distance. Finally, in section 6.5, we present our conclusions.

6.1 Preliminaries

6.1.1 Interference Temperature Model as Underlay technique for DSA

In the IT model, SUs equipped with cognitive radio technology must firstly sense the available spectrum band to compute the existing interference. In this approach, SUs treat PUs, other SUs, interference, and noise all as interference. Afterwards, they must adjust their transmission power to avoid raising the interference temperature above a predefined threshold which is assumed to be established by the FCC. This threshold represents the maximum quantity of interference that a PU can tolerate. Therefore, SUs must guarantee that the existing interference temperature, added to the interference caused by their transmissions, does not exceed the interference temperature limit (T_L).

The Interference Temperature $T_I(f_c, B)$ is defined as:

$$T_I(f_c, B) = \frac{P_I(f_c, B)}{kB},$$

where $T_I(f_c, B)$ is estimated in Kelvin, the average interference power P_I is measured in Watts and, centered at f_c, covers a bandwidth B measured in Hertz and k is the Boltzmann's constant.

In [14], two different interference temperature models were presented: the Ideal and the Generalized one. The Ideal model tries to limit interference specifically to PUs signals. Therefore, the a priori knowledge of PUs activity is needed. This model can be written as:

$$T_I(f_i, B_i) + \frac{M_i P}{kB_i} \leq T_L(f_i) \quad \forall\, 1 \leq i \leq n,$$

where P is the average power of SUs operating with the center frequency f_c and bandwidth B. The band [f_c−B/2, f_c+B/2] overlaps n PUs signals, with respective frequencies f_i

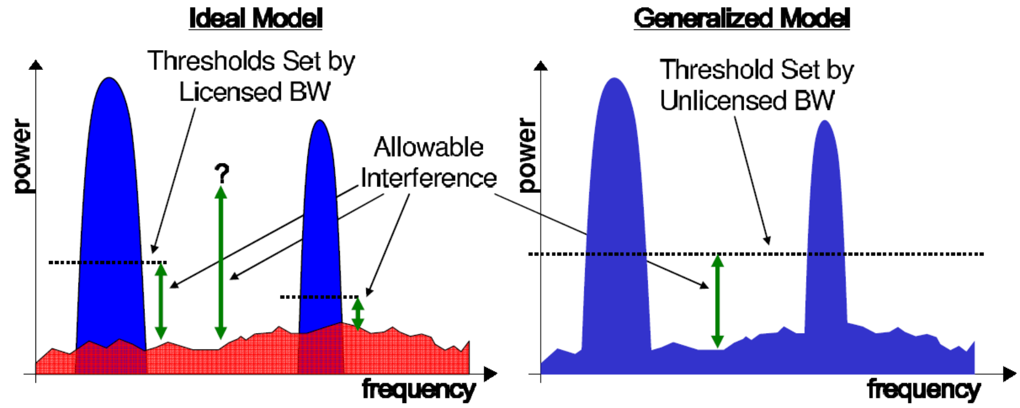

Figure 6.2: Ideal and Generalized interpretations of the Interference Temperature model [14].

and bandwidth B_i. T_L is the interference temperature limit. As the purpose of this model is to restrict the interference received by PUs, the constant M_i (with fractional value between 0 and 1) represents the attenuation between the primary receiver and the secondary transmitter. This constant is assumed to be fixed by a regulatory body.

For the Generalized model, the a priori knowledge of PUs activity is not required. So this model can be applied in the entire bandwidth regardless the exact location of the PUs signals. The interference temperature limit in the Generalized model can be expressed as following:

$$T_I(f_c, B) + \frac{MP}{kB} \leq T_L(f_c).$$

Here B is the entire frequency range, and not just PUs frequency band. Since the parameters of the PUs receivers are unknown, the constraint is in terms of SUs transmitter's parameters [14].

Figure 6.2 plots the Ideal and Generalized interpretations of the Interference Temperature Model.

6.1.2 Poisson Point Process

Poisson point processes are the basis of stochastic-geometry modeling of communication networks [4, 5]. This modeling consists of treating the given architecture of the network as random and analyzing it in a statistical way. Poisson point processes can model both static and dynamic systems. In the static case, communication devices do not move even if they are active or inactive. This approach represents a network where there is no control over the deployment of each element in the target region, therefore the number of elements and their positions are random. On the other hand, in dynamic systems with users independently located, the process represents a snapshot of the network. In the static and the dynamic systems the physical meaning of the network elements is preserved and reflected in the model but the geographical location of communication devices is no longer fixed but modeled by random points. Consequently, any particular detailed pattern of locations is no longer of interest. Instead, the method allows catching the essential spatial characteristics of the network performance through the intensities of these point processes.

In some cases the random number of users is over dimensioned under this hypothesis, since this system would allow an arbitrarily large number of users in a system where resources, such as power or bandwidth, are limited. More details on point processes can be found in [46, 17, 44, 43].

The main definitions and equations for the Poisson point processes used in our analysis were formerly presented in [18].

A configuration ϕ in $\mathbf{R}^k$ is a set $\{x_n,\, n \geq 1\}$ where for each $n \geq 1$, $x_n \in \mathbf{R}^k$, $x_n \neq x_m$ for $n \neq m$ and each compact subset of $\mathbf{R}^k$ contains only a finite subset of ϕ. We denote by $\Gamma_{\mathbf{R}^k}$ the set of configurations in $\mathbf{R}^k$. Equipped with the vague topology of discrete measures, $\Gamma_{\mathbf{R}^k}$ is a complete, separable metric space. A point process ω is a random configuration with values in $\Gamma_{\mathbf{R}^k}$, i.e., $\omega = \{X_n, n \geq 1\} \in \Gamma_{\mathbf{R}^k}$. For a Borel set $A \subset \mathbf{R}^k$, we denote by $\omega(A)$ the random variable which counts the number of atoms of ω in A:

$$\omega(A) = \sum_{n \geq 1} \mathbf{1}_{X_n(\omega) \in A},\ n \in \mathbf{N} \cup \{+\infty\}.$$

Poisson point processes are particular instances of point processes such that:

Definition 1. *Let λ be a σ finite measure on $\mathbf{R}^k$. A point process ω is a Poisson process of intensity λ whenever the following two properties hold.*

i) For any compact subset $A \in \mathbf{R}^k$, $\omega(A)$ is a Poisson random variable of parameter $\Lambda(A) = \int_A \lambda(dx)$, i.e.,

$$\mathbf{P}(\omega(A) = k) = e^{-\Lambda(A)} \frac{\Lambda(A)^k}{k!}.$$

ii) For any disjoint subsets A and $B \subset \mathbf{R}^k$, the random variables $\omega(A)$ and $\omega(B)$ are independent.

The notion of point process can be extended to configurations in $\mathbf{R}^k \times X$ where X is a subset of $\mathbf{R}^m$. A configuration is then typically of the form $\{(x_n,\, y_n),\, n \geq 1\}$ where for each $n \geq 1$, $x_n \in \mathbf{R}^k$ and $y_n \in X$. We keep writing $(x_n,\, y_n)$ as a couple, though it could be thought as an element of $\mathbf{R}^{k+m}$, to stress the asymmetry between the spatial coordinate x_n and the mark y_n. For a marked point process, the set of locations is denoted by $\omega = \{X_n,\, n \geq 1\}$ and the set of both locations and marks by $\omega' = \{(X_n,\, Y_n),\, n \geq 1\}$. A marked point process with position dependent marking is a marked point process for which the law of Y_n, the mark associated to the atom located at X_n, depends only on X_n through a kernel K:

$$\mathbf{P}(Y_n \in B \,|\, \omega) = K(X_n,\, B),\ \text{for any } B \subset X.$$

If K is a probability kernel, i.e., if $K(x,\, X) = 1$ for any $x \in \mathbf{R}^k$ then it is well known that ω' is a Poisson process of intensity $K(x,\, \mathrm{d}y)\mathrm{d}\lambda(x)$ on $\mathbf{R}^k \times \mathbf{R}^m$. For $f : \mathbf{R}^k \times \mathbf{R}^m \to \mathbf{R}$ a measurable non-negative function, let

$$F = \int f \, \mathrm{d}\omega' = \sum_{n \geq 1} f(X_n,\, Y_n).$$

The Laplace transform of F is given by [72]:

$$\mathbb{E}\left[e^{-sF}\right] = \exp\left(-\int (1 - e^{-sf(x,y)}) K(x,\, \mathrm{d}y) d\lambda(x)\right) \tag{6.1}$$

As consequence, we obtain the well known and useful Campbell formula:

Theorem 1. *Let ω' be a marked Poisson process on $\mathbf{R}^k \times \mathbf{R}^m$. Let λ be the intensity of the underlying Poisson process and K the kernel of the position dependent marking. Then,*

$$\mathbb{E}[F] = \int_{\mathbf{R}^k \times \mathbf{R}^m} f(x,\, y)\, K(x,\, dy) d\lambda(x).$$

Definition 2. *For $F : \Gamma_{\mathbf{R}^k} \to \mathbf{R}$, for any $x \in \mathbf{R}^k$, we define*

$$D_x F(\omega) = F(\omega \cup \{x\}) - F(\omega).$$

Note that for $F = \int f \mathrm{d}\omega$, $D_x F = f(x)$, for any $x \in \mathbf{R}^k$. The main result on which our inequalities are based, is quoted from [34, 78] :

Theorem 2 (Concentration inequality)**.** *Assume that ω is a marked Poisson process on $\mathbf{R}^k \times \mathbf{R}^m$ of intensity λ and kernel $K(x,y)$. Let $f : \mathbf{R}^k \to \mathbf{R}^+$ a measurable non-negative function and let*

$$F(\omega) = \int f \;\; K(x,dy)\omega(dx) = \sum_{n \geq 1} f(X_n(\omega), Y_n(\omega)).$$

Assume that $|D_x F(\omega)| \leq s$ for any $x \in \mathbf{R}^k$. Let

$$m_F = \mathbb{E}[F] = \int f(x) \quad K(x,dy)\lambda(dx)$$

and

$$v_F = \int |D_x F(\omega) \;\, K(x,dy)|^2 \lambda(dx).$$

Then, for any $t \in \mathbf{R}^+$,

$$\mathbf{P}(F - m_F \geq t) \leq \exp\left(-\frac{v_F}{s^2}\; g\left(\frac{t\, s}{v_F}\right)\right), \tag{6.2}$$

where $g(x) = (1+x)\ln(1+x) - x$.

6.1.3 Physical features of the system

We consider a system in which the position of users are given by Poisson point processes. So the Poisson point process, ω_j on $\mathbf{R}^2$, with intensity λ_j, represents the positions of user of kind j. Moreover, their individual transmission power is given by μ_j. We associate PUs to the index $j = 1$, SUs that are transmitting to $j = 2$ and interferers or the base interference to $j = 3$. Besides, the marked Poisson point process ω_2' on $\mathbf{R}^2 \times \mathbf{R}^2$ associates, for each point X_i from ω_2 another point Y_i uniformly distributed over a disc $D_2(X_i)$ of radius R_2 centered at X_i, in such way that Y_i is the position of the SU receiving the signal of a SU placed at X_i.

