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Spatial spectrum reuse in heterogeneous wireless networks: interference management and access control

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ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Χωρική επαναχρησιμοποίηση φάσματος σε ετερογενή ασύρματα δίκτυα: διαχείριση παρεμβολών και έλεγχος πρόσβασης

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ABSTRACT

Historically, the spatial spectrum reuse has been the most efficient approach for improving cellular system capacity. Based on this observation, the 3rd Generation Partnership Project (3GPP) has proposed new spatial spectrum reuse schemes, towards fulfilling the International Mobile Telecommunications-Advanced (IMT-Advanced) requirements for the 4G networks. In this direction, a major shift is realized from wide-range cells with high transmit power (*macrocells*) to low-power small-sized cells (*femtocells)*, while a lot of effort is allocated to the spatial spectrum reuse by enabling *Device-to-Device (D2D) communications*, i.e., direct communications in a cellular network, without the intervention of the base station.

The scope of this thesis is to deal with challenges arising from the introduction of femtocells and D2D communications in cellular networks standardized by 3GPP Release 8 and beyond, i.e., Long Term Evolution (LTE) and LTE-Advanced (LTE-A). More specifically, for the case of femtocells, the interference management problem is studied, while for the D2D communications the radio resource management and the spectrum access challenges are addressed.

First, a comprehensive description of the physical layer and architecture of the LTE/LTE-A networks is provided, and the current standardization efforts for the introduction of femtocells and D2D communications are described. Subsequently, different control channel interference management schemes for femtocell-overlaid LTE/LTE-A networks are studied, while an innovative power control scheme for the femtocell downlink transmissions is proposed, utilizing the end user's quality of experience. This work brings to the surface new research challenges, where the end user's satisfaction level plays an active role in network management and service provisioning. However, the further investigation of these challenges is out of this thesis' scope.

Considering the much more dynamic environment defined by the D2D communications in a cellular network, the major research effort is then shifted to the resource and interference management problem for D2D communications. Assuming a predefined set of D2D pairs in a cellular network, an interference information collection mechanism and a D2D resource allocation scheme, based on the graph-coloring theory, are proposed. Evaluation results showed that even high spatial spectrum reuse levels can be achieved, the interference collection and processing problem is quite complex, while additional signaling is needed. Taking this into account, a contention-based approach is proposed. Under this approach, the D2D devices compete for accessing the spectrum following a procedure similar with that used in WiFi (Wireless Fidelity) networks. Performance analysis shows that the efficiency of the proposed scheme depends on the number of competing devices. Towards restricting the number of competing devices, only to those that are in proximity and, thus, in valid positions for D2D communication, the device discovery problem is studied.

According to the 3GPP standardization efforts, the solution of the device discovery problem requires frequent transmission of discovery signals from each device, either announcing its presence in a specific area, or requesting discovery information from a target device. Adopting the second option, enhancements in the 3GPP standardized access network are proposed, enabling a resource request / allocation procedure for device discovery transmissions. In parallel, a spatial spectrum reuse scheme is designed and evaluated, as an effort to reduce the consumption of radio resources for discovery transmissions. Analytical and simulation results show that, under certain conditions for the network density, a number of discovery transmissions can be enabled in a multi-cellular network even if no interference information is available.

SUBJECT AREA: Wireless Communication Systems and Networks

KEYWORDS: Spatial spectrum reuse, interference management, device-to-device communications, device discovery, femtocells, LTE/LTE-A networks.

ΠΕΡΙΛΗΨΗ

Διαχρονικά, η κυρίαρχη σχεδιαστική επιλογή για την βελτίωση της φασματικής απόδοσης των ασύρματων δικτύων κινητών επικοινωνιών είναι η χωρική επαναχρησιμοποίηση φάσματος, η δυνατότητα δηλαδή να επαναχρησιμοποιείται το ίδιο κομμάτι φάσματος πολλές φορές στο χώρο με την προϋπόθεση ότι διατηρούνται χαμηλά τα επίπεδα των παρεμβολών.

Στα σύγχρονα δίκτυα κινητών επικοινωνιών μελετώνται δύο νέοι τρόποι χωρικής επαναχρησιμοποίησης φάσματος: α) η ανάπτυξη *φεμτοκυψελών (femtocells)*, η ανάπτυξη δηλαδή μικρών κυψελών για εξυπηρέτηση κυρίως εσωτερικών χώρων στην ευρύτερη περιοχή κάλυψης μία κύριας κυψέλης, και β) η ενεργοποίηση επικοινωνιών *συσκευής-σε-συσκευή (Device-to-Device – D2D),* απευθείας δηλαδή επικοινωνιών χωρίς την διαμεσολάβηση του σταθμού βάσης της κυψέλης.

Σκοπός της παρούσας διατριβής είναι να μελετηθούν και να αντιμετωπιστούν οι προκλήσεις που προκύπτουν από την εισαγωγή φεμτοκυψελών και την υιοθέτηση επικοινωνιών συσκευής-σε-συσκευή σε κυψελωτά δίκτυα προτυποποιημένα από την 3GPP (3rd Generation Partnership Project). Πιο συγκεκριμένα, μελετώνται τα προβλήματα της διαχείρισης του φάσματος και των παρεμβολών, καθώς και θέματα πρόσβασης στο φάσμα για Long Term Evolution (LTE) και LTE-Advanced (LTE-A) δίκτυα με φεμτοκυψέλες και με επικοινωνίες συσκευής-σε-συσκευή.

Για το σκοπό αυτό, αρχικά μελετήθηκαν τα LTE/LTE-A κυψελωτά δίκτυα ως προς το φυσικό επίπεδο, την αρχιτεκτονική και τις παρεμβολές, αποτυπώνοντας και την τρέχουσα κατάσταση στο τομέα της προτυποποίησης των φεμτοκυψελών και των επικοινωνιών συσκευής-σε-συσκευή. Ακολούθησε μια συγκριτική μελέτη μηχανισμών διαχείρισης παρεμβολών σε κανάλια ελέγχου ενός LTE/LTE-A δικτύου με φεμτοκυψέλες και ένας καινοτόμος μηχανισμός ελέγχου ισχύος για μεταδόσεις φεμτοκυψελών, βασισμένος στην ποιότητα εμπειρίας στο τελικό χρήστη. Η δουλειά αυτή άνοιξε νέους ερευνητικούς ορίζοντες, όπου το επίπεδο ικανοποίησης του τελικού χρήστη παίζει ενεργό ρόλο στη διαχείριση του δικτύου και την παροχή των υπηρεσιών. Παρόλα αυτά, η περεταίρω μελέτη προς την κατεύθυνση αυτή είναι εκτός του σκοπού της παρούσας διατριβής.

Στην συνέχεια, το κύριο βάρος της μελέτης μεταφέρθηκε στο πρόβλημα της διαχείρισης του φάσματος και των παρεμβολών στο πολύ πιο δυναμικό περιβάλλον ενός κυψελωτού δικτύου όπου επιτρέπονται οι επικοινωνίες συσκευής-σε-συσκευή. Σε πρώτη φάση, θεωρήθηκε ένα σύνολο από ζεύγη συσκευών που επικοινωνούν μεταξύ τους με επικοινωνίες συσκευής-σε-συσκευή και προτάθηκε ένας μηχανισμός συλλογής πληροφορίας παρεμβολών και ένα σχήμα ανάθεσης πόρων βασισμένο στη θεωρία γράφων. Το κύριο αποτέλεσμα της μελέτης αυτής ήταν πως αν και υψηλά επίπεδα χωρικής επαναχρησιμοποίησης μπορούν να επιτευχθούν, η συλλογή και η επεξεργασία πληροφορίας παρεμβολών είναι ένα πολύπλοκο πρόβλημα το οποίο απαιτεί και επιπλέον πόρους σηματοδοσίας. Έτσι, προτάθηκε και αναλύθηκε μίας λύση βασισμένη στον ανταγωνισμό. Πρακτικά οι χρήστες των επικοινωνιών συσκευής-σε-συσκευή εφαρμόζουν ένα σχήμα ανταγωνισμού όμοιο με αυτό που χρησιμοποιείται στα δίκτυα WiFi (Wireless Fidelity), προσαρμοσμένο όμως στο φυσικό επίπεδο των LTE/LTE-A δικτύων. Μαθηματική ανάλυση του σχήματος έδειξε ισχυρή εξάρτηση των επιδόσεων από το πλήθος των χρηστών που ανταγωνίζονται για το φάσμα. Σε μια προσπάθεια περιορισμού του πλήθους των ανταγωνιζόμενων χρηστών μόνο σε αυτούς που βρίσκονται σε γειτνίαση, και άρα μονό σε αυτούς που η άμεση επικοινωνία τους είναι εφικτή, μελετήθηκε το πρόβλημα της ανίχνευσης γειτονικής συσκευής.

Με βάση τις τρέχουσες προδιαγραφές της 3GPP, για την επίλυση του προβλήματος ανίχνευσης γειτονικής συσκευής, μία συσκευή είτε ανακοινώνει με μετάδοση περιοδικών μηνυμάτων την παρουσία της σε μια συγκεκριμένη περιοχή, είτε αιτείται από κάποια συγκεκριμένη συσκευή πληροφορία ανίχνευσης. Υιοθετώντας τη δεύτερη περίπτωση, προτάθηκαν βελτιώσεις στο LTE/LTE-A δίκτυο πρόσβασης ώστε να επιτρέπεται η ανάθεση φάσματος για μεταδόσεις ανίχνευσης γειτονικών συσκευών. Παράλληλα, δεδομένου ότι και για τις μεταδόσεις αυτές απαιτείται η κατανάλωση φάσματος, σχεδιάστηκε και αξιολογήθηκε μία λύση βασισμένη στη χωρική επαναχρησιμοποίηση φάσματος. Το βασικό συμπέρασμα ήταν ότι λόγω των χαμηλών απαιτήσεων ποιότητας των μηνυμάτων ανίχνευσης, κάτω από ορισμένες συνθήκες πυκνότητας του δικτύου, μπορεί να επιτραπεί η χωρική επαναχρησιμοποίηση του κυψελωτού φάσματος για μεταδόσεις ανίχνευσης συσκευής.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Συστήματα ασύρματων επικοινωνιών και δίκτυα

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Χωρική επαναχρησιμοποίηση φάσματος, διαχείριση παρεμβολών, επικοινωνίες συσκευής-σε-συσκευή, ανίχνευση συσκευής, φεμτοκυψέλες, LTE/LTE-A δίκτυα

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ΣΥΝΟΨΗ

Η ραγδαία αύξηση των τηλεπικοινωνιακών αναγκών για αξιόπιστη επικοινωνία με υψηλές ταχύτητες, και εγγυημένη ποιότητα, από οπουδήποτε και οποτεδήποτε, έχει εισάγει νέες προκλήσεις στο σχεδιασμό των σύγχρονων δικτύων κινητών επικοινωνιών. Βασική απαίτηση είναι η σχεδίαση λύσεων για δυναμικότερη και αποδοτικότερη χρήση του φάσματος, του σημαντικότερου ίσως πόρου των ασύρματων επικοινωνιών. Κυρίαρχη σχεδιαστική επιλογή προς την κατεύθυνση αυτή αποτελεί η *χωρική επαναχρησιμοποίηση φάσματος,* η δυνατότητα δηλαδή να επαναχρησιμοποιείται το ίδιο κομμάτι φάσματος πολλές φορές στο χώρο με την προϋπόθεση ότι διατηρούνται χαμηλά τα επίπεδα των παρεμβολών.

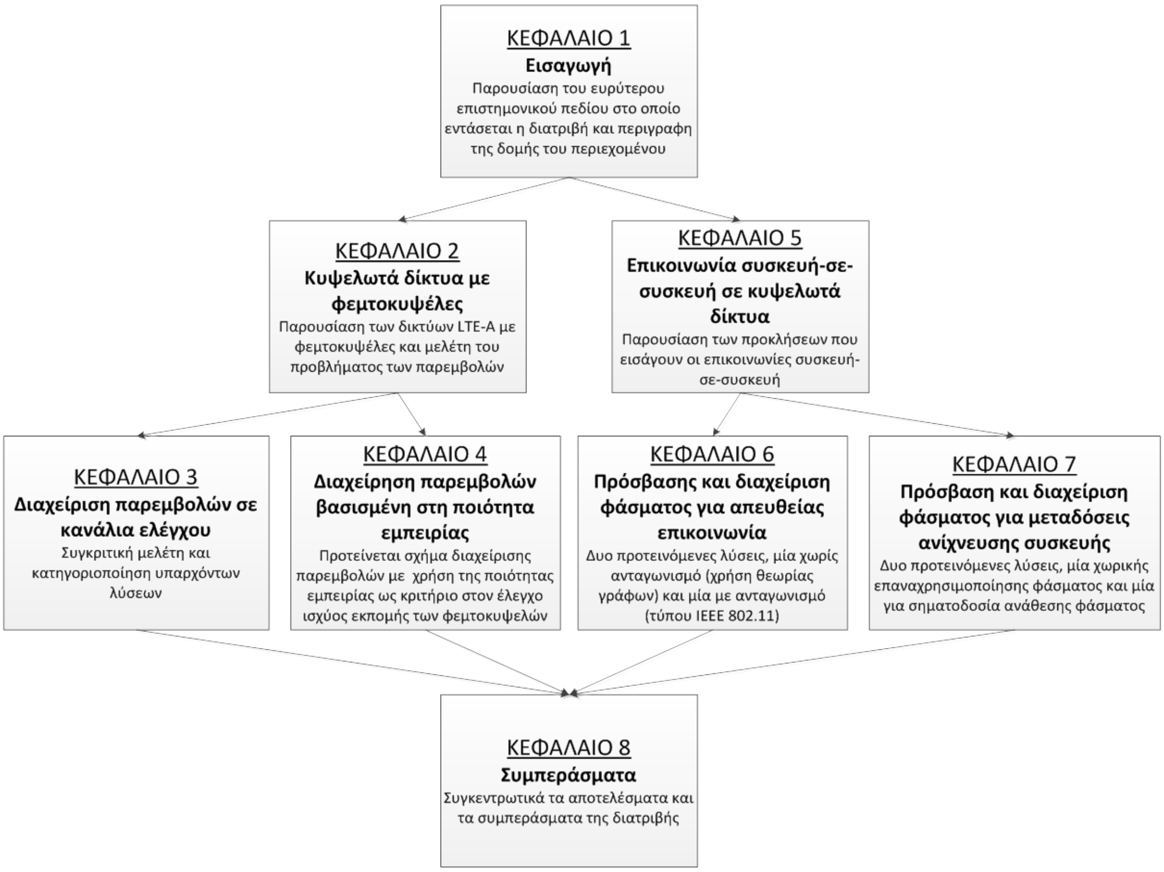
Διαχρονικά, στα δίκτυα κινητών επικοινωνιών, η χωρική επαναχρησιμοποίηση φάσματος πραγματώνεται με την ανάθεση του ίδιου φάσματος συχνοτήτων σε γειτονικές κυψέλες, γειτονικές δηλαδή περιοχές όπου κάθε μία εξυπηρετείται από διαφορετικό σταθμό βάσης. Μια πρακτική που σε συνδυασμό με την συνεχή σμίκρυνση των κυψελών, έχει παίξει σπουδαίο ρόλο στην ραγδαία βελτίωση της φασματικής χωρητικότητας τα τελευταία χρόνια, επαληθεύοντας έως και πρόσφατα τον νόμο του Moore περί διπλασιασμού της ασύρματης χωρητικότητας κάθε 30 μήνες.

Στα σύγχρονα δίκτυα κινητών επικοινωνιών, μελετώνται νέα σχήματα χωρικής επαναχρησιμοποίησης φάσματος, που αναμένεται να αλλάξουν άρδην το τρόπο χρήσης των ασύρματων πόρων σε ένα δίκτυο. Πιο συγκεκριμένα, μελετάται: α) η ανάπτυξη *φεμτοκυψελών (femtocells)*, η ανάπτυξη δηλαδή μικρών κυψελών για εξυπηρέτηση κυρίως εσωτερικών χώρων στην ευρύτερη περιοχή κάλυψης μία κύριας κυψέλης, και β) η ενεργοποίηση επικοινωνιών *συσκευής-σε-συσκευή (Device-to-Device – D2D)*, απευθείας δηλαδή επικοινωνιών χωρίς την διαμεσολάβηση του σταθμού βάσης της κυψέλης. Και τα δύο σχήματα αναμένεται να καλύψουν, εκτός της ανάγκης για αποδοτικότερη χρήση του φάσματος, και ένα σύνολο ετερογενών απαιτήσεων που έχουν προκύψει στα σύγχρονα δίκτυα κινητών επικοινωνιών όπως: α) η βελτίωση του συνεχώς μειούμενου κέρδους ανά μεταδιδόμενο bit πληροφορίας για τους τηλεπικοινωνιακούς παρόχους, β) η επαρκής και αξιόπιστη ασύρματη κάλυψη εσωτερικών χώρων, γ) η μείωση του όγκου δεδομένων που περνάει από το δίκτυο υποδομής, και δ) η ανάπτυξη νέων υπηρεσιών που εκμεταλλεύονται την γειτνίαση μεταξύ των συσκευών.

Η 3GPP (3^{rd} Generation Partnership Project) παρέχει ήδη τις βασικές προδιαγραφές για την ανάπτυξη δικτύων με φεμτοκυψέλες από το Release 8 και το Release 10 του προτύπου, για δίκτυα LTE (Long Term Evolution) και LTE-A (LTE-Advanced), αντίστοιχα, ενώ στο Release 12 ξεκίνησε η μελέτη για τη προτυποποίηση των απευθείας επικοινωνιών υπό τον όρο Proximity Services (ProSe).

Η παρούσα διδακτορική διατριβή εστιάζει στην επίλυση των προκλήσεων που προκύπτουν από την εισαγωγή φεμτοκυψελών και την υιοθέτηση επικοινωνιών συσκευής-σε-συσκευή σε ασύρματα κυψελωτά δίκτυα LTE/LTE-A.

Το περιεχόμενο της διατριβής χωρίζεται σε οκτώ κεφάλαια και ακολουθεί τη δομή που φαίνεται στο παρακάτω σχήμα.



Πιο συγκεκριμένα,

Στο πρώτο κεφάλαιο, το οποίο αποτελεί την εισαγωγή, αποτυπώνεται το γενικότερο θέμα το οποίο πραγματεύεται η διατριβή. Στο κεφάλαιο αυτό, ορίζονται τα κίνητρα, ο σκοπός και η συνεισφορά της διατριβής, ενώ επιπρόσθετα, δίνεται η δομή του κειμένου και μια συνοπτική περιγραφή του περιεχομένου κάθε κεφαλαίου.

Στο δεύτερο κεφάλαιο γίνεται μια περιεκτική επισκόπηση των LTE/LT-A δικτύων και των προκλήσεων που εισάγουν οι φεμτοκυψέλες και οι απευθείας επικοινωνίες σε αυτά. Πιο συγκεκριμένα, αρχικά περιγράφονται οι βασικές οντότητες της αρχιτεκτονικής ενός 3GPP δικτύου και οι βασικές δομές στο φυσικό επίπεδο. Στη συνέχεια παρουσιάζονται οι αρχές λειτουργίας των φεμτοκυψελών και το πρόβλημα των παρεμβολών. Το δεύτερο κεφάλαιο εμπεριέχει βασικές γνώσεις για τα LTE/LTE-A κυψελωτά δίκτυα που είναι απαραίτητες για τη μελέτη των υπόλοιπων κεφαλαίων, και κυρίως των κεφαλαίων 3 και 4.

Στο τρίτο κεφάλαιο γίνεται μια συγκριτική μελέτη τεχνικών διαχείρισης παρεμβολών σε 3GPP δίκτυα με φεμτοκυψέλες. Η μελέτη εστιάζει στην ανάγκη για διαχείριση των παρεμβολών σε κανάλια ελέγχου του δικτύου, δίνοντας μια συγκριτική εικόνα των πλεονεκτημάτων και των μειονεκτημάτων των υπαρχόντων λύσεων. Πιο συγκεκριμένα, θεωρείται ένα LTE-A δίκτυο με φεμτοκυψέλες, όπου το ίδιο κομμάτι φάσματος χρησιμοποιείται από φεμτοκυψέλες και κύριες κυψέλες/μακροκυψέλες (co-channel deployment) ενώ υιοθετείται και η λειτουργία closed subscriber group (CSG) για τις φεμτοκυψέλες, όπου μόνο ένα συγκεκριμένο σύνολο εγγεγραμμένων χρηστών μπορεί να εξυπηρετηθεί χωρίς τη δυνατότητα μεταπομπής μη εγγεγραμμένων χρηστών. Υπό αυτό το σενάριο, το πρόβλημα των παρεμβολών επιδεινώνεται απαιτώντας πιο έξυπνες και καινοτόμες προσεγγίσεις για την επίλυσή του. Μια πιθανή κατηγοριοποίηση των υπαρχόντων προσεγγίσεων είναι σε παρεμβολές σε κανάλια που φέρουν δεδομένα και σε παρεμβολές σε κανάλια που φέρουν πληροφορία ελέγχου/συγχρονισμού/σηματοδοσίας. Η πλειοψηφία των προσεγγίσεων στη βιβλιογραφία ασχολείται με το πρόβλημα της παρεμβολής στα κανάλια δεδομένων, θεωρώντας ότι οι τεχνικές διαχείρισης παρεμβολών που χρησιμοποιούνται για την προστασία καναλιών δεδομένων, στις περισσότερες περιπτώσεις, εφαρμόζεται επίσης για την προστασία των καναλιών ελέγχου (π.χ., τεχνική ελέγχου ισχύος). Ωστόσο, ο σχεδιασμός προσαρμοσμένων τεχνικών διαχείρισης παρεμβολών για την προστασία των καναλιών ελέγχου είναι απαραίτητος για τους ακόλουθους λόγους: α) η σημασία της πληροφορίας που φέρουν τα κανάλια ελέγχου, β) η ιδιαιτερότητα του LTE-A συστήματος να χρησιμοποιεί μια προκαθορισμένη περιοχή των πόρων που εκτείνεται σε όλο το εύρος ζώνης χωρίς δυνατότητα δυναμικής ανάθεσης στο πεδίο των συχνοτήτων, και γ) την ανάγκη να αποφευχθούν παρανοήσεις σχετικά με τον συγχρονισμό την πρόσβαση ή την ανάθεση πόρων, καθώς στα κανάλια αυτά δεν υπάρχει η δυνατότητα επαναμετάδοσης χαμένης πληροφορίας. Λαμβάνοντας όλα τα παραπάνω υπόψη, στο τρίτο κεφάλαιο της διατριβής προτείνεται μία κατηγοριοποίηση των σημαντικότερων τεχνικών διαχείρισης παρεμβολών για κανάλια ελέγχου, ενώ προσφέρεται και μια σύγκριση μελέτη των επιδόσεων τους. Για το λόγο αυτό, ορίστηκαν τέσσερις διαφορετικές κατηγορίες τεχνικών: α) τεχνικές που εφαρμόζονται στο πεδίο της συχνότητας, β) τεχνικές που εφαρμόζονται στο πεδίο του χρόνου, γ) τεχνικές ελέγχου ισχύος, και δ) τεχνικές ανάθεσης ασύρματων πόρων. Η αξιολόγησή τους επικεντρώθηκε στην παρεμβολή που προκαλείται σε κανάλια ελέγχου στη κατερχόμενη ζεύξη από σταθμούς βάσης φεμτοκυψελών σε χρήστες μίας μακροκυψέλης. Όπως προέκυψε, οι μη συνεργατικές τεχνικές – τεχνικές που εφαρμόζονται ανεξάρτητα σε κάθε φεμτοκυψέλη – έχουν μειωμένη επίδοση, κυρίως σε πυκνό δίκτυο φεμτοκυψελών. Από την άλλη μεριά, συνεργατικές τεχνικές απαιτούν αξιόπιστη και έγκαιρη ανταλλαγή πληροφορίας, κάτι που τις καθιστά πολύπλοκες σε πυκνά δίκτυα. Επίσης, οι τεχνικές ελέγχου ισχύος μετάδοσης μπορούν να εφαρμοστούν συνοδευτικά με κάθε άλλη τεχνική για προστασία χρηστών-θυμάτων παρεμβολής βελτιώνοντας σημαντικά τις επιδόσεις, απαιτείται όμως έλεγχος της επιβάρυνσης που προκαλείται στους εξυπηρετούμενους χρήστες.

Στο τέταρτο κεφάλαιο προτείνεται μια μέθοδο διαχείρισης παρεμβολών βασισμένη στη τεχνική ελέγχου ισχύος μετάδοσης των φεμτοκυψελών. Η καινοτομία της μεθόδου έγκειται στο οτι χρησιμοποιεί ως βασικό κριτήριο για την επιλογή ισχύος μετάδοσης το βαθμό ικανοποίηση του τελικού χρήστη. Μέχρι σήμερα, η πλειοψηφία των μεθόδων διαχείρισης παρεμβολών με την τεχνική ελέγχου ισχύος επικεντρώνονται στη διασφάλιση της παρεχόμενης ποιότητας υπηρεσίας (Quality of Service – QoS), μετρούμενη κυρίως σε τιμές σήματος προς παρεμβολή συν θόρυβο (SINR). Σε όλες αυτές τις προσεγγίσεις η επίδοση φράσσεται από το ζητούμενο κατώφλι ποιότητα υπηρεσίας στους εξυπηρετούμενους χρήστες, ετσι π.χ. ένας σταθμός βάσης μίας φεμτοκυψέλης δε μπορεί να μειώσει την ισχύ εκπομπής του και άρα τις παρεμβολές κάτω από εκείνη την τιμή που εξασφαλίζει την ελάχιστη ζητούμενη ποιότητα υπηρεσίας στους εξυπηρετούμενους χρήστες. Ωστόσο, μια πιο ελκυστική μέθοδος για να αξιολογηθεί η ποιότητα της παρεχόμενης υπηρεσίας (ειδικά για υπηρεσίες πραγματικού χρόνου) είναι η μέτρηση του επιπέδου ικανοποίησης των τελικών χρηστών. Επί του παρόντος, η σύνδεση μεταξύ της απόδοσης του δικτύου και την ικανοποίηση των τελικών χρηστών δεν είναι αυστηρά καθορισμένη. Για να δώσουμε ένα παράδειγμα, η ίδια ρυθμαπόδοση για την ίδια παρεχόμενη υπηρεσία μπορεί να αξιολογηθεί τελείως διαφορετικά από δύο χρήστες.

Αναγνωρίζοντας τη σημασία της ποσοτικοποίησης της ικανοποίησης των τελικών χρηστών, η ITU (International Telecommunication Union) πρότεινε τον όρο ποιότητας εμπειρίας (Quality of Experience – QoE). Η QoE είναι ο πιο σημαντικός παράγοντας για την απόφαση ενός χρήστη σχετικά με την συνέχιση της συνδρομής του σε μια υπηρεσία, και το γεγονός αυτό εξηγεί την εμφάνιση μοντέλων μετάβασης από το υπάρχων μοντέλο διαχείρισης δικτύου με βάση την QoS σε ένα νέο βασισμένο στην QoE. Λαμβάνοντας υπόψη τα παραπάνω, στο τέταρτο κεφάλαιο της διατριβής, εξετάζεται εάν και σε ποιο βαθμό οι παρεμβολές σε ένα δίκτυο με φεμτοκυψέλες αντικατοπτρίζονται σε διακυμάνσεις στην ικανοποίηση των τελικών χρηστών. Η μελέτη επικεντρώνεται σε υπηρεσίες φωνής (Voice over IP (VoIP)) και αρχικά μελετάται η υποβάθμιση της ποιότητας εμπειρίας των χρηστών μιας μακροκυψέλης λόγω της εισαγωγής φεμτοκυψελών. Στη συνέχεια, εξετάζεται η σχέση μεταξύ της λαμβανόμενης τιμής SINR και της QoE σε ένα χρήστη και προτείνεται ένας μηχανισμό επιλογής ισχύος μετάδοσης για των φεμτοκυψελών βασισμένο στο QoE. Τέλος, ο βασικός μηχανισμό επιλογής ισχύος μετάδοσης που προτείνεται από τη 3GPP για τις φεμτοκυψέλες των LTE-A δικτύων συγκρίνεται με τον προτεινόμενο μηχανισμό, αποδεικνύοντας πως η χρήση του QoE στη διαχείριση των παρεμβολών είναι ευεργετική. Όπως αποδεικνύεται, με την χρήση του QoE αντί της του QoS, μπορούμε να βελτιώσουμε την απόδοση των συμβατικών λύσεων διαχείρισης παρεμβολών, χωρίς να επιβαρύνουμε την αντίληψη που έχει ο χρήστης για την ποιότητα της υπηρεσίας που λαμβάνει. Πρακτικά μπορούμε να προσαρμόσουμε κατάλληλα τα κατώφλια εξυπηρέτησης ενός χρήστη σε χαμηλότερες τιμές QoS διατηρώντας όμως το QoE, μειώνοντας την ισχύ εκπομπής στις φεμτοκυψέλες και παράλληλα τις συνολικές παρεμβολές που προκαλούνται στο δίκτυο.

Στο πέμπτο κεφάλαιο παρουσιάζονται οι βασικές αρχές των συσκευή-σε-συσκευή επικοινωνιών σε LTE/LTE-A κυψελωτά δίκτυα, και γίνεται μια βιβλιογραφική επισκόπηση λύσεων όπου η χωρική επαναχρησιμοποίηση φάσματος χρησιμοποιείται για την συνύπαρξη συμβατικών κυψελώτων επικοινωνιών και απευθείας επικοινωνιών. Επιπλέον, συνοψίζεται η τρέχουσα κατάσταση στο τομέα της προτυποποίησης των επικοινωνιών συσκευής-σε-συσκευή, ενώ περιγράφεται και το πρόβλημα της ανίχνευσης γειτονικών συσκευών, μια από τις σημαντικές προκλήσεις που εισάγεται με τις συσκευή-σε-συσκευή επικοινωνίες. Το πέμπτο κεφάλαιο συμπληρώνει τις βασικές γνώσεις για τα LTE/LTE-A κυψελωτά δίκτυα, οι οποίες δίνονται στο κεφάλαιο 2, παρέχοντας στον αναγνώστη το κατάλληλο υπόβαθρο ώστε να μελετήσει τις λύσεις που προτείνονται στα κεφάλαια 6 και 7.

Στο έκτο κεφάλαιο μελετάται το πρόβλημα πρόσβασης και διαχείρισης των ασύρματων πόρων για απευθείας επικοινωνία μεταξύ χρηστών σε κυψελωτά δίκτυα. Πιο συγκεκριμένα, προτείνονται δύο λύσεις, μία με πρόσβαση όπου ο σταθμός βάσης αναθέτει ασύρματους πόρους για απευθείας επικοινωνία μεταξύ χρηστών εκμεταλλευόμενος πληροφορία για τις αναμενόμενες παρεμβολές στο δίκτυο, και μία για πρόσβαση με ανταγωνισμό όπου υιοθετούνται οι βασικές αρχές λειτουργίας του προτύπου IEEE 802.11.

Για τη λύση που γίνεται εκμετάλλευση πληροφορίας παρεμβολών από το σταθμό βάσης, προτείνεται ένας μηχανισμός βασισμένος στη θεωρία γράφων. Η καινοτομία του συγκεκριμένου μηχανισμού έγκειται στο τρόπο δημιουργίας του γράφου και στην χρήση ενός σχήματος μετρήσεων για την συλλογή της απαραίτητης πληροφορίας βασισμένο στο φυσικό επίπεδο των LTE δικτύων. Ο γράφος σχηματίζεται πριν από κάθε ανερχόμενη ζεύξη από κόμβους που αποτυπώνουν είτε τα ζεύγη συσκευών που έχουν αιτηθεί φάσμα για πιθανή απευθείας επικοινωνία, είτε τις συσκευές στις οποίες έχει ανατεθεί φάσμα για μετάδοση στην ανερχόμενη ζεύξη του κυψελωτού δικτύου. Ακμές ορίζονται μεταξύ δύο κόμβων όταν υπάρχει ένδειξη παρεμβολής μεταξύ των συσκευών που αντιπροσωπεύουν οι κόμβοι. Για την απόκτηση της πληροφορίας παρεμβολών στο δίκτυο, οποιοσδήποτε μηχανισμός μετρήσεων/ανίχνευσης ή εκμετάλλευσης πληροφορίας θέσης μπορεί να χρησιμοποιηθεί, παρόλα αυτά προτείνεται η χρήση μιας περιόδου ανίχνευσης στο πλαίσιο της ανερχόμενης ζεύξης, όπου οι συσκευές που θέλουν να έχουν απευθείας επικοινωνία ανιχνεύουν μεταδόσεις συμβατικών χρηστών της κυψέλης. Με τον τρόπο αυτό σχηματίζονται λίστες παρεμβολέων οι οποίες αποστέλλονται στο σταθμό βάσης και χρησιμοποιούνται για το σχηματισμό του γράφου. Η ανάθεση των ασύρματων πόρων για τις απευθείας επικοινωνίες γίνεται με τεχνικές χρωματισμού γράφων όπου κάθε χρώμα αντιστοιχίζεται σε ένα κομμάτι του φάσματος. Η μέθοδος υπόσχεται υψηλά ποσοστά χωρικής επαναχρησιμοποίησης του φάσματος, αναδεικνύει όμως και τη πολυπλοκότητα του προβλήματος, θέτοντας σε πρώτο πλάνο την αναζήτηση λύσεων όπου δεν απαιτείται συγκέντρωση πληροφορίας παρεμβολών.

Για την πρόσβαση με ανταγωνισμό, γίνεται μια προσαρμογή της Distributed Coordination Function (DCF), μιας διαδικασία η οποία χρησιμοποιείται σε δίκτυα προτυποποιημένα κατά IEEE 802.11, στο φυσικό επίπεδο των LTE δικτύων όπου η μετάδοση γίνεται σε προκαθορισμένα πλαίσια για την ανερχόμενη και τη κατερχόμενη ζεύξη. Οι απευθείας επικοινωνίες λαμβάνουν χώρα κατά την ανερχόμενη ζεύξη του κυψελωτού δικτύου, ενώ ορίζονται τέσσερα σενάρια λειτουργίας: α) για τις απευθείας μεταδόσεις χρησιμοποιείται προκαθορισμένο φάσμα, ανεξάρτητο των κυψελωτών μεταδόσεων, και έχει προηγηθεί λειτουργία ανίχνευσης (οι συσκευές γνωρίζουν ότι γειτνιάζουν), β) για τις απευθείας μεταδόσεις χρησιμοποιείται προκαθορισμένο φάσμα, ανεξάρτητο των κυψελωτών μεταδόσεων, αλλά δεν έχει προηγηθεί λειτουργία ανίχνευσης (οι συσκευές δεν γνωρίζουν αν γειτνιάζουν), γ) για τις απευθείας μεταδόσεις χρησιμοποιείται το ίδιο φάσμα με αυτό των κυψελωτών μεταδόσεων, και έχει προηγηθεί λειτουργία ανίχνευσης (οι συσκευές γνωρίζουν ότι γειτνιάζουν), και δ) για τις απευθείας μεταδόσεις χρησιμοποιείται το ίδιο φάσμα με αυτό των κυψελωτών μεταδόσεων, αλλά δεν έχει προηγηθεί λειτουργία ανίχνευσης (οι συσκευές δεν γνωρίζουν ότι γειτνιάζουν). Για τα σενάρια αυτά, γίνεται αναλυτική μελέτη των αναμενόμενων επιδόσεων από πλευράς ρυθμαπόδοσης, καθυστέρησης, και κατανάλωσης ενέργειας. Όπως προέκυψε η απόδοση του σχήματος εξαρτάται κατά κύριο λόγο από το πλήθος των χρηστών/συσκευών που ανταγωνίζονται, ενώ η πρότερη γνώση για το αν ο χρήστης/συσκευή-δέκτης είναι σε κοντινή απόσταση για την εγκαθίδρυση της απευθείας επικοινωνίας (επίλυση προβλήματος ανίχνευσης γειτονικής συσκευής) βελτιώνει αισθητά τις επιδόσεις.

Στο έβδομο κεφάλαιο μελετάται ένα από τα θεμελιώδη προβλήματα στις επικοινωνίες συσκευής-σε-συσκευή, το πρόβλημα της ανίχνευσης συσκευών που γειτνιάζουν. Το πρόβλημα εξετάζεται από δύο σκοπιές. Στη πρώτη προτείνεται μια σειρά αλλαγών στο συμβατικό τρόπο σηματοδοσίας για ανάθεση φάσματος ώστε ο σταθμός βάσης ενός LTE-A δικτύου να μπορεί να αναθέσει φάσμα για μεταδόσεις μηνυμάτων ανίχνευσης συσκευής. Στη δεύτερη περίπτωση προτείνεται ένας κεντρικοποιημένος μηχανισμός χωρικής επαναχρησιμοποίησης φάσματος για την ενεργοποίηση μεταδόσεων ανίχνευσης γειτόνων.

Για την σηματοδοσία που απαιτείται για ανάθεση πόρων σε μεταδόσεις ανίχνευσης γειτόνων, οι προτεινόμενες βελτιώσεις εστιάζουν στην ενσωμάτωση πληροφορίας σε υπάρχοντα μηνύματα ελέγχου στο δίκτυο πρόσβασης, αποφεύγοντας την εμπλοκή του δικτύου πυρήνα. Πιο συγκεκριμένα, οι αλλαγές αυτές είναι σύμφωνες με το πρότυπο του LTE-A συστήματος, και αφορούν κυρίως την εισαγωγή μιας επιπλέων ταυτότητας στις συσκευές των τελικών χρηστών όμοια με αυτή που χρησιμοποιεί ο σταθμός βάσης κατά την διαδικασία ανάθεση πόρων.

Για την χωρική επαναχρησιμοποίηση, η προτεινόμενη λύση εκμεταλλεύεται την τεχνική Fractional Frequency Reuse (FFR) κατά τις ανωφερείς μεταδόσεις στο κυψελωτό δίκτυο. Πιο συγκεκριμένα, ο σκοπός του προτεινόμενου σχήματος είναι διττός: α) να παρέχει το βέλτιστο μέγεθος του εσωτερικού μέρους μίας κυψέλης (cell-center area) όπως αυτό ορίζεται από την FFR τεχνική, και β) να ποσοτικοποιήσει πιθανές ευκαιρίες μεταδόσεις σημάτων ανίχνευσης στο φάσμα που χρησιμοποιείται από χρήστες που βρίσκονται στο εσωτερικό μέρος της κυψέλης, εκτιμώντας παράλληλα την επίπτωση στις κυψελωτές επικοινωνίες. Για την ποσοτικοποίηση αυτή ένας συντονιστής χρησιμοποιεί εκτιμήσεις του φόρτου του δικτύου και τις κατανομής των χρηστών, αποφεύγοντας την συλλογή και εκμετάλλευση πληροφορίας θέσης ή παρεμβολών. Ο συντονιστής ενημερώνει κάθε σταθμό βάσης για το μέγεθος στο οποίο πρέπει να οριστεί το εσωτερικό μέρος της κυψέλης του και για τον μέγιστο αριθμό των επιπλέων μεταδόσεων που μπορεί να επιτρέψει. Τα βασικότερα πλεονεκτήματα της προτεινόμενης λύσης συνοψίζονται στο ότι δεν απαιτείται καμία πληροφορία παρεμβολών μεταξύ των χρηστών, ενώ η αναμενόμενη επιβάρυνση των κυψελωτών μεταδόσεων είναι εγγυημένα χαμηλότερη ενός κατωφλίου. Παράλληλα, η λύση μπορεί να λειτουργεί και ως μια συμβατική FFR τεχνική, για προστασία από δια-κυψελική (inter-cell) παρεμβολή στις περιπτώσεις που η αναμενόμενη επιβάρυνση από την επαναχρησιμοποίηση του φάσματος δεν είναι αποδεκτή. Για το σχήμα αυτό παρέχονται αναλυτικά αποτελέσματα τα οποία και επιβεβαιώθηκαν με την χρήση προσομοίωσης.

Στο όγδοο κεφάλαιο ολοκληρώνεται η διατριβή. Στο κεφάλαιο αυτό γίνεται μια συνοπτική αναφορά στα θέματα τα οποία μελετήθηκαν, ενώ εμπεριέχονται συγκεντρωτικά όλα τα συμπεράσματα της έρευνας και περιγράφονται τα αποτελέσματα που προέκυψαν.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This thesis is original work by the author, D. Tsolkas, published in international scientific journals, conference proceedings, and book chapters. It was realized from April 2010 to July 2014 under the supervision of Prof. Lazaros Merakos, and the surveillance of Dr. Nikos Passas. The content has been organized in a comprehensive structure of eight chapters, which can be easily followed by the reader. For the readers' convenience, at the end of each chapter summarized conclusions and a list with the cited references are provided. Readers that are familiar with 3GPP Release 8 and beyond specifications can skip the study of chapters 2 and 5, which provide the fundamental physical layer and architectural background, as well as a description of the femtocell interference management problem and the D2D communication aspects in LTE/LTE-A networks.

In parallel to the preparation of this thesis, D. Tsolkas participated in the realization of European and National research projects, such as, the CrossFire, EMPhATiC, E3, SMART-NRG, PeerAssist, and Bus&Erxetai projects. Moreover, he has contributed to new proposals for research projects in the concept of the European research program HORIZON 2020, while he has supervised numerous undergraduate and postgraduate theses at the dept. of Informatics and Telecommunications, in the National and Kapodistrian University of Athens.

The entire research was conducted in the Green, Adaptive and Intelligent Networking Group (GAIN), a research group inside the Communication Networks Laboratory (CNL) of the National and Kapodistrian University of Athens, while It has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

Dimitris Tsolkas,

July, 2014

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1. INTRODUCTION

1.1 Thesis motivation and scope

Nowadays, wireless communication services and broadband Internet access have converged to deal with the present requirements for ubiquitous and highly reliable communications. International Mobile Telecommunications-Advanced (IMT-Advanced) quantifies these requirements promising an all-Internet Protocol (IP) packet switched network with data rates analogous to those provided by wired communication systems.

In this direction, a new architecture of cellular networks introduces a major paradigm shift from wide-range cells with high transmit power (macrocells) to low-power small-sized cells. The success of this shift relies on capitalizing on the performance improvements derived by increasing the spatial spectrum utilization and enhancing the indoor coverage. Historically, spatial spectrum reuse has been, by far, the most efficient approach in improving cellular system capacity, compared to approaches such as the the adoption of efficient modulation schemes. Also, the enhancement of indoor coverage will be essential in the near future, since the majority of the voice and data traffic will originate from indoor users. To this end, the 3rd Generation Partnership Project (3GPP) standardized a novel type of small-sized cells called *femtocells* or *femtos*. Femtocells are expected to be the most energy-efficient and cost-effective solution for improving spatial spectrum utilization and indoor coverage. Since the licensed spectrum resources are expensive and scarce, femtocells are expected to spatially reuse licensed spectrum under the so-called co-channel deployment. Installed by the consumers in an unplanned manner, they also provide the option to serve only a limited set of subscribed users through the so-called closed subscriber group (CSG) mode, changing in that way the landscape of cellular networks in the following years. However, before operators and consumers reap the benefits provided by femtocells, several challenges must be addressed, including the mitigation of the generated interferences.

In parallel to the femtocell proliferation, one of the prominent topics considered toward achieving IMT-Advanced requirements is the Device-to-Device (D2D) communications, i.e., direct communications in a cellular network, without the intervention of the base station, when the transmitter and the receiver are in close proximity. Differing from conventional approaches, such as Bluetooth and WiFi-direct, D2D communications utilize licensed spectrum, while no manual network detection-selection is needed. Comparing to the very appealing cognitive radio communications, where secondary transmissions are allowed in parallel with primary cellular transmissions, D2D communications are established by standard/primary cellular users, reaping the benefits of being synchronized and controlled by the central (primary) base station. The introduction of D2D communications in cellular networks is expected to be beneficial from a variety of perspectives. The short distance between D2D users results in better channel conditions, leading to higher data rates, lower delays and lower energy consumption. Additionally, D2D users are connected through a direct link and the intermediate transmission to a base station is avoided, saving network resources and processing effort from the network. Also, the coexistence of cellular and D2D links can lead to more efficient spectrum utilization and higher spatial spectrum reuse, while new business models, probably with a new charging policy for users, may be designed. However, D2D communications do not come without a cost. On the one hand, interference-free conditions between D2D and cellular transmissions, as well as among D2D pairs are required, while on the other hand, the device discovery problem should be faced, i.e., the need for a D2D transmitter to know whether the target receiver is in its vicinity and, thus, in valid distance to start a D2D communication.

The 3GPP (3rd Generation Partnership Project) already provides the fundamental specifications for the femtocells in Release 8 and Release 10 for LTE (Long Term Evolution) and LTE-A (LTE-Advanced) networks, respectively, while the first efforts for standardizing D2D communications begun in Release 12*,* under the term Proximity Services (ProSe).

Taking all the above into account***, the scope of this thesis is to deal with challenges arising from the introduction of femtocells and D2D communications in LTE/LTE-A cellular networks.*** More specifically, the interference management problem in femtocell-overlaid cellular networks is studied, while the radio resource management and the spectrum access challenges arising in cellular networks with D2D communications are examined.

1.2 Thesis contributions

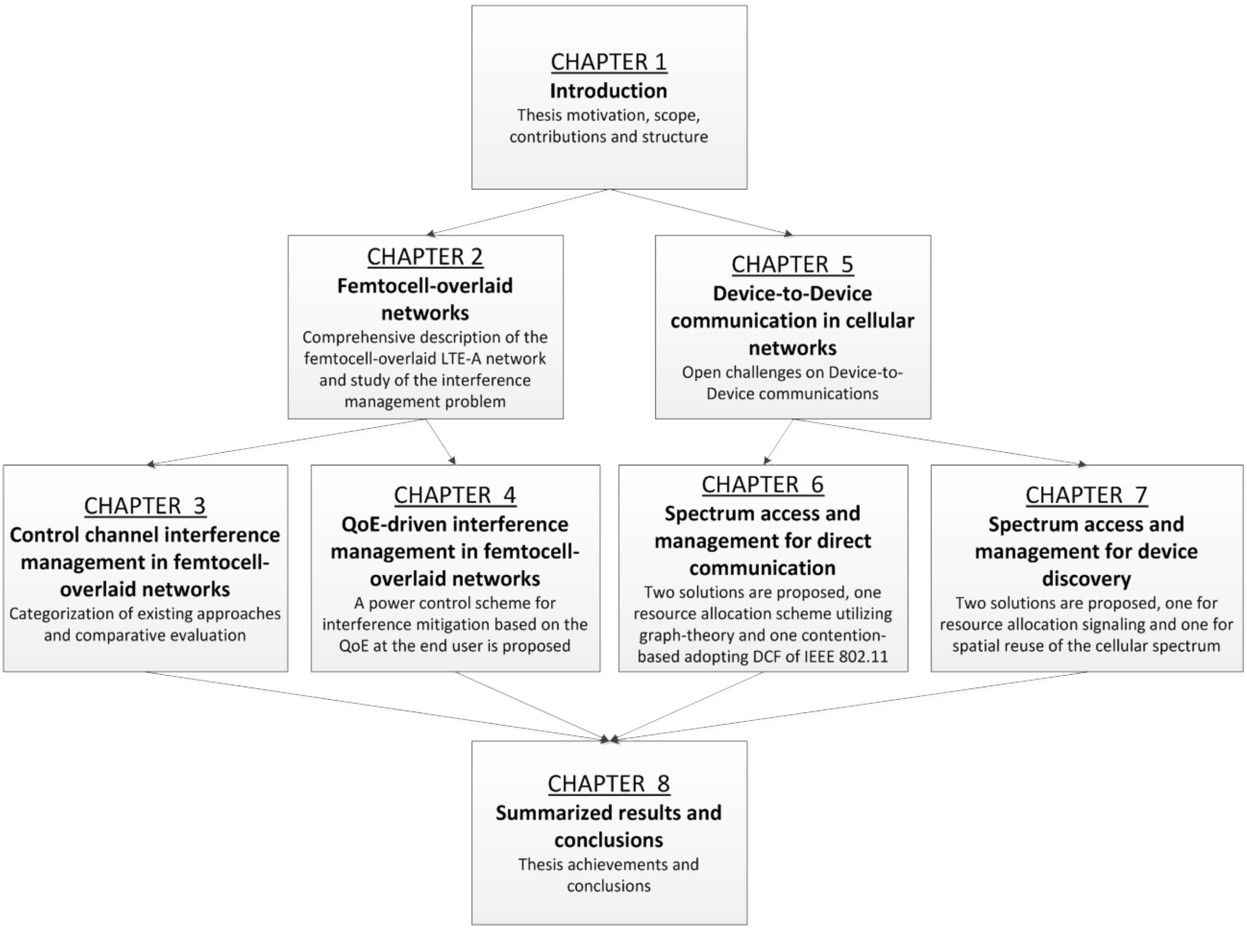
In this thesis the reader can find a comprehensive description of the architectural and physical layer aspects of the LTE/LTE-A networks, as well as, the current standardization efforts for D2D communications and the main specifications for solving the device discovery problem. However, the dominant contributions of this thesis are summarized below:

- A thorough study of fundamental and emerging interference schemes for femtocell-overlaid LTE-A networks, and a qualitative and quantitative performance comparison from the perspective of control channel protection is provided. The focus is on the downlink control channel interference caused by femtocells to macrocell users located in the total macrocell area or in a target femtocell area, while the impact of the femtocell deployment density on such interference is assessed.
- An examination on whether and in what extent the interferences in a femtocell-overlaid network are reflected as variations in the end-users' satisfaction is provided. Additionally, the relation between the SINR (signal to interference plus noise ratio) and the perceived Quality of Experience (QoE) at an interference-victim is studied and formulated towards designing a QoE-aware power control interference management scheme.
- A graph-coloring secondary resource allocation scheme for D2D communications is proposed. Under this scheme, interference information together with the primary resource allocation (for the cellular uplink transmissions) are represented by an enriched node contention graph (eNCG), which is utilized by graph-coloring algorithms to provide a secondary allocation for D2D communications.
- A spectrum access scheme for D2D communication peers in an LTE network based on a contention process is proposed, providing the performance analysis in terms of normalized throughput, access delay and energy consumption. The solution borrows the distributed coordination function (DCF) of the IEEE 802.11 standard and adapts it to the LTE UL physical layer structure.
- Euclidian geometry is used to estimate the access and discovery probabilities (i.e., the probability a D2D transmitter to be outside the interfering area of a cellular transmitter and the probability the target D2D receiver to be located in transmitter's range) in an interference isolated cell.
- A set of enhancements is proposed in the conventional resource request/allocation procedure of an LTE-A access network towards allowing the allocation of spectrum resources for discovery transmissions. The proposed enhancements abide by the specification for device discovery provided by 3GPP.
- The spatial spectrum reuse opportunities posed by the FFR technique in the UL period of a multi-cellular LTE network are analytically studied and a D2D

coordinator is proposed towards exploiting these opportunities for discovery transmissions. Simulations are used to validate the results of the theoretical study.

1.3 Thesis structure

This thesis consists of eight chapters, following the conceptual structure depicted in the figure bellow. Chapter 2 provides a comprehensive description of the femtocell-overlaid LTE-A network and studies the interference management problem. Chapter 3 provides a categorization and a comparative evaluation of the existing control channel interference management schemes. Chapter 4 includes a power control scheme for interference mitigation in femtocell-overlaid networks based on the QoE at the end user. Chapter 5 summarizes the open challenges on device-to-device communications, including the current standardization efforts by 3GPP. Chapter 6 provides two solutions on spectrum access and management for direct communications, one resource allocation scheme utilizing graph-theory and one contention-based adopting principles of the DCF of the IEEE 802.11 standard. Chapter 7 proposes two solutions on spectrum access and management for device discovery, one for resource allocation signaling and one for spatial reuse of the cellular spectrum. Finally, chapter 8 summarizes the overall achievements and conclusions.



2. FEMTOCELL-OVERLAID NETWORKS

The modern needs for ubiquitous and high reliable services introduce a major paradigm shift from conventional cellular networks to heterogeneous networks, where macrocells coexist with femtocells [1]. Femtocells are indoor low-power cells introduced in order to improve the spatial spectrum utilization and amplify the indoor coverage, promising high QoS to the end-users. Moving to this direction, Long Term Evolution (LTE) and its resent amendment LTE-Advanced (LTE-A) are the first to apply the mixed cellular network and face in practice the challenges of a two-tier heterogeneous network. This chapter provides a comprehensive description of the LTE/LTE-A networks, and defines the interference management problem in such networks.

2.1 LTE-A Architecture

The LTE-A system is divided into two basic subsystems (Fig.2-1) [2]: the Evolved – Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). Its architecture has been simplified avoiding the hierarchical structures and providing increased scalability and efficiency. The EPC subsystem is a flat all-IP system designed to support higher packet data rates and low latency in serving flows. Also, its target is to operate under multiple radio access technologies, to increase system's capacity, and to support seamless mobility. The basic entities that are used to this purpose are the Mobility Management Entity (MME), the Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW). On the other hand, the E-UTRAN subsystem implements the access network introducing a spatial coexistence of large-sized base stations, called evolved NodeBs (eNBS), small-sized indoor base stations, called Home eNBs (HeNBs), and mobile terminals called User Equipments (UEs). Commonly, the UEs served by the eNBs and HeNBs are referred to as macrocell UEs (MUEs) and Femtocell UEs (FUEs), respectively.

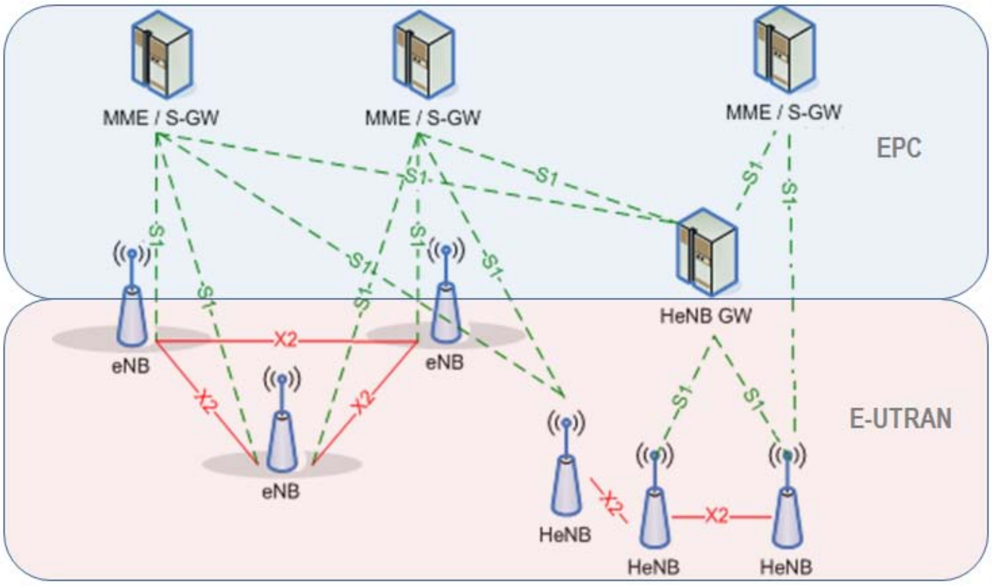


Figure 2-1: LTE-A architecture

Each (H)eNB has an IP address and is part of the all-IP network, while it is interconnected to other (H)eNBs through the X2 interface (Fig.2-1). This interconnection allows collaboration among (H)eNBs in order to perform functions such as handover and interference management. Note that in a 3GPP Release 10 network the X2 interface is not specified for connection between HeNBs and eNBs; however, in 3GPP

Release 12 networks [3] the X2 gateway (X2 GW) is used for this interconnection. HeNBs are considered as low-power eNBs and realize the access network of the femtocells by spatially reusing the spectrum bands assigned to eNBs. Since HeNBs are closer to the end-users than the eNBs they experience better channel conditions improving the indoor coverage.

However, HeNBs have the option to serve only a specific set of subscribed devices by adopting the so-called close subscribed group (CSG) mode, and they can be unpredictably switch on and off by the consumers, exacerbating the generated interference problem.

2.2 LTE-A Physical Layer

2.2.1 Multiple access technique

Orthogonal frequency division multiplex (OFDM) was selected as the basis for the LTE/LTE-A physical layer. OFDM is a technology that dates back to the 1960's. It was considered for 3G systems in the mid-1990s before being determined too immature. Developments in electronics and signal processing since that time has made OFDM a mature technology widely used in other access systems like IEEE 802.11 (WiFi) and 802.16 (WiMAX) and broadcast systems (Digital Audio/Video Broadcast – DAB/DVB). The OFDM technology is based on using multiple narrow band sub-carriers spread over a wide channel bandwidth. The subcarriers are mutually orthogonal in the frequency domain which mitigates inter-symbol interference (ISI) (Fig. 2-2).

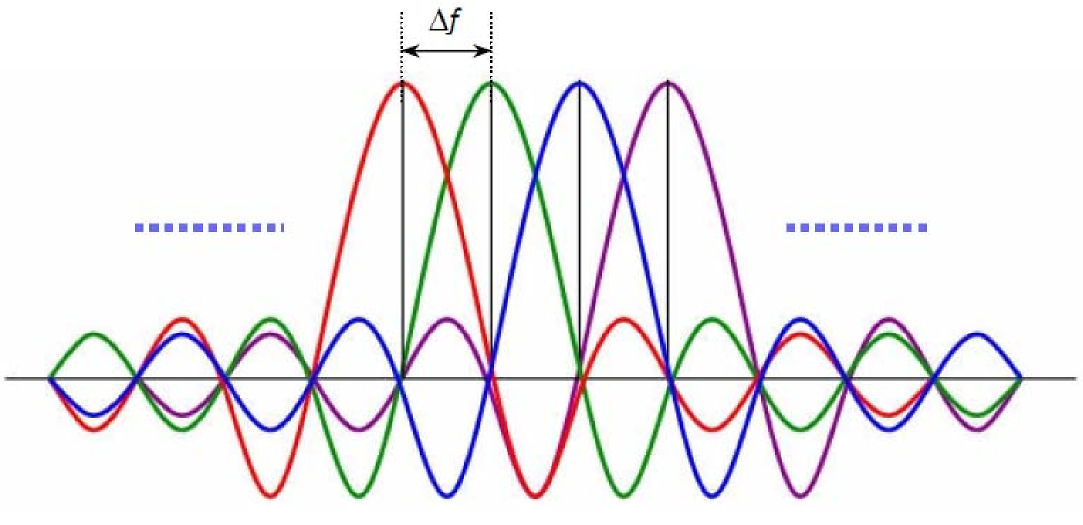


Figure 2-2: OFDM subcarrier spacing

The main advantages of the OFDM technique are summarized as follows:

- Decreased inter-symbol interference.
- Low requirements for intra-cell interference cancellation.
- Flexible utilization of frequency spectrum.
- High spectral efficiency due to the orthogonality between sub-carriers.
- Optimization of data rates for all users in a cell by transmitting on the best (i.e. non-faded) subcarriers for each user via Orthogonal Frequency Division Multiple Access (OFDMA).

In the LTE/LTE-A DL the OFDMA technique is used to multiplex traffic by allocating specific patterns of subcarriers in the time-frequency space to different users. In addition to data traffic, control channels and reference symbols can be interspersed.

Control channels carry information on the network and cell while reference symbols assist in determining the propagation channel response. However, despite its many advantages, OFDMA has certain drawbacks such as high sensitivity to frequency offset and high peak-to-average power ratio (PAPR). To this end, in the UL the Single Carrier FDMA (SC-FDMA) with cyclic prefix is adopted targeting at reducing the PAPR. However, the drawback of the SC-FDMA is the relatively inter-symbol interference for due to the single carrier modulation, which requires a low-complexity block equalizer at the eNB receiver to correct for the distorting effects of the radio channel.

2.2.2 Frame structure

In the time domain, the transmissions in an LTE-A network are organized into radio frames of 10 ms, while each radio frame is divided into 10 subframes, while either the FDD (Frequency Division Duplex) or the TDD (Time Division Duplex) approach can be used. In the TDD case the seven different configurations can be used as shown in Table 2-1

Table 2-1: TDD configuration types

index	Special subframe frequency	Configuration									
		0	1	2	3	4	5	6	7	8	9
0	5ms	D	S	U	U	U	D	S	U	U	U
1	5ms	D	S	U	U	D	D	S	U	U	D
2	5ms	D	S	U	D	D	D	S	U	D	D
3	10ms	D	S	U	U	U	D	D	D	D	D
4	10ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5ms	D	S	U	U	U	D	S	U	U	D

Each subframe consists of 2 slots, while each slot consists of 6 or 7 OFDM symbols for the extended or the normal cyclic prefix (CP), respectively (Fig 2-3). Scheduling is done in a subframe basis.