Let $p_j(x,y)$ be the received power experimented by a user located at $y \in \mathbf{R}^2$ with respect to a transmitter of kind j at $x \in \mathbf{R}^2$. We use the propagation power loss as the simplified model for path loss being a function of distance. This is based on Hata's model:

$$p_j(x,y) = \min\left(\mu_j, \mu_j\left(\frac{r_0}{\|x-y\|}\right)^{\alpha}\right), \tag{6.3}$$

where r_0 and α are positive constants. In this approximation α is the path loss coefficient and we take $r_0 = 1$, where r_0 is a reference distance from the antenna far field. Due the

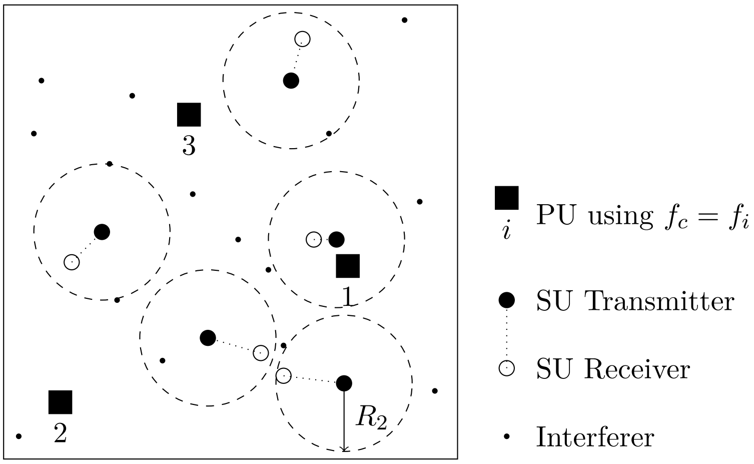

Figure 6.3: Example of a configuration with PUs, SUs (transmitters and receivers) and interferers.

strong attenuation as a function of distance, the existence of the noise and the sensibility of the SUs, we assume that SUs are only able to communicate with some other ones closer than a distance R_2. The total interference power experimented by a point x with respect to all users of kind j is given by $Q_j(x)$. We illustrate a possible realization of the model in Figure 6.3, representing all kinds of users. Note that, to each SU transmitting, it must exist a SU receiving, which does not cause interference. Along this work, since R_2 is considered small enough to consider that a pair of SUs (i.e. SU transmitter and SU receiver) causes the same interference to other users, so, in terms of interference, SUs are considered as a single point.

6.2 Secondary User Mean Capacity

In this section, we consider that the constraint given by the temperature model holds for the mean of the quantities, and then, based on the physical model we analyze the mean capacity of the network. First, we develop the calculations and then we present the numerical results.

6.2.1 Calculations of the mean capacity

The mean total network capacity of the SUs is based on the mean per-link capacity and the constraints of the IT model. Therefore, taking into account the IT model restrictions, we develop the necessary expressions to estimate the mean capacity for the Ideal and the Generalized IT models. In order to achieve this, we consider the following lemma.

Lemma 1. *Let ω_j be a Poisson point process with intensity measure λ representing the positions of active users of kind j over $\mathbf{R}^2$ transmitting with a power μ_j. If $Q_j(x)$ is the total interference power experimented by a point $x \in \mathbf{R}^2$, then*

$$\mathbb{E}\left[Q_j(x)\right] = \frac{\mu_j \lambda_j \pi \alpha}{(\alpha - 2)}. \tag{6.4}$$

Proof. Given the invariance under translation of a stationary Poisson point process denoted by: $\mathbb{E}\left[Q_j(x)\right] = \mathbb{E}\left[Q_j(0)\right]$. So, it suffices to use Theorem 1 for $f(x) = p_j(x, 0)$ as defined in Eq. 6.3:

$$\begin{aligned}
\mathbb{E}\left[Q_j(0)\right] &= \mathbb{E}\left[\sum_{X_i \in \omega} p_j(X_i, 0)\right] \\
&= \int_{\mathbf{R}^2} p_j(x,0)\lambda_j(x)dx \\
&= \lambda_j \int_0^{2\pi}\int_0^{\infty} \min\left(\mu_j, \mu_j\left(\frac{1}{r}\right)^{\alpha}\right) r dr d\theta \\
&= \mu_j\lambda_j 2\pi\left(\int_0^1 r dr + \int_1^{\infty} \frac{1}{r^{\alpha}} r dr\right) \\
&= \frac{\mu_j\lambda_j\pi\alpha}{(\alpha-2)},
\end{aligned}$$

concluding the proof. □

For the Ideal case, we must calculate the maximum allowed SUs Transmission Power μ_2^{id}. As noted in section 6.1.1, the Ideal interference temperature model attempts to limit interference specifically to licensed signals. This means that the objective is to guarantee that

$$\frac{P_I(f_i, B_i)}{kB_i} + \frac{M_i P}{kB_i} \leq T_L(f_i).$$

The left side of the equation represents the total temperature allowed to interferers with respect to a PU using the center frequency f_i, placed at x_i, and we can rewrite it as

$$Q_2(x) + Q_3(x) \leq T_L(f_i)kB_i.$$

To guarantee that this inequality holds at least for the mean of interferences, we take the mean in both sides, using Lemma 1 and solving for μ_2^{id}, resulting in the maximum allowed transmission power to be used by SUs:

$$\mu_2^{id} \leq \frac{(\alpha-2)T_L kB_i - \lambda_3\mu_3\pi\alpha}{\lambda_2\pi\alpha}. \tag{6.5}$$

Now we calculate the maximum mean allowed SUs transmission power μ_2^{gen} following the Generalized model. As noted in section 6.1.1, the main difference between the Generalized and the Ideal model is that in the Generalized model, the a priori knowledge of PUs activity is not required. Thus, the Generalized model is written as:

$$\frac{P_I(f_c, B)}{kB} + \frac{MP}{kB} \leq T_L(f_c).$$

As the parameters of the PUs receivers are unknown, the constraint is in terms of the parameters of the SUs. Therefore, B is the entire SUs frequency range and not just PUs frequency band. Again, since SUs treat PUs, other SUs, interference, and noise all as interference, we notice that for the Generalized model we take into account the power from the others PUs (averaging the PUs power over the SUs bandwidth) and evaluates T_L over the entire frequency range B. If the analyzed PU is placed at $x \in \mathbf{R}^2$, then we rewrite this condition as a function of Q_j:

$$\frac{B_i}{B}Q_1(x) + Q_2(x) + Q_3(x) \leq T_L(f_c)kB.$$

Assuring that, in average, this inequality holds, we take the mean, we applying Lemma 1 and solving for μ_2^{gen}, we obtain:

$$\mu_2^{gen} \leq \frac{(\alpha-2)T_L kB - \lambda_3\mu_3\pi\alpha - \frac{B_i}{B}\lambda_1\mu_1\pi\alpha}{\lambda_2\pi\alpha}. \tag{6.6}$$

Since we are interested in the calculation of the capacity using the Shannon-Hartley theorem [63], the per-link capacity $C(x,y)$ of a user at $x \in \mathbf{R}^2$, receiving a signal from a user at $y \in \mathbf{R}^2$ such that $\|x-y\| \leq R_2$, is given by:

$$C(x,y) = B\log_2\left(1 + \frac{p_2(x,y)}{\mathbb{E}\left[I(x)\right]}\right).$$

The mean interference power $\mathbb{E}\left[I(x)\right]$ caused by the interferers, other SUs and PUs at x, is given by

$$\mathbb{E}\left[I(x)\right] = \frac{B_i}{B}Q_1(x) + Q_2(x) + Q_3(x).$$

Since y is uniformly distributed around x, then x is uniformly distributed over y and the mean capacity per link $C(x)$ in the disc is given by:

$$C(x) = \int B\log_2\left(1 + \frac{p_2(x,y)}{\mathbb{E}\left[I(x)\right]}\right)\frac{\mathbb{1}_{\{\|x-y\|\leq R_2\}}}{\pi R_2^2}dy. \tag{6.7}$$

By Lemma 1, $\mathbb{E}\left[Q_j(x)\right]$ does not depend on y, and $p_2(x,y)$ depends only on the distance between x and y, so $C(x) = C$. Let us define

$$K \triangleq \frac{\mu_2}{\mathbb{E}\left[I(x)\right]} = \frac{\mu_2(\alpha-2)}{\pi\alpha\left(\frac{B_i}{B}\mu_1\lambda_1 + \mu_2\lambda_2 + \mu_3\lambda_3\right)}. \tag{6.8}$$

Then, we can rewrite C as follows:

$$C = \int_0^{R_2}\int_0^{2\pi}\frac{B}{\pi R_2^2}\log_2\left(1 + K\min(1, r^{-\alpha})\right) r d\theta dr. \tag{6.9}$$

Defining $h : \mathbf{R}_+ \times (2,\infty) \to \mathbf{R}_+$ as follows

$$h(r,t) \triangleq \int_0^r \ln\left(1 + \frac{1}{x^t}\right) x\, dx, \tag{6.10}$$

we rewrite Eq. 6.9 as

$$C = \frac{2BK^{\frac{2}{\alpha}}}{R_2^2\ln(2)}\left[\frac{\ln(1+K)}{2K^{\frac{2}{\alpha}}} + h\left(\frac{R_2}{K^{\frac{1}{\alpha}}}, \alpha\right) - h\left(\frac{1}{K^{\frac{1}{\alpha}}}, \alpha\right)\right]. \tag{6.11}$$

The per-link capacity in the Ideal case, C^{id}, is obtained taking $\mu_2 = \mu_2^{id}$, while the one in the Generalized case, C^{gen}, results of taking $\mu_2 = \mu_2^{gen}$. It is possible to find analytical expressions for $h(r,t)$ when t is an integer.

Lemma 2. *Let $\beta_n = \pi(2n-1)$ for n integer. For t an odd integer, the expression of $h(r,t)$ is given by:*

$$h(r,t) = \frac{r^2}{2}\ln\left(1+\frac{1}{r^t}\right) - \frac{1}{2}\ln\left(1+\frac{1}{r}\right) - \frac{1}{2}\sum_{n=1}^{\lfloor t/2\rfloor}\left(\cos\left(\frac{2\beta_n}{t}\right)\ln\left(\frac{1}{r^2}+\frac{2}{r}\cos\left(\frac{\beta_n}{t}\right)+1\right) + 2\sin\left(\frac{2\beta_n}{t}\right)\arctan\left(\frac{r\sin(\frac{\beta_n}{t})}{1+r^2\cos(\frac{\beta_n}{t})}\right)\right).$$

If $t/2$ is odd, we obtain the following expression for $h(r,t)$:

$$h(r,t) = \frac{r^2}{2}\ln\left(1+\frac{1}{r^t}\right) + \frac{1}{2}\ln\left(1+\frac{1}{r^2}\right) - \frac{1}{2}\sum_{n=1}^{\lfloor t/4\rfloor}\left(\cos\left(\frac{2\beta_n}{t}\right)\ln\left(\frac{1}{r^4}+\frac{2}{r^2}\cos\left(\frac{2\beta_n}{t}\right)+1\right) - 2\sin\left(\frac{2\beta_n}{t}\right)\arctan\left(\frac{r^2\sin(\frac{2\beta_n}{t})}{1+r^4\cos(\frac{2\beta_n}{t})}\right)\right),$$

and if $t/2$ is pair, then

$$h(r,t) = \frac{r^2}{2}\ln\left(1+\frac{1}{r^t}\right) - \frac{1}{2}\sum_{n=1}^{\lfloor t/4\rfloor}\left(\cos\left(\frac{2\beta_n}{t}\right)\ln\left(\frac{1}{r^4}+\frac{2}{r^2}\cos\left(\frac{2\beta_n}{t}\right)+1\right) - 2\sin\left(\frac{2\beta_n}{t}\right)\arctan\left(\frac{r^2\sin(\frac{2\beta_n}{t})}{1+r^4\cos(\frac{2\beta_n}{t})}\right)\right).$$

Proof. First we differentiate the right-hand terms with respect to r and after several elementary but tedious manipulations we have:

$$\frac{\partial h(r,t)}{\partial r} = r\ln\left(1+\frac{1}{r^t}\right)\cdot$$

Then, it suffices to use the Fundamental Theorem of Calculus on the right-hand term of Eq. 6.10 to obtain that

$$\frac{\partial}{\partial r}\left(\int_0^r \ln\left(1+\frac{1}{x^t}\right)x\,dx\right) = r\ln\left(1+\frac{1}{r^t}\right)\cdot$$

So both sides of Eq. 6.10 differ at most by a constant. Since these two functions are analytical at $r=0$, it suffices to see that

$$h(0,t) = \int_0^0 \ln\left(1+\frac{1}{x^t}\right)x\,dx = 0,$$

thus the proof is concluded. □

We can use this lemma to obtain expressions for two typical values of α.