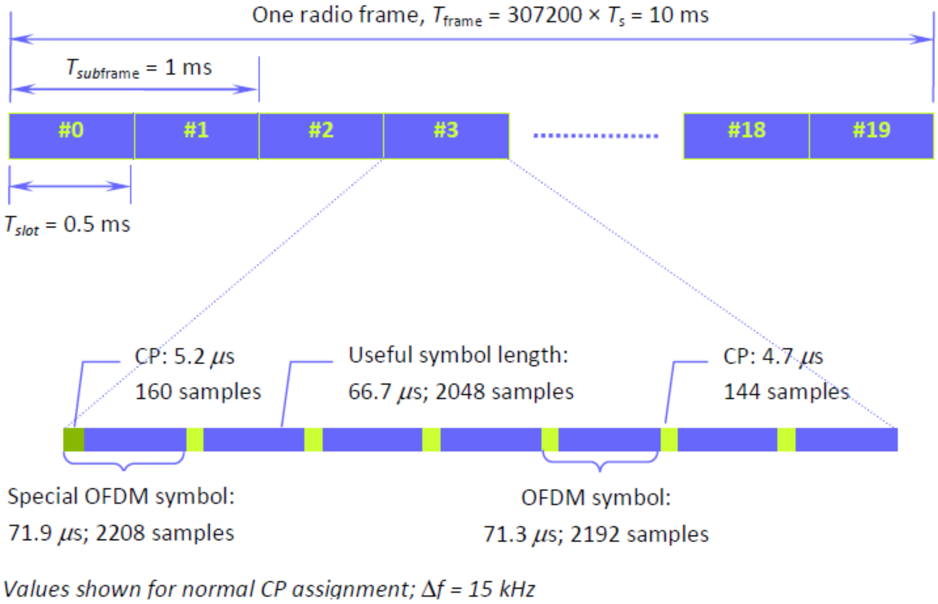


Figure 2-3: Frame structure (FDD) [4]

In the frequency domain, the number of subcarriers ranges from 128 to 2048, depending on channel bandwidth, with 512 and 1024 for 5 and 10 MHz, respectively. The subcarriers are organized into resource blocks of 180 KHz each, i.e., 12 subcarriers define a resource block (RB). One resource block for the period of one slot defines a physical resource block (PRB). A PRB is the minimum allocation unit and, in case of normal CP, consists of 12x7=84 resource elements (REs). A RE is the minimum resource unit and is defined by 1 subcarrier for the period of 1 OFDM symbol, as shown in Fig. 2-4.

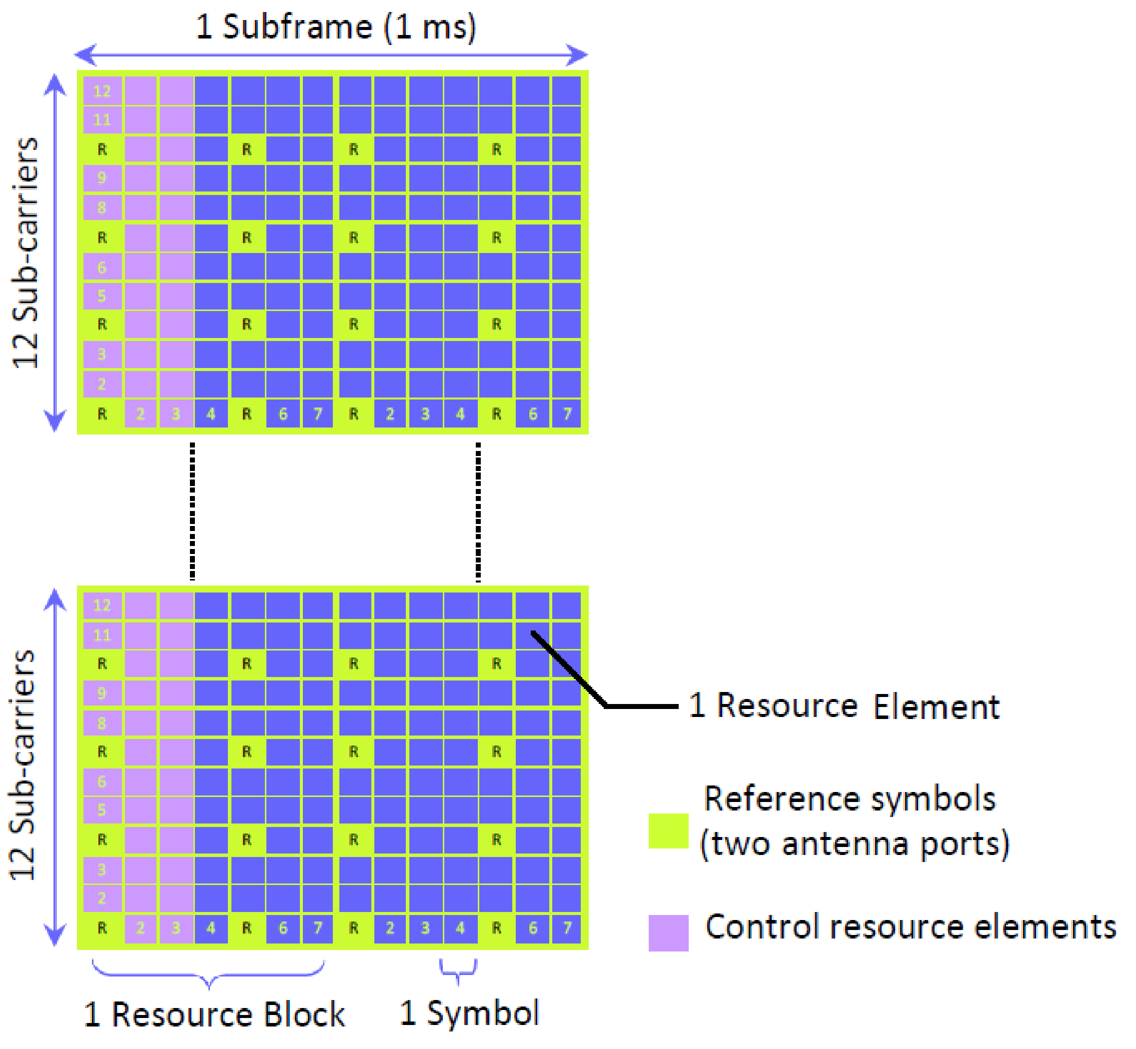


Figure 2-4: Frequency domain structure of LTE/LTE-A downlink [4]

Focusing on the downlink (DL) (Fig. 2-4), a PRB contains predefined REs for data, control, broadcast, synchronization, and antenna reference signals. The control REs occupy up to 3 OFDM symbols at the beginning of the subframe, and form the control region of the subframe. The control region includes the physical control format indicator channel (PCFICH), the physical hybrid-automatic repeat request (H-ARQ) indicator channel (PHICH), and the physical downlink control channel (PDCCH). The PCFICH is a very important channel transmitted at the first OFDM symbol in each subframe. It carries the control format indicator (CFI), specifying the number of OFDM symbols used for the control channel region. The PHICH includes an indicator to acknowledge (or not) a successful reception of an uplink (UL) transmission from a UE, while the PDCCH carries the UE specific resource assignments for data transmissions. The synchronization and broadcast REs occupy the middle six PRBs of the available bandwidth providing the physical cell identity (PCI) of the cell, and the physical broadcast channel (PBCH), respectively. The antenna reference REs include common reference signals (CRS) for each available antenna port and are used for mobility measurements and for demodulation of the DL control and data channels.

On the UL, the frequency domain structure is quite similar to that used in the DL. However, there are two types of reference signals: the Demodulation Reference Signals (DM-RS) and the Sounding Reference Signal (SRS) (Fig 2-5).The DM-RS are used to enable coherent signal demodulation at the eNodeB. These signals are time multiplexed with uplink data and are transmitted on the fourth or third SC-FDMA symbol of an uplink slot for normal or extended CP, respectively, using the same bandwidth as the data. The Sounding Reference Signal (SRS) is used to allow channel dependent (i.e. frequency selective) uplink scheduling as the DM-RS cannot be used for this purposes since they are assigned over the assigned bandwidth to a UE. The SRS is introduced as a wider band reference signal typically transmitted in the last SC-FDMA symbol of an UL subframe.

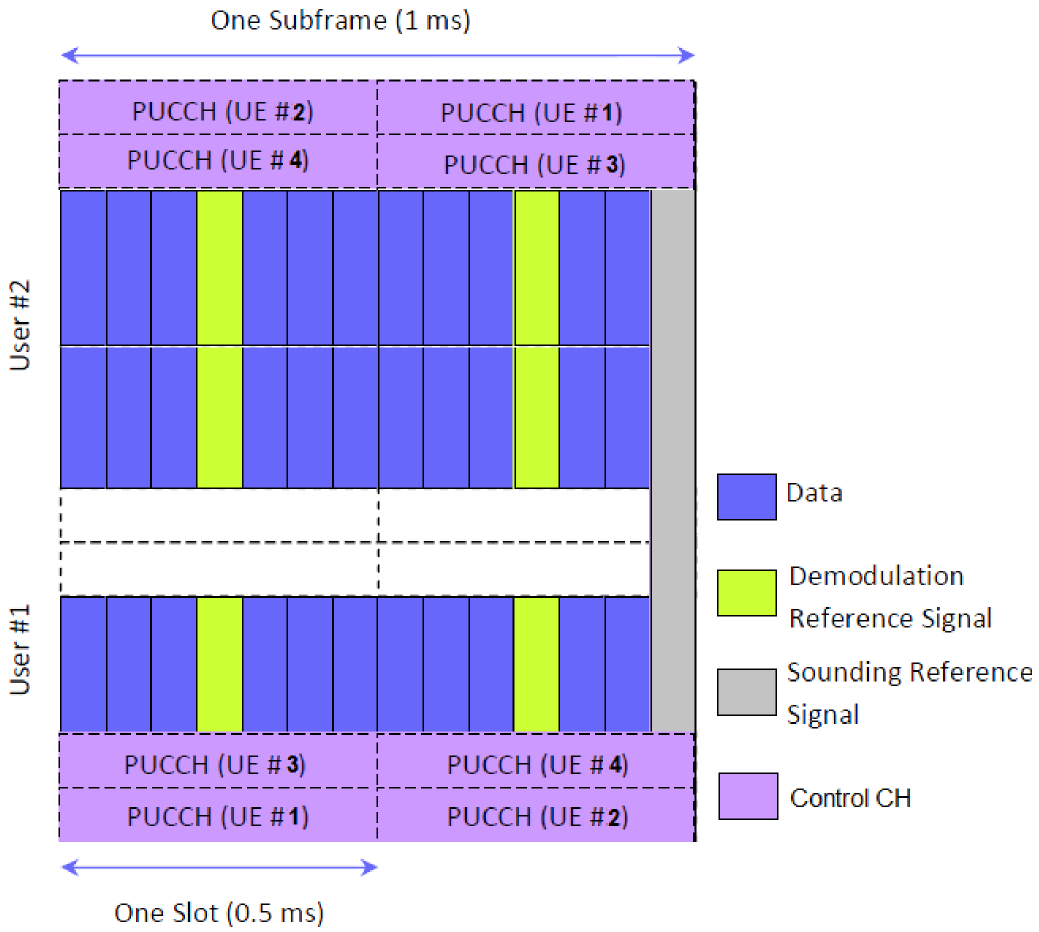


Figure 2-5: Frequency domain structure of LTE/LTE-A uplink [4]

For the LTE-A case the utilized bandwidth can be extended up to 100 MHz (from 20MHz which is the maximum in the conventional LTE case) using the carrier aggregation technique.

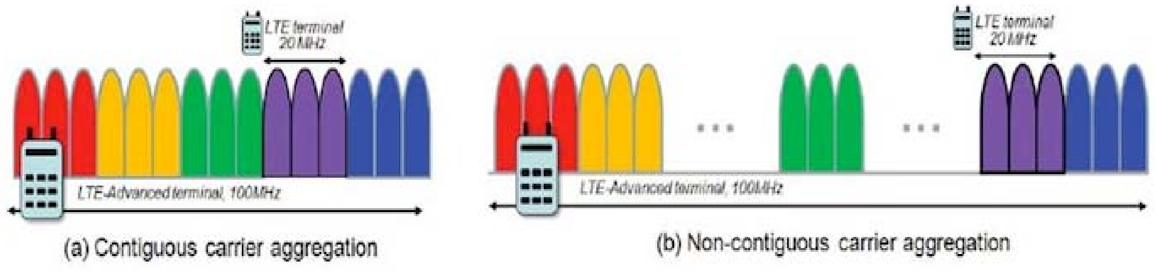


Figure 2-6: Carrier aggregation technique

Carrier aggregation technique provides:

- Scalable expansion from 20MHz to 100MHz by aggregating carriers, each group of carrier is referred to as a component carrier (CC). The available bandwidths of each CC are 10 MHz and 20 MHz.
- Continuous (adjacent) or non-continuous CC located in the same or different spectrum bands can be aggregated (Fig. 2-6)

There are two categories of CC:

- Primary component carrier. This is the main carrier in any group, consist of a primary downlink CC and an associated uplink primary CC
- Secondary component carrier. The additional CC used for bandwidth expansion.

The most important physical layer parameters of LTE/LTE-A are summarized in Table 2-2.

Table 2-2: Physical layer parameters LTE/LTE-A

Parameter	values					
Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	905
OFDM Symbols/Subframe	7/6 (short/long CP)					

2.3 Interference problem in femtocell-overlaid networks

The coexistence of macrocells and femtocells can offer benefits at many levels to both operators and consumers. Typically, macrocells are deployed based on network planning/dimensioning methods, whereas femtocells are deployed randomly inside the macrocells, requiring a high quality IP connection to the operator's core network (e.g., DSL line, or fiber). Regarding LTE-A networks, an interconnection through the X2 interface is available among (H)eNBs, while each base station is connected through the S1 interface to a mobility management entity (MME) and a serving gateway (S-GW). In practice, HeNBs are considered as low power eNBs that spatially reuse the spectrum bands assigned to eNBs. They have the option to serve only a specific set of subscribed UEs (CSG mode), while they can be unpredictably switched on and off by the consumers, burdening in that way the interference management problem. More specifically the interference problem in femtocell-overlaid networks is very challenging for the following reasons:

- Femtocell proliferation creates a highly dense network,
- femtocells are deployed by the end-consumers i.e., in a random/unplanned deployment manner,
- a heterogeneous network is created (two-tier network) and femtocells are expected to spatially reuse licensed spectrum defining the co-channel deployment, and
- femtocells can provide the option to serve only a limited set of subscribed users through the closed subscriber group (CSG) mode (no handover option for non-subscribed users)

Other reasons that can exacerbate the interference problem are the achieved synchronization level and the subframe configuration used in the TDD case (see Table 2-1). A comprehensive description of the interference problem in femtocell-overlaid networks can be found in [5].

Assume now that macrocells and femtocells are synchronized, meaning that the uplink (UL) and downlink (DL) periods of both sub-networks have the exact same timing. In this kind of scenario, the parallel transmissions of eNBs and HeNBs during the DL, as well as of MUEs and FUEs during the UL may cause serious interference problems. To be more precise, during the UL, the MUEs may cause interference to the HeNBs, especially when MUEs are operating very close to a building where a HeNB is located. The same thing is valid during the DL, when transmitting HeNBs may also cause interference to closely located macro-receivers. In these two cases, the interference problem is locally present. All the potential interference scenarios are depicted in Table 2-3.

Table 2-3: Interference types in a femtocell-overlaid LTE-A network

Index	Aggressor	Victim	UL/DL	Cross/Co tier
1	Macro UE	Home eNB	UL	Cross-tier
2	Macro eNB	Femto UE	DL	Cross-tier
3	Femto UE	Macro eNB	UL	Cross-tier
4	Home eNB	Macro UE	DL	Cross-tier
5	Femto UE	Home eNB	UL	Co-tier
6	Home eNB	Femto UE	DL	Co-tier

The interference problem is much more severe during the DL regarding the eNB's transmissions, which may affect the femtocells' operation, since the eNB's signal is spread throughout the whole macrocell. As a consequence, such interference conditions are high likely to happen. Thus, it is made clear that the DL period is very challenging in terms of interference, and mechanisms need to be deployed in order to avoid, reduce or manage it. One more reason that the DL is very challenging is that it concerns the perceived quality of communication from all the receiving mobile users, who may have various types of devices, may be communicating at different environments (open area, car, home etc.), or may even have different expectations of the offered service. Even though UL interference problems may still be very severe, these are handled by the technologically-advanced base stations and are not directly revealed to the users.

2.3.1 LTE-A standardized interference management tools

LTE-A standardized procedures can be exploited for interference managements purposes. These procedures, referred here as *interference management tools* are:

- ***Measurements***. Measurements can be collected through a connected mode UEs attached to (H)eNB, and UL Receiver function and DL Receiver function within (H)eNB. Some of the the most useful measurement for interference management are: the Reference Signal Received power (RSRP), the Reference Signal received Quality (RSRQ), the Received Interference Power (RIP) the Reference Signal Transmission Power and the Physical and Global Cell ID. Different approaches can be used for exploiting one or more of these measurements; however the most common approach is the exploitation by a resource allocation or power control interference management scheme.
- ***Exchange of X2 Interference indicators***. Three indicators have been defined for inter-cell interference protection in LTE-A networks:
  - ***Relative Narrowband Transmit Power Indicator (RNTP).*** This message contains information about the transmission power level that will be used in each resource block (RB) for the DL transmission. One bit per RB indicates if it is expected the transmission power to exceed a predefined threshold (every 200ms).
  - ***High Interference Indicator (HII).*** HII can be considered as an RNTP indicator for the UL transmissions. One bit per PB indicates if a neighbor (H)eNB should expect high interference power in the near future. (every 20 ms)
  - ***Overload Indicator (OI).*** OI is referred to the UL transmissions, however it is triggered only when high-interference is detected by an (H)eNB (every 20 ms)
- ***Carrier Aggregation with Cross carrier scheduling***. Refers to the ability to schedule a UE transmission/reception in multiple secondary CCs, while the allocation (control) messages are transmitted in a particular primary CC. One of the advantages of this tool is that is provides interference avoidance in the very important control channels with no decrease in the available spectrum. However, side effects arise, such as the problems on mapping the PDCCH of multiple CC in the control region of the primary CC and the backwards incompatibility with Rel.8,9 UEs.

- ***Use of Almost blank subframes (ABS)***. ABSs can be constructed either by configuring the multicast/broadcast over single-frequency network (MBSFN) subframes or by avoiding to schedule unicast traffic in certain subframes. Data and control channels are not included, making room for interference-free transmissions/receptions by victim UEs. The main advantage of ABSs is that interference-free resources for control and data channels are provided to victim UEs. However, the cost is that the bases station that uses the ABS loses resources, while channel measurements made by UEs deteriorate including in their average estimations measurements of empty (blank) subframes.

2.4 References

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3. CONTROL CHANNEL INTERFERENCE MANAGEMENT IN FEMTOCELL-OVERLAID NETWORKS

In a femtocell-overlaid (or femto-overlaid) LTE-A network, where femtocells operate under the co-channel deployment and the closed subscriber group (CSG) mode, multiple types of interference can be found. A possible classification divides them into data and control channel interferences. The majority of the approaches in the literature deals with the interference problem in data channels (e.g., [1, 2]), assuming that the Interference Management (IM) techniques used for data channel protection are, in most cases, also applicable to control channel protection (e.g., power control). However, tailoring the design of IM techniques to the protection of the control channels is worthwhile for the following reasons: the importance of the control channel context; the peculiarity in LTE-A of using, for the basic control signaling, a predefined resource area that spans over the whole bandwidth; and the need to avoid misperceptions about radio link or access failures because of degraded control channels. Moreover, as described in [3], macrocell users in a femto-overlaid LTE-A network are expected to experience a control channel coverage hole for 20% of the time, on the average, putting the protection of control channels in high priority.

Motivated by the reasons mentioned above, this chapter focuses on control channel IM in LTE-A networks overlaid by CSG femtocells. A categorization of fundamental and emerging IM schemes and a performance comparison from the perspective of control channel protection are provided. Four different categories of IM approaches are considered (frequency-domain, time-domain, power control, and resource allocation), and the advantages and limitations of each approach are presented. The evaluation focuses on the downlink (DL) control channel interference caused by femtocells to macrocell users located in the total macrocell area or in a target femtocell area; also, the impact of the femtocell deployment density on such interference is assessed.

3.1 Control channel interference management

Let us consider a femto-overlaid LTE-A network, where femtocells operate under the co-channel scenario and the (H)eNBs are synchronized, i.e., the DL subframes of all macrocells and femtocells are time synchronized [4]. The widely-accepted evaluation process in [5] shows that the most severe interference is suffered by macrocell UEs (MUEs) during the DL subframe, and is caused by HeNBs in CSG mode. Focusing on this type of interference, the impact on MUE receivers varies according to the importance of the interfered REs. Taking into account the LTE-A physical layer, the protection of data, control, reference, broadcast, and synchronization REs can be done separately, while existing IM schemes could perform differently for each RE type. On this basis, several characteristics of control channels make the designing of IM for control REs very appealing. Since control REs span over the whole system bandwidth, IM schemes can take advantage of adaptive resource allocation tools and potential channel gains in some subcarriers. From a more general perspective, the protection of the control channels strives to keep the signal to interference plus noise ratio (SINR) at the MUE receivers above a specific decoding threshold. Compared with the case of data channels, in control channel protection a potential surplus in the received SINR value is less important, while a possible deficit is much more critical.

In LTE-A networks, channel measurements, exchange of interference indicators, and multiple input multiple output (MIMO) techniques can be valuable tools for the design of effective by IM schemes. The most commonly used measurements are the reference signal received power, which is the average received power (by HeNB or UE) from the reference signal over a desired channel bandwidth. Also, special interference indicators are exchanged among (H)eNBs by utilizing the X2 interface. From the perspective of DL inter-cell interference, the MIMO – broadcast channel is an attractive scenario involving the use of pre-interference cancellation techniques [6]. However, the physical characteristics of the transmitted signal must be known to the interferer aggressor, which in our case is a different base station (HeNB).

Channel measurements and interference indicators support two fundamental approaches in control channel IM: power control (PC) and resource allocation (RA), which are explained later in this section. On the other hand, LTE-A has introduced the carrier aggregation (CA) technique with cross-carrier scheduling, in the frequency domain, and the use of almost blank subframes (ABSs), in the time domain, as the main tools for combating control channel interference.

3.1.1 Frequency-domain approach

LTE-A allows the scalable expansion from 20MHz channel bandwidth, the maximum available in previous LTE releases, to 100MHz. However, a 100MHz portion of continuous spectrum is rarely available, and the most effective way to achieve this is through the CA technique. With CA, multiple component carriers (CCs) of smaller bandwidth are aggregated to utilize fragmented spectrum. CA is defined for continuous (adjacent) or non-continuous CCs located in the same or different spectrum bands. Each UE uses a primary CC for basic functionalities, such as radio link failure monitoring, while other (secondary) CCs can be used dynamically for data transmissions. However, for backward compatibility reasons, each individual CC inherits the basic physical layer design, and includes reference and broadcast signals.

From the perspective of IM, CA can be considered as a frequency-domain interference avoidance/mitigation technique, involving functionalities that exploit the availability of multiple CCs. The most suitable functionality for control channel protection is the cross-carrier scheduling (Fig. 3-1), which refers to the ability to schedule a UE transmission/reception in multiple CCs, while the allocation messages are transmitted on a particular primary CC. More specifically, a carrier indicator field (CIF) of 3 bits is included in the downlink control information (DCI) of the PDCCH. CIF is used to indicate on which CC the UE data is transmitted, while DCI includes the UE resource allocations for the DL and UL transmissions. Since in the control region of a single CC more than one DCI messages (equal to the number of aggregated CCs) are included, the mapping of the PDCCH on the control region is an additional problem. On the other hand, the primary CC that will include the control signaling must have a 20MHz bandwidth to guarantee the maximum achievable data rates of non-CA capable UEs (LTE Rel. 8/9).

In any case, cross-carrier scheduling allows (H)eNBs to select a different CC for their control signaling to avoid conflicts with neighbor cell transmissions [7]. On this basis, a dynamic and sophisticated selection scheme of the appropriate primary CC is needed, especially under high density femtocell deployments, where multiple interference aggressors exist. Taking into account that the selection of a CC is correlated with many factors, such as the traffic distribution, the relative location of (H)eNBs, and the fact that a CC in higher frequencies can lead to better utilization, the optimal selection of a CC for each (H)eNB is a very challenging task.

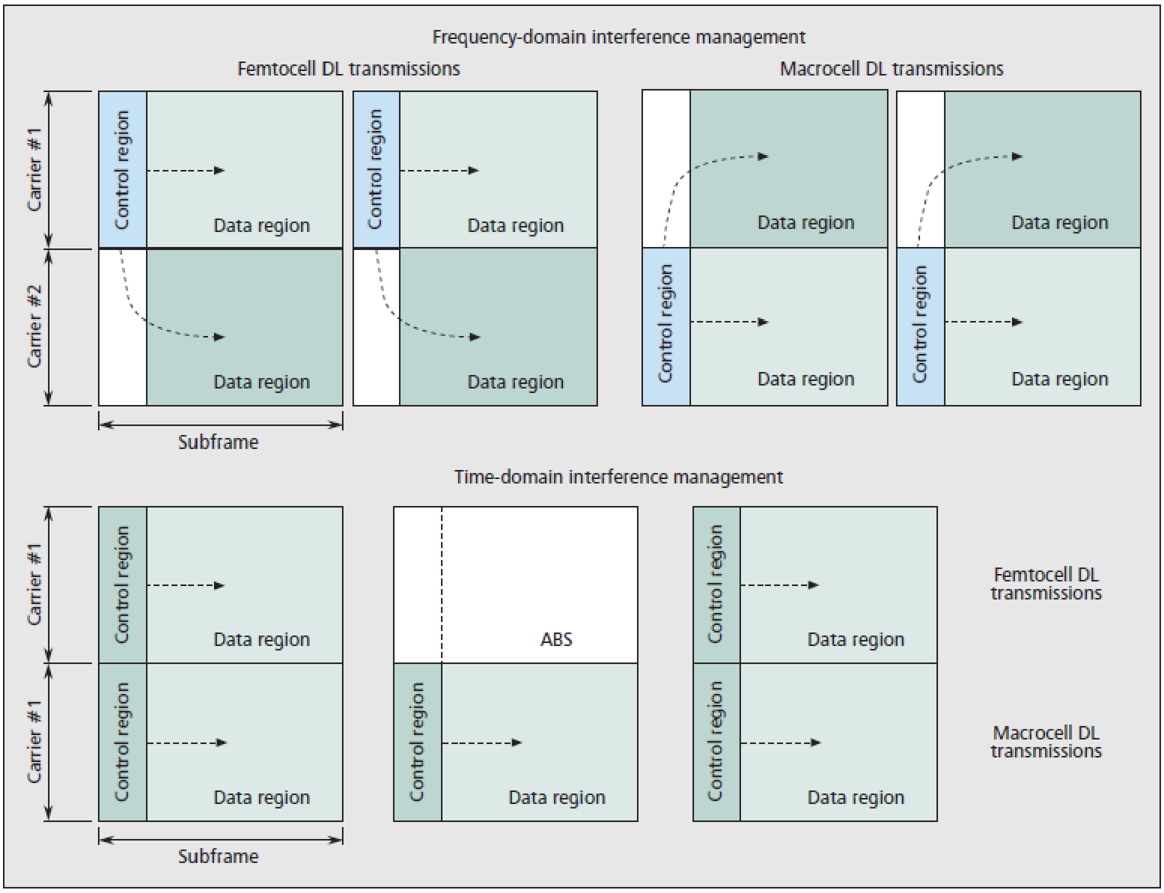

Figure 3-1: CA with cross-carrier scheduling and ABS IM schemes

3.1.2 Time-domain approach

ABSs are proposed by 3GPP as the basic control and data channel IM scheme in the time domain. ABSs can be constructed either by configuring the so-called multicast/broadcast over single-frequency network (MBSFN) subframes, or by avoiding to schedule unicast traffic in certain subframes [8]. In the former case, an ABS includes only reference signals, while in the latter it includes all the reference, synchronization, and broadcast signals maintaining the connection with the serving UEs. In both cases, data and control channels are not included, making room for interference-free transmissions/receptions by victim UEs. The neighbor (H)eNBs can be informed about the ABS transmissions in order to transmit control signals and/or allocate resources for victim UEs in these subframes, taking advantage of the mute period of the aggressor (H)eNB (Fig. 3-1). To this end, two types of ABS bitmap patterns can be exchanged through the X2 interface to configure ABSs among (H)eNBs [8]. The first one is called ABS Pattern, and is referred to as the time-domain Relative Narrow-Band Transmit Power (RNTP) indicator. It uses each bit of the ABS bitmap to inform the receiving (H)eNBs of its intention to send on a per-subframe basis. The second bitmap resolves a side effect caused by using ABSs; as few transmissions are included in ABSs, channel measurements made by UEs deteriorate, including their average estimations measurements of non-transmitting (blank) subframes. Thus, the second ABS bitmap, called Measurement Subset, informs the receiving (H)eNBs on the set of subframes that can be used for measurements by the UEs.

A simplification of the ABS idea can be found in [9], where the HeNBs left blank 2/3 of their control region in specific subframes introduced by the eNB to gain in the reception of control signals at victim MUEs. Also, the reverse idea of muting eNBs instead of

HeNBs can lead to better performance in terms of cell identification [10]. In general, the use of ABSs is an altruistic IM approach, where each (H)eNB agrees to spend some resources to reduce the interference to 'foreign' UEs (i.e., UEs served by other (H)eNBs located in their vicinity). The decision on whether and when to configure ABSs in a network involves a trade-off between avoiding to affect the performance of serving UEs and improving the performance of interfering UEs. This trade-off imposes a careful design of ABS patterns, capable of encapsulating the dynamic nature of a dense femto-overlaid network.

3.1.3 Power control approach

PC takes place at (H)eNBs and refers to power assignment for DL and UL transmissions. DL cross-tier interference (e.g., from HeNBs to MUEs) can significantly deteriorate a PC scheme, due to the fact that a victim MUE located in a HeNB transmission range receives much lower power from the far located serving eNB than from the aggressor HeNB. 3GPP proposes two basic PC schemes to alleviate cross-tier interference, which can potentially be used for control channel protection [4]. The first one requires exhaustive network optimization to derive basic parameters used in the PC formula. The second one is more practical and uses the reference signal received power (RSRP) measure available at the HeNBs, combined with an estimation of the path loss between the HeNB and the victim MUE. The latter value can be derived at the HeNB through X2, S1, or over the air coordination with the eNB/MUE. The mathematic formula that describes this scheme is as follows:

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

where P_{Tx} and $P_{eNB-HeNB}$ represent the transmit power of the HeNB (interference aggressor) and the measured received power from the eNB, respectively, while $PL_{HeNB-MUE}$ depicts the pathloss between the HeNB and the victim MUE. P_{max} and P_{min} parameters refer to predefined maximum and minimum transmit power settings, respectively, and depend on the device type. 3GPP PC schemes have launched the design of more sophisticated approaches, focusing mainly on protecting victim MUEs, while guaranteeing the service quality at femtocell UEs (FUEs). In general, using PC for control channel IM requires reliable measurements and information about the existence of a victim MUE. However, PC is an efficient and backward compatible method for interference mitigation, which can follow the dynamic nature of generated interference in femto-overlaid networks and is applied only when victim UEs are located inside the transmission range of an aggressor (H)eNB. Finally, PC can be supplementary to other IM techniques with no deterioration on the use of spectrum resources.

3.1.4 Resource allocation approach

Interference-aware RA can reduce the interference perceived in data channels by allocating interference-free resources to victim MUEs. This idea can also be exploited for control channel protection to reduce the conflicts between neighbor cells when the control region is sparsely utilized. LTE-A adopts a mapping technique to pseudo-randomize the locations of control channels inside the control region [4][11]. In more detail, the PCFICH carries the CFI, i.e., the number of OFDM symbols used for control signaling at the beginning of a subframe. The CFI information is included in a 32 bits long codeword transmitted in 16 REs. These REs are grouped in the frequency domain in four RE groups and allocated in the control region according to a PCI-based formula described in [4]. The PDCCH and the PHICH are allocated in a similar way in the rest of the control region. In this way, the PCI value indirectly determines the allocation of all control channels, making room for control channel protection through the use of PCI manipulation techniques (e.g., [11]). The idea is to use smart PCI allocation to indirectly avoid conflicts on the control channels of neighbor cells. However, the performance of this approach depends on the utilization level of the control region, having no effect in case of a fully utilized control region. A heavily loaded control region may occur due to bad channel conditions, where more resources for the PDCCH of each user are used. Also, a cell may serve a large number of low-rate voice over IP flows, filling up in that way the control region with control channels. On the other hand, the offloading of the control region can be achieved by using semi-persistent-scheduling [7]. Also, in case that CFI=1 or CFI=2, instead of using one or two OFDM symbols to carry the control channel information, respectively, an idea is to expand the control region to carry 3 OFDM symbols providing more space for RA. In any case, as the femtocells are expected to serve a low number of users, the RA techniques can be used as an extra shield against control channel interference.

3.2 Performance Evaluation

In this section, we evaluate the DL control channel interference perceived by MUEs located inside a femto-overlaid LTE-A macrocell. For this evaluation, the system level simulator available in [12] was adopted and used with the appropriate adjustments. At first, we assume a fully utilized control region, i.e., a scenario where each base station fills up the control region of each transmitted subframe. The performance of CA with cross-carrier scheduling, ABS, and PC IM schemes is assessed, targeting at the level of control channel interference generated in the total area served by an eNB sector (macrocell). Subsequently, we focus on specific indoor interference-hot areas inside the macrocell, and derive the impact of HeNBs deployment density on the mean SINR and the block error rate (BLER) perceived by victim MUEs. Finally, we examine how the offloading of the control region allows the use of RA approaches for control channel interference mitigation.

For the case of CA with cross-carrier scheduling, we assume 4 CCs of 10 MHz each, while each cell selects randomly one of them for control signaling at its initial configuration. For the use of ABSs, coordination between each HeNB and eNB is considered. Also, in case that the MUEs perceive interference from multiple HeNBs, the eNB allocates the control information of the victim MUEs in ABSs transmitted by the strongest interferer. Additionally, the 3GPP PC scheme 2 [4] is selected for evaluation, depicting the peculiarities of alleviating interference in control channels by manipulating the transmission power of HeNBs. For the case of a non-fully utilized control region, the selected RA IM scheme assumes coordination among neighbor HeNBs for maximizing mutually disjoint allocations of the PDCCH.

Theoretically, each control channel IM scheme has to maintain the SINR level perceived by victim UEs above a specified threshold, which will be referred to as *Control Channel Decoding Threshold (CCDT)*. A radio link failure in PDCCH is avoided with BLER<1%. Towards this goal, each (H)eNB utilizes channel quality information to select for each control channel transmission the most appropriate modulation/coding and aggregation level for the PDCCH. For our analysis, we assume the frequency division duplex (FDD) is used in the 2GHz frequency band. We further assume that Quadrature Phase-Shift Keying (QPSK) 1/12 is used in an additive white Gaussian noise (AWGN) channel, resulting in a CCDT value of -5dB for BLER=1% [13]. The parameters values used in the simulation are summarized in Table 3-1.

Table 3-1: Evaluation parameters – Interference management schemes

Parameter	Value
eNBs deployment grid	Hexagonal
HeNB deployment grid	Random
eNBs reuse factor	1
Duplex mode	FDD
Inter-eNB distance	1000m
Frequency	2GHz
Channel Bandwidth	10MHz (4x10MHz for CA)
Cyclic prefix (CP)	Normal
eNB antenna type	3GPP TR36.942
eNB antenna transmission scheme	2x2
eNB TX power	43dBm
HeNB antenna type	Omnidirectional
HeNB TX power	20dBm fixed and 3GPP 36.921 PC [4]
Number of Dual-Stripe Blocks	21 per sector
Number of floors per stripe	3
Apartment size	10x10m
Target Block distance from eNB	225m
Probability of HeNB being in an Apartment	0.1
Pathloss model	Dual-stripe based on 3GPP 36.814 [14]
Environment	Urban
Penetration losses	20dB
Control Channel Decoding Threshold	-5dB
Channel model	AWGN
Control channel modulation	QPSK (1/12)

At first, we calculate the cumulative distribution function (CDF) of SINR values that can be potentially perceived by MUEs in a femtocell-overlaid area served by a specific eNB sector. Fig. 3-2a shows the performance of CA with cross-carrier scheduling and ABS schemes, compared to a baseline scenario with no use of IM and a conventional one where no femtocells are used. Both IM schemes shift the CDF curve to the right, substantially lowering the frequency of occurrence of SINR lower than the CCDT. However, a tail of very low level SINRs remains in both the CA and ABS curves, corroborating the assertion that the elimination of interference in interference-hot areas, such as close to HeNBs or in macrocell edges, is very challenging. Also, note that in Fig. 3-2a the ABS scheme perform slight better than the CA with cross-carrier scheduling scheme; this is especially so because the assumed coordination with the eNB cancels the interference caused by the coordinated HeNB (typically the stronger interferer).

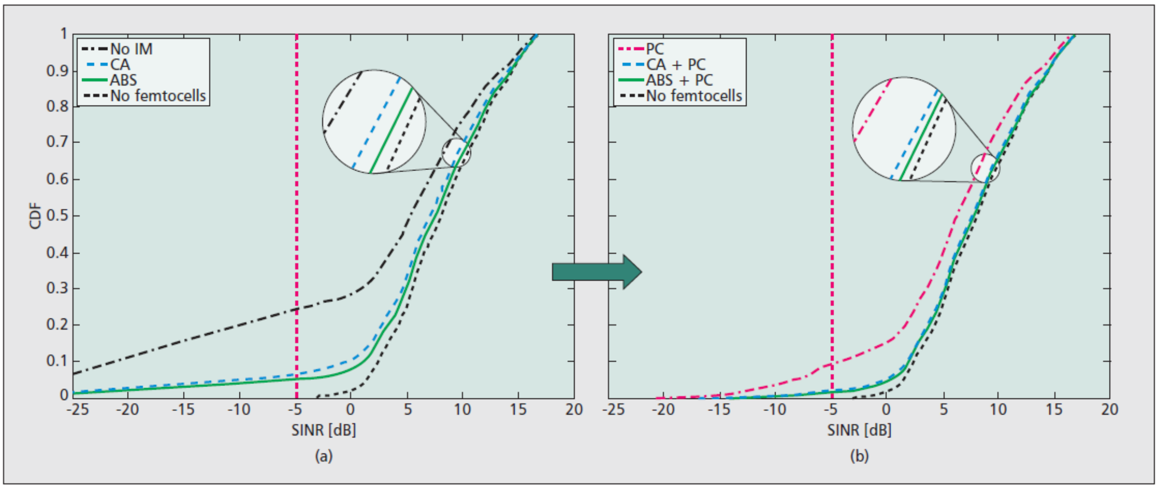

Figure 3-2: Control channel interference in total cell area, assuming fully loaded control region

Next we reconsider the scenario of Fig. 3-2a, but now we also use PC, in addition to CA or ABS. As shown in Fig. 3-2b, the combined schemes of PC with CA and ABS, referred to as CA+PC and ABC+PC, respectively, attain even better performance, which is now much closer to that of the "No femtocells" case than either of the three schemes (i.e., CA, ABS, PC) operating alone. The comparison of the results in Fig. 3-2a and Fig. 3-2b also reveals the substantial shortening of the CDF tails for low SINR values achieved by the combined schemes.

While indoor MUEs are subject to high interference, outdoor MUEs are protected through the insulation provided by the external walls of the buildings. Thus, for a deeper understanding of the efficiency of each IM scheme, we evaluate the mean SINR and the BLER values perceived by visiting MUEs in a single femtocell area (indoors), under different femtocell deployment densities. The target building block is located 225m away from the eNB, simulating the case where the femtocell aggressor is neither at the cell edges nor very close to eNB.

As shown in Fig. 3-3a, an increased number of HeNBs per building block (from 2 to 18) strongly affects the efficiency of the ABS scheme because the blank frames are used only by the stronger interferer (in coordination with the eNB). On the contrary, CA with cross carrier scheduling is applied to the whole set of HeNBs, independently of the MUEs presence, and the impact of the femtocell density is considerably decreased. In the case of CA, practically the number of interference aggressors is divided by the number of the available CCs, decreasing in that way the number of interferers. However, as the selection of the CCs by each HeNB is random, the interference caused by the target HeNB (the stronger interferer) cannot be avoided, and, although the mean SINR is slightly affected, instant fading can occur. Also, note in Fig. 3-3a that a PC scheme applied to all HeNBs attains a better mean SINR performance than the other schemes for HeNB densities up to 8 HeNBs per building block.

Fig. 3-3b shows the obtained results on BLER as a function of the HeNB density. Note that, even for very low femtocell deployment densities, the use of an IM scheme is mandatory, since, with no IM, BLER is unacceptably high. Also, observe from Fig. 3-3 that even a slight mean SINR deficit may lead to high BLER degradation; this behavior underlines the importance of CCDT in designing control channel IM schemes.

Next we relax the assumption for a fully utilized control region, and measure the mean SINR values on the PDCCH at a single victim MUE located inside a single femtocell area. We consider multiple HeNBs inside a building block and different PDCCH loads in the control region. As shown in Fig. 3-3c, the less the load in the control region, the less the interference at the victim MUE. Observe from the figure that for loads that fill the control region not more than 30% and up to 5 HeNBs per building block, the mean SINR on the PDCCH remains above the CCDT.

As shown in Fig. 3-3d, the use of PC results in significant performance improvement; observe that with 10 HeNBs per building block, the mean SINR value on PDCCH exceeds the CCDT. Fig. 3-3d practically shows that if we manage to achieve the maximum number of disjoint PDCCH allocations among neighbor HeNBs and eNB, a simple PC scheme can guarantee the successful reception of PDCCH by a victim MUE located inside a femto-overlaid building.

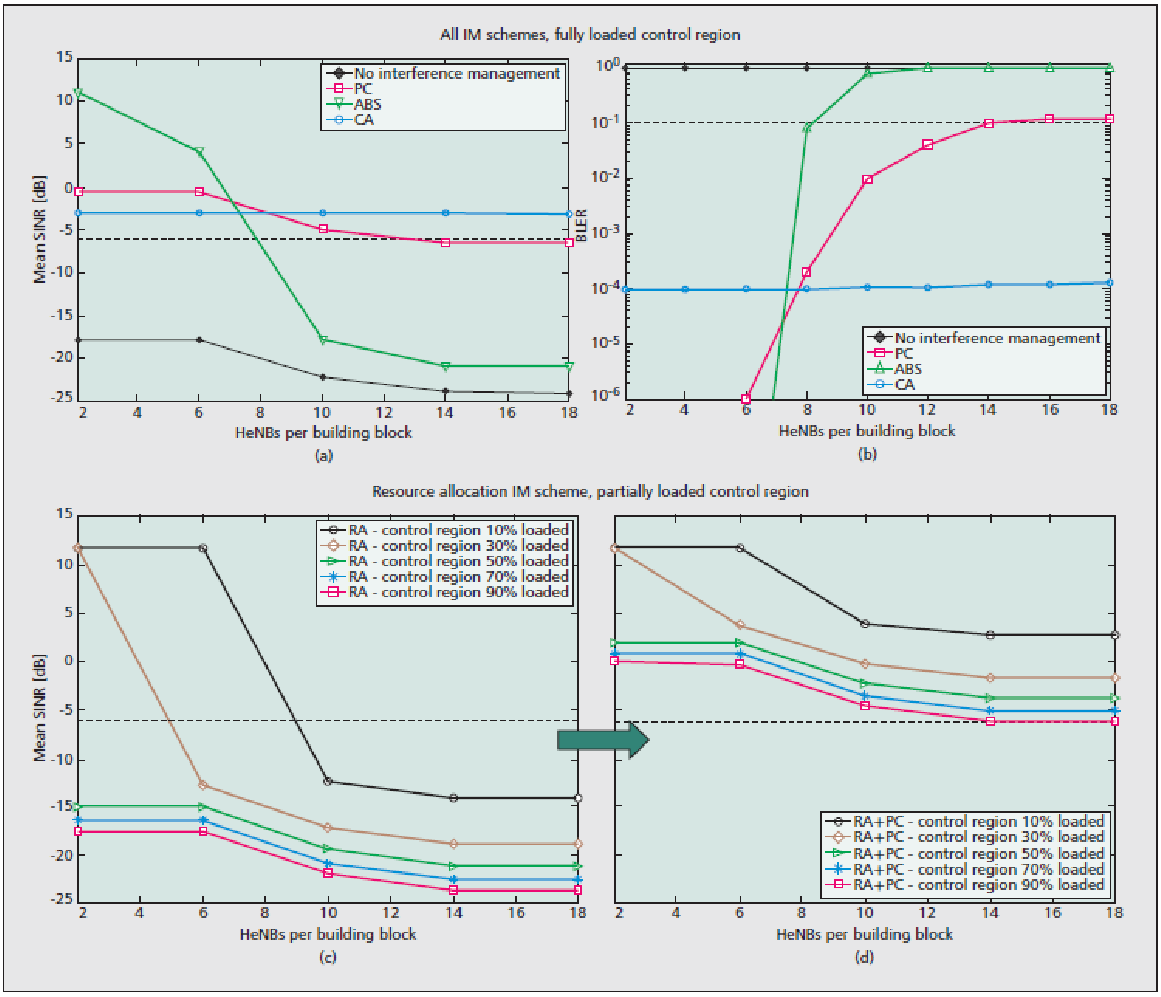

Figure 3-3: Control channel interference in a single femtocell area (indoors). Upper part: impact of femtocell deployment density for all IM schemes with fully loaded control region (a) on mean SINR values and (b) on corresponding BLER curves. Lower part: impact of femtocell deployment density with partially loaded control region on mean SINR values (c) for the RA scheme and (d) for joint RA - PC scheme.

3.3 Conclusions

This work highlights the importance of control channel protection in femto-overlaid networks, providing an overview of control channel IM schemes tailored to an LTE-A network. The analysis has focused on the DL control channel interference perceived by MUEs, revealing the weak and strong aspects of each IM. Performance evaluation results depict the effect of the femtocell deployment density and control region load on the fundamental frequency-domain, time-domain, PC, and RA approaches, both in the total cell area and in target interference-hot areas inside the cell. On the one hand, coordination seems to be a dominant feature for the CA with cross carrier scheduling and ABS schemes, while both schemes can guarantee interference avoidance from coordinated interference aggressors. On the other hand, PC and RA can be adapted to the interference level, while they can alleviate interference caused by uncoordinated nodes. Finally, for the reader's convenience, the advantages and disadvantages of each scheme are summarized in Table 3-2.

Table 3-2: Comparison of control channel interference management schemes

Control Channel IM	Advantages	Disadvantages
Carrier Aggregation (CA) with cross-carrier scheduling	▪ Preventive method, any new establishment of HeNB can select at its first configuration an appropriate CC. ▪ Suitable for dense femtocell deployments allowing the use of different CC by neighbor HeNBs.	▪ Reliable measurements and/or centralized coordination are required at the first configuration. ▪ Unable to follow the dynamic nature of HeNBs, i.e., the unpredictable switch on and off. ▪ Problems on mapping the PDCCH of multiple CC in the control region of the primary CC.
Almost Blank Subframes (ABS)	▪ Control channel interference of the stronger interference aggressor can be avoided. Thus, better performance than CA or PC in low femtocell deployment densities can be achieved. ▪ Reactive approach. A HeNB protects "foreign" UEs only when they are located in its vicinity.	▪ Frequent coordination among (H)eNBs is needed (exchange of ABS patterns). ▪ Throughput performance of serving FUEs deteriorates. ▪ Side effect in UEs channel measurements.
Power Control (PC)	▪ Performance stability even in high femtocell deployment densities because the adaptation is proportional to the interference level. ▪ Reactive approach. A HeNB protects "foreign" UEs only when they are located in its vicinity. ▪ No deterioration in spectrum resources.	▪ Reliable measurements and/or exchange of interference indicators are needed. ▪ Negative impact on the performance of serving FUEs may occur.
Resource Allocation (RA)	▪ Preventive and dynamic method. HeNBs can allocate resources taking into account possible conflicts with neighbor HeNBs and victim UEs. ▪ No deterioration in spectrum resources.	▪ Effective only under low control region loads. ▪ Good performance if combined with PC.

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4. QOE-DRIVEN INTERFERENCE MANAGEMENT IN FEMTOCELL-OVERLAID NETWORKS

The majority of IM approaches for femto-overlaid cellular networks focus on guaranteeing the provided Quality of Service (QoS), promising mainly a high Signal to Interference plus Noise Ratio (SINR) at interfered (victim) users. However, a more attractive and suitable way to evaluate the quality of a provided service (especially for real-time services) is by measuring the end-users' satisfaction. Currently, the connection between network performance and end-users' satisfaction is not strictly defined. To give an example, the same throughput value may result to differently perceived data rates, giving in that way totally different impressions of the same provided service [1]. Recognizing the importance of quantifying the end-users' satisfaction, ITU has suggested the term Quality of Experience (QoE) as "the overall acceptability of an application or service, as perceived subjectively by the end-user" [2]. QoE is the most important factor for a user's decision on retaining a service or giving it up and this fact explains the emergence of shifting from QoS to QoE network management. Moreover, since interference is one of the key quality-deteriorating factors and has a direct impact on the users' perceived QoE, the design of QoE-driven IM mechanisms seems very appealing.

In this chapter, we examine whether and in what extent the interferences in a femtocell-overlaid network are reflected as variations in the end-users' satisfaction. Firstly, we focus on Voice over IP (VoIP) services in an LTE-A network, and quantify the QoE deterioration of macrocell VoIP users due to the interference from femtocells. Sequentially, we examine the relation between the SINR and the perceived QoE at an interference-victim. Finally, we exploit these results to compare the basic Power Control (PC) IM scheme proposed by 3GPP [3] and a simple QoE-aware PC scheme, revealing the importance of involving QoE in the IM process.

4.1 QoE and QoS Relationship

The "Quality of Service (QoS)" term was originally defined by ITU as "the collective effect of service performance which determines the degree of satisfaction of a user of the service" [4]. However, during the years, the study of QoS has lost this user-oriented approach and these days it is considered as just a subset of the more general QoE notion. Hence, QoS is no longer considered sufficient for the thorough characterization of a product or service as opposed to the most appealing QoE notion.

The reason to differentiate between QoS and QoE and to adopt QoE as the most suitable criterion for quality evaluation is twofold: First of all, QoS handles purely technical aspects regarding a service and does not incorporate any kind of human-related quality-affecting factors. This means that the same QoS level might not guarantee the same QoE level for two different users. Apart from the system's technical characteristics, other factors such as the context of use, the user-specific characteristics such as users' experiences and expectations, the delivered content and the pricing of a service make a significant impact on the finally perceived QoE as well [5]. The second reason for this differentiation is that, QoS does not reflect the impact that the technical factors have on the user's quality perception, since there is no straightforward connection defined. This implies that, for instance, the constant amelioration of one technical parameter does not linearly and infinitely improve the user's experience. Actually, this observation alone justifies why the need for the QoE notion has arisen. Based on this gap between the QoS and QoE, some formulas have emerged recently trying to map QoS parameters to the overall QoE value. Two different approaches have dominated in the literature: the perception-centric and the stimulus-centric one.

The stimulus-centric approach is based on the “WQL hypothesis” inspired by the so-called “Weber-Fechner Law (WFL)” [6], which describes the effect of a physical stimulus on the human perception according to the principles of psychophysics. This law claims that the relationship between stimulus and perception is logarithmic, which drives the conclusion that in order for a stimulus’ change to be reliably detected by an observer, this has to differ from its original value by a constant fraction. From this law, the notion of “just noticeable differences” emerges, which describes the smallest detectable difference between two sequential levels of a particular stimulus.

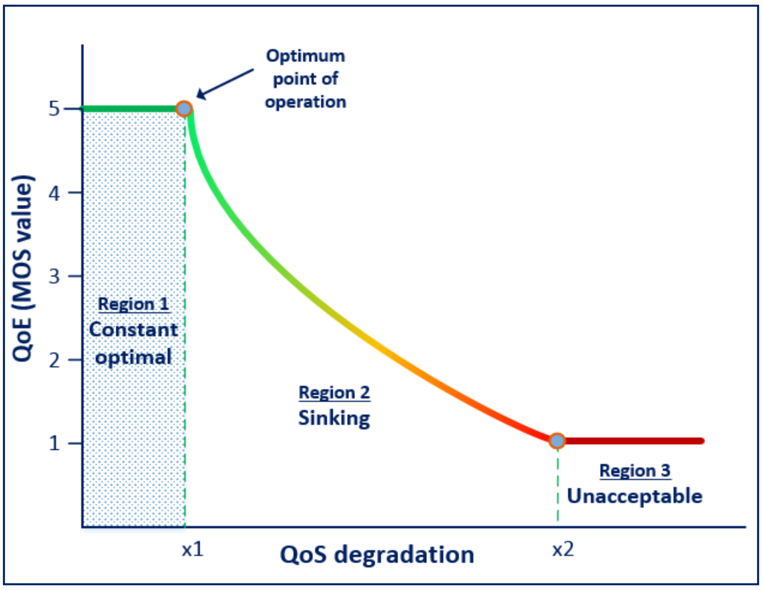

Figure 4-1: The IQX hypothesis

Regarding the perception-centric QoS-QoE mapping, the so-called “IQX hypothesis” [7] has been proposed. According to this approach, the relationship between the QoE and one QoS degrading parameter is negative exponential and the change of QoE actually depends on the current level of QoE. The mapping curve between the QoE and the QoS disturbance consists of three clearly distinguishable regions, as shown in Fig. 4-1. The first one is the constant optimal region (Region 1 in Fig. 4-1), where the QoE is always excellent, regardless some initial impairments of one technical quality-affecting parameter. To be more precise, the QoE is not affected inside this region at all, either because some mechanisms inside the system provide some kind of tolerance to such impairments or simply because the human perception (e.g. vision or hearing) is not capable of distinguishing such changes. The second region of the QoS-QoE curve is characterized by sinking QoE in an exponential way (so that QoS disturbances are more impactful when the QoE is higher), while the third and last region refers to unacceptable quality.

The clear discrimination among these three regions may be exploited by service providers not only for their own economic benefit but also for the common good. Regarding the providers’ benefit perspective, since there can clearly be identified a region (Region 1) where the QoE is constantly excellent regardless some technical parameters’ deterioration, the providers could deliberately deteriorate the performance of some technical parameters so that all users operate just on the turning point between Regions 1 and 2 (the point x1 in Fig. 4-1, perhaps with some safety margin). This could be made possible by reducing resources such as spectrum resources or transmission power. As a result, all end-users will be pushed to operate on x1 instead of any other “western” point of Region 1, since such a thing would not add to quality and also would consume resources for no reason. As a direct consequence, redundant resources could be released and saved to be provided to other users (for the common good) to who it would really make an impact on the perceived QoE (i.e. for users operating at Region 2 or 3, trying to “push” them towards Region 1’s optimum point of operation).

4.2 QoE-aware Interference Management

The co-existence of femto- and macro-users operating on the same constrained resource pool causes interference problems in the network, while the study of the QoE could be beneficial for existing or future IM schemes.

The most common and direct way to mitigate the interferences is to adopt a PC-based IM scheme. However, an important trade-off is recognized when PC-based IM schemes are used; sufficient transmitted energy is required in order to ensure a specific QoS level at the receiver, but at the same time increasing the energy will cause higher interferences in the network and less battery life for the terminal. Consequently, the goal behind PC is to carefully limit the transmission power of the interference aggressor guaranteeing the required SINR at the target receiver. A simple yet efficient PC mechanism would be able to estimate the exact, minimum transmission power of the sender that would lead to the exactly sufficient SINR at the target receiver for faultless communication with guaranteed QoS level. In this way, interference would be smoothed, and in parallel, energy would be saved.

Taking this into account, we propose the introduction of QoE criteria to the estimation of this minimum transmission power, exploiting the operation inside the afore-mentioned Constant Optimal Region in terms of QoE (Region 1 in Fig. 4-1), abbreviated hereafter as COR. Although the existence of this region has been extensively discussed and widely accepted in the literature, to the best of the authors’ knowledge, there have not been any studies yet that try to identify and measure the potential benefit of exploiting it for IM. We propose the decrease of the transmit power of all affecting base stations (eNBs and HeNBs) in order to cause the minimum sufficient SINR at the target device (MUEs and FUEs respectively) without any impact on the user perceived quality. Increasing the SINR further would lead to interference problems without any corresponding increase in the perceived quality, and thus, this is considered redundant and costly in terms of energy and resources.

The proposed QoE-aware scheme can be applied as an additional rule in any exist-ing PC scheme. For instance, this rule may be applied on top of the PC scheme proposed by 3GPP [3]. The mathematic formula that describes this 3GPP-standardized scheme is as follows:

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

where P_{Tx} and $P_{eNB-HeNB}$ represent the transmit power of the HeNB (interference aggressor) and the measured received power from the eNB, respectively, while $PL_{HeNB-MUE}$ depicts the pathloss between the HeNB and the victim MUE. P_{max} and P_{min} parameters refer to predefined maximum and minimum transmit power settings, respectively, and depend on the device type.

Having defined the already standardized PC scheme, we present the proposed QoE-aware PC rule:

“If the estimated transmission power of the PC scheme is higher than the threshold power that leads to the lowest SINR in the constant optimal QoE region (i.e., optimum point of operation of Fig. 4-1), reduce this power up to its threshold value, using a safety margin”.

This leads to an enhanced formula that incorporates the proposed QoE-aware rule on top of the 3GPP PC scheme, as follows:

$$P'_{Tx} = max\left(P_{min}, P_{Tx(3GPP)} - \Delta P_{COR,opt}\right), \quad if\ \Delta P_{COR,opt} > 0$$

where $\Delta P_{COR,opt}$ is the decrease in transmission power that moves the SINR from the SINR point that the $P_{Tx(3GPP)}$ defines, up to the “eastern” optimum point in the constant optimal region (COR). This formula will be applied only if the $P_{Tx(3GPP)}$ scheme provides a QoE score inside the constant optimal region, so that the $\Delta P_{COR,opt}$ is positive, and thus makes sense. The QoE score is measured using the Mean Opinion Score (MOS) scale, which is presented in the next section.

In the following, we provide the background for QoE estimation in VoIP services towards estimating the constant optimal QoE region and the gain of applying the proposed QoE-aware PC rule to a femtocell-overlaid LTE-A network.

4.3 QoE of the VoIP Service

4.3.1 Measuring the QoE of the VoIP Service

VoIP is one of the dominant services that will be provided by the LTE-A network. The VoIP requirements for the E-UTRAN sub-system are described in [8]. Practically, the VoIP service must be realized completely in packet switched (PS) domain and perform at least as efficiently (in terms of latency and bit rate) as the VoIP over Universal Mobile Telecommunications System (UMTS) in the circuit switched (CS) do-main. Moreover, according to ITU, a VoIP user is considered to be in outage if less than 98% of its VoIP packets have been delivered successfully to the user within a permissible delay bound of 50 ms, while the percentage of users in outage must be less than 2% [9]. However, these bounds do not reflect the level of end-users’ satis-faction. The end-users’ satisfaction measured in QoE is a strongly subjective term and also one of the dominant factors for assessing a provided service. The most common measure of the QoE is the Mean Opinion Score (MOS) scale recommended in [10]. The MOS ranges from 1 to 5, with 5 representing the best quality, and is commonly produced by averaging the results of a subjective test, where end-users are called under a controlled environment to rate their experience with a provided service. However, this subjective methodology (use of questionnaires) is cost-demanding and practically inapplicable for real-time monitoring of the VoIP performance.