Lemma 3. *The expression of $h(r,3)$ is given by:*

$$h(r,3) = \frac{1}{4}\ln\left(\frac{r^2-r+1}{r^2+2r+1}\right) + \frac{\sqrt{3}\pi}{12} + \frac{r^2}{2}\ln\left(1+\frac{1}{r^3}\right) + \frac{\sqrt{3}}{2}\arctan\left(\frac{(2r-1)}{\sqrt{3}}\right)$$

and the expression of $h(r,4)$ is the following one

$$h(r,4) = \arctan r^2 + \frac{r^2}{2}\ln\left(1+\frac{1}{r^4}\right).$$

Then, it is possible to calculate the mean total SUs capacity C_{total} in a secondary cell of radius R, defining a disc D. Using theorem 1 on the marked Poisson point process ω_2', we obtain:

$$C_{total} = \int\int_D C(x,y)\frac{\mathbb{1}_{\{\|x-y\|\leq R_2\}}}{\pi R_2^2}dy\lambda dx.$$

However, Eq. 6.11 shows that the inner integral does not depend on x, so we can rewrite Eq. 6.12 as

$$C_{total} = C\int_D \lambda dx = C\lambda\int_D dx = C\lambda\pi R^2. \tag{6.12}$$

Applying the maximum allowed SUs transmission power μ_2, obtained by the IT model, we obtain the total capacity of a network. We denote C_{total}^{id} for the Ideal case when $\mu_2 = \mu_2^{id}$ and C_{total}^{gen} when $\mu_2 = \mu_2^{gen}$.

6.2.2 Numerical Analysis of the Mean Capacity of the Secondary Network

In this section, we demonstrate the application of the equations previously developed. We examine the achievable per-link capacity C of a secondary network and the total capacity C_{total} of this network under some typical situations. For this analysis, we consider the PU as a UMTS network and the SU as an UWB network, WiMedia. We develop this analysis following the Ideal and the Generalized IT models.

Concerning to UMTS or the primary network, we consider a PUs intensity λ_1 of 0.02 users per km^2. This value corresponds to 60 active MSs in a macro-cell with radius equal to 30 km. According to [74], the transmission power μ_1 of the UMTS MSs is equal to 250 mW or 24dBm and the PUs bandwidth B_i is 5 MHz.

For the secondary network or WiMedia, the bandwidth B is 528 MHz [77] and we consider R_2 equal to 10 m as the communication range of the SUs (i.e. maximum distance between a secondary transmitter and a secondary receiver). This value corresponds to the range of the IEEE 802.15.3a specification using UWB. Depending on the interference temperature model, the transmission power μ_2 is defined as μ_2^{id} or μ_2^{gen} and the SUs intensity λ_2 is equal to 3 users per m^2.

The IT model includes not only power from primary and secondary transmitters but also the interference power of another source of interference known as base interference. However, to provide an upper bound on the achievable capacity by the secondary network, we consider environments with no interference (i.e. $\lambda_3 = 0$). Finally, the last parameter to complete the system is Interference Temperature Limit T_L. This parameter was set

Users Type	Users Intensity (λ_j)	System Bandwidth	Transmission Power (μ_j)	Cell Radius
PU UMTS	0.02 users/km^2	5 MHz	250 mW 24 dBm	30 km
SU WiMedia	3 users/m^2	528 MHz (Ideal model) 585 MHz (Generalized model)	μ_2^{id} μ_2^{gen}	100 m
Base Interference	0 users	N/A	N/A	N/A

Table 6.1: Users Parameters.

to 50000 K, same as other studies of the IT model developed to quantify the capacity achieved by the secondary network and the interference caused to the primary network such as [14]. Table 6.1 summarizes the principal parameters and the variables used in our analysis.

6.2.2.1 Mean Capacity of the Secondary Network

Considering the parameters presented before, for the Ideal case we use Lemma 3 to obtain the SUs capacity for $\alpha = 3$ and $\alpha = 4$. For $\alpha = 3$, we obtain an average SUs transmission power (μ_2^{id}) of -99 dBm. With this SU power, the achievable per link capacity C^{id} using Eq. 6.11 is 5.8 kbps. Therefore, the total achievable capacity C_{total}^{id} of the secondary network in a secondary cell of radius R is equal to 545 Mbps. This value is obtained using Eq. 6.12. In the case of $\alpha = 4$, the average SUs transmission power is -97.37 dBm and the achievable per-link capacity C^{id} is 9.22 kbps. Thus, the total achievable capacity C_{total}^{id} for the case $\alpha = 4$ is 869 Mbps.

For the Generalized model, with a SUs bandwidth equal to 528 MHz, the communication between SUs is not possible. To allow the transmission of SUs we must increase the bandwidth B of the secondary network, which is in fact one of the characteristics of WiMedia's medium access control (MAC) layer [76]. The WiMedia MS incorporates a MAC layer providing multimedia QoS and a physical layer based on multi-band orthogonal frequency-division multiplexing (MB-OFDM). This technology is well known to have robust link characteristics while the multi-band aspect allows spectrum flexibility and support different channel modes. WiMedia's MAC layer uses a bandwidth reservation system called Distributed Reservation Protocol (DRP). The DRP provides a bandwidth reservation system which assures QoS support for multimedia traffic. This ensures that the streaming media will continue to have the bandwidth it needs once a reservation is established and without interference from other users [76]. Therefore and in order to study the performance of the Generalized model, the bandwidth B of the secondary network was increased of 57 MHz. So, we increase the SUs bandwidth from 528 MHz (i.e. minimum channel bandwidth of WiMedia systems) to 585 MHz.

Considering the same parameters used for the Ideal case, but now with a SUs bandwidth B of 585 MHz, applying again Lemma 3 with a path loss exponent $\alpha = 3$, we obtain analytically an average SUs transmission power μ_2^{gen} of -104 dBm. With this SU power, the achievable per link capacity C^{gen} using Eq. 6.11 is 2.22 kbps. Therefore, the total achievable capacity C_{total}^{gen} using Eq. 6.12 of the secondary network present in a cell with 100 m radius R is 209 Mbps. In the case of $\alpha = 4$, we obtain better performances compared

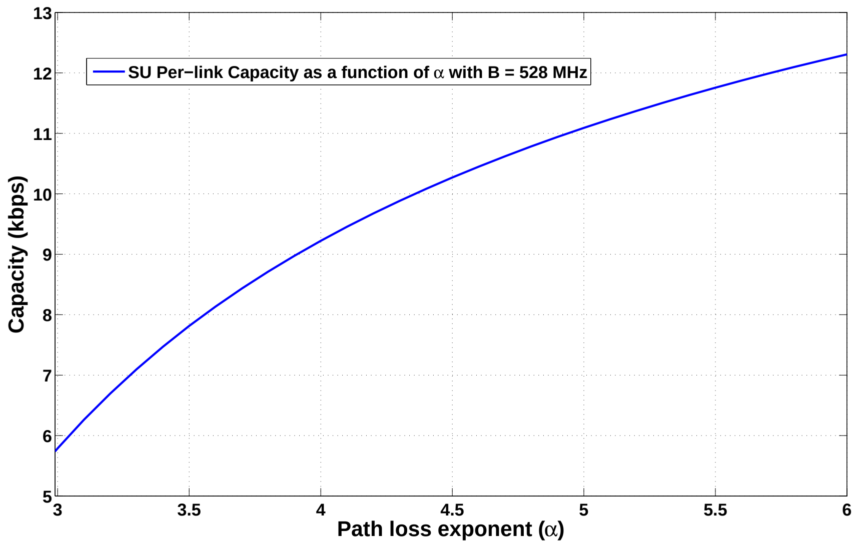

Figure 6.4: Mean SU per-link capacity (kbps) as a function of the path loss exponent α for the Ideal case with a SUs intensity λ_2 equal to 3 users per m^2.

to the case $\alpha = 3$. The average SUs transmission power is -81.44 dBm and the achievable per-link capacity C^{gen} is 297 kbps. Thus, the total achievable capacity C^{gen}_{total} for the case $\alpha = 4$ is 27.9 Gbps.

6.2.2.2 Mean Capacity of the Secondary Network as a Function of the Path Loss Exponent

In order to study the behavior of the achievable per-link capacity of the SUs following the Ideal and the Generalized models, in Figure 6.4 and Figure 6.5 we analyze the performance of C in Eq. 6.11 as a function of the path loss exponent α. These figures present the achievable capacities C^{id} and C^{gen} for typical values of α. Therefore, we consider values from $\alpha = 3$ to $\alpha = 6$. These path loss exponents are used in relatively lossy environments (i.e. $\alpha = 3$) and in indoor environments (i.e. from $\alpha = 4$ to $\alpha = 6$).

To understand the behavior of C^{id} and C^{gen} as a function of α plotted in Figure 6.4 and Figure 6.5, we must take into account two different effects: the transmission effect and the reception one. In the transmission effect, with the increase of α, mobile users generate less interference and hence, the available transmission power of the SUs μ_2^{id}, μ_2^{gen} and the value of K also increase. These results are justified by Lemma 1, Eq. 6.5, Eq. 6.6 and Eq. 6.8. On the other hand, the reception effect occurs due to the attenuation of the radio signal as it propagates through space. Here, the received signal decreases with the increase of the path loss exponent. In this case, the reception effect appears for values of α higher than 6. With the SU total per-link capacity ranging from 5.8 kbps to 12.31 kbps, from Figure 6.4, we can observe that the Ideal IT model is robust against the variation of path loss exponent α. However, from Figure 6.5, we notice that the Generalized IT model is more sensitive against the different values of α. In order to have a system more robust it suffices to increase the channel bandwidth of the secondary network.

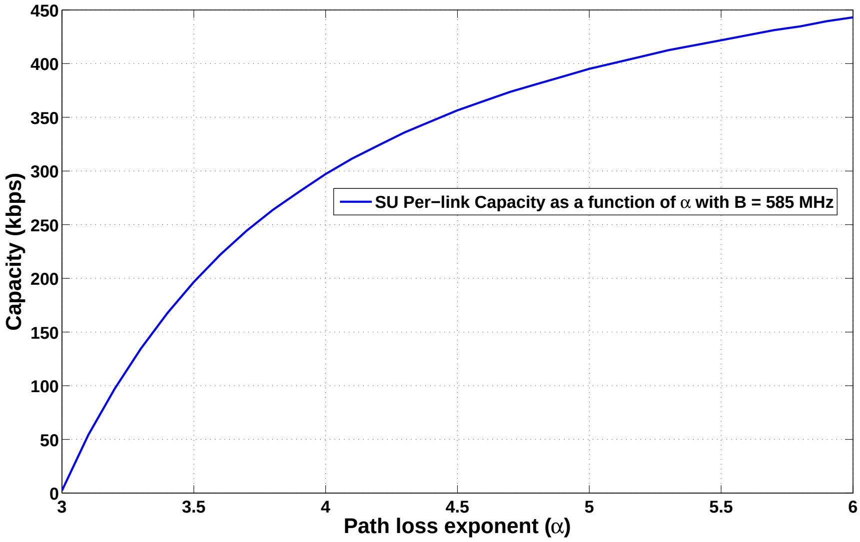

Figure 6.5: Mean SU per-link capacity (kbps) as a function of the path loss exponent α for the Generalized case with a SUs intensity λ_2 equal to 3 users per m^2.