On the other hand, objective methods have been proposed to measure the speech quality. These methods can be classified into intrusive and non-intrusive methods. Intrusive methods, such as the Perceptual Speech Quality Measure (PSQM) and the PESQ (Perceptual Evaluation of Speech Quality), estimate the distortion of a refer-ence signal that travels through a network by mapping the quality deterioration of the received signal to MOS values. However, the need for a reference signal is a draw-back for using intrusive methods for QoE monitoring. To this end, non-intrusive methods have been defined such as the E-model and the ITU P.563 [11]. Since the ITU P.563 method has increased computational requirements, making it inappropriate for monitoring in real-time basis, we adopt the easier to be applied E-model described in the next section.

4.3.2 The E-model

The E-model has been proposed by the ITU-T for measuring objectively the MOS of voice communications by estimating the mouth-to-ear conversational quality as perceived by the user at the receive side, both as listener and talker [12]. It is a parametric model that takes into account a variety of transmission impairments producing the so-called transmission Rating factor (R factor) scaling from 0 (worst) to 100 (best). Then a mathematic formula is used to translate this to MOS values. In the case of the baseline scenario where no network or equipment impairments exist, the R factor is given by:

$$R = R_0 = 94.2$$

However, delays and signal impairments are involved in a practical scenario and hence the R factor is given by:

$$R = R_0 - I_s - I_d - I_{ef} + A$$

where:

I_s : the impairments that are generated during the voice traveling into the network,

I_d : the delays introduced from end-to-end signal traveling,

I_{ef} : the impairments introduced by the equipment and also due to randomly distributed packet losses,

A : allows for compensation of impairment factors when there are other advantages of access to the user (Advantage Factor). It describes the tolerance of a user due to a certain advantage that he/she enjoys, e.g., not paying for the service or being mobile. Typical value for cellular networks: $A = 10$.

Focusing on parameters which depend on the wireless part of the communication (transmissions between (H)eNB and UEs) it holds that [13]:

$$I_d = 0.024d + 0.11(d - 177.3)H(d - 177.3)$$

where:

$$H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases}$$

and d is the average packet delivery delay. Also, assuming that the codec G.729a is used, the packet loss rate, referred here as p, affects the parameter I_{ef} as follows [13]:

$$I_{ef} = 11 + 40 \ln(1 + 10p)$$

The R factor can be used as an assessment value; however, we transform it to MOS values to retrieve results comparable with results provided by subjective methods. The transformation formula is as follows:

$$MOS = \begin{cases} 1, & if\ R < 0, \\ 1 + 0.035R + R(R - 60)(100 - R) \cdot 7 \cdot 10^{-6}, & if\ 0 \leq R \leq 100, \\ 4.5, & if\ R > 100\,. \end{cases}$$

In the next section, we focus on the deterioration caused in parameters d and p in a femto-overlaid LTE-A network and on the resulting user perceived quality.

4.4 Performance Evaluation

Towards quantifying the need for QoE-aware IM schemes, we first evaluate the im-pact of macrocell-femtocell coexistence on VoIP users' QoE. We assume an LTE-A network that consists of a target hexagonal macrocell with 6 neighboring cells and multiple femtocells inside the target cell area. Each femtocell is deployed with some probability inside a 10mX10m apartment, while 25 apartments define a 50mX50m square building block. Multiple building blocks are uniformly distributed inside the target cell area, while the femtocells reuse the licensed spectrum of the target macrocell, exacerbating the interference problem. For this scenario, we have expanded the open source system level simulator described in [14] to derive the QoS fluctuations, and used the E-model to translate them to MOS. The main simulation parameters are:

Table 4-1: Evaluation Parameters – QoE-based interference management

Parameter	Value
Number of eNBs	7
Macrocell radius	500 m
eNBs TX power	43 dBm
Femtocell building block	5x5 building block
Apartment side	10 m
Building block deployment	10 (x25 apartments)
HeNB presence probability in an apartment	50%
HeNBs TX power	20 dBm
HeNBs deployment	Co-channel
MUEs distribution	Uniform (inside the macrocell area)
FUEs distribution	Uniform (inside the apartments)
UEs in the system	Scalable
Traffic load per user	1 VoIP call
VoIP codec	G.729a
Duplex mode	FDD (focus on downlink)
Channel bandwidth/cell	10MHz
Scheduling algorithm	Proportional fair
Flow duration	5 seconds
QoE model	E-model

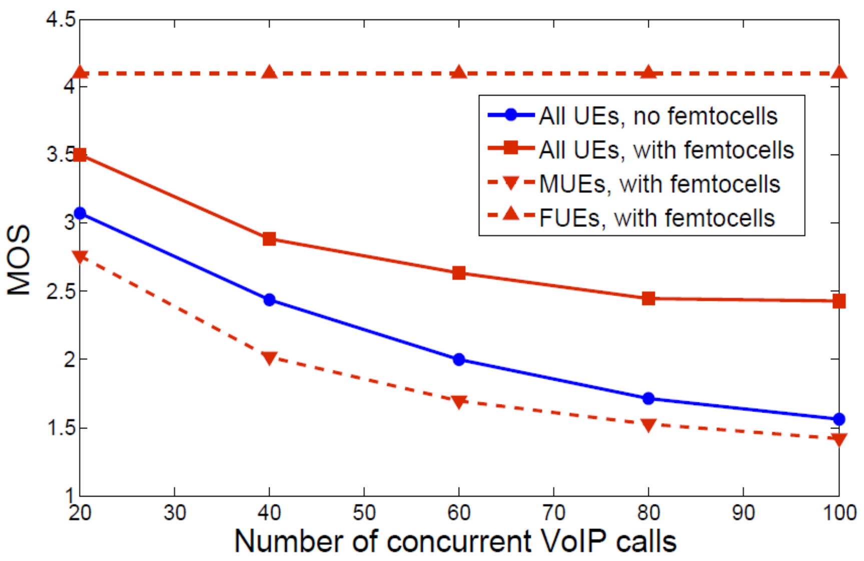

Figure 4-2: Impact of the number of VoIP calls on QoE

At first, we examine the impact of femtocell deployment on the QoE performance of all types of end-users (MUEs and FUEs), assuming an increasing number of con-current

VoIP calls inside a target macrocell area. More specifically, 10 building blocks are uniformly distributed inside the target macrocell area, while each HeNB is located with 50% probability into an apartment of a building block. We consider that the HeNBs operate in CSG mode and also that the 50% of VoIP flows are originated indoors, while the rest of them outdoors. The results concerning the QoE of the users, represented using the MOS scale, are shown in Fig. 4-2.

As shown in this figure, on average, the femtocell proliferation improves the QoE experienced by VoIP users (the “All UEs, no femtocells” case has lower performance than the “All UEs, with femtocells” case). Nevertheless, this improvement is mainly caused due to the high QoE performance of VoIP calls served by femtocells, reaping femtocell benefits such as the proximity gain (“FUEs, with femtocells” case). Note that since each femtocell serves a low number of VoIP calls (practically 1 or 2) the increase on the total number of VoIP calls has negligible impact on FUEs’ QoE, maintaining the high QoE performance. On the contrary, the QoE of MUEs seems to deteriorate due to the interference caused by the HeNBs (“MUEs, with femtocells” case). This observation validates the need for more investigation on how to mitigate the interferences caused to MUEs.

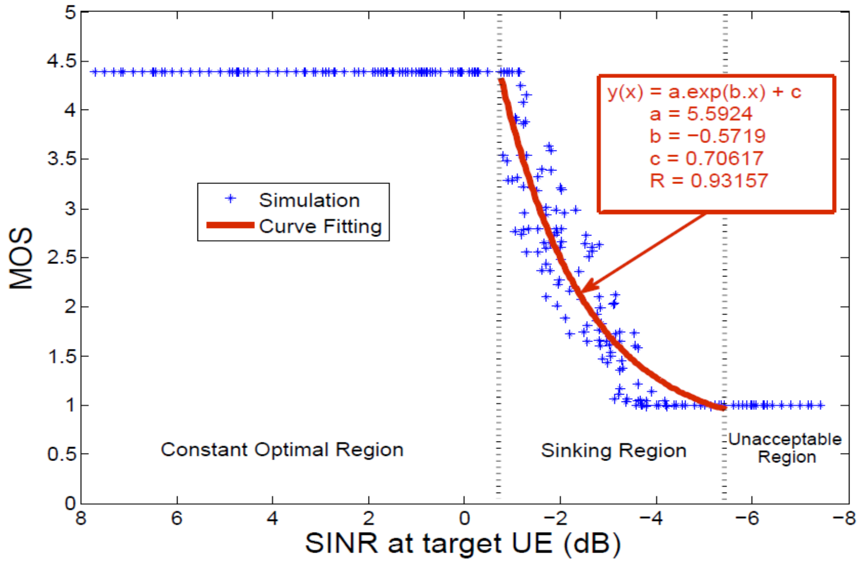

Figure 4-3: Impact of SINR degradation on QoE

Moving one step further, in Fig. 4.3 we prove the existence of the constant optimal region discussed in section 4.1 for any UE. To this end, we focus on a single building block and we monitor the performance of the VoIP call of a single user located close to a femtocell-overlaid building block, while the SINR at this user is constantly de-graded. The reason of the SINR deterioration might be lower transmitted power from the serving base station or higher interferences imposed or even worse channel conditions, without any loss of generality. We depict the results in MOS (y axis) and SINR degradation (x axis) and perform curve fitting to define the function that best de-scribes the simulated data. We observe that the IQX hypothesis is indeed validated, while there is a quite large COR available for exploitation. The optimum point of operation is identified for an SINR threshold value of around -0.8dB for this scenario.

Having defined the constant optimal region for our scenario, we apply the proposed QoE-aware PC rule on top of the PC scheme proposed by the 3GPP, using the formulas of section 4.2. In Fig. 4-4, we compare these two formulas depicting the resulting transmission power by each one of them, for constant and guaranteed QoE at FUEs. This means that all resulting plots have been derived ensuring the same maximum MOS value, both for the 3GPP scheme and for the QoE-aware PC scheme (blue & red curves in Fig. 4-4 respectively). As shown in this figure, the QoE-aware PC rule significantly reduces the required transmission power and thus the interference perceived by victim MUEs, maintaining in parallel the required high QoE level at the served FUEs.

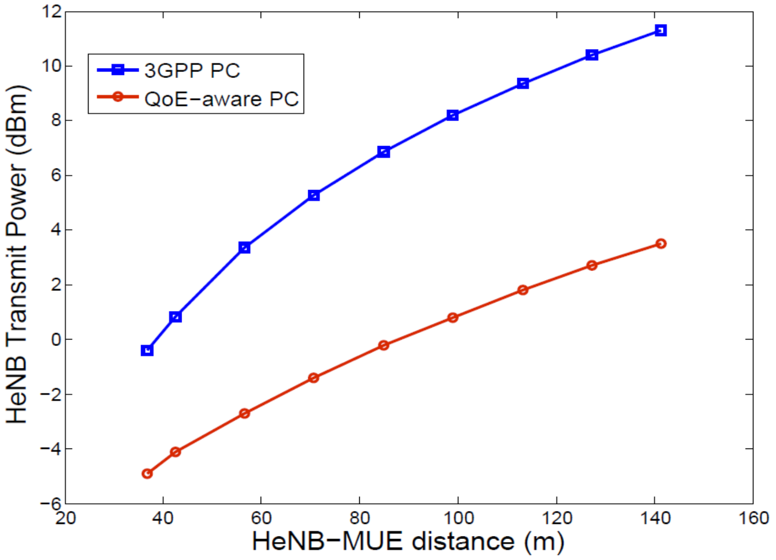

Figure 4-4: Performance of QoE-enhanced 3GPP PC

4.5 Conclusions

In this chapter, we focused on VoIP services in an LTE-A network, and quantified the QoE deterioration of macrocell users due to the interference from femtocells. Sequentially, we examined the relation between the QoE and the perceived SINR at an interference victim, defining the constant optimal region for the SINR. For all SINR values in this region the QoE is constant and in high level, making room for reducing the transmission power with no impact on the service perception of end-users. Finally, we exploited these results to compare the basic power control (PC) interference management (IM) scheme proposed by 3GPP and a simple QoE-aware PC scheme, revealing the importance of involving the QoE notion in the IM process.

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5. DEVICE-TO-DEVICE COMMUNICATION IN CELLULAR NETWORKS

The term *device-to-device (D2D) communication* in LTE networks [1] refers to direct short-range transmissions between UEs, without intervention of an eNB. Considering the numerous benefits of this type of communication, this chapter summarizes the open challenges on enabling D2D communications in LTE networks, while describes the current D2D specifications defined by 3GPP, and the state-of-the-art approaches for coexisting D2D and cellular transmissions.

5.1 Device-to-device communication

Differing from conventional approaches, such as Bluetooth and WiFi Direct, D2D communication utilize licensed spectrum with quality of service (QoS) guarantees for both data and voice communications, while no manual network detection/selection is required. Compared to the very appealing cognitive radio communication, where secondary transmitters detect spectrum holes of cellular (primary) users, D2D communication refers to transmissions coordinated by the cellular network, reaping the benefits of being synchronized and controlled by the eNB.

The introduction of D2D communications in cellular networks is expected to be beneficial from a variety of perspectives, shifting the current cellular communication paradigm to a more flexible and dynamic state. The short distance between D2D peers provides better link conditions and, thus, more efficient connection with lower energy consumption. The utilization of the spectrum and network resources is enhanced, since the intermediate transmissions to eNB are avoided, while the coexistence of cellular and D2D transmissions in shared spectrum can lead to higher overall spectral efficiency. From the operators' point of view, new business models, probably with new charging policies, may be designed, while new types of services may be launched for commercial and public protection scenarios.

D2D standardization efforts have already begun in Release 12 of LTE system, in which the issue is examined under the perspective of enabling *proximity services (ProSe)* for in-coverage and out-of-coverage UEs [2]. In the research field, many solutions have been designed dealing with different aspect of D2D communication. A thorough review of the state-of-the-art solutions reader can be found in [3].

One of the main challenges that need to be addressed prior the introduction of D2D communications to cellular networks, is the discovery of devices in close proximity. The device discovery problem refers to the need of a potential D2D transmitter to know whether the target receiver is in its vicinity and, thus, in valid distance to start a D2D communication. The solution of this problem requires frequent transmission of discovery signals with which a UE announces its presence on a specific area or requests discovery information from a target UE. In both of the cases consumption of radio resources is needed. Moreover, considering the current efforts for launching D2D communications into the market, the discovery transmitters will rapidly increase, consuming in a more intense and massive way radio resources. Taking this into the spatial reuse of the uplink (UL) cellular spectrum is a good candidate towards reducing the consumption of radio resources for discovery transmissions.

5.2 State-of-the-art on coexistence of direct and cellular transmissions

The main challenge in coexistence of direct and cellular transmissions lies in the design of efficient interference management. From this perspective, in the literature two basic approaches have been defined: i) the spectrum underlay, where direct transmissions reuse spectrum portions utilized by cellular transmitters, and ii) the spectrum overlay, where direct transmissions use temporarily empty spectrum portions. A comparison of the two approaches can be found in [4] and [5], in terms of transmission capacity and throughput, respectively. The key challenge in both cases is the mitigation of the generated interferences. To this end, a widely accepted choice is the exploitation of the UL cellular period, where the only cellular interference victim is the immobile eNB, e.g., [6]-[8]. This approach shifts the major interference problem to the protection of the D2D receivers, which by itself is quite challenging, since, in both the underlay and the overlay approaches, the interferences caused by neighboring transmissions (either cellular or direct) are far from negligible. This is an important concern, considering that the current trend is to reduce the cell size for achieving higher spatial network capacity. This trend poses the need for more research on controlling the inter-cell interference perceived by D2D receivers in multi-cellular networks.

Currently, the interference problem is dealt with interference-aware Resource Allocation (RA) and Power Control (PC) schemes, e.g., [9]-[12]. The eNB selects appropriate spectrum resources and power levels for the D2D transmitters, taking into account information on the interferences among D2D and cellular nodes. An important issue here is how the eNB acquires the interference information. To this end, different mechanisms have been introduced, exploiting mainly measurements guided by the eNB, e.g., [10], [13], [14]. However, even if accurate information is available at the eNB, the enabling of D2D transmissions through interference-aware RA and PC procedures is a very complex and hard to optimize problem. In a more distributed approach, the ability of spatially reusing the spectrum is studied in [15], where topology informed users transmit concurrently and in the same band with users of a carrier sense multiple access with collision avoidance (CSMA/CA) system. Nevertheless, acquiring the interference/topology information consumes network resources, while information accuracy is highly dependent on network topology changes. Taking the above into account, the design of spatial spectrum reuse solutions that reduce the need for interference/topology information at the eNB is an important open challenge

Considering the device discovery problem, a solid and comprehensive study of the state-of-the-art protocols for device discovery can be found in [16]. A promising solution has been proposed by Qualcomm under the term FlashLinQ in [17]. In addition to the device discovery, this scheme includes (i) timing and frequency synchronization derived from cellular spectrum, (ii) link management, and (iii) channel-aware distributed power, data rate, and link scheduling. Other approaches deal with the functional enhancements required in cellular networks for enabling direct transmissions in spatial spectrum reuse opportunities [18],[19].

5.3 D2D aspects in 3GPP

In parallel to the research effort from academia, 3GPP has recently begun working on integrating D2D communications in LTE Release 12. For the better study of the problem 3GPP has adopted the following terminology [2]:

***ProSe direct communication*:** a communication between two or more UEs in proximity that are ProSe-enabled, by means of user plane transmission using E-UTRA technology via a path not traversing any network node.

***ProSe-enabled UE*:** a UE that supports ProSe requirements and associated procedures. Unless explicitly stated otherwise, a ProSe-enabled UE refers both to a non-public safety UE and a public safety UE.

***ProSe-enabled Public Safety UE*:** a ProSe-enabled UE that also supports ProSe procedures and capabilities specific to Public Safety.

ProSe-enabled non-public safety UE**:** a UE that supports ProSe procedures and but not capabilities specific to public safety.

ProSe direct discovery**:** a procedure employed by a ProSe-enabled UE to discover other ProSe-enabled UEs in its vicinity by using only the capabilities of the two UEs with rel.12 E-UTRA technology.

EPC-level ProSe discovery**:** a process by which the EPC determines the proximity of two ProSe-enabled UEs and informs them of their proximity.

Based on this terminology two direct communication modes are proposed: i) the network independent and ii) the network authorized mode. The first mode of operation does not require any network assistance to authorise the connection and communication is performed by using only functionality and information available locally to the UE(s). This mode is applicable:

- only to pre-authorized ProSe-enabled Public Safety UEs,
- regardless of whether the UEs are served by E-UTRAN or not,
- to both one-to-one and one-to-many direct communication.

The second mode of operation for ProSe direct communication always requires network assistance by the EPC to authorise the connection. This mode of operation applies:

- to ProSe one-to-one direct communication,
- when both UEs are "served by E-UTRAN", and
- for Public Safety UEs it may apply when only one UE is served by E-UTRAN.

For these communication modes and considering the registered public land mobile network (PLMN), the direct communication path and coverage status (in coverage or out of coverage), a number of different possible communication scenarios are defined as shown in Table 5-1, while a comprehensive illustration of these scenarios is provided in Fig. 5-1. However, these scenarios do not cover all the possible scenarios for direct communication, and 3GPP in working on adding more scenarios especially for the case of group communication.

Table 5-1: D2D communication scenarios in LTE networks

Scenario	In/Out coverage		Serving PLMN/Cell
	UE-A	UE-B	
A	Out	Out	No serving PLMN/Cell
B	In	Out	No serving PLMN/Cell for UE-B
C	In	In	Same PLMN/Cell
D	In	In	Same PLMN – different cell
E	In	In	Different PLMN/Cell both UEs are in both cells' coverage
F	In	In	Different PLMN/Cell UE-A is in both cells' coverage UE-B is in serving cell's coverage
G	In	In	Different PLMN/Cell both UE are in its own serving cell's coverage)

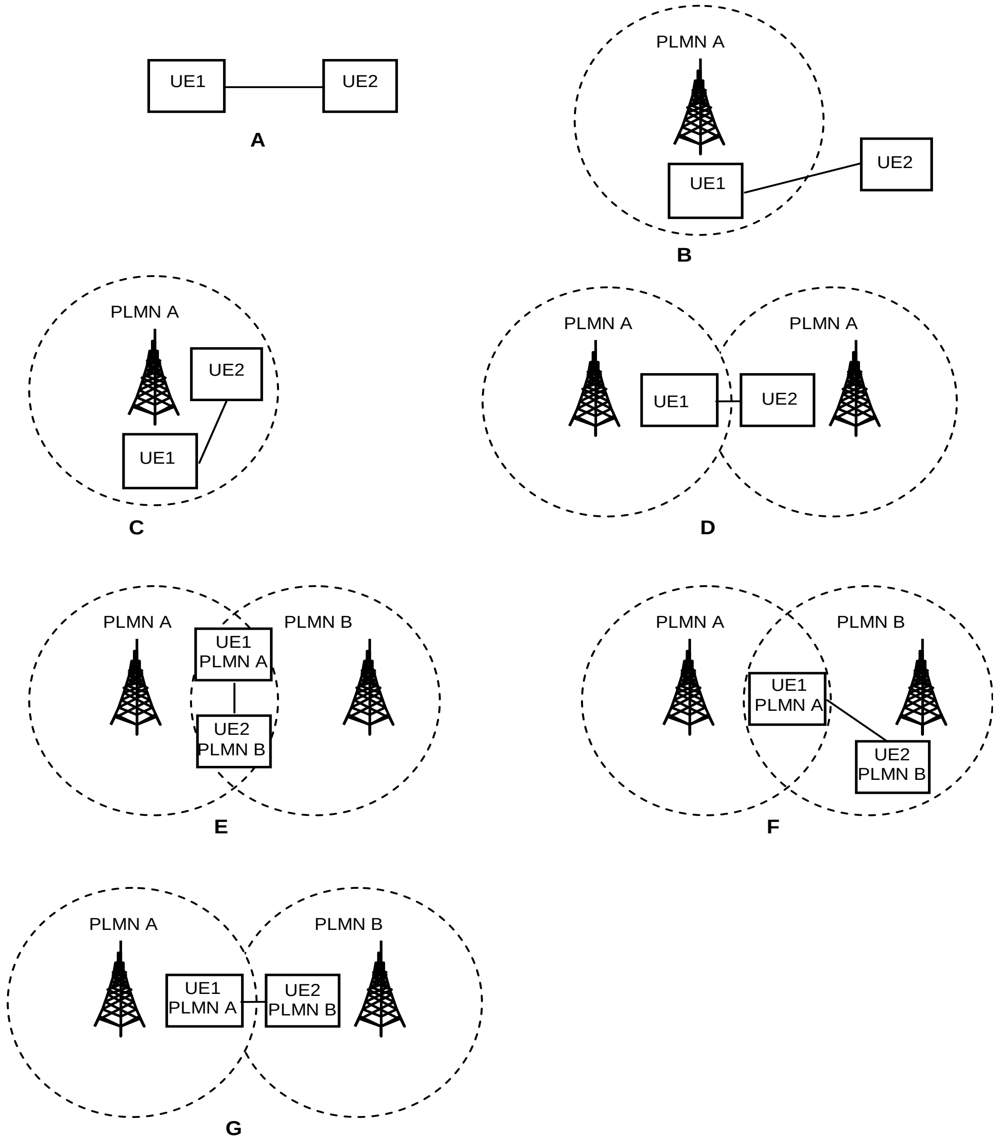

Figure 5-1: 3GPP direct communication scenarios [2]

5.3.1 D2D reference Architecture

Towards supporting the scenarios defined above enhancements are required to the LTE architecture. Fig. 5-2 depicts this architecture and aims to fulfill the following requirements posed by 3GPP.

- Enable the operator to control the ProSe discovery feature in its network, authorize the functionality required for the ProSe discovery functions for each UE.
- Enable the ProSe communication or ProSe-assisted WLAN Direct communication and seamless service continuity when switching user traffic between an infrastructure paths and a ProSe communication path of the ProSe-enabled UEs
- Enable HPLMN operator to authorize ProSe-enabled UE to use ProSe communication separately for the HPLMN and for roaming in VPLMNs.
- Enable an authorized 3rd party ProSe application to interact with 3GPP network in order to utilise the ProSe services offered by the network.

- Be able to control ProSe communication between ProSe-enabled UEs when the UEs are served by a same eNB or different eNBs.
- Accommodate the ProSe related security functions related to privacy, support for regulatory functions including Lawful Interception, and authentication upon ProSe discovery and ProSe communication
- Enable the operator to authorize and authenticate the third party applications before making use of the ProSe feature.
- Accommodate for charging by the operators (HPLMN or VPLMN) for the utilization of the ProSe functionality.

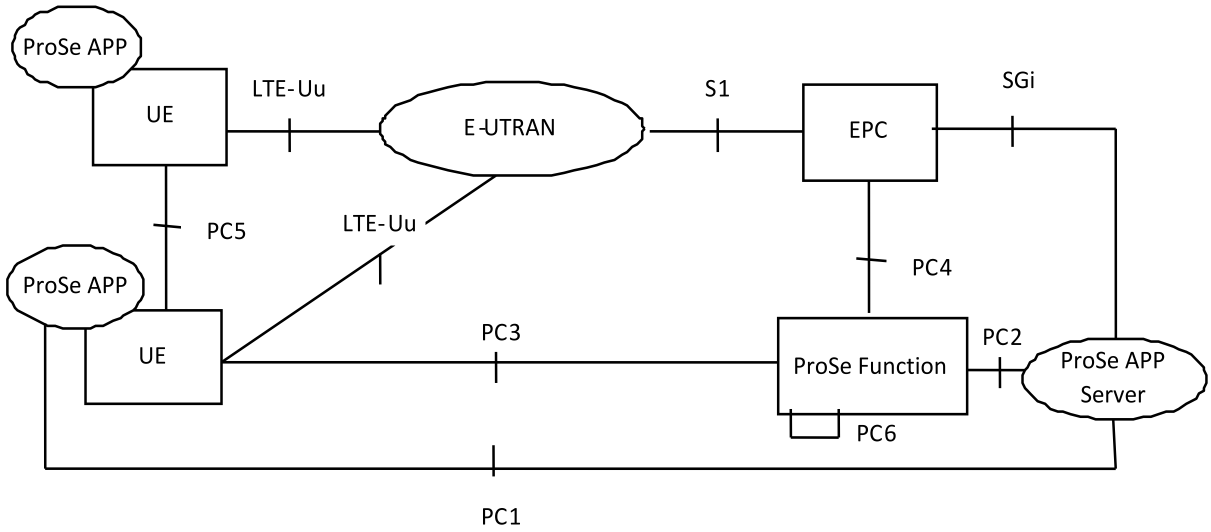

Figure 5-2: D2D-enhanced LTE architecture [2]

As depicted in Fig. 5-2, additional to the entities of the conventional LTE architecture a number of new entities is required. These entities are the following:

Application servers (ProSe App Server) incorporates the ProSe capability for building the application functionality, e.g. in the Public Safety cases they can be specific agencies (PSAP) or in the commercial cases social media. These applications are defined outside the 3GPP architecture but there may be reference points towards 3GPP entities. The Application server can communicate towards an application in the UE.

Applications in the UE (ProSe UEs App) use the ProSe capability for building the application functionality. Example may be for communication between members of Public Safety groups or for social media application that requests to find buddies in proximity.

ProSe Function in the network (as part of EPS) defined by 3GPP has a reference point towards the ProSe App Server, the EPC and the UE. The functionality may include but not restricted to: interworking via a reference point towards the 3rd party applications, authorization and configuration of the UE for discovery and direct communication, enable the functionality of the EPC level ProSe discovery, and provide functionality for charging (via or outside of EPC, e.g. offline charging).

Note that for the interconnection of the new entities and the connection with the conventional LTE entities, 7 new interfaces/reference points are defined named as PC1, PC2, PC3, PC4, PC5, PC6 and SGi (Fig. 5-2).

5.3.2 ProSe device discovery

3GPP has already defined two basic device discovery approaches: the EPC-level, where the core network resolves the discovery by utilizing location information, and the direct one, where each UE is responsible for indicating UEs in its vicinity. For the first approach the following assumptions apply [2]:

- The solutions need to support scenarios where UEs are registered to the same or different PLMNs, including when roaming;
- EPC-level ProSe discovery may be used independently or as a prelude to establishment of direct path (i.e. E-UTRA ProSe Communication path or WLAN Direct communications path) or infrastructure path between ProSe enabled UEs;
- EPC-level ProSe discovery solution shall take into consideration the user- and/or application-related discoverability settings (e.g. UE is discoverable only by UEs that are explicitly permitted);
- EPC-level ProSe discovery solutions shall take into consideration the interactions with other capability settings (e.g. Presence, TS 23.141 [17]);
- EPC-level ProSe discovery solutions shall take into consideration the device capabilities.

For the direct discovery, there are two types of discovery: open and restricted. Open applies where there is no explicit permission that is needed from the UE being discovered, while restricted discovery only takes place with explicit permission from the UE that is being discovered. ProSe direct discovery can happen in coverage and out of coverage. Out of coverage is only applicable to Public Safety. For ProSe direct discovery at least the following issues need to be clarified [2]:

- what is the procedure of ProSe direct discovery? e.g. discovery using direct radio signals, etc.
- how to carry out required signalling between involved entities? e.g. whether a ProSe-enabled UE announces itself and allows itself to be discovered by others or a ProSe-enabled UE requests that other ProSe-enabled UEs reply if in proximity to the requesting ProSe-enabled UE
- whether it is necessary to optimally manage and trigger the ProSe direct discovery mechanism from the network e.g. activate it only in specific geographical location?

In general, the direct approach is considered more flexible and scalable, since it operates under local-level requirements, shifting the complexity to the end-users, while it is also applicable in out-of-coverage discovery scenarios.

There are two roles for the UE in ProSe discovery:

- Announcing UE: The UE announces certain information that could be used from UEs in proximity that have permission to discover.
- Monitoring UE: The UE that receives certain information that is interested in from other UEs in proximity.

Considering the direct discovery approach, the resource allocation can follow either a procedure where a spectrum portion is allocated to all or group of UEs for discovery transmissions, discovery Type 1 in [20], or a procedure where resources are allocated on a per UE basis, discovery Type 2 in [20]. However, in both of the cases, the consumption of radio resources is inevitable. For the second case, the resources can be allocated for each specific transmission instance of discovery signals or can be allocated in a semi-persistent way, while only an UE in RRC CONNECTED mode may request resources for transmission of D2D discovery messages from the eNB via RRC.