6.2.2.3 Mean Capacity of the Secondary Network as a Function of the SUs Intensity

Now, using the parameters presented before, we analyze the behavior of the achievable capacity obtained by the secondary network when the SUs intensity λ_2 is increased (i.e. when different load conditions are considered). Figure 6.6 presents the achieved mean SU per-link capacity as a function of the SUs intensity following the Ideal IT model. As we can see in this figure, with the increase of the SUs intensity the allowable SUs transmission power μ_2^{id} decreases and hence, the achievable SUs capacity is diminished. These results can be verified in Eq. 6.8 and Eq. 6.9. We also notice in this figure that the achievable per-link capacity in the case of $\alpha = 4$ is slightly higher compared to the case $\alpha = 3$. In the case of the mean total secondary network capacity C_{total}^{id} as a function of the SUs intensity λ_2, the achieved capacity remains almost constant. For the Ideal case with $\alpha = 3$, the value of C_{total}^{id} was 545 Mbps and 869 Mbps for the case $\alpha = 4$. This behavior obey Eq. 6.12 presented in section 6.2.1.

Figure 6.7 and Figure 6.8 plot the achieved mean SU per-link capacity C^{gen} as a function of the SUs intensity for the Generalized IT model. Here again, in order to analyze the performance of the Generalized, model the SUs bandwidth B was increased from 528 MHz to 585 MHz. In Figure 6.7 and Figure 6.8 we observe the same behavior occurred for the Ideal case plotted in Figure 6.6. This is that the achieved mean SU per-link capacity is higher for the case $\alpha = 4$ than for the case $\alpha = 3$. These results are justified by Lemma 1, Eq. 6.5, Eq. 6.6 and Eq. 6.8. These expressions states that with the increase of α, MSs generate less interference and hence the available transmission power of the SUs μ_2^{id} or μ_2^{gen} and the value of K also increase. However, from Figure 6.7 and Figure 6.8, we confirm the behavior plotted in Figure 6.5, which indicates that the Generalized IT model is more sensitive to the path loss exponent α than the Ideal IT model considering this bandwidth. For the Generalized approach, in Figure 6.8 we notice that the maximum achievable mean

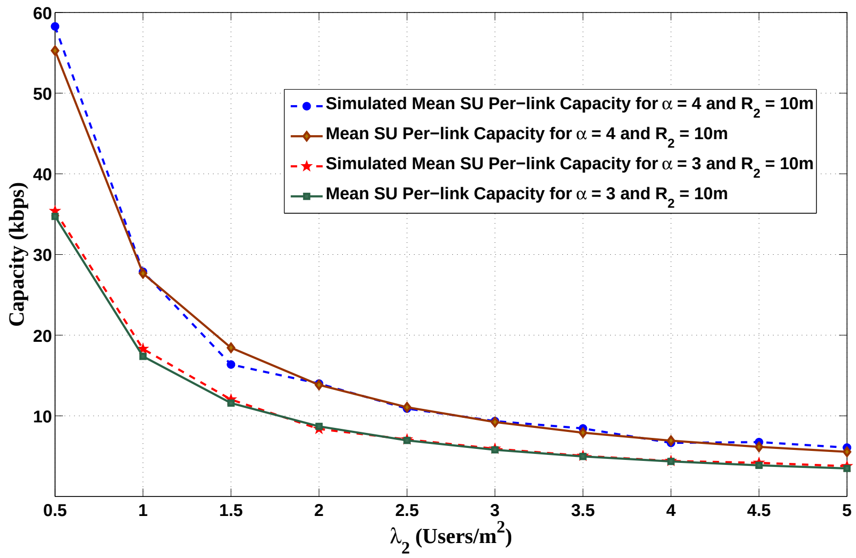

Figure 6.6: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for the Ideal IT model with $B = 528$ MHz for the cases $\alpha = 3$ and $\alpha = 4$.

SU per-link capacity for $\alpha = 4$ is 1.74 Mbps, while the maximum capacity for $\alpha = 3$ in Figure 6.7 is only 13.5 kbps. In the case of the mean total secondary network capacity C^{gen}_{total} as a function of the SUs intensity λ_2, the achieved capacity remains almost constant. We observed the same behavior in the Ideal model. For the Generalized case with $\alpha = 3$, the value of C^{gen}_{total} was 209 Mbps and 27.9 Gbps for the case $\alpha = 4$.

In order to directly compare the performances in terms of mean SU per-link capacity of the Ideal and the Generalized IT models, we have set the SUs bandwidth (B) to 585 MHz for both approaches in Figure 6.9 and Figure 6.10. Figure 6.9 plots the mean SU per-link capacity for the case $\alpha = 3$ and Figure 6.10 for the case $\alpha = 4$. As we can see in Figure 6.9 the Ideal model outperforms the Generalized approach for the case $\alpha = 3$. However, for $\alpha = 4$ the Generalized case obtains better performance due to the higher allowable SUs transmission power μ_2^{gen}. This behavior can be verified in Eq. 6.6.

6.3 Upper bound of PU Outage Probability

The latter section considers the constraint given by the Interference Temperature model with respect to the mean SUs transmission power. Although this result can present an idea of the power that SUs are allowed to use and so the SU network capacity, it cannot predict how probable the occurrence of an outage of the PU network is. Here, we use the concentration inequalities from Malliavin calculus to find an upper bound probability P_{sup} of outage of a PU due the interference caused by the SUs as a function of μ_2. Therefore, the system can be designed, such that the outage probability of the PUs is smaller than $q = P_{sup}$.

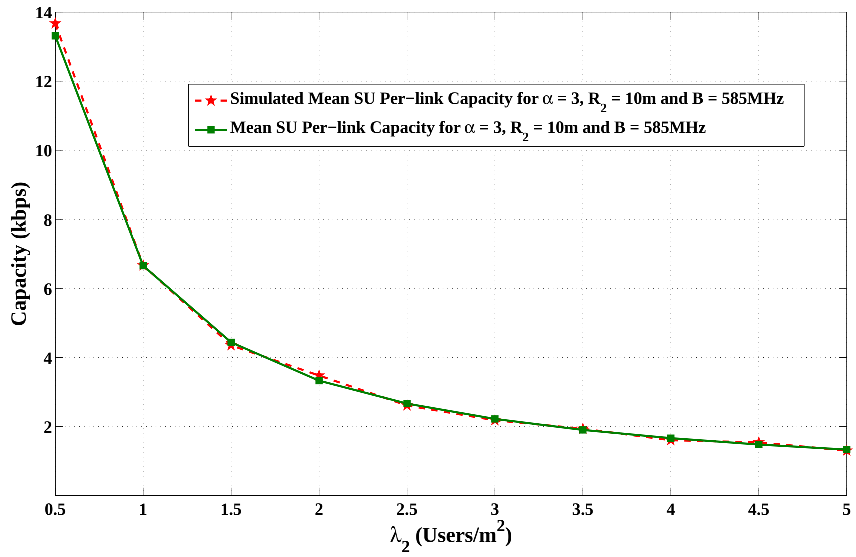

Figure 6.7: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for the Generalized IT model with $B = 585$ MHz for the case $\alpha = 3$.

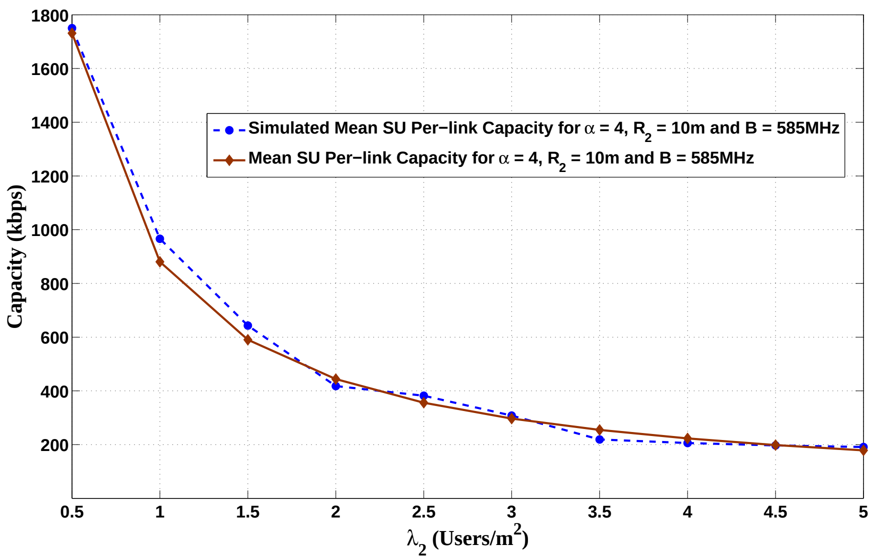

Figure 6.8: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for the Generalized IT model with $B = 585$ MHz for the case $\alpha = 4$.

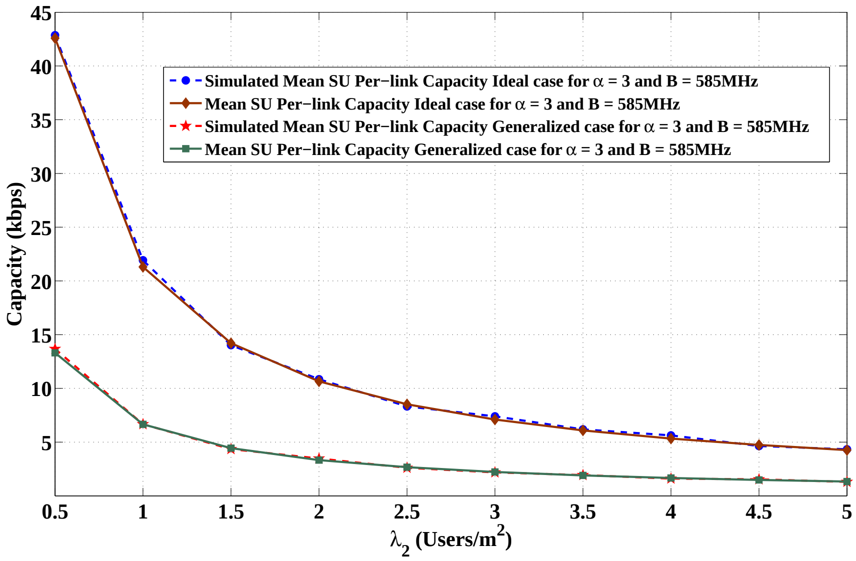

Figure 6.9: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for the Ideal and Generalized IT models with $B = 585$ MHz for the case $\alpha = 3$.

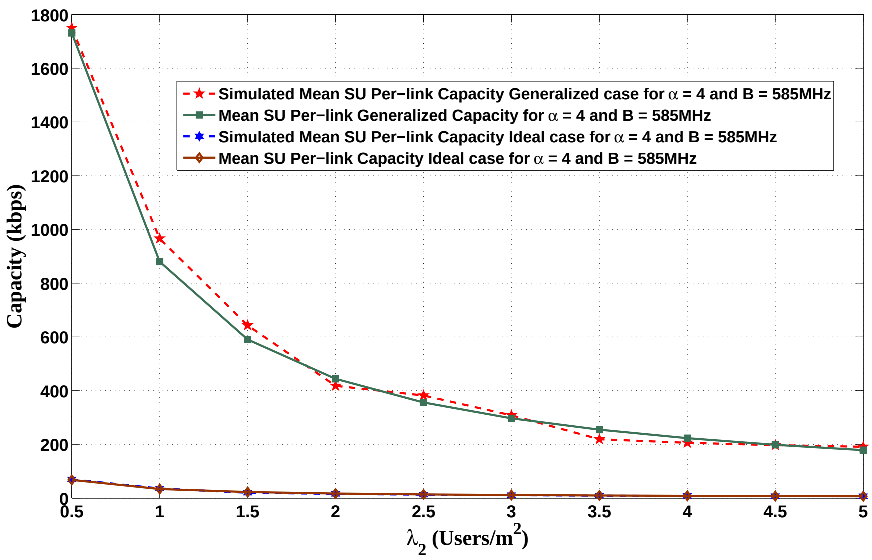

Figure 6.10: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for the Ideal and Generalized IT models with $B = 585$ MHz for the case $\alpha = 4$.

6.3.1 Calculations Upper bound of PU Outage Probability

Using the IT model and considering the Ideal case, we want to find an upper bound for the probability of the following event:

$$T_L(f_i)kB_i \geq \sum_{x_i \in \omega_2} p_2(x_i, 0) + \sum_{x_i \in \omega_3} p_3(x_i, 0) \triangleq F,$$

where the PU to be analyzed is placed at the origin.

Lemma 4. *Let ω_A and ω_B be two independent Poisson point processes on $\mathbf{R}^n$ with intensities λ_A and λ_B. Define G_A and G_B as follows:*

$$\begin{aligned} G_A(\omega_A) &= \sum_{X_i \in \omega_A} f_A(X_i), \\ G_B(\omega_B) &= \sum_{X_i \in \omega_B} f_B(X_i), \end{aligned}$$

for f_A and f_B two non-negative measurable real-valued functions. Then

$$G = G_A(\omega_A) + G_B(\omega_B)$$

can be seen as a marked Poisson point process with intensity $\lambda = \lambda_A + \lambda_B$ and kernel

$$K(x, y) = f_A(x)\delta\left(y - \frac{\lambda_A}{\lambda_A + \lambda_B}\right) + f_B(x)\delta\left(y - \frac{\lambda_B}{\lambda_A + \lambda_B}\right).$$

Proof. We use Eq. 6.1 to obtain

$$\begin{aligned} \mathbb{E}\left[e^{-sG}\right] &= \mathbb{E}\left[e^{-s(G_A+G_B)}\right] = \mathbb{E}\left[e^{-sG_A}\right]\mathbb{E}\left[e^{-sG_B}\right] \\ &= \exp\left(-\int(1 - e^{-sf_A(x)})d\lambda_A(x)\right) \\ &\quad \times \exp\left(-\int(1 - e^{-sf_B(x)})d\lambda_B(x)\right) \\ &= \exp\left(-\int(1 - e^{-s})K(x, dy)d(\lambda_A + \lambda_B)(x)\right), \end{aligned}$$

which concludes the proof. □

Lemma 5. *Let ω be a marked Poisson point processes on $\mathbf{R}^n \times \mathbf{R}^m$ with intensity λ and kernel $K(x, y)$ and define G as follows:*

$$G(\omega) = \sum_{X_i \in \omega} f(X_i, Y_i),$$

for f a non-negative measurable real-valued function. Then, for $t \in \mathbf{R}^n$

$$D_t(G) = \int f(t, y)K(t, dy)$$

Proof. The proof follows straightforwardly from the application of Definition 2 on $F(\omega)$. □

We set $m_F \triangleq \mathbb{E}[F]$ and

$$v_F \triangleq \int |D_x F(\omega)\ K(x,dy)|^2 \lambda(dx).$$

We obtain P_{sup} via concentration inequalities, using Theorem 2

$$\mathbf{P}(F \geq t + m_F) \leq \exp\left(-\frac{t}{2s} g\left(1 + \frac{ts}{v_F}\right)\right).$$

where $g(x) = (1+x)\ln(1+x) - x$. Using Lemmas 4 and 5, we obtain that

$$\begin{aligned} m_F &= \mathbb{E}\left[\sum_{x_i \in \omega_2} p_2(x_i, 0)\right] + \mathbb{E}\left[\sum_{x_i \in \omega_2} p_2(x_i, 0)\right], \\ v_F &= \mathbb{E}\left[\sum_{x_i \in \omega_2} p_2^2(x_i, 0)\right] + \mathbb{E}\left[\sum_{x_i \in \omega_2} p_2^2(x_i, 0)\right], \end{aligned}$$

and we use Lemma 1 to find m_F:

$$m_F = \frac{\alpha\pi(\mu_2\lambda_2 + \mu_3\lambda_3)}{(\alpha - 2)}. \tag{6.13}$$

To find v_F, it suffices to use the same lemma exchanging α by 2α and μ_j by μ_j^2:

$$v_F = \frac{2\alpha\pi(\mu_2^2\lambda_2 + \mu_3^2\lambda_3)}{(2\alpha - 2)}. \tag{6.14}$$

Since the function $\max(\mu_j, \mu_j r^{-\alpha})$ is decreasing with respect to r,

$$s = \max(\mu_2, \mu_3).$$

Assuming $\mu_2 \geq \mu_3$ and taking $T_L(f_i)kB_i = t + m_F$, then

$$\mathbf{P}(F \geq T_L(f_i)kB_i) \leq \exp\Bigg(-\frac{T_L(f_i)kB_i - m_F}{2\mu_2} \ln\left(1 + \frac{(T_L(f_i)kB_i - m_F)\mu_2}{v_F}\right)\Bigg) = P_{sup}. \tag{6.15}$$

This inequality holds for $m_F \leq T_L(f_i)kB_i$. The generic case is similar and it suffices to define

$$F \triangleq \frac{B_i}{B} \sum_{x_i \in \omega_1} p_1(x_i, 0) + \sum_{x_i \in \omega_2} p_2(x_i, 0) + \sum_{x_i \in \omega_3} p_3(x_i, 0),$$

so

$$m_F = \frac{\alpha\pi(\frac{B_i}{B}\mu_1\lambda_1 + \mu_2\lambda_2 + \mu_3\lambda_3)}{(\alpha - 2)},$$

and

$$v_F = \frac{2\alpha\pi\left(\left(\frac{B_i}{B}\mu_1\right)^2 \lambda_1 + \mu_2^2\lambda_2 + \mu_3^2\lambda_3\right)}{(2\alpha - 2)}.$$

In the generic case, s is given by

$$s = \max\left(\frac{B_i}{B}\mu_1, \mu_2, \mu_3\right),$$

and from here we apply Theorem 2.

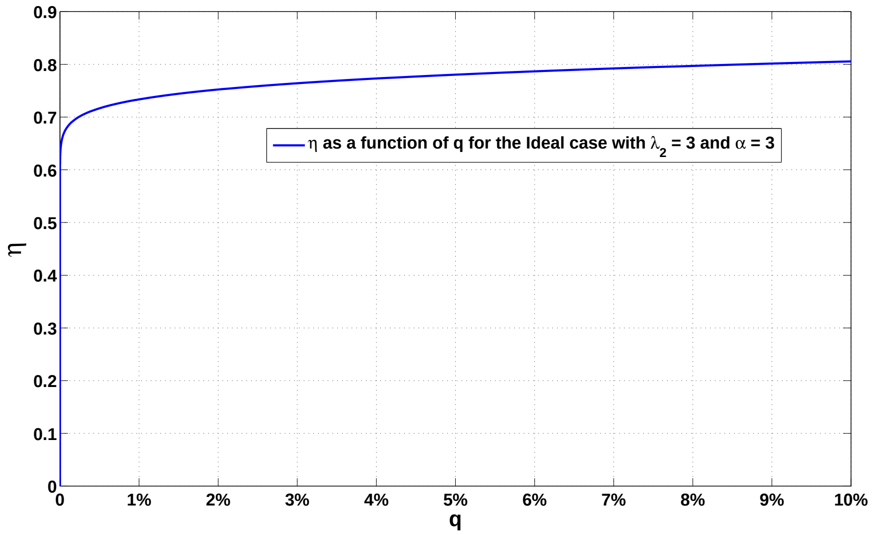

Figure 6.11: Fraction of the transmission power (η) as a function of the outage probability of the PUs (q) for the Ideal case with $\alpha = 3$.

6.3.2 Results Upper bound of PU Outage Probability

In this section, we take into account a specific outage probability of PUs to design the allowed transmission power of SUs following the Ideal IT model. We use the same parameters considered in Section 6.2.2 to compare this power with the results of that section such that we can evaluate the trade-off of system reliability and capacity. Besides, we set $\lambda_2 = 3$ users/m^2 and we analyze the results for $\alpha = 3$ and $\alpha = 4$.

We define μ_2^q as the transmission power such that the outage probability of PUs is smaller than q in the Ideal case and η as the fraction of this transmission power with respect to μ_2^{id} calculated in the previous section, i.e. $\mu_2^q = \eta(q)\mu_2^{id}$. Since $q(\eta)$ is a bijection on $(0, 1)$, there exists a function $\eta(q)$. We denote also C^q as the mean capacity per link of a SU as a function of q. Setting $\lambda_3 = 0$, we can rewrite Eq. 6.15 as a function of these variables to obtain:

$$q = \exp\left(\frac{\lambda_2 \pi \alpha}{2(\alpha - 2)} \frac{\eta(q) - 1}{\eta(q)} \ln\left(1 + \frac{2(\alpha - 1)}{(\alpha - 2)} \frac{1 - \eta(q)}{\eta(q)}\right)\right).$$

The function $\eta(q)$ is presented in Figures 6.11 and 6.12 for $\alpha = 3$ and $\alpha = 4$ respectively.

We can notice from Figure 6.11 and Figure 6.12, that in order to guarantee that the outage probability of PUs remains between 1% and 5%, we must reduce the SUs transmission power μ_2^{id} between a 26% and a 22% respectively for the case $\alpha = 3$ and between a 34% and a 28% respectively for the case $\alpha = 4$.