In chapter 7, the reader can find solutions compliant to ProSe direct discovery principles and especially to discovery Type 2 where resources are allocated on a per UE basis for transmission of direct discovery messages.

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6. SPECTRUM ACCESS AND MANAGEMENT FOR DIRECT COMMUNICATION

In this chapter, the problem of finding radio resources for D2D communications in an LTE network is studied. The idea is to spatially reuse UL cellular spectrum for D2D communications. More specifically, two different approaches are proposed. In the first one, eNBs are responsible for collecting interference information and allocating resources to D2D pairs, while in the second one, eNBs allocate a spectrum portion for D2D communications and the D2D transmitters follow a contention-based approach to access the spectrum.

6.1 Separated resource allocation for direct communications

The approach described in this section requires the eNB to apply a resource allocation for the D2D peers by exploiting interference information. An interference information collection mechanism provides the network topology to the eNB and spatial spectrum opportunities of the uplink period are assigned to requests for D2D communications. To this end, the network topology including the resource allocation for the cellular transmissions is represented by an enriched node contention graph (eNCG) and is utilized by graph-coloring algorithms to provide an interference-free D2D allocation. Results show that spatial spectrum opportunities can sufficiently serve the D2D transmissions, increasing at the same time the total data rates in the network.

6.1.1 System model

6.1.1.1 UL opportunities

Assume a typical LTE system [1] and the time division duplex technique (TDD). The total UL period consists of a number of adjacent UL subframes. Based on this structure, eNB is responsible for allocating parts of the UL period (resource allocation units) to user equipments (UEs). Let us refer to these parts as *UL opportunities*. We aim at establishing D2D communications by spatially reusing the resources of these UL opportunities.

6.1.1.2 Spatial spectrum reuse

The region under study is a circular cell area, with an eNB in its center and a number of UEs randomly distributed inside it. During a UL opportunity, a single UE transmits data to eNB, while the area outside its transmission range can be utilized for establishing D2D communications [2]. Note that this kind of spatial spectrum reuse assumes that the D2D transmitter is closer to the D2D receiver than to the eNB. A general perspective of this assumption is to focus on indoor and short area direct communications.

The parallel transmissions (cellular and D2D) must ensure mutual interference-free conditions. On the one hand, the interference caused by the D2D transmissions to eNB (the unique cellular receiver during a UL period) is controlled by reversing the view of the standard power control mechanism. According to this mechanism, eNB adjusts UE’s transmit power to ensure a satisfactory connection, however, for a D2D transmission eNB uses this mechanism in the opposite way and limits the transmit power of the D2D transmitter to protect itself.

On the other hand, the interference caused by cellular transmissions to D2D communications is avoided through an interference information mechanism which informs eNB for the interference conditions in each UE’s vicinity. Although deferent mechanisms can be adopted, for the completeness of the proposed scheme an LTE specific mechanism is proposed in the next section.

6.1.2 Interference information collection mechanism

As mentioned above, UEs adopt a mechanism to detect and inform eNB for the interference conditions in their vicinity. This information is used by eNB to build the network topology and reallocate the spectrum resources ensuring interference-free conditions. The proposed mechanism consists of three steps: i) the interpretation, ii) the monitoring, and iii) the information submission step, while it is depicted in Fig. 6-1.

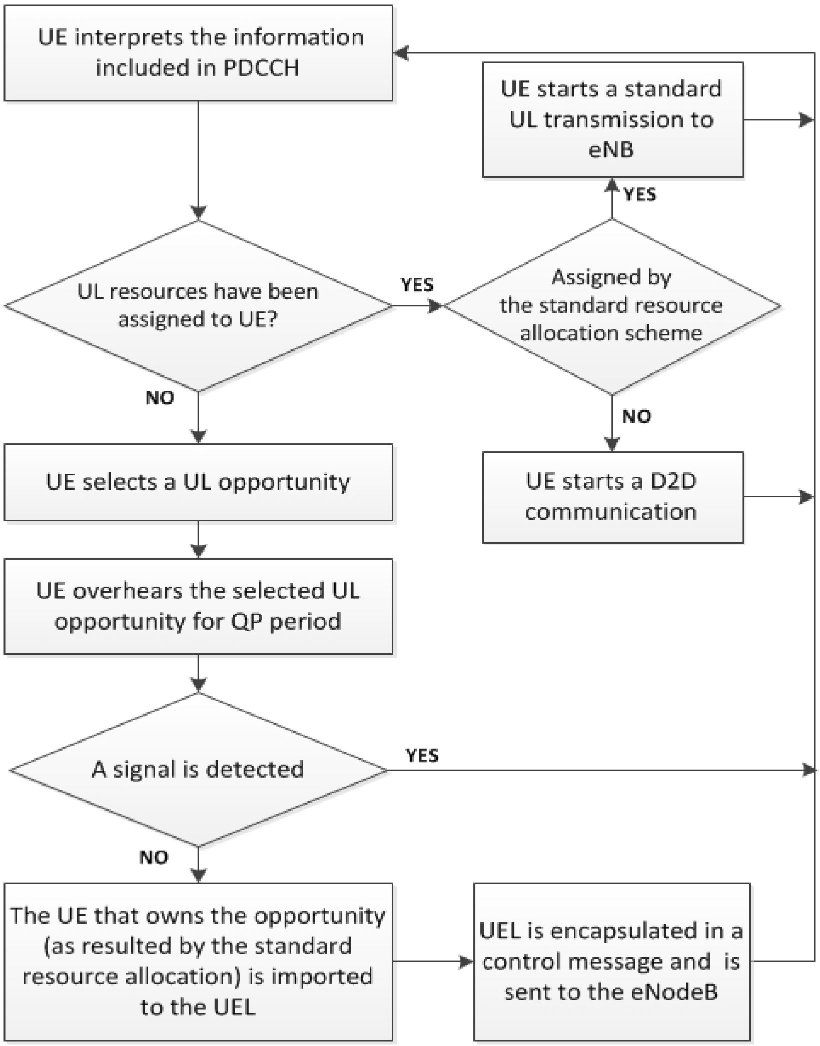

Figure 6-1: Flow chart of the extra UE's functionality

In the first step, the information included in the physical downlink control channel (PDCCH) is interpreted providing to UEs the knowledge of which UL opportunity was allocated to which UE. This is the standard way eNB informs UEs for the resource allocation scheme and, thus, it is a common procedure followed by all UEs. According to this information, a UE that has no allocation, selects a UL opportunity (assigned to another UE) and starts the monitoring step.

In the monitoring step, the selected UL opportunity is monitored for a short period called *quiet period (QP)*, as shown in Fig. 6-2. QP is used by the UE to detect (or not) the existence of a cellular transmission, i.e., to check if it is interfered by the UE that transmits in this UL opportunity. If a cellular transmission is not detected the UE adds the identifier of the transmitting UE to a list which is referred to as *User Equipment List (UEL)*. Every time that no spectrum has been assigned to UE, the procedure is repeated keeping UEL up to date and reliable for a certain time period that assumes no or negligible UEs' mobility.

The third step takes place periodically in the physical uplink control channel (PUCCH). Each time a UE transmits a resource request message or channel measurements, encapsulates its UEL in PUCCH providing to eNB information for the interferences in its vicinity.

According to the proposed scheme, the D2D communication requests are served by D2D transmissions during UL opportunities. The main goal is to decongest eNB and release more resources for inter-cell communications.

A secondary resource allocation procedure is added to eNB to decide on these D2D transmissions. The result of each secondary allocation is encapsulated to physical downlink control channel (PDCCH) to inform D2D transmitters about which UL opportunities to use. Also, the interference information transmitted by UEs (UELs) is required to be stored and available before any secondary allocation decisions.

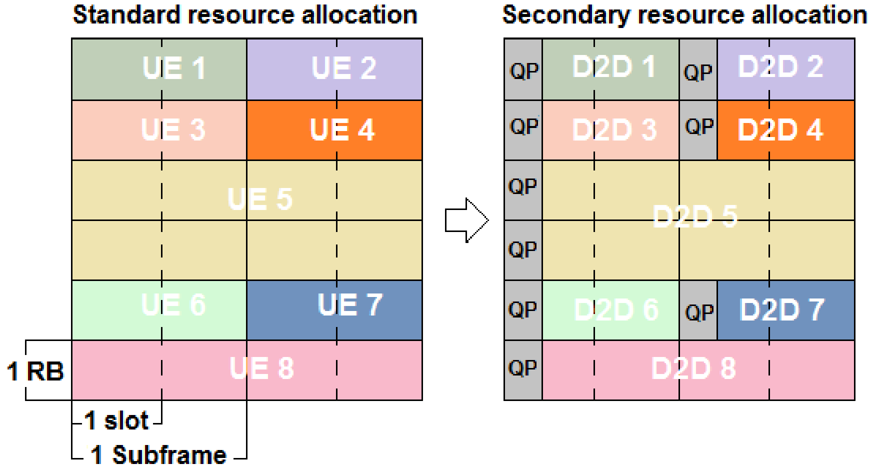

Figure 6-2: The LTE UL period (two UL subframes here)

6.1.3 Resource allocation scheme

6.1.3.1 Graph representation of the network topology

Before eNB allocates the UL opportunities, the information of UELs combined with the results of the standard resource allocation is depicted as a graph. In general, a network topology can be represented by a node contention graph (NCG) or a link contention graph (LCG). In NCG, the UEs are represented by vertices, while edges indicate that two vertices are in the interfering range of each other. In our approach a NCG representation is enriched with the primary resource allocation constructing the reference graph for the secondary resource allocation. The interference information is transformed to the graph according to the following three rules:

1. Vertices represent either UEs with allocated resources (cell UEs) or pairs of intra-cell communication requests.
2. Edges represent interferences between vertices implying that connected vertices cannot use the same spectrum (resources) simultaneously.
3. Extra edges connect the cell UEs with each other, visualizing the primary resource allocation.

Fig. 6-3 depicts the graph representation of a network topology according to these rules. Vertices 1 and 2 represent two different UEs with allocated colors (resources) according to the standard resource allocation scheme, while vertices 3 to 6 represent different intra-cell communication requests which are colored by the proposed allocation scheme. Each edge of the graph represents existence of interference between the nodes it connects. For example, node 1 is connected with nodes 4 and 5, and, thus, the intra-cell communication requests represented by nodes 4 and 5 cannot be served by the same resources allocated to node 1. Following the third rule, an extra edge between nodes 1 and 2 is added visualizing the standard resource allocation, i.e., it confirms that the colors assigned to these nodes are different. In that way, the graph is enriched with the allocations that occur by the standard resource allocation and allows for an interference-free secondary resource allocation, as explained next.

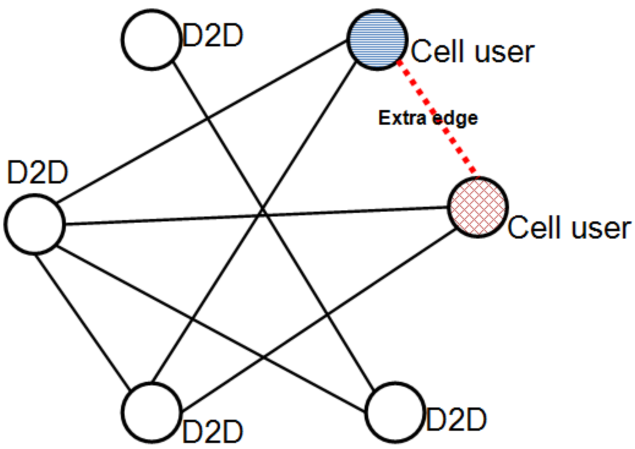

Figure 6-3: Graph representation of a network topology

6.1.3.2 Graph-coloring secondary resource allocation

Since the network topology and the primary resource allocation have been depicted as a graph, the secondary resource allocation can take advantage of the graph-coloring theory [3] to allocate the spatial spectrum resources to requests for intra-cell communications. For each intra-cell communication request there is a list of opportunities that can be assigned according to the UELs submitted to the eNB. To this end, we adopt the *list-coloring theory* which is a type of graph-coloring theory where each vertex can be restricted to a list of allowed colors [4].

Given a graph *G* and a set *L(v)* of colors for each vertex *v*, a list coloring is a choice function that maps every vertex *v* to a color of the list *L(v)*. A list coloring is generally assumed to be proper, if no two adjacent vertices receive the same color.

The objective of the secondary resource allocation is to maximize the spectrum utilization taking advantage of simple, fast, and efficient graph-coloring algorithms [5].

Greedy Algorithm

This coloring algorithm handles colors (UL opportunities) one after another and performs a “greedy” assignment each time. The algorithm performs as if nodes are ranked according to their link degrees from highest to lowest, so that nodes with more edges incident to them are served first. Then the colors are assigned sequentially upon availability providing as final output a partition of the vertex set of the graph into independent sets, where each set occupies one color.

Random Sequential Algorithm (RS)

The random sequence algorithm still performs a greedy type of color assignment, with the only difference being that the nodes are ranked randomly, independent of their characteristics. Then sequential coloring takes place, as in the previous case.

Repeat Random Sequential Algorithm (RRS)

The repeated random sequence algorithm starts with one greedy color assignment and then loops through random permutations trying to find an optimal coloring until a specific predefined amount of time has elapsed.

6.1.4 Performance Evaluation

For the evaluation of the proposed scheme, we adopt the parameters provided in Table 6-1. Let an eNB located in the center of a cell region and a number of UEs randomly distributed around it. Assume the LTE frame structure type 2 (Time Division Duplex-TDD) and the uplink-to-downlink configuration type 0, i.e., each UL period consists of 3 contiguous UL subframes. Also, consider that UEs of category 3 are used transmitting with 16QAM modulation. The QP is defined by 4 symbols of 285.7 μs (for normal CP there are 14 symbols per subframe, thus, $\frac{4}{14} \cdot 1\,ms = 285.7\,\mu s$). The UL resources are assigned to requests for cellular communication according to a Round Robin (RR) scheduling [6], while the proposed graph-coloring scheme reallocates them to requests for D2D communications.

Table 6-1: Evaluation parameters – Graph coloring approach

Parameter	Value
Cell radius	1.5 km
Frame structure	Type 2 (TDD)
Frame duration	10ms
UL/DL configuration	0
UL duration	3 ms (3 adjacent subframes)
CP length	7 symbols/slot
Available bandwidth	20 MHz
Number of RB	100 RB
Quiet Period (QP)	285.7 μs (4 symbols)
Standard Scheduler	Round Robin
UEs' distribution	Uniform
UE class	Cat. 3
Modulation	16QAM

First, we estimate the period of time required to achieve a sufficient representation of the network topology in eNB. This time refers to the initialization of the proposed scheme assuming that eNB has no knowledge of the network topology or interferences among UEs. Next, we study how efficiently the intra-cell communications can be satisfied by D2D transmissions allocated to UL opportunities. Sequentially, we calculate the spatial spectrum reuse for increased number of UEs and different graph-coloring algorithms (Greedy, RS and RRS) and we derive, in terms of data rates, the offloading provided to the inter-cell communications through the additional secondary allocation.

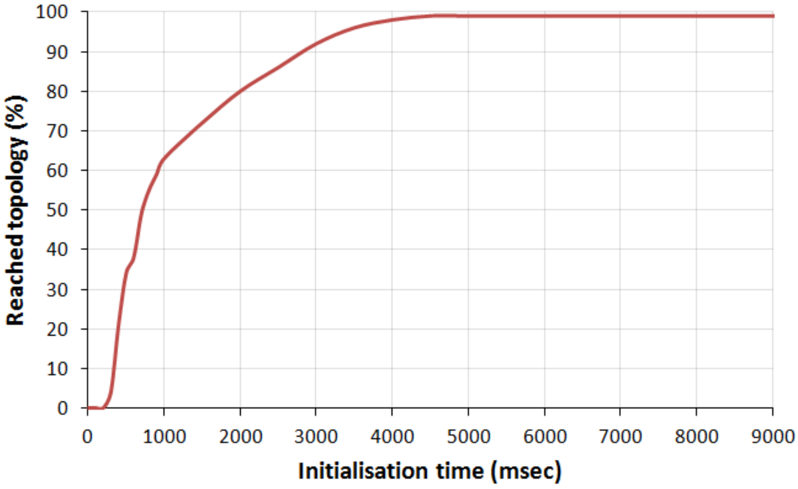

Figure 6-4: Reaching the network topology to eNB

For the system initialization a period of time is needed for eNB to reach a reliable representation of the network topology. Assuming the simulation model described above and 180 UEs that every 10 ms (TDD frame) send the interference information to eNB, the curve shown in Fig. 6-4 is derived. As shown, about 4 seconds are enough for eNB to collect the required information and build 98% of the network topology. After this period, the topology can be up to date according to the interference information messages sent periodically to eNB.

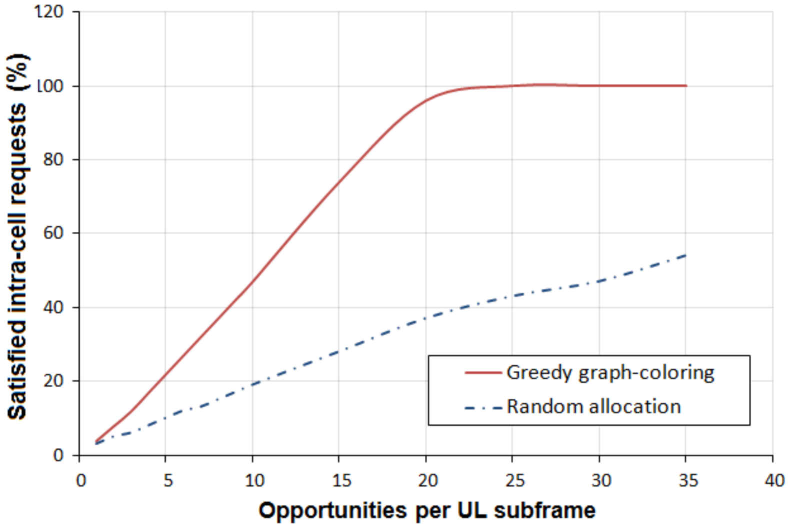

Figure 6-5: Comparison of graph-coloring and random resource allocation

Assuming 100 UEs uniformly distributed around eNB, we study how efficiently the intra-cell communications can be satisfied by D2D transmissions allocated to UL opportunities. We compare the proposed graph-color based allocation (Greedy Algorithm) and a random allocation which randomly allocates the UL opportunities to requests for intra-cell transmissions (Fig. 6-5). Results show that in both cases, as the number of UL opportunities increases, the percentage of satisfied requests for intra-cell transmissions increases as well. However, for the same number of UL opportunities, the graph-coloring scheme satisfies more intra-cell requests than the random scheme. Additionally, with more than 20 available opportunities, the graph-coloring scheme can satisfy 100% of the applied intra-cell requests.

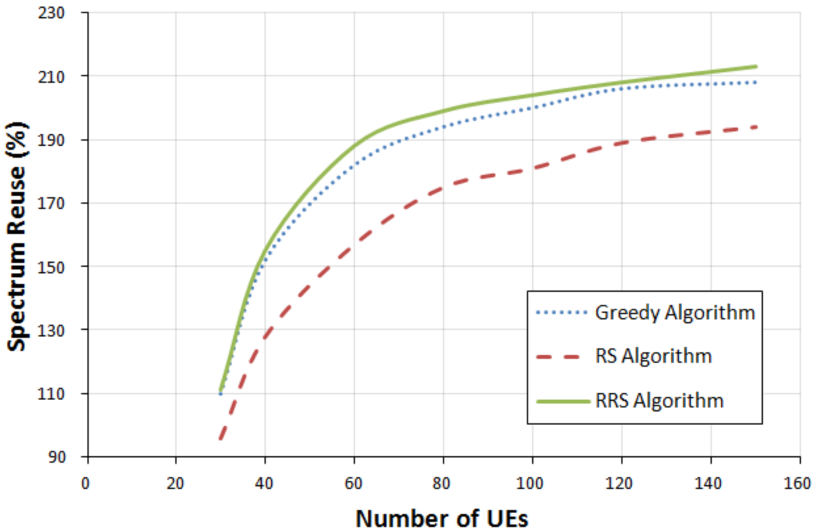

Figure 6-6: Comparison of graph-coloring algorithms

In Fig. 6-6, we provide a comparison among the different graph-coloring algorithms that can be used for the proposed secondary resource allocation scheme in terms of spectrum reuse. All algorithms attain considerable improvement, especially for large number of UEs, with RRS performing better than the Greedy and the RS algorithms, achieving up to 210% of spectrum reuse. However, the provided improvement in comparison to the Greedy one is quite small, considering a disproportionate increase in computational complexity expected with RRS.

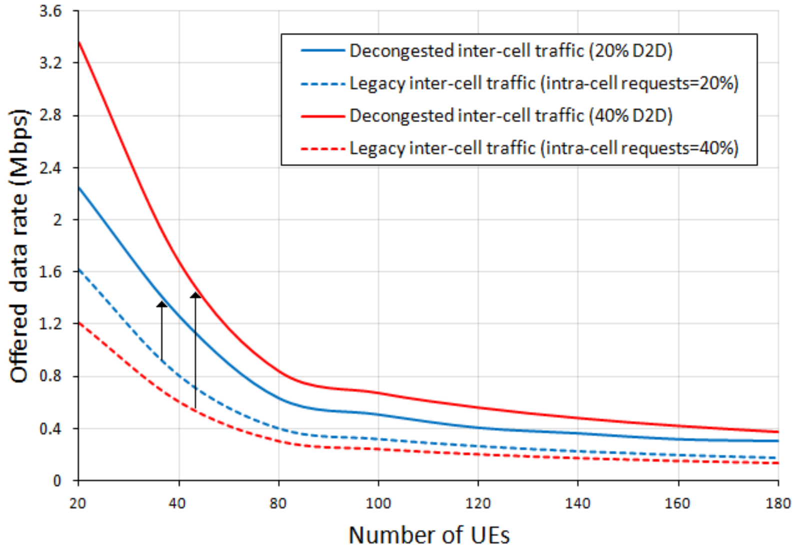

Figure 6-7: Decongestion of the inter-cell traffic

For the intra-cell communications, the transition from using standard mode to exploiting UL opportunities results in a decongestion of the inter-cell traffic in terms of data rates. Fig. 6-7 depicts the mean data rate offered to an inter-cell transmission with (solid line) and without (dashed line) the proposed secondary allocation scheme. Two different scenarios are assumed. In the first scenario, the intra-cell communication requests are 20% of the total requests (blue curves), while in the second one, they are increased to 40% (red curves). As can be observed in Fig. 6-7, in the second scenario, the extra data rate offered to an inter-cell communication is higher than that in the first one due to the increased number of transmissions served by UL opportunities. Also, for both scenarios, the offered gain decreases for an increased number of UEs. This is because the spectrum resources are limited, and as the number of UEs increases, the impact of spectrum reusing to each UE in reduced.

6.2 Contention-based access for direct communications

In contrast approaches where the collection and processing of interference information is required, in this section we propose a spectrum access scheme for D2D communication peers in an LTE network based on a contention process, providing the performance analysis in terms of throughput, delay and energy consumption.

6.2.1 Access model and communication scenarios

Consider an LTE network where D2D and cellular communications coexist in a cell area. For simplicity, we referred to UEs that attend to communicate directly as $eUEs$. The proposed access model for $eUEs$ borrows the distributed coordination function (DCF) of the IEEE 802.11 standard [7]. According to this function, each potential transmitter monitors the channel activity before a transmission attempt and if the channel is idle for a period of time, a four-way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS), takes place [8]. More information about the DCF can be found in Appendix I.The key difference of the proposed scheme and the conventional DCF procedure is that the communication channel is now divided into slots that equals the UL period of the LTE system. Practically, the communication channel composed by a number of contiguous (for FDD LTE) or non- contiguous (for TDD LTE) UL subframes. Fig. 6-8 illustrates how the DCF function is applied to an UL LTE channel.

In more detail, if eUE_i wants to send data to UE_j, it monitors the channel at the beginning of the UL opportunity looking for an idle period similar to the DCF interframe space (DIFS) of the IEEE 802.11 standard. Then, eUE_i waits for a random back-off time and sends an RTS message. On receipt of a CTS message sent by eUE_j, eUE_i can start transmitting for the rest of the UL period.

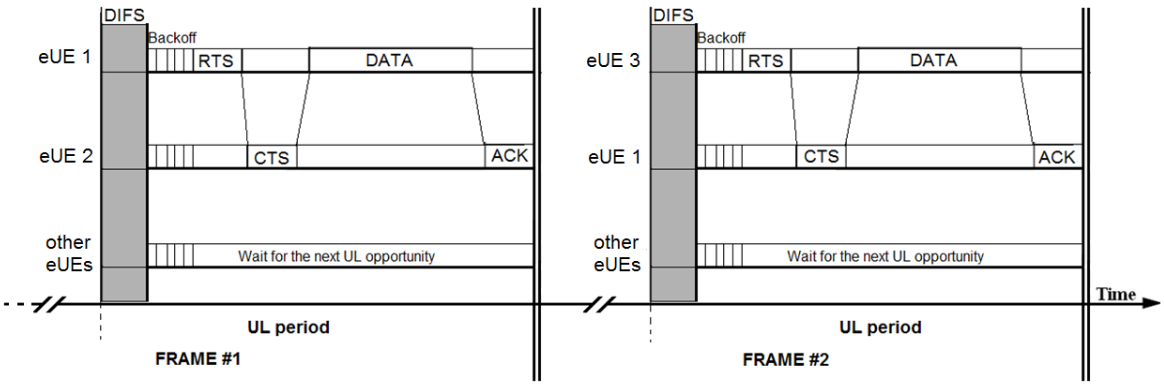

Figure 6-8: Applying DCF in the TDD LTE UL period (each UL period consists of one or more UL subframes)

Based on the access model described above, four communication scenarios are defined:

Scenario A1: D2D pair knows that there is no interference from the UL cellular transmission and the device discovery procedure has been applied and guarantees that D2D peers are in proximity.

Scenario A2: D2D pair knows that there is no interference from the UL cellular transmission. However, device discovery is not considered and a D2D transmitter tries to communicate without knowing whether the target D2D receiver is in its vicinity. The performance of this scenario strongly depends on the probability the communication peers to be located in a close proximity. We refer to this probability as *Proximity Probability* and it is studied in the next subsection.

Scenario B1: shared spectrum is used by cellular UL and D2D communications and the D2D pair is not aware whether there is interference from the cellular UL transmission. Practically, as the eUEs are synchronized to the eNB, the idle period at the beginning of the UL opportunity is used as quiet period for all the eUEs allowing them to recognize the existence (or not) of UEs activity in their receiving area. The access of the D2D communication peers in the spectrum depends on the probability to not indicate during the DIFS period the existence of UE's transmission. This probability is referred to as *Access Probability* and it is studied in the next subsection. Also, for this scenario a device discovery procedure has been applied and guarantees that D2D peers are in proximity.

Scenario B2: shared spectrum is used by cellular UL and D2D communications and the D2D pair is not aware whether there is interference from the cellular UL transmission. However, the device discovery result is not reliable and the D2D transmitter tries to communicate without knowing whether the D2D receiver is in its vicinity. The performance of this scenario strongly depends on both the Access and Proximity probabilities.

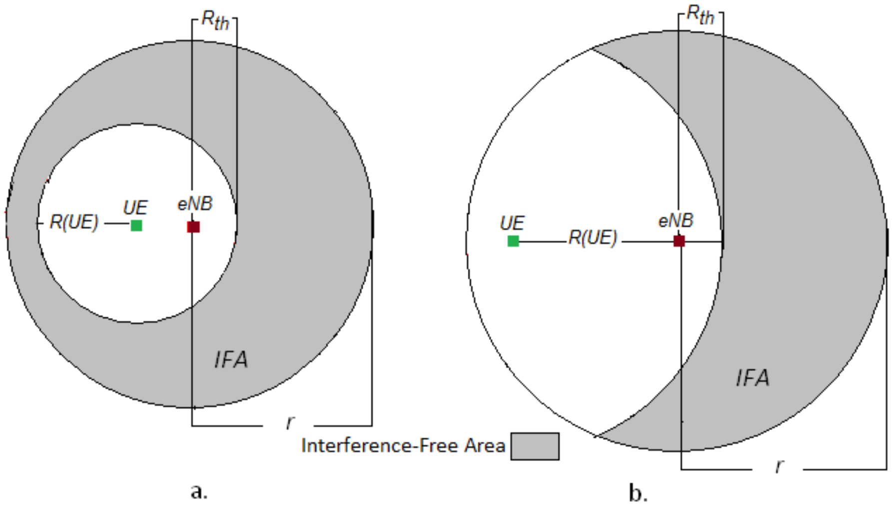

Figure 6-9: illustration of the Interference-free area in two different cases: $\boldsymbol{R(UE) \leq \frac{r+R_{th}}{2}}$ **and** $\boldsymbol{R(UE) > \frac{r+R_{th}}{2}}$

6.2.1.1 Access probability study

This study applies to scenarios B1 and B2, where shared spectrum is used for cellular and direct transmissions. Assume that UEs and eUEs are uniformly distributed inside a circular cell area where the eNB is located in the center of this area. Also consider the case that eUE_i wants to reuse a UL spectrum portion to directly transmit to eUE_j. To avoid interference from the UE that utilizes the same spectrum portion, both eUEs must be located outside UE's interfering range, i.e., the range defined by a specific threshold in the acceptable interference level, and also inside the cell area to maintain the connection with the eNB. The set of locations inside the cell for which both the two constraints are hold, is defined as the Interference-Free Area (IFA). Denoting by r the cell radius, by $R(x)$ the interfering range of node x, and by $d(x,y)$ the distance between nodes x and y, Fig. 6-9 depicts IFA in two different cases: $R(UE) \leq \frac{r+R_{th}}{2}$ (Fig. 6-9a) and

$R(UE) > \frac{r+R_{th}}{2}$ (Fig. 6-9b), where R_{th} denotes the distance that the cellular signal travels beyond the eNB reducing to a predefined non-interference threshold.

Based on the definition of the IFA, and the proposed access protocol, an eUE will access the UL channel if it is located in the IFA, since in that case, during the DIFS the signal from the UE will be bellow the interference threshold. Thus, the access probability of an eUE_i is

$$P_{access}(eUE_i) \equiv P\big(d(UE, eUE_i) \geq R(UE)\big) \cdot P(d(eNB, eUE_i) \leq r) \quad \text{(6-1)}$$

where, $P\big(d(UE, eUE_i) \geq R(UE)\big)$ is the probability that the UL cellular transmission does not interfere the eUE_i and $P(d(eNB, eUE_i) \leq r)$ the probability of eUE_i being into the cell area. Appendix II provides an estimation of this probability using Euclidean geometry, while curve (a) in Fig. 6-10 depicts this estimation for R_{th} equal to 10% of the cell radius. Based on curve (a), on for the specific scenario the expected access probability can be found using the expected distance of the UE to the eNB, which for uniform UE distribution is $\mathrm{r} \cdot \frac{\sqrt{2}}{2}$, and, thus, on average it holds that $P_{access} \cong 0.6$.

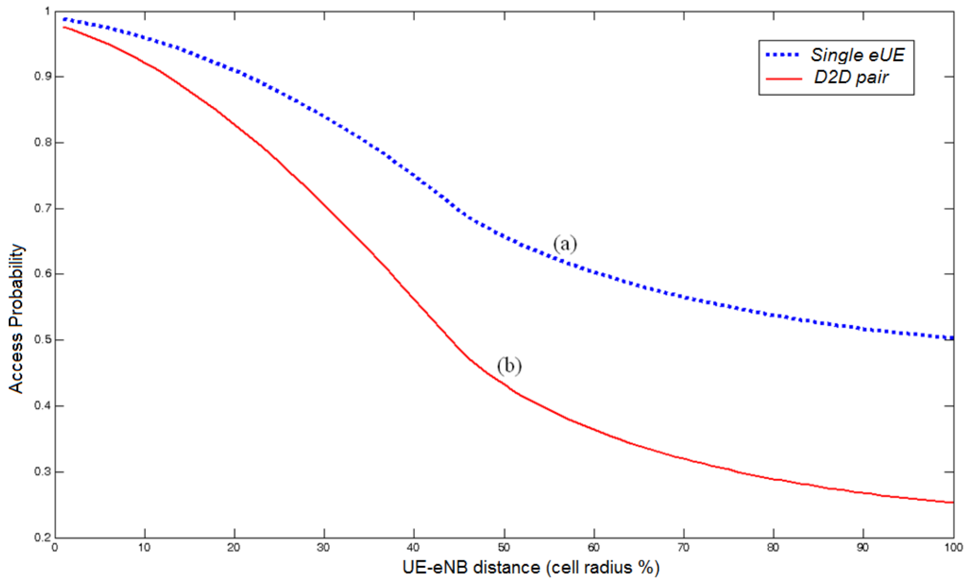

Figure 6-10: Access probability for a eUE (a) and a D2D pair (b)

Moving one step further, the probability of both eUE_i and eUE_j being inside the IFA at the same time is calculated by multiplying probabilities $P_{access}(eUE_i)$ and $P_{access}(eUE_j)$. The resulted probability is illustrated by curve (b) in Fig. 6-10 and represents the maximum percentage of the cell region where the spectrum can be reused for direct transmissions.

6.2.1.2 Proximity probability study

For the direct communication where the spectrum is spatially reused the appropriate power should be used to avoid interfering eNB, in other words, eNB should be outside the interfering range of eUE_i and eUE_j. For a reasonable power requirement at a D2D receiver higher than the interference threshold that defines the interfering range, the following conditions apply:

$$R(eUE_i) \geq d\big(eUE_i, eUE_j\big) \quad \text{(6-2)}$$

$$R\big(eUE_j\big) \geq d\big(eUE_i, eUE_j\big) \quad \text{(6-3)}$$

Consequently, a direct connection between eUE_i and eUE_j is referred to as ***valid*** if and only if the locations of eUE_i and eUE_j are inside the IFA and also constraints (6-2) and (6-3) are hold. We denote as ***proximity probability***, P_{direct}, the probability two $eUEs$ (let eUE_i and eUE_j) to consist a valid D2D pair. The maximum probability P_{direct} equals to the probability the eUE_j to be located inside the eUE_i transmission region and closer to the eUE_i than the eNB as illustrated by region C (Fig. 6-11).

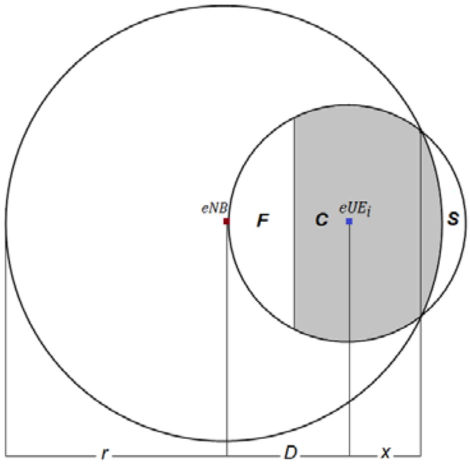

Figure 6-11: The maximum valid region for a D2D communication

As shown in Appendix III, area C is:

$$C = \pi \cdot D^2 - F - S \quad (6\text{-}4)$$

where $D = d(eNB, eUE_i)$ and,

$$F = D^2 \cdot \cos^{-1}\left(\frac{1}{2}\right) - \frac{D^2 \cdot \sqrt{3}}{4} \quad (6\text{-}5)$$

$$S = \begin{cases} D^2 \cdot \cos^{-1}\left(\frac{x}{D}\right) - x \cdot \sqrt{D^2 - x^2} - r^2 \cdot \cos^{-1}\left(\frac{D+x}{r}\right) + (D+x) \cdot \sqrt{r^2 - (D+x)^2} & for\ \frac{r}{2} < D \leq \frac{r}{\sqrt{2}} \\ \pi \cdot D^2 - D^2 \cdot \cos^{-1}\left(\frac{x}{D}\right) + x \cdot \sqrt{D^2 - x^2} - r^2 \cdot \cos^{-1}\left(\frac{D-x}{r}\right) + (D-x) \cdot \sqrt{r^2 - (D-x)^2} & for\ \frac{r}{\sqrt{2}} < D < r \end{cases} \quad (6\text{-}6)$$

$$x = \begin{cases} \frac{r^2 - 2 \cdot D^2}{2 \cdot D} & for\ \frac{r}{2} < D \leq \frac{r}{\sqrt{2}} \\ \frac{2 \cdot D^2 - r^2}{2 \cdot D} & for\ \frac{r}{\sqrt{2}} < D \leq r \end{cases} \quad (6\text{-}7)$$

Thus, for a given D it holds that:

$$P_{direct}|_D = \frac{C}{\pi \cdot r^2} \quad (6\text{-}8)$$

All the possible locations of the eUE_j for a valid direct link establishment are inside the transmission area of the eUE_i which is bounded by the distance $D = d(eUE_i, eNB)$. Thus, the cumulative distribution function (CDF) of the random variable D is given by (10).

$$CDF_D = \frac{\pi \cdot D^2}{\pi \cdot r^2} \quad (6\text{-}9)$$

Taking the derivative of CDF_D we derive the probability density function (PDF) of D, denoted here as PDF_D, as follows:

$$PDF_D = \frac{d\ CDF_D}{dD} = \frac{2 \cdot D}{r^2} \quad (6\text{-}10)$$

Consequently, averaging over all possible choices of D, the proximity probability is as follows:

$$P_{direct} = \int_0^r \frac{2\cdot D}{r^2}\cdot\frac{C}{\pi\cdot r^2}\ dD = \int_0^r \frac{2\cdot D}{r^2}\cdot\frac{\pi\cdot D^2}{\pi\cdot r^2} dD - \int_0^r \frac{2\cdot D}{r^2}\cdot\frac{\left[D^2\cdot\cos^{-1}\left(\frac{1}{2}\right)-\frac{D^2\cdot\sqrt{3}}{4}\right]}{\pi\cdot r^2} dD - \int_{\frac{r}{2}}^r \frac{2\cdot D}{r^2}\cdot\frac{S}{\pi\cdot r^2} dD \tag{6-11}$$

For normalized cell radius and applying (6-4), (6-5), and (6-6) in (6-11) then:

$$P_{direct} = \int_0^1 2\cdot D^3\, dD - \int_0^1 \frac{2\cdot D^3}{\pi}\cdot\left(\cos^{-1}\left(\frac{1}{2}\right) - \frac{D^2\cdot\sqrt{3}}{4}\right) dD -$$

$$\Bigg(\int_{\frac{1}{\sqrt{2}}}^1 2\cdot D^3 dD + \int_{\frac{1}{2}}^1 \frac{\sqrt{(2D^2)^2-1}}{2\cdot\pi\cdot D} dD - \int_{\frac{1}{2}}^{\frac{1}{\sqrt{2}}} \frac{\sqrt{(2\cdot D)^2-1}}{2\cdot\pi\cdot D} dD + \int_{\frac{1}{\sqrt{2}}}^1 \frac{\sqrt{(2\cdot D)^2-1}}{2\cdot\pi\cdot D} dD +$$

$$\int_{\frac{1}{2}}^{\frac{1}{\sqrt{2}}} \frac{D}{\pi}\cdot\sqrt{(2\cdot D)^2-1} dD - \int_{\frac{1}{\sqrt{2}}}^1 \frac{D}{\pi}\cdot\sqrt{(2\cdot D)^2-1}\ dD - \int_{\frac{1}{2}}^1 \frac{2\cdot D}{\pi}\cdot\cos^{-1}\left(\frac{1}{2\cdot D}\right) dD -$$

$$\int_{\frac{1}{\sqrt{2}}}^1 \frac{2\cdot D^3}{\pi}\cdot\cos^{-1}\left(1-\frac{1}{2\cdot D^2}\right) dD + \int_{\frac{1}{2}}^{\frac{1}{\sqrt{2}}} \frac{2\cdot D^3}{\pi}\cdot\cos^{-1}\left(\frac{1}{2\cdot D^2}-1\right) dD\ \Bigg) \cong 0.2512 \tag{6-12}$$

6.2.2 Performance Analysis

6.2.2.1 Normalized Throughput

We define as *normalized throughput* the percentage of an UL opportunity that is used for opportunistic payload data exchange. Since during a UL opportunity the IEEE 802.11 DCF function is applied, existing models can be used to calculate the normalized throughput. In the following, we apply to the proposed mode the IEEE 802.11 DCF modeling provided in [8, 9].

Assume a binary exponential back-off procedure with minimum and maximum back-off window sizes W and 2^bW, respectively. Also assume that n users are located inside the IFA and competing for a UL opportunity. According to [8, 9], the normalized throughput is:

$$S(n) = \frac{P_S(n)\cdot P_{tr}\cdot T[data]}{(1-P_{tr})\cdot\sigma + P_S(n)\cdot P_{tr}\cdot T_S + (1-P_S(n))\cdot P_{tr}\cdot T_C} \tag{6-13}$$

where

- n is the number of competing users,
- $P_S(n)$ is the successful transmission probability,
- P_{tr} is the probability that there is at least one transmission in a specific timeslot,
- $T[data]$ is the payload duration,
- σ is the timeslot duration, i.e., the time interval between two consecutive back-off time counter decrements,
- T_S is the successful transmission duration, and,
- T_C is the collision duration.

The probability that a station transmits in a specific timeslot, denoted by τ, depends on the conditional collision probability p, which is also dependent on the number of users n, and is given by

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^b\right)} \quad (6\text{-}14)$$

where p denotes the probability that a transmitted packet encounters a collision. By definition p is also the probability that at least one of the remaining $n-1$ users transmits in the same timeslot; thus, it holds

$$p = 1-(1-\tau)^{n-1} \quad (6\text{-}15)$$

The solution of the nonlinear system defined by (25) and (26) provides the probabilities τ and p for a specific number of competing users.

Given τ, p, and n, the probability of a successful transmission $P_s(n)$ is the probability that only one user transmits given that at least one transmission occurs; the probability P_{tr} that at least one transmission occurs, is given by $P_{tr} = 1-(1-\tau)^n$.

However, under the proposed system model, the successful transmission probability depends on the communication scenario. More specifically,

$$P_s(n) = \left\{ \begin{array}{ll} \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tr}} & scenario\ A1 \\ \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tr}} \cdot P_{direct} & scenario\ A2 \\ \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tr}} \cdot P_{access} & scenario\ B1 \\ \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tr}} \cdot P_{direct} \cdot P_{access} & scenario\ B2 \end{array} \right\} \quad (6\text{-}16)$$

The payload duration $T[data]$, the successful transmission duration T_s, and the collision duration T_c involved in the throughput expression in (6-13) are strongly dependent on the spectrum access protocol. For the protocol considered here, these parameters satisfy the following equations:

$$T[data] = UL_{size} - (DIFS + C(p)\cdot\sigma + RTS_{size} + CTS_{size} + 3\cdot \mathrm{SIFS} + ACK_{size}) \quad (6\text{-}17)$$

$$T_s = UL_{size} \quad (6\text{-}18)$$

$$T_c = RTS_{size} + 2\cdot \mathrm{SIFS} + CTS_{size} \quad (6\text{-}19)$$

where,

- UL_{size} denotes the duration of the UL opportunity,
- $C(p)$ is the expected number of slots that must be counted down before a transmission occurs,
- RTS_{size} and CTS_{size} are the durations of RTS and CTS transmissions, respectively,
- ACK_{size} is the duration of the acknowledgment (ACK) transmission,
- $DIFS$ (DCF Inter-Frame space) is the quiet period at the beginning of the UL opportunity, and,
- $SIFS$ (Short Inter-Frame Space) is the minimum duration needed between a sequence change from a transmission to a reception and vice versa.

6.2.2.2 Access delay

Using the analysis of previous works on IEEE 802.11 DCF, the expected number of waiting slots during the back-off procedure, $C(p)$, is given by (6-20):

$$C(p) = W \cdot \left(\frac{(1-p)-p\cdot(2\cdot p)^b}{1-2\cdot p} - 1\right) \tag{6-20}$$

where p is the collision probability and W the contention window size.

As shown from (6-17), the duration of a UL opportunity contains: i) the DIFS waiting time at the beginning of the opportunity, ii) the back-off waiting slots $C(p)$, iii) the duration of RTS and CTS transmissions, denoted here as RTS_{size} and CTS_{size}, respectively, iv) the duration of the payload data transmission (transmitted by the winner of the contention), and, v) the duration of the ACK transmission, denoted here as ACK_{size}. Taking this into account, the average access delay for an direct connection establishment is

$$T[total] = DIFS + RTS_{size} + CTS_{size} + C(p) \cdot T[waiting] + 3 \cdot \text{SIFS} + ACK_{size} \tag{6-21}$$

where $T[waiting]$ represents the average waiting time before an eUE transmission, and is defined as follows:

$$T[waiting] = (1 - P_{tr}) \cdot \sigma + P_{tr} \cdot \big(1 - P_s(n)\big) \cdot T_c + P_s(n) \cdot P_{tr} \cdot (T_s + DL_{size}) \tag{6-22}$$

The first term of the sum represents the waiting time if no transmission occurs (i.e., the duration of a single timeslot). The second term represents the waiting time if a collision occurs, i.e., the T_c duration. The third term represents the waiting time if a successful transmission occurs, i.e., the T_s duration and the waiting time during the DL period before the new attempt. Note that under the proposed access scheme, if another successful transmission occurs during the back-off procedure, the attempt is postponed for the next UL opportunity and, thus, the DL duration, denoted here as DL_{size}, must be included. The DL_{size} depends on the adopted system and in most of the cases it changes dynamically based on the traffic load in the uplink and downlink.

6.2.2.3 Energy consumption

During an direct communication there is no participation of the BS, and the energy consumption for an eUE contains: i) the energy spared during the eUE waiting to access the channel, ii) the energy needed to directly transmit the data to the destination, and iii) the energy needed to receive the acknowledgment. Let us denote the transmission power as PWR_{trans}, the power required for sensing the channel (the spectrum opportunity) as PWR_{sense}, and the power needed for receiving data as $PWR_{receive}$. Taking into account these definitions, the energy consumption for these three actions on the average case is:

$$E[total] = E[access] + E[data] + E[ack] \tag{6-23}$$

where:

$$E[access] = PWR_{sense} \cdot DIFS + C(p) \cdot \sigma \cdot PWR_{sense} + PWR_{trans} \cdot RTS_{size} + PWR_{receive} \cdot CTS_{size} \tag{6-24}$$

$$E[data] = PWR_{trans} \cdot T[data] \tag{6-25}$$

$$E[ack] = PWR_{receive} \cdot ACK_{size} \tag{6-26}$$

However, the parameters PWR_{trans}, PWR_{sense}, and $PWR_{receive}$, depend on the distance between transmitter and receiver. Also, the power used during the RTS/CTS exchange depends on the selected communication scenario. In scenarios A1 and B1, eUEs knows that the target receiver is in transmitter's vicinity and, thus, the minimum required power is used for both data and RTS/CTS message exchange. In contrast, in scenario A2 and B2 there is no knowledge of the power that must be used by the eUE transmitter and the opportunistic receiver during the establishment of a direct connection, and, thus, the maximum power that guarantees the interference threshold at eNB is used.

6.2.3 Performance Evaluation

6.2.3.1 Throughput, delay, and energy results

Let a cell region with radius 1000m, an eNB located at the center of this cell, and a number of UEs uniformly distributed inside the cell area. Assume that all users are equipped with omni-directional antennas and their transmitting regions are represented by disc regions around them.

One of the bursts defines the UL opportunity that is exploited by the eUEs according to the communication scenarios A1, A2, B1, and B2. The parameters depicted in Table 6-2 are used for the exploitation of the UL opportunity.

Table 6-2: Evaluation parameters – Contention-based approach

Parameter	Value
RTS	300bit
CTS	300bit
UL opportunity size	5000μs
DIFS	50μs
SIFS	10μs
slot	20μs
Min cont. Window	5 slots
Max back off stage	32 (2^5)
Channel bit Rate	1Mb/s
P_{direct}	0.25
P_{access}	0.6

In Fig. 6-12, we depict the normalized throughput for the D2D communication scenarios A1, A2, B1, and B2. As expected, in all scenarios the normalized throughput decreases for an increasing number of competing eUEs. However, in scenario A1, the normalized throughput offered to a single D2D pair ranges between 40% and 75%, in scenario A2 between 25% and 50%, in scenario B1 between 35% and 69%, and in scenario B2 between 18% and 40%.

Note that each UL opportunity can be reused concurrently by multiple D2D pairs, and, thus, the total additional throughput for a UL opportunity is a multiple of the throughput depicted in Fig. 6-12. Another important observation is that the use of a discovery procedure (scenarios A1 and B2) is very important, since in that case the achievable throughput is increased while the number of eUEs restricted to them which potentially can establish a D2D connection.

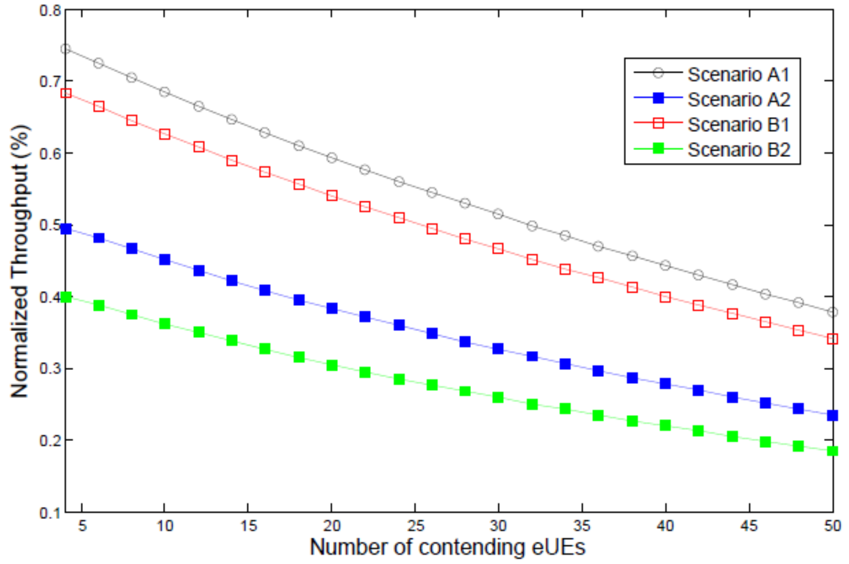

Figure 6-12: Achievable normalized throughput of a single D2D pair

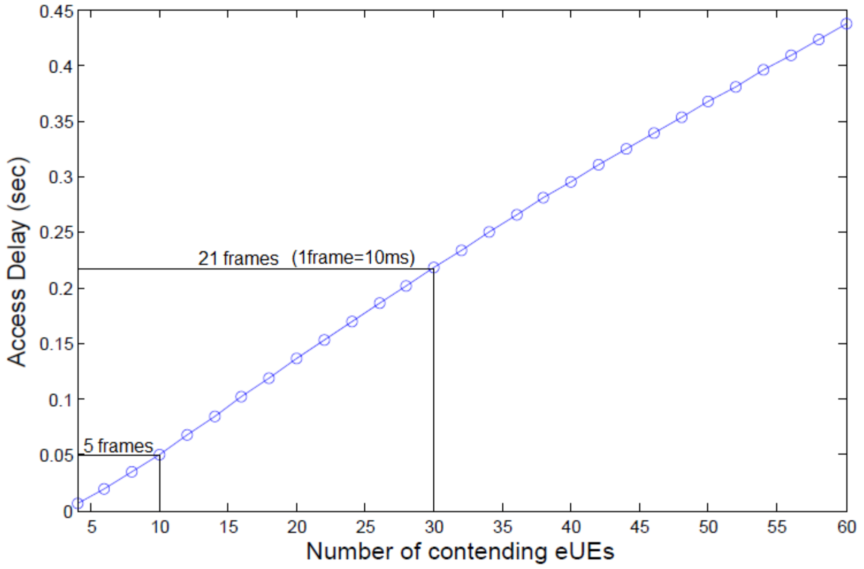

Figure 6-13: Access Delay for a D2D communication

From the access delay point of view, Fig. 6-13 shows that, as the number of competing eUEs increases, the access delay linearly increases as well. Converting the access delay to waiting frames (the frame duration is 10ms), we indicatively note that for 10 eUEs about 5 waiting frames are needed on the average, while for 30 eUEs the number of waiting frames increases to 21.

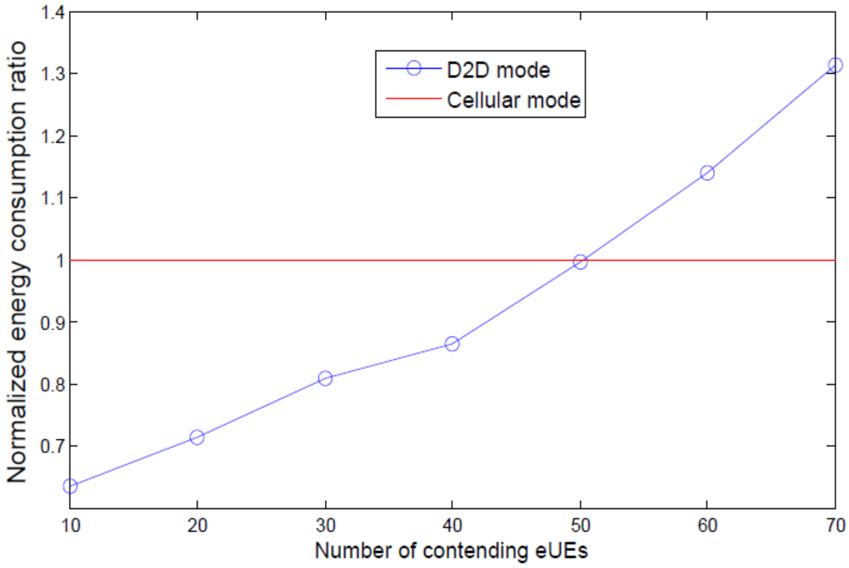

Figure 6-14: Comparison between energy consumptions of cellular and D2D modes

Finally, Fig. 6-14 provides a comparison in terms of energy consumption between a cell communication between two UEs located in the same cell and a D2D communication between these two UEs. In the vertical axis the ratio of the energy consumption in the cellular and D2D case is depicted, while the horizontal axis refers to the number of competing users. As can be observed, under the cellular mode, the transmitter has to send data to the eNB and then the eNB transmits the data to the appropriate receiver. In contrast, under the D2D communication mode, a direct connection is established between the transmitter and the receiver requiring lower energy consumption. However, for more than 50 competing eUEs, the energy that is consumed increases above the cellular case, mainly due to the increased number of collisions and time waiting to access the UL opportunity.

6.2.3.2 Spatial spectrum reuse

In scenario B1, the eUEs use the minimum power required for the RTS/CTS and data exchanges; thus, the closer the locations of the opportunistic transmitter and receiver, the larger the number of concurrent transmissions inside the IFA, i.e., the larger the spatial spectrum reuse factor. In this scenario, the number of valid direct connections can be considered as an upper bound of the spatial spectrum reuse factor. This upper bound can be reached as the opportunistic transmitter and receiver comes closer, minimizing the area covered by their signals. This reasonable statement is verified in Fig. 6-15. This figure illustrates results from simulating an infrastructure-based system with an eNB in the center of a cell area, and a cellular UE that transmits to the eNB from a fixed location inside the cell. The eUEs of the system are uniformly distributed inside the IFA and the number of valid direct connections located in mutually independent areas i.e., the spatial spectrum reuse factor, is calculated. As shown in Fig. 6-15, the relation between the spatial spectrum reuse factor and the number of valid direct connections depends on the distance between the transmitter and receiver of each D2D pair. The dashed line represents the maximum spatial spectrum reuse factor, which is equal to the total number of valid direct connections inside the IFA. Figure 6-15 clearly shows how the calculated spatial reuse factor approaches this maximum as the distance between D2D transmitters and receivers decreases.

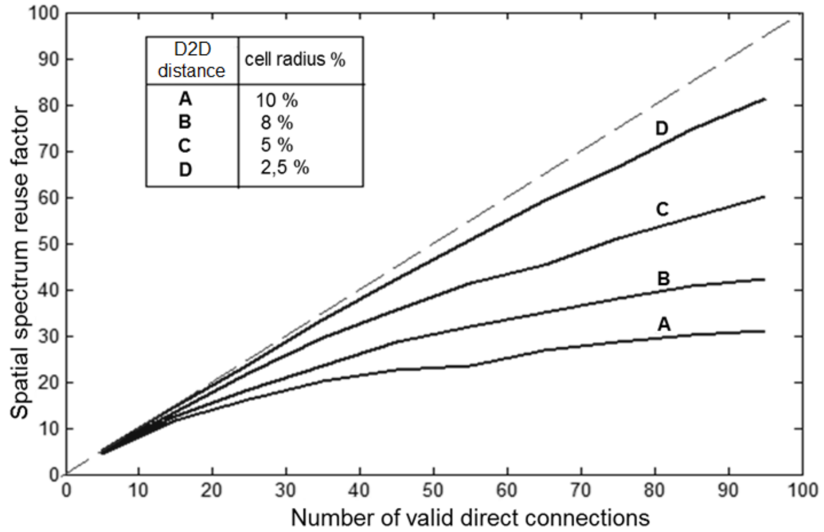

Figure 6-15: Spatial spectrum reuse for scenario B1

For the case of scenario B2, Fig. 6-16 illustrates the achievable spatial spectrum reuse factor according for an infrastructure-based system with an eNB in the center of a cell area and an cellular UE that transmits to the eNB from a fixed location inside the cell. Results for variable number of valid direct connections are depicted assuming eUEs uniformly distributed inside the IFA. The dashed line represents the maximum spatial spectrum reuse factor. As it is shown, in the average case the spatial spectrum reuse factor is strongly correlated with the location of the UE inside the cell area.

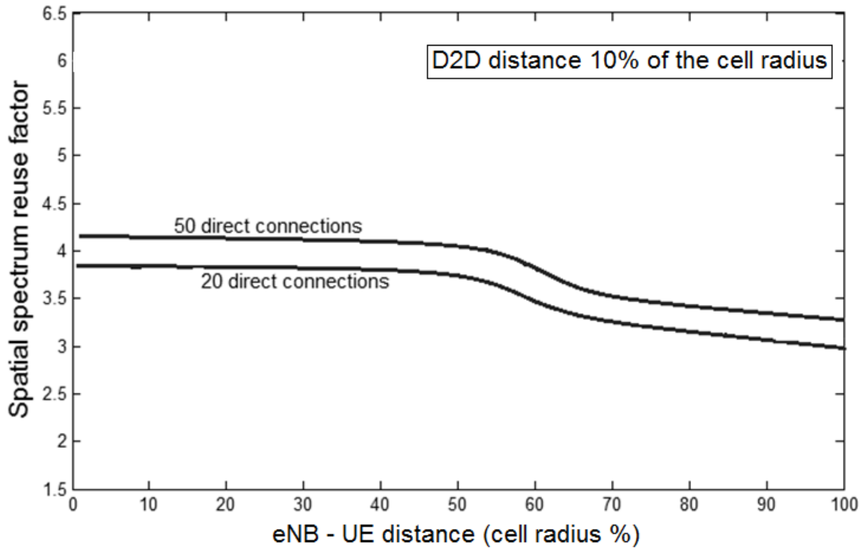

Figure 6-16: Spatial spectrum reuse for scenario B2

6.3 Conclusions

In this chapter, the problem of finding spectrum for D2D communications in LTE networks has been studied. More specifically, two different approaches have been proposed to spatially reuse UL cellular spectrum for D2D communications. In the first approach, a graph coloring secondary resource allocation scheme has been proposed. Spatial spectrum opportunities in the UL period are utilized serving intra-cell communication requests. To support this, extra functionality is added to UEs informing eNB for the interference conditions in their vicinities. This information, enriched with the results of the standard resource allocation procedure, is depicted as a graph utilized by graph-coloring algorithms providing an interference-free secondary resource allocation scheme. Results show that high spatial spectrum reuse factors can be achieved, however the problem of gathering and processing interference information is quite challenging. In the second approach a contention-based scheme has been proposed, where the D2D pairs compete to access the spectrum utilized by a cellular UL transmitter. In this approach no need for interference information collection is required. However, the performance is highly correlated with the number of competing pairs, raising the discovery problem which can restrict the number of users that compete to those that are in close proximity with their target peers.

6.4 References

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7. SPECTRUM ACCESS AND MANAGEMENT FOR DEVICE DISCOVERY

In this chapter, the focus is shifted to the device discovery problem. A set of enhancements in the conventional resource request/allocation procedure of an LTE-A access network is proposed, towards allocating spectrum for discovery transmissions. Additionally, a centralized interference-unaware D2D coordination scheme is designed, targeting at exploiting spatial spectrum opportunities for device discovery transmissions.

7.1 Access network enhancements for device discovery

To provide a resource request/allocation procedure for discovery transmissions the conventional procedure used for the cellular transmissions in an LTE-A network is exploited. For the conventional cellular transmissions in an LTE-A network, a procedure where UEs request for radio resources to the eNB and the eNB allocates the available spectrum to the received requests is adopted. This procedure is depicted in Fig. 7-1, while a detailed description can be found in [1].

The spectrum assignment for DL and UL transmissions is an eNB responsibility, and thus, each eNB uses MAC layer identities called *Cell Radio Network Temporary Identifiers* (C-RNTIs) to uniquely identify its serving UEs [1]. When a UE requests for resources, after a random access procedure, messages for establishing an RRC (Radio Resource Control) connection are exchanged between eNB and UE (the UE from idle mode transit to connected mode). During this procedure, a unique C-RNTI is assigned by the eNB to the requested UE. Note that the C-RNTIs are very important for the radio resource allocation procedure, since the coding/decoding of the physical downlink control channel (PDCCH) that includes the resource allocation grant is based on the C-RNTIs. Practically, each UE uses its C-RNTI to decode the individual resource allocation message transmitted to it by the eNB, and, consequently, to identify the spectrum portion that it will use for reception (DL) or transmission (UL).

7.1.1 Resource request/allocation grant cycle for discovery transmissions

Differing from the conventional resource allocation procedure, in the resource allocation for discovery transmissions the eNB must inform both the transmitter and receiver about the allocation grant, tuning them to the same allocated resources. Although the transmitter's C-RNTI is known at the eNB (it is included in the spectrum request message), the eNB is not aware of transmitter's C-RNTI. Thus, it cannot inform the potential receiver about the time and frequency that will be used. A simple solution is to indicate each device discovery transmissions as broadcast, implying that all UEs should decode the discovery signal. However, this blind transmission could lead to unnecessarily consumption of processing resources and energy at UEs. On the contrary, a one-to-one (or one-to-many) device discovery can be defined, where a discovery transmission refers to a specific discoveree (or specific group of discoverees). This is a reactive discovery approach, where the discoverer examines whether a specific discoveree is in its vicinity. Focusing on the latter case, we propose the introduction of a new MAC layer identity, called *DMO-ID*. The main characteristic of this identity is that it is generated at each UE by using the application layer identity. In this way, when the application layer identity of a target UE is known at a UE that wants to announce its expression code, the target DMO-ID can be precisely produced. The serving eNB, having a mapping between standardized identifiers (C-RNTIs) and DMO-IDs, uses the former ones as in the cellular communications in order to inform both peers about the resource allocation grant. In the following, we assume the case that individual DMO-IDs are used to simplify the description of the proposed scheme.

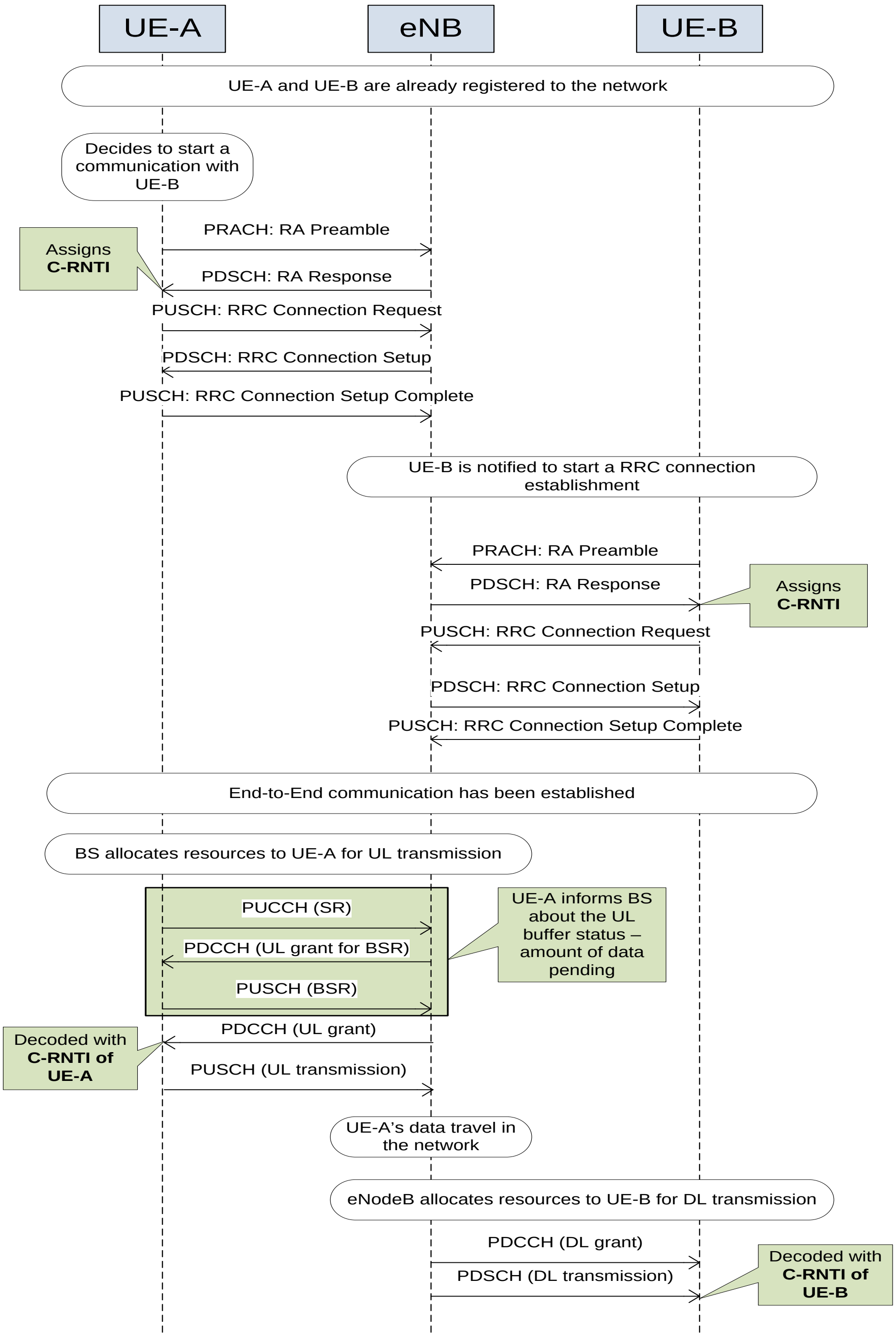

Figure 7-1: Signaling in conventional cellular communication

The proposed scheme can be summarized in the following three steps:

1. Each UE produces its DMO-ID and transmits it to the serving eNB during RRC connection establishment. Upon the reception of DMO-IDs, eNB maps them to C-RNTIs.
2. When the eNB decides that data should be directly transmitted, the UE transmitter includes the DMO-ID of the target UE in a resource request message (as explained later in this section).

3. The eNB allocates radio resources to this request and informs both the peers, tuning indirectly them at the same spectrum portion. The UE transmitter sends the discovery message using the allocated spectrum portion, while the target UE (UE receiver) tunes to the same spectrum region trying to receive the data.

To apply these procedures in an LTE-A network, enhanced functionality is required at the access network (EUTRAN), as explained in the following. Note that for enhancement in the core network (beacon establishment) the approach proposed in [2] can be adopted.

7.1.1.1 DMO-ID production and notification at the eNB

Conventionally, each UE initiates a contention-based access to the network by transmitting a preamble sequence on the physical random access channel (PRACH). As a result, it is supplied with a temporary random C-RNTI by the eNB via the random access response message. Assuming that contention resolution due to potential preamble collisions is not required or is already resolved, this temporary C-RNTI will be promoted to normal C-RNTI, to be used for unique identification inside the cell, for as long as this UE stays in connected mode. The random access procedure is successfully completed upon the reception and the acknowledgement of the RRC Connection Setup message by the UE. To enable the DMO, each UE registers to the network following the standard procedure, including, however, its DMO-ID in the RRC Connection Request message, transmitted via the physical UL shared channel (PUSCH), as shown in Fig. 7-2. This is the same message where the initial UE identity (International-/Temporary Mobile Subscriber Identity - IMSI/S-TMSI) is included. The DMO-ID is introduced as a new information element in the RRC connection request message [1]. Assuming that both UEs are in connected mode the eNB has acquired their DMO-IDs and, consequently, creates an one-to-one mapping between C-RNTIs and DMO-IDs.

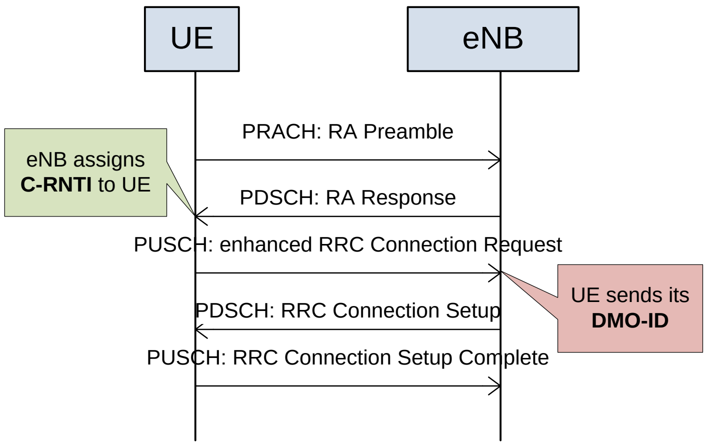

Figure 7-2: DMO-ID notification at eNB during RRC connection establishment

7.1.1.2 DMO resource request

Let UE-A want to announce its discovery message to UE-B. Assume that both UEs have already submitted their DMO-ID using the DMO-ID information element in the RRC connection establishment. Normally, when a UE has data to transmit, the Buffer Status Report (BSR) procedure is initiated. According to this procedure, a Regular BSR informs the serving eNB via the PUSCH about the amount of data pending for transmission in its UL buffers. Note that, if no BSR is already allocated (i.e., no other transmissions are already initiated), a single-bit Scheduling Request (SR) on the physical UL control channel (PUCCH) precedes the BSR request.

In addition to the standard information that any UE includes in the BSR request, the UE-A produces the DMO-ID of the target UE (UE-B) and adds it to the request Fig.7-3. An unused Media Access Control (MAC) Control Element inside the BSR request is used for that purpose, differentiating a discovery spectrum request from a cellular one. This element utilizes space currently reserved for future use, and it is indexed in the MAC Protocol Data Unit (PDU) sub-header by the Logical Channel ID (LCID) value equal to 11000. The new element is called DMO-ID element and is appended to the existing LCID values, such as the common control channel (CCCH), the C-RNTI and the Padding [3]. The enhanced MAC PDU structure is shown in Fig. 7-4.

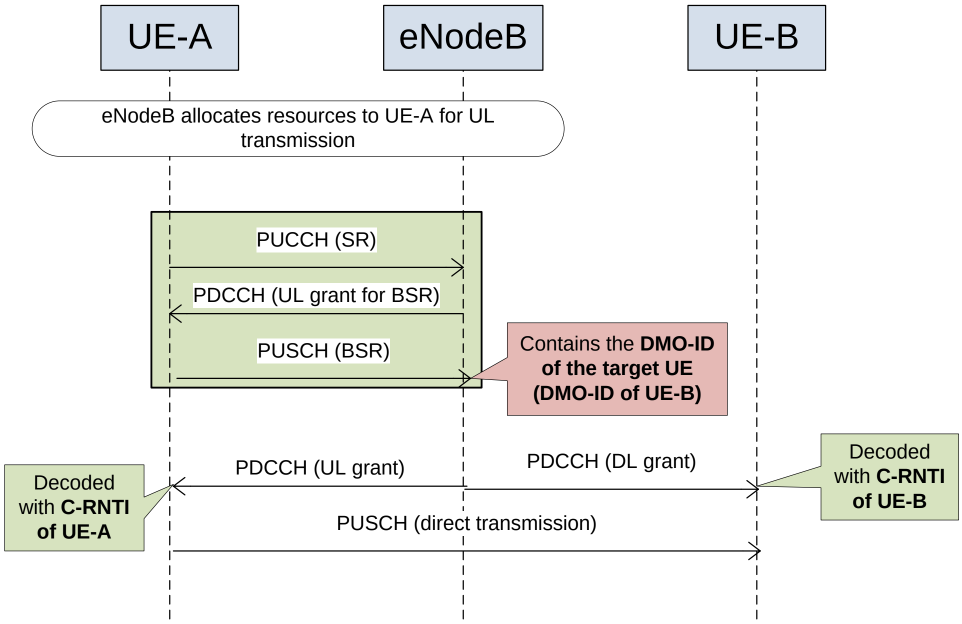

Figure 7-3: Enhanced Resource request procedure for DMO

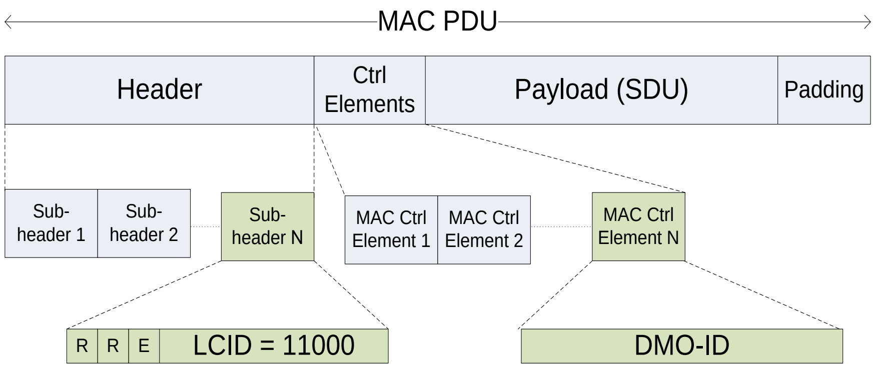

Figure 7-4: Enhanced MAC PDU in the BSR message

In this figure, the extra MAC sub-header for the DMO-ID is depicted as the last sub-header of the MAC header. As already mentioned, the DMO-ID is produced by using the application layer identity. All UEs use the same algorithm/technique for the DMO-ID production; thus, provided that the application layer identity of a target UE is known its DMO-ID can be faultlessly produced. The selection of an efficient algorithm for this transformation is out of this chapter's scope. However, any mapping algorithm, keys, etc. can be used as in the case of the mapping the application layer identity to the expression codes. Upon the reception of a resource request, the eNB indentifies the C-RNTIs of the requesting and the destination UE in this mapping table and uses the corresponding C-RNTIs to encode two allocation messages (allocation grant) for the UEs; one for the UE transmitter (discoveree) and one for the UE receiver (discoverer).

7.2 Spatial spectrum reuse for device discovery

In this section, we focus on the UL period of a multi-cellular LTE network, and propose a centralized interference-unaware D2D coordination scheme which spatially reuses cellular spectrum for device discovery transmissions. We assume that the network adopts the Fractional Frequency Reuse (FFR) inter-cell interference coordination technique, thus, each cell area is divided into a cell-center and a cell-edge area. According to FFR principles, a portion of the available spectrum is utilized by all the cells, under the constraint of allocating it to transmissions from users located at the cell-center area [4],[5]. The target of the proposed scheme is twofold: i) to provide the optimal size of the cell-center area, and ii) to quantify the opportunities for discovery transmission in the spectrum used by UEs in cell-center area, under limited and controlled impact on the performance of the cellular transmissions. For this quantification, a D2D coordinator utilizes estimations on the network density and the distribution of the transmitting UEs, under an interference-unaware approach. The D2D coordinator informs eNBs about the potential transmission opportunities and each one of them configures the size of the cell-center area and enables a limited number of discovery transmissions. The proposed approach offers the following advantages:

- Spatial spectrum reuse opportunities are utilized for device discovery transmissions, taking advantage of the low demands of this type of transmissions.
- An interference-unaware scheme is provided based on modeling the network at a central coordinator, without the need for gathering and processing interference information.
- The interference at discovery receivers, a key challenge when UL radio resources are spatially reused for direct transmissions, is mitigated by utilizing the characteristics of the FFR technique, a reliable and efficient technique, already used for inter-cell interference protection.
- In the proposed scheme the additional discovery transmissions are enabled under controlled impact on cellular ones, while it can also operate as an optimized FFR scheme for inter-cell interference protection.

7.2.1 System Model

7.2.1.1 The main idea

In the UL period of an LTE network, the FFR technique is used for mitigating the inter-cell interference. According to this technique, the available spectrum, denoted here by B, is divided into two parts with different frequency reuse factors. The one part of the available spectrum, denoted here by B_1, is used in all cells, while the other part, denoted here by B_2, is divided among different cells following a non-unit reuse factor. Hence, each cell is assigned the B_1 band plus a fragment of the B_2 band, equal to B_2/RF, where RF denotes the reuse factor (usually, RF=3). The partially-reused spectrum band (B_2/RF) is assigned to UEs located close to the cell edge, since the stronger inter-cell interference is generated by UL transmissions of such UEs. On the other hand, the UL transmissions from UEs located close to the center of the cell (inside the so-called cell-center area) are more protected from inter-cell interference, and thus, the fully-reused spectrum (B_1) is utilized.

The interference isolation provided to the transmissions in the fully-reused spectrum motivates the investigation for transmission opportunities in the same spectrum. The idea is to enable discovery transmissions in the fully-reused spectrum with a controlled impact on the cellular transmissions. This idea is endorsed by the fact that QoS and interference constraints for the device discovery transmissions are relaxed, making such transmissions a good candidate for spatial spectrum reuse.

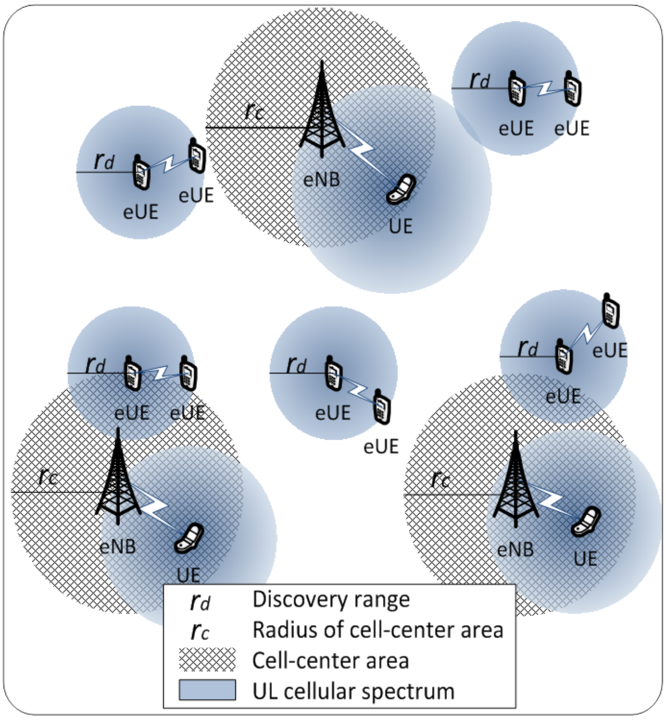

Figure 7-5: System Model

7.2.1.2 Adopted scenario

Following the LTE principles, in the adopted system model, the available spectrum in each cell (i.e., the bands $B_1 + B_2/RF$) is divided into resource allocation units, referred to as resource blocks (RBs). One RB is the minimum allocation unit, and thus, in the UL each RB is assigned to a single UE for transmitting to the serving eNB. Hereinafter, we focus on a specific RB in the band B_1, called *target RB*, and we investigate the challenge of utilizing this RB for device discovery transmissions. The capability of device discovery is provided to all the UEs of the network; however, to simplify our description, the UEs that use the target RB for device discovery transmissions will be referred to as *eUEs* (enhanced UEs). The cellular UL transmissions in the target RB will be referred to as the *cellular system*, denoted by c, whereas the device discovery transmissions in the target RB (transmissions by eUEs) will be referred to as the *discovery system*, denoted by d. The two systems coexist inside an interference isolated area denoted by Ω, while the following assumptions hold:

Assumption 1 – The transmitted signals from any node i of system j, $j \in \{c, d\}$, are affected by: i) Rayleigh fading with factor δ_{ij}, which follows the exponential distribution with unit mean, and ii) path loss degradation described by the simplified model D_{ij}^{-a}, where D_{ij} is the distance of transmitter i from the target receiver in system j, $j \in \{c, d\}$, and a is the path loss exponent.

Assumption 2 – For a target RB, the number of transmitting UEs and eUEs in the area Ω is distributed according to a stationary Poisson Point Process (PPP) with density λ_c and λ_d, respectively.

The cellular network adopts an FFR scheme where each eNB in the area Ω can allocate the target RB to a UE only when it is located at a distance, D_{ic}, smaller than a specific distance r_c, where the distance r_c defines the radius of the cell-center area. Additionally, the target RB can be allocated to a number of device discovery transmissions considering that the potential receiver is located at a distance r_d from the transmitter, where r_d is the target discovery range. Practically, for the transmitting nodes in system c it holds that $D_{ic} \leq r_c$ while for the potential transmissions of the discovery system d it holds that $D_{id} = r_d$. An illustration of the proposed system model is depicted in Fig. 7-5.

7.2.2 Discovery transmission opportunities under optimized FFR

According to the system model described above, all the receivers in the target area Ω are interfered by transmitters of both c and d systems, while due to the stationarity of the Poisson process, they have the same statistics for signal reception, and thus, a typical receiver can be used for interference analysis [6] (Fig. 7-6). We use the following notation:

- P_{ij}: transmit power used by transmitter i in system j, $j \in \{c, d\}$,
- P_k: transmit power used by the target transmitter from the typical receiver, $k \in \{c, d\}$,
- D_k: distance of the target transmitter to the typical receiver, $k \in \{c, d\}$, and
- δ_k: the Rayleigh fading factor for the transmitting power P_k , $k \in \{c, d\}$.

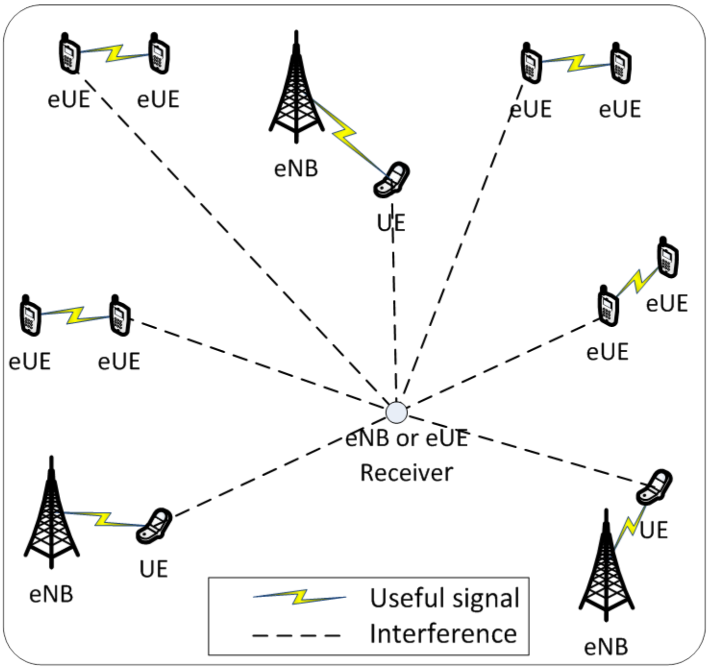

Figure 7-6: Interference at a typical receiver of the network

For negligible thermal noise, the signal to interference ratio (SIR) at the typical receiver of system k, $k \in \{c, d\}$, must be above a predefined threshold u_k:

$$SIR_k = \frac{P_k \cdot \delta_k \cdot D_k^{-\alpha}}{\sum_{j \in \{c,d\}} \sum_{x_{ij} \in \Pi_j} P_{ij} \cdot \delta_{ij} \cdot D_{ij}^{-a}} > u_k \qquad (7\text{-}1)$$

For an interference-free coexistence of systems c and d, the outage probability of each system (i.e., the probability the received SIR to be below the SIR threshold, u_k) must be below a target outage probability threshold:

$$\mathrm{P}(SIR_k \leq u_k) \leq \theta_k \tag{7-2}$$

where θ_k is the target outage probability threshold of system k, $k \in \{c, d\}$.

7.2.2.1 Optimized FFR without discovery transmissions

In the conventional case with no additional discovery transmissions in the target RB, under the assumptions 1 and 2, the outage probability of the cellular system, is as given bellow [7]:

$$\mathrm{P}(SIR_c \leq u_c) = 1 - e^{-\lambda_c \cdot D_c^2 \cdot u_c^{2/a} \cdot G} \tag{7-3}$$

where, $G = (2\pi/a) \cdot \Gamma(2/a) \cdot \Gamma(1-(2/a))$, and $\Gamma(\mathrm{x}) = \int_0^\infty \mathrm{y}^{\mathrm{x}-1} \cdot \mathrm{e}^{-\mathrm{y}} \mathrm{dy}$ (the gamma function).

Using (7-3) in (7-2), yields the following constraint for D_c:

$$D_c \leq r_c = \left[\frac{-ln(1-\theta_c)}{\lambda_c \cdot u_c^{2/a} \cdot G}\right]^{1/2} \tag{7-4}$$

where, the maximum value of the D_c is the distance r_c. We propose the use of the value r_c as the radius of the cell-center area, since this value guarantees the constraint defined in (7-2) even if all the transmitting UEs are located at the edge of the cell-center area. The result depicted in (7-4) also validates the reasonable statement that under an FFR scheme where the cell-center area radius defined by the r_c value, then the denser the cellular system the smaller the optimal size of the cell-center area.

7.2.2.2 Impact of enabling discovery transmissions

In the case that discovery transmissions exist in the target RB, under assumptions 1 and 2, the outage probability of system k, $k \in \{c, d\}$ is as given bellow [7], [8]:

$$\mathrm{P}(SIR_k \leq u_k) = 1 - e^{-K_k \cdot \sum_{j \in \{c,d\}} \gamma_{kj} \cdot \lambda_j} \tag{7-5}$$

where $\gamma_{kj} = \left(\frac{P_{ij}}{P_k}\right)^{2/a}$, and $K_k = G \cdot D_k^2 \cdot u_k^{2/a}$ with $G = (2\pi/a) \cdot \Gamma(2/a) \cdot \Gamma(1-(2/a))$, and $\Gamma(\mathrm{x}) = \int_0^\infty \mathrm{y}^{\mathrm{x}-1} \cdot \mathrm{e}^{-\mathrm{y}} \mathrm{dy}$.

Using (7-5) in (7-2), yields the following constraints involving the outage probability thresholds θ_c and θ_d of the cellular and discovery systems, respectively:

$$\gamma_{dc}^{-1} \cdot \lambda_d + \lambda_c \leq \varepsilon_c \tag{7-6}$$

$$\lambda_d + \gamma_{dc} \cdot \lambda_c \leq \varepsilon_d \tag{7-7}$$

where, $\varepsilon_c = -\frac{\ln(1-\theta_c)}{K_c}$, and $\varepsilon_d = -\frac{\ln(1-\theta_d)}{K_d}$.

Under these constraints, the optimal spatial density of the system d, λ_d^{opt}, is as follows (Lemma 1 in [8]):

$$\lambda_d^{opt} = \min\{\varepsilon_d, \gamma_{dc} \cdot \varepsilon_c\} - \gamma_{dc} \cdot \lambda_c \tag{7-8}$$

As can be observed in (8), the optimal spatial density depends on the power ratio γ_{dc}, and is maximized for $\gamma_{dc} = \frac{\varepsilon_d}{\varepsilon_c}$, in which case (8) yields

$$\lambda_d^{opt'} = \varepsilon_d \cdot (1 - \varepsilon_c^{-1} \cdot \lambda_c) \tag{7-9}$$

Let f denote the *spatial spectrum reuse factor* for the target RB. The parameter f indicates how many discovery transmissions correspond to one UL cellular transmission in the area Ω. Let f_{max} denote the maximum spatial spectrum reuse factor, we have

$$f_{max} = \frac{\lambda_d^{opt'}}{\lambda_c} = \frac{\varepsilon_d \cdot (1 - \varepsilon_c^{-1} \cdot \lambda_c)}{\lambda_c} \tag{7-10}$$

Using (7-10) yields

$$\varepsilon_d - \frac{\varepsilon_d \cdot \lambda_c}{\varepsilon_c} \geq f \cdot \lambda_c \tag{7-11}$$

where $\varepsilon_c = -\frac{\ln(1-\theta_c)}{K_c}$ and $K_c = G \cdot D_c^2 \cdot u_c^{2/a}$, and thus, the constraint in (7-11) is equivalent to the following upper bound on the D_c distance:

$$D_c \leq r_c' = \left[\frac{-\ln(1-\theta_c) \cdot (\varepsilon_d - f \cdot \lambda_c)}{\lambda_c \cdot \varepsilon_d \cdot u_c^{2/a} \cdot G}\right]^{1/2} \tag{7-12}$$

where, the maximum value of the D_c distance, denoted by r_c', defines the radius of the cell-center area that should be used for enabling the discovery transmissions with respect to the constraints of the cellular and discovery systems. Using (7-4) in (7-12) yields

$$r_c' = r_c \cdot q \tag{7-13}$$

where $q = \left[1 - \frac{f \cdot \lambda_c \cdot G \cdot D_d^2 \cdot u_d^{2/a}}{-\ln(1-\theta_d)}\right]^{1/2}$.

The factor q quantifies the impact of the discovery transmission characteristics (target outage probability, transmission range, etc.) on the optimal radius of the cell-center area. As can be observed from the definition of q, for reasonable characteristics for the discovery transmissions, i.e., for $\theta_d < 1$, $D_d > 0$, and $u_c > 0$, we have that $q < 1$, and thus, there is no way of holding the cellular transmission constraints without shrinking the radius of the cell-center area. On the other hand, in the case that discovery transmissions are enabled under no cell-center area shrinking, the expected degradation of the cellular transmission performance depends on the selected discovery characteristics, and it is quantified as follows. Lets denote by u_c', the new achievable SIR value of the cellular system in the case that the discovery transmissions are enabled. Using equations (7-12) and (7-4) in (7-13), it holds that

$$u_c' = u_c \cdot Q \tag{7-14}$$

where $Q = q^a$. As depicted in (7-14), the factor Q is a fanction of q, while it is the key parameter that quantifies the expected impact of the enabling of discovery transmissions, on