Now, using Figure 6.13 and Figure 6.14, we evaluate the achieved performance in terms of mean SU per-link capacity for different values of the PUs outage probability following the Ideal IT model. Figure 6.13 plots the mean SU per-link capacity as a function of the SUs intensity (λ_2) for the case $\alpha = 3$ and Figure 6.14 for the case $\alpha = 4$. Both figures show the achievable mean SU per-link capacity for 1%, 3% and 5% of the PUs outage probability and also plots the original case without restriction on the SUs transmission

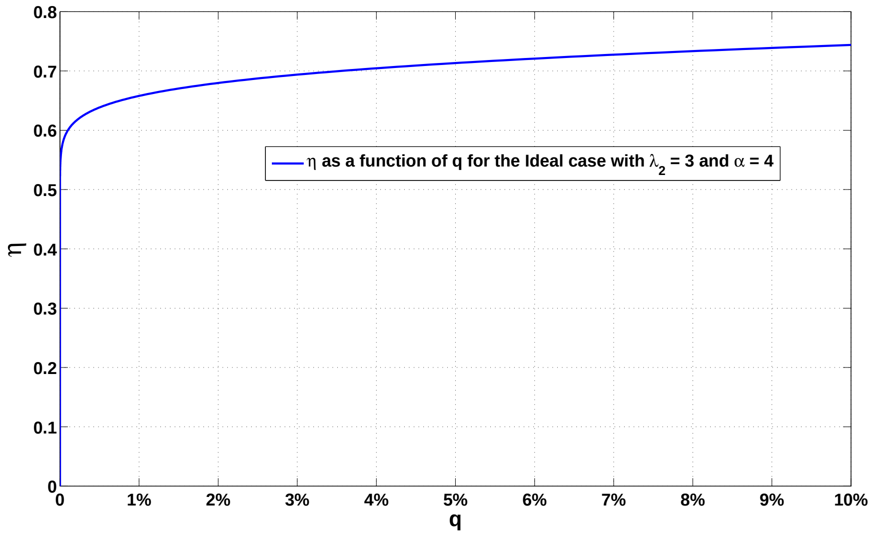

Figure 6.12: Fraction of the transmission power (η) as a function of the outage probability of the PUs (q) for the Ideal case with $\alpha = 4$.

power μ_2^{id}. As we can see in Figure 6.13 and Figure 6.14 with the increase of λ_2, the difference between the restricted cases and the non restricted case become shorter. This means that in order to guarantee that the outage probability of PUs remains between 1% and 5%, for a scenario with a large number of SUs, the restriction of the SUs transmission power μ_2^{id} does not lead to a significant reduction with respect to the mean SU per-link capacity.

6.4 Mean Interference, Mean SUs Transmission Power and Mean SUs Capacity Taking into Account the Reference Distance

Previous sections presented the analysis of the interference caused to a primary network, the allowed mean transmission power of SUs and the achievable mean capacity of the SUs under the assumption that the reference distance (r_0) is equal to 1. Nevertheless, in the analysis of specific technologies such as UMTS and WiMedia, this parameter must be adjusted.

In this section, we develop the necessary expressions to estimate the mean interference power, the maximum allowed SUs transmission power and the mean capacity of the SUs taking into account the reference distance (r_0). This analysis is performed for the Ideal and the Generalized IT models.

6.4.1 Mean Interference Power Taking into Account the Reference Distance

In order to develop the expression of the mean interference power taking into account the reference distance r_0, we modify Lemma 1 as follows:

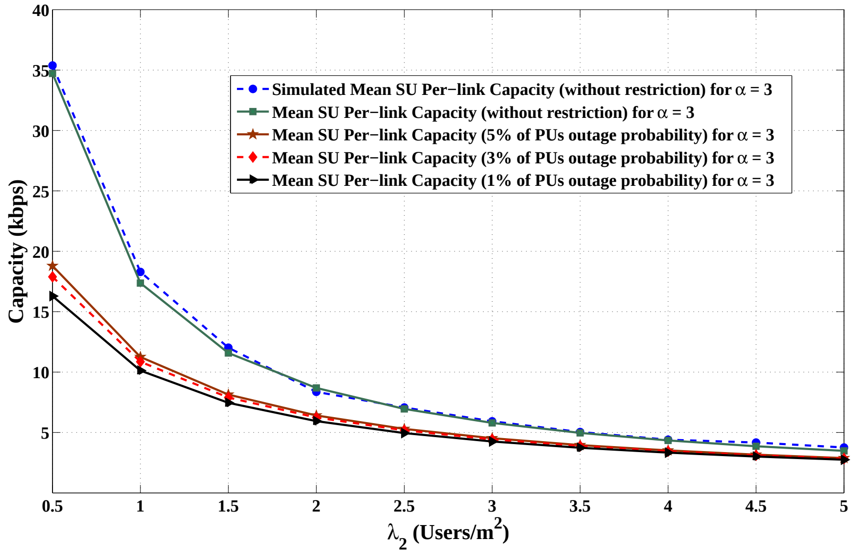

Figure 6.13: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for different values of the PUs outage probability following the Ideal IT model with $B = 528$ MHz for the case $\alpha = 3$.

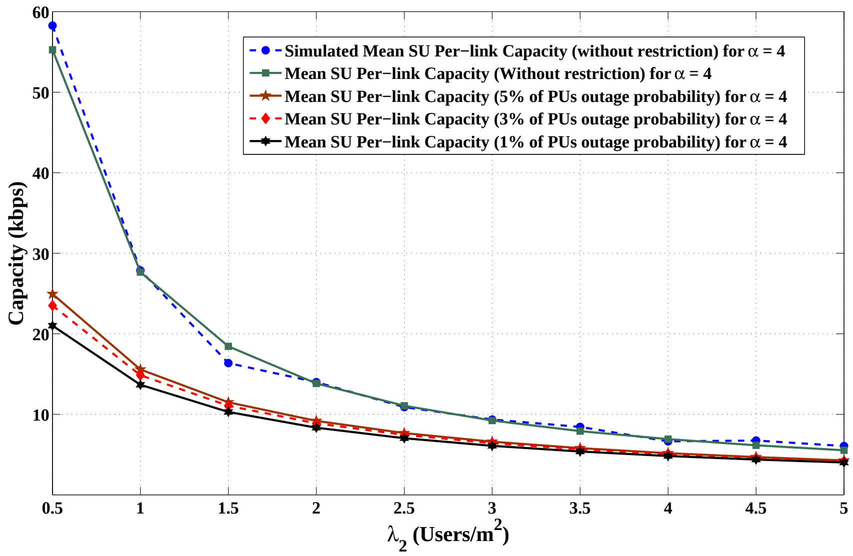

Figure 6.14: Mean SU per-link capacity (kbps) as a function of the SUs intensity λ_2 for different values of the PUs outage probability following the Ideal IT model with $B = 528$ MHz for the case $\alpha = 4$.

Lemma 6. *Let ω_j be a Poisson point process with intensity measure λ representing the positions of active users of kind j over $\mathbf{R}^2$ transmitting with a power μ_j. If $Q_j(x)$ is the total interference power experimented by a point $x \in \mathbf{R}^2$, then*

$$\mathbb{E}\left[Q_j(x)\right] = \frac{\mu_j \lambda_j \pi \alpha r_0^2}{(\alpha - 2)}. \tag{6.16}$$

Proof. Given the invariance under translation of a stationary Poisson point process denoted by: $\mathbb{E}\left[Q_j(x)\right] = \mathbb{E}\left[Q_j(0)\right]$. So, it suffices to use Theorem 1 for $f(x) = p_j(x, 0)$ as defined in Eq. 6.3:

$$\begin{aligned}
\mathbb{E}\left[Q_j(0)\right] &= \mathbb{E}\left[\sum_{X_i \in \omega} p_j(X_i, 0)\right] \\
&= \int_{\mathbf{R}^2} p_j(x, 0)\lambda_j(x)dx \\
&= \lambda_j \int_0^{2\pi} \int_0^{\infty} \min\left(\mu_j, \mu_j \left(\frac{r_0}{r}\right)^{\alpha}\right) r dr d\theta \\
&= \mu_j \lambda_j 2\pi \left(\int_0^{r_0} r dr + \int_{r_0}^{\infty} \frac{r_0^{\alpha}}{r^{\alpha}} r dr\right) \\
&= \frac{\mu_j \lambda_j \pi \alpha r_0^2}{(\alpha - 2)},
\end{aligned}$$

concluding the proof. □

6.4.2 Mean SUs Transmission Power Taking into Account the Reference Distance

In this section, we estimate the maximum allowed SUs transmission power μ_2^{id} and μ_2^{gen} taking into account the variable of the reference distance r_0.

As presented in section 6.1.1, the Ideal interference temperature model attempts to limit interference specifically to licensed signals. This means that the objective is to guarantee the following condition:

$$Q_2(x) + Q_3(x) \leq T_L(f_i)kB_i.$$

To guarantee that this inequality holds at least for the mean of interferences, we take the mean in both sides, we use Lemma 6 and solving for μ_2^{id}, we obtain the maximum allowed transmission power to be used by SUs following the Ideal IT model:

$$\mu_2^{id} \leq \frac{(\alpha - 2)T_L kB_i - \lambda_3 \mu_3 \pi \alpha r_0^2}{\lambda_2 \pi \alpha r_0^2}. \tag{6.17}$$

Now we calculate the maximum mean allowed SUs transmission power μ_2^{gen} following the Generalized model. As noted in section 6.1.1, the Generalized model takes into account the power from other PUs (averaging the PUs power over the SUs bandwidth) and evaluates T_L over the entire frequency range B. If the analyzed PU is placed at $x \in \mathbf{R}^2$, then we rewrite this condition as a function of Q_j's:

$$\frac{B_i}{B} Q_1(x) + Q_2(x) + Q_3(x) \leq T_L(f_c)kB.$$

Assuring that, in average, this inequality holds, we take the mean, apply Lemma 6 and solving for μ_2^{gen}, we obtain:

$$\mu_2^{gen} \leq \frac{(\alpha-2)T_L kB - \lambda_3\mu_3\pi\alpha r_0^2 - \frac{B_i}{B}\lambda_1\mu_1\pi\alpha r_0^2}{\lambda_2\pi\alpha r_0^2}. \tag{6.18}$$

6.4.3 Mean SUs Capacity Taking into Account the Reference Distance

As presented in section 6.2.1, we are interested in the calculation of the mean per-link capacity. Therefore, using the Shannon-Hartley theorem [63], the per-link capacity $C(x,y)$ of a user at $x \in \mathbf{R}^2$ receiving a signal from a user at $y \in \mathbf{R}^2$ such that $\|x-y\| \leq R_2$, is given by:

$$C(x,y) = B\log_2\left(1 + \frac{p_2(x,y)}{\mathbb{E}\left[I(x)\right]}\right).$$

The mean interference power $\mathbb{E}\left[I(x)\right]$ caused by the interferers, other SUs and PUs at x, is given by

$$\mathbb{E}\left[I(x)\right] = \frac{B_i}{B}Q_1(x) + Q_2(x) + Q_3(x).$$

Since y is uniformly distributed around x, then x is uniformly distributed over y and the mean capacity per link $C(x)$ in the disc is given by:

$$C(x) = \int B\log_2\left(1 + \frac{p_2(x,y)}{\mathbb{E}\left[I(x)\right]}\right)\frac{\mathbb{1}_{\{\|x-y\|\leq R_2\}}}{\pi R_2^2}dy. \tag{6.19}$$

By Lemma 6, $\mathbb{E}\left[Q_j(x)\right]$ does not depend on y and $p_2(x,y)$ depends only on the distance between x and y, so $C(x) = C$. Let us define

$$K \triangleq \frac{\mu_2}{\mathbb{E}\left[I(x)\right]} = \frac{\mu_2(\alpha-2)}{\pi\alpha r_0^2\left(\frac{B_i}{B}\mu_1\lambda_1 + \mu_2\lambda_2 + \mu_3\lambda_3\right)}. \tag{6.20}$$

Then, we can rewrite C as follows:

$$C = \int_0^{R_2}\int_0^{2\pi}\frac{B}{\pi R_2^2}\log_2\left(1 + K\min\left(1, \frac{r_0^\alpha}{r^\alpha}\right)\right)rd\theta dr. \tag{6.21}$$

Using Eq. 6.10 we rewrite Eq. 6.21 as

$$C = \frac{2BK^{\frac{2}{\alpha}}r_0^2}{R_2^2\ln(2)}\left[\frac{\ln(1+K)}{2K^{\frac{2}{\alpha}}} + h\left(\frac{R_2}{K^{\frac{1}{\alpha}}r_0}, \alpha\right) - h\left(\frac{1}{K^{\frac{1}{\alpha}}}, \alpha\right)\right]. \tag{6.22}$$

The per-link capacity in the Ideal case, C^{id}, is obtained taking $\mu_2 = \mu_2^{id}$, while the one in the Generalized case, C^{gen}, results of taking $\mu_2 = \mu_2^{gen}$. Analytical expressions for $h(r,t)$ can be found using Lemma 3 as presented in section 6.2.1.

It is possible to calculate the mean total SUs capacity C_{total} in a secondary cell of radius R, defining a disc D. Using theorem 1 on the marked Poisson point process ω_2', we obtain:

$$C_{total} = \int\int_D C(x,y)\frac{\mathbb{1}_{\{\|x-y\|\leq R_2\}}}{\pi R_2^2}dy\lambda dx.$$

However, Eq. 6.22 shows that the inner integral does not depend on x, so we can rewrite Eq. 6.12 as

$$C_{total} = C \int_D \lambda dx = C\lambda \int_D dx = C\lambda\pi R^2 \tag{6.23}$$

Applying the maximum allowed SUs transmission power μ_2, obtained by the IT model, we obtain the total capacity of a secondary network. We denote C_{total}^{id} for the Ideal case when $\mu_2 = \mu_2^{id}$ and C_{total}^{gen} when $\mu_2 = \mu_2^{gen}$.

6.4.4 Expressions of the Upper Bound of PU Outage Probability Taking into Account the Reference Distance

To conclude this analysis taking into account the reference distance r_0, the expressions of m_F and v_F used to estimate an upper bound of PUs outage probability are obtained using 6 as follows:

$$m_F = \frac{\alpha\pi r_0^2(\frac{B_i}{B}\mu_1\lambda_1 + \mu_2\lambda_2 + \mu_3\lambda_3)}{(\alpha-2)},$$

and

$$v_F = \frac{2\alpha\pi r_0^2\left(\left(\frac{B_i}{B}\mu_1\right)^2\lambda_1 + \mu_2^2\lambda_2 + \mu_3^2\lambda_3\right)}{(2\alpha-2)}.$$

6.4.4.1 Results of the Mean SUs Transmission Power and the Mean Per-Link Capacity Taking into Account the Reference Distance

Using the parameters presented in Table 6.1, we analyze the behavior of the allowed mean SUs transmission power and the mean per-link capacity of the secondary network for different values of the reference distance r_0.

The reference distance can be obtained using the free-space path loss equation. In this equation, the received signal falls off inversely proportional to the square of the distance between the transmitter and the receiver [25]. In this case and applying the free-space path loss equation, the reference distance r_0 can be computed as follows:

$$r_0 = \frac{\lambda'}{4\pi}, \tag{6.24}$$

where λ' is the wavelength of a radio signal transmitted by the users.

In our numerical analysis we consider as the PUs a UMTS network and as the secondary network an UWB system, WiMedia. Assuming that both systems operate in the UMTS band (i.e. 2 GHz), the reference distance r_0 using Eq. 6.24 is equal to 0.0119 m. Therefore, considering the parameters from Table 6.1 and using Eq. 6.17, for the Ideal model we obtain a mean SUs transmission power μ_2^{id} of -61 dBm for the case $\alpha = 3$. With this SU power, the achievable per link capacity C^{id} using Eq. 6.22 is 151.25 kbps. In the case of $\alpha = 4$, the average SUs transmission power is -59 dBm and the achievable per-link capacity C^{id} is 63.03 kbps. For the Generalized approach, using Eq. 6.18, we obtain a mean SUs transmission power μ_2^{gen} of -40 dBm for the case $\alpha = 3$. Again, with this SU power, the achievable per link capacity C^{gen} using Eq. 6.22 is 169.40 kbps. In the case of $\alpha = 4$, the

Frequency Band	**Path Loss**	**Transmission Power** (μ_2^{id})	**Transmission Power** (μ_2^{gen})	**Capacity** (C^{id})	**Capacity** (C^{gen})
2 GHz	$\alpha = 3$	-60 dBm	-40 dBm	151.25 kbps	169.4 kbps
	$\alpha = 4$	-59 dBm	-38 dBm	63.03 kbps	56.94 kbps
3 GHz	$\alpha = 3$	-57 dBm	-37 dBm	117.27 kbps	130.56 kbps
	$\alpha = 4$	-55 dBm	-35 dBm	49.99 kbps	47.75 kbps
6 GHz	$\alpha = 3$	-53 dBm	-32 dBm	74.39 kbps	82.67 kbps
	$\alpha = 4$	-51 dBm	-30 dBm	21.79 kbps	24.15 kbps
10 GHz	$\alpha = 3$	-47 dBm	-26 dBm	53.15 kbps	58.89 kbps
	$\alpha = 4$	-45 dBm	-24 dBm	13.14 kbps	14.6 kbps

Table 6.2: SUs Transmission Power and SUs Per-Link Capacity for Different Values of the Frequency Band for the Ideal and the Generalized IT Models.

average SUs transmission power is -38 dBm and the achievable per-link capacity C^{id} is 56.94 kbps.

Nevertheless, if we assume that both systems operate in the WiMedia band (i.e. from 3 GHz to 10 GHz), the reference distance r_0 varies from 0.008 m to 0.0024 m. If we consider the parameters from Table 6.1 and using Eq. 6.17 for the Ideal case, we obtain a mean SUs transmission power μ_2^{id} ranging from -57 dBm to -47 dBm for the case $\alpha = 3$ and from -55 dBm to -45 dBm for the case $\alpha = 4$. With these values of SUs transmission power, the achievable mean SUs per-link capacity C^{id} varies from 117.27 kbps to 53.15 kbps for the case $\alpha = 3$ and from 49.99 kbps to 13.14 kbps for the case $\alpha = 4$.

For the Generalized approach, using Eq. 6.18, we obtain a mean SUs transmission power μ_2^{gen} ranging from -37 dBm to -26 dBm for the case $\alpha = 3$ and from -35 dBm to -24 dBm for the case $\alpha = 4$. With these values of SUs transmission power, the achievable mean SUs per-link capacity C^{gen} varies from 130.56 kbps to 58.89 kbps for the case $\alpha = 3$ and from 47.75 kbps to 14.56 kbps for the case $\alpha = 4$.

It is worth mentioning that, these results fulfill the requirements of output power (i.e. -60 dBm) of UWB transmitters for WPAN applications [20]. Moreover, the values of the SUs transmission power obtained in our analysis are higher than the minimum receiver sensitivity (i.e. -80.8 dBm) specified by the WiMedia Alliance [77]. In addition, by adjusting the value of the reference distance r_0, we clearly improved the performance in terms of capacity of our model.

In Table 6.2, we present the allowed mean SUs transmission power and the mean per-link capacity for different values of the frequency band, following the Ideal and the Generalized IT models, for the cases $\alpha = 3$ and $\alpha = 4$.

6.5 Conclusion

In this chapter we proposed the utilization of the Poisson point process as a new analytical method to be applied in the IT model. Using our proposal, we evaluated the interference caused to the primary network, the allowed SUs transmission power to guarantee that the PUs activity is not affected by the transmission of the SUs and the achieved secondary network capacity. Afterwards, we demonstrated the application of our model by a numerical analysis considering as the PU a UMTS network and as the secondary network an UWB system. Finally, we determined an upper bound on the outage probability of the primary network by the use of Concentration Inequalities. Our results showed that for this scenario, which takes the reference distance r_0 equal to one, the secondary network achieves a limited performance in terms of capacity, compared to the real capabilities of an UWB standard (e.g IEEE 802.15.3a) in a non-primary/secondary user context. However, if the parameter of the reference distance is adjusted or if the secondary network operates with a larger channel bandwidth better performances can easily be obtained. Furthermore, we have demonstrated that SUs communication is possible without causing any damage to PUs following the Ideal and the Generalized IT models. Moreover, we have established that in order to guarantee that only 1% of the PUs is affected by the SUs transmission, it will only cost approximately 25% of the mean allowable SUs transmission power and 20% for a PUs outage probability below 5%. In addition we have demonstrated that, for a scenario with a large number of SUs, the restriction of the SUs transmission power does not lead to a significant reduction of the achievable capacity of the secondary network. Finally, we demonstrated the feasibility of our model by the analysis of the appropriate value of the reference distance in the frequency bands of UMTS and WiMedia. In this analysis we showed that, by adjusting the value of the reference distance r_0, we clearly improve the performance of our model. The results for the maximum allowed SUs transmission power, following the Ideal and the Generalized approaches, confirm that our model meets the WiMedia requirements of output power and receiver sensitivity.

Chapter 7

Conclusion and Perspectives

7.1 Thesis Conclusions

This thesis addresses the issue of improving the link performance and the capacity in DSA networks. The objective of our research was to provide different solutions in order to maintain reliable communications between SUs preserving undisturbed at all time the activity of primary networks. Through this thesis, different proposals were presented and analyzed to achieve this objective. These proposals differed in the network architecture, in the network orientation and in the spectrum access technique for spectrum sharing. Our main contributions to this domain as presented in chapter 4, chapter 5 and chapter 6 are:

- An extensive analysis of existing multi-channel MAC protocols proposed to increase network throughput, to improve spectrum utilization and to reduce interference caused by secondary use of the spectrum in an opportunistic (i.e. Overlay) manner.
- A proposal of a Cognitive Beacon Channel (CBC) using existing 3GPP technologies following a centralized or a coordinated architecture for DSA networks. This cognitive control channel helps to improve spectrum awareness by conveying signalization to mobile users in a multi-radio access technology environment.
- A new analytical method to be applied in the Interference Temperature model relying on the Poisson Point Process. This model evaluates the achieved capacity of a secondary network, the interference caused to a primary network and the allowed transmission power of SUs to guarantee that activity of the PUs is not affected by their transmissions.
- The determination of an upper bound, by the use of Concentration Inequalities, on the outage probability of the primary network when the SUs transmit following the Interference Temperature model.

In chapter 3, we provided a general introduction to DSA networks and presented the issues and challenges in such environments. We also presented existing wireless access technologies which could be the principal actors, as PUs or SUs (if they are equipped with CR technology), in next generation wireless networks. As we stated in this thesis, to make possible an efficient dynamic access a proper balance among technology, policy and business must prevail. For that purpose, standardization bodies such as the IEEE, the ITU-R and the ETSI among others, have continued working on standards related specifically to DSA and CR.

In chapter 4, we presented an overview of different multi-channel MAC protocols allowing DSA in distributed Ad-hoc networks. These protocols are principally based on the MAC mechanism of the IEEE 802.11 standard. We made a comparison of the key features of each protocol according to the number of transceivers (TRx), the need for synchronization, the need for a common control channel and the different ways to make rendezvous. In our analysis, we showed that most of the cognitive MAC protocols are based or inspired on multi-channel MAC protocols proposed for non-cognitive networks. Thus, they inherit their operation characteristics and of course their merits and demerits. In engineering, every enhancement comes with a trade-off and in the case of the multi-channel MAC protocols for DSA, this condition remains. Some examples of the trade-offs described by our analysis are:

The implementation of single TRx protocols is easier compared with multiple TRx protocols. Nevertheless, in single TRx protocols the hidden terminal problem arises together with the problem of channel switching delay. In general, multiple TRx protocols perform better than single TRx protocols under a wide range of situations because they can achieve higher throughputs and they can easily avoid the MCHTP. However, these protocols are more complex and more expensive than single TRx protocols. In the case of the protocols employing a Dedicated Control Channel, they can be affected by the possibility of bottleneck under some operating conditions. In that case, multiple rendezvous channel can alleviate the congestion problem but raises the challenge of ensuring the idle transmitter and receiver visit the same rendezvous channel. Finally, Split Phase and Dedicated Control Channel protocols explicitly separate control packets from data packets. This division can lead to generate more successful rendezvous. Nevertheless, this process is useless to improve performance when there are few available data channels or when they are already congested.

Due to the large quantity of multi-channel MAC protocols proposed in literature to improve spectrum utilization, we consider that showing how each protocol confronts the numerous problems that arise in DSA and by pinpointing the aforementioned trade-offs of each protocol, we have facilitated the accurately selection of the appropriate protocol to be implemented in future distributed DSA networks. Nevertheless, as we described in this thesis, to obtain the necessary parameters for spectrum access in distributed Ad-hoc networks, a mobile station has to scan the entire spectrum looking for occupancy information. This scanning process may require a lot of time and can greatly impact the battery consumption in mobile devices. To overcome this problem, in chapter 5, we proposed the use of a Cognitive Beacon Channel (CBC) as an assistant for mobile stations, to select an appropriate network according to user's requirements (e.g. radio access technology (RAT), frequency channel, secondary use of the spectrum, etc). To implement the CBC, we proposed the utilization of the logical channels of GSM (RACH, AGCH and TCH) and the logical BCH (MIB and SIBs) of UMTS. We compared the performances (i.e. delay to retrieve the cognitive channel, total user density, cognitive channel range and required net bit rate) of our propositions with the On-demand and the Broadcast CPC implementations in the E2R II project. As we showed, our GSM implementation slightly outperforms the On-demand proposition in the E2R II project. However, our proposal using UMTS signaling clearly outperforms the Broadcast approach in the E2R II project. This result is due to the fact that MSs know exactly when to decode their corresponding information. This characteristic leads to a reduction of power consumption in mobile devices and hence, mobile users can increase the usage time of their equipment, which is one of the most desirable features of next generation mobile devices.

Moreover, our UMTS proposal is neither sensitive to the number of meshes covered by the CBC nor the number of requests sent by the users.

Adapting the utilization of the logical channels of GSM and UMTS to convey the CBC, we took advantage of two existing technologies, proved to be efficient and accepted worldwide. Moreover, we demonstrated that both 3GPP technologies also possess the required capabilities to convey signalization with an acceptable throughput in a multi-Radio Access Technology (multi-RAT) environment. Furthermore, using the information conveyed by the CBC in the GSM or UMTS bands, DSA could be accomplished without MSs have to scan the entire spectrum in order to find spectrum usage information. In addition, if a proper detection of spectrum holes in PUs bands is carried out by spectrum owners, they could economically promote the release of frequency bands for the sake of improved spectrum usage. Consequently, cellular operators could actually benefit from the secondary usage of their spectrum if renting procedures are carried out.

The proposals for dynamic access to spectrum presented in chapter 4 and chapter 5 differ in the network architecture and in the network orientation. Whereas chapter 4 presented several approaches for DSA in distributed Ad-hoc networks, chapter 5 presented our proposition of dynamic access using a centralized cellular network architecture. Nevertheless, the common characteristic of these proposals is the use of an opportunistic spectrum access technique for spectrum sharing (i.e. Overlay). This technique is based on avoidance of PUs through the use of spectrum holes for data transmission.

The other spectrum access technique, proposed as possible solution to the dynamic spectrum access/allocation problem, is known as Underlay. In this technique, communication between SUs is allowed in PUs bands if the transmission power of SUs is low enough that it does not harm the PUs. As we stated in this thesis, the Underlay approach imposes severe restrictions on transmitted power levels and so it requires operating over ultra wide bandwidths. The principal characteristic of the Underlay approach is the fact that SUs attempt to coexist with PUs instead of trying to avoid PUs signals. Under this framework, in chapter 6 we proposed the utilization of the Poisson point process as a new analytical method to be applied in the Interference Temperature model. The IT model is an Underlay approach proposed by the FCC as another way to dynamically manage and allocate spectrum resources. The Poisson point process is mathematical tool that helped us to evaluate, in a simple fashion, the achievable capacity by a secondary network, the interference caused to the primary network and the outage probability of the primary network. For this purpose, we firstly developed the necessary expressions to estimate the mean base interference, the mean interference caused by other SUs and the mean interference caused by active PUs. Using these results, we estimated the allowed SUs transmission power to guarantee that the PUs activity will not be affected by the SUs transmission. The later analysis was performed for the Ideal and the Generalized IT models. Afterwards, using the Shannon-Hartley theorem, we derived the expressions of the mean SU per-link capacity and the total secondary network capacity. Finally, by the use of Concentration Inequalities, we determine an upper bound on the outage probability of the primary network when the secondary network transmits.

In order to obtain numerical results using our expressions in a realistic scenario, we examined the achievable capacity of an UWB system, WiMedia, as a secondary network and a UMTS network as the primary network. Our results showed that for this scenario, which takes the reference distance r_0 equal to one, the secondary network achieves a limited performance in terms of capacity, compared to the real capabilities of an UWB standard (e.g IEEE 802.15.3a) in a non-primary/secondary user context. However, these performances can easily be improved if the parameter of the reference distance is adjusted or if the secondary network operates with a larger channel bandwidth, which is one of the characteristics of WiMedia's MAC layer. Furthermore, in chapter 6, we demonstrated that SUs communication is possible causing minor damage to PUs following the Ideal and the Generalized interference temperature model. Moreover, by the use of Concentration Inequalities, we established that in order to guarantee that only 1% of the PUs is affected by the SUs tranmission, it will only cost approximately 25% of the mean allowable SUs transmission power and 20% for a PUs outage probability below 5%. In adition we demonstrated that, for a scenario with a large number of SUs, the restriction of the SUs transmission power does not lead to a significant reduction of the achievable per-link capacity of the secondary network. At the end of chapter 6, we demonstrated the feasibility of our model by the analysis of the appropriate value of the reference distance in UMTS and WiMedia frequency bands. In this analysis we showed that by adjusting the value of the reference distance r_0, we clearly improve the performance of our model. The results of the maximum allowed SUs transmission power, following the Ideal and the Generalized approaches, confirm that our model meets the WiMedia requirements of output power and receiver sensitivity. It is worth mentioning that the results for the SUs capacity and their damage over PUs presented through our analysis, are improved as long as the intensity of SUs and the bandwidth of the secondary system are increased, which is a tendency of the next generation wireless networks.

Finally, the results obtained from our research work indicated that the efficient DSA is feasible and can be done with the current wireless technologies in the market. We also confirmed that reliable communication between SUs, preserving undisturbed at all time the activity of primary networks, is possible following different DSA techniques and different DSA architectures for spectrum sharing. Thus, from our results we can state that by implementing the proposed techniques for the secondary use of the spectrum, we can improve the link performance and the capacity in future DSA systems.

7.2 Perspectives and Future Work

We consider that improving the link performance and the capacity in DSA systems is not a trivial task. Therefore, to provide efficient DSA we must rely on robust spectrum sharing techniques to avoid interference. In the case of opportunistic spectrum access (i.e. Overlay), essentials attributes to achieve DSA are: precise detection of spectrum holes, efficient mobility management protocols and optimal reconfiguration decision making. In the case of Underlay techniques, precise estimation of existing interference and proper control of transmission power are crucial actions to avoid rising the interference temperature limit. In addition to mitigating interference, the new sharing radios will need to have a more accurate estimation of the communication channel in not only frequency but in time and space as well. This implies more complicated transmit signal generation and a more complicated receiver to process the incoming energy. Therefore, all the improvements of the aforementioned issues will represent an overall enhancement of this new paradigm of DSA.

Along our research work and during the conception phase of our DSA proposals, we identified certain issues that drew our attention and we are convinced would be interesting research topics. This thesis presented different approaches allowing DSA and these proposals differed in the network architecture, in the network orientation and in the spectrum access technique for spectrum sharing. Future work involves a detailed analysis of

QoS on SUs transmissions in the proposed approaches. QoS metrics such as delay, jitter or packet loss will be analyzed to extend the capabilities of the secondary use in our proposed architectures.

Focusing on the implementation of our Cognitive Beacon Channel, a detailed analysis of the capacity of the broadcast channel (MIB and SIBs) of UMTS is recommended in order to have a precise estimation of how many SIBs can be devoted to transmit the spectrum information to SUs. The purpose of this analysis is twofold: first to estimate the maximum load, in terms of SUs, that the network can support and second to determine the maximum quantity of information, in terms of bits, that the CBC can convey. In the case of our CBC implementation using GSM, this analysis is unnecessary because it is assumed that a traffic channel (TCH) is assigned to each SU.

As a part of a future work, we will extend our analysis of the use of the Poisson point process in cognitive radio networks to other network environments. Following the Ideal and the Generalized IT model, we will evaluate the interference caused to the primary network, the allowed SUs transmission power to guarantee that the PUs activity won't be affected by the transmission of the SUs and the achieved secondary network capacity. The aforementioned analysis will be carried out taking into account different wireless access technologies (e.g. WLAN, WiMAX, LTE, Zigbee, etc). The aim of this analysis is to compare the performances of different wireless networks in a primary/secondary user context.

Our research focused primarily on the technical aspects of DSA, however, we are aware that these future networks do not differ with current networks only in the use of CR technology but also in business models and management strategies, specially in the case of secondary use of the spectrum in licensed bands. Therefore we consider that business-related issues in DSA process should be addressed to avoid reluctance from spectrum owners and to improve the transparency and efficiency of this process. In this perspective, we have identified two research areas that could improve DSA in licensed bands: new business models for secondary access and efficient accounting mechanisms.

- New Business Models for Secondary Access: Spectrum owners of license bands are important elements under our architecture as they are supposed to share their resources to offer secondary use to mobile users. Therefore, providing intelligent and efficient incentives that motivate the spectrum owners to authorize secondary access is paramount. New business models can provide solutions about how to commercialize the secondary use of the spectrum. Hence, it is necessary to come up with new models that provide a clear business strategy to allow all the participants of these new architectures to be economically rewarded.

- Efficient Accounting Mechanisms: The billing issue is paramount when offering secondary use on licensed bands, cellular operators will not deploy any secondary architecture if there is no way to bill mobile users. Thus, we consider that new accounting mechanisms to provide efficient distributed billing platform would motivate the network operators or service providers to participate in the paradigm of DSA.

We are certain that by addressing the aforementioned technical and business related issues, the performance of our proposals for DSA will improve considerably and could be considered for future deployment.

Publications

Submission to IEEE Journal

- R. Soulé, E. Ferraz and P. Martins. Poisson Point Process and Interference Temperature Model in Cognitive Radio Networks. In *the Journal of IEEE Transactions on Vehicular Technology (on-going submission).* Vehicular Technology Society, September 2011.

Conference Proceedings

- R. Soulé and P. Godlewski. An Overview of DSA via Multi-Channel MAC Protocols. In *Proceedings of the 10th IFIP Annual Mediterranean Ad Hoc Networking (Med-Hoc-Net)*, Juan-les-Pins, France, June 2010.
- R. Soulé, P. Godlewski and P. Martins. Cognitive Beacon Channel via GSM and UMTS. In *Proceedings of the 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Turkey, Istanbul, September 2010.

Book Chapter

- R. Soulé, P. Godlewski and P. Martins. Analysis of multi channel MAC protocols for Dynamic Spectrum Access. In *Advances in Vehicular Networking Technologies*, ISBN 978-953-307-241-8, April 2011.

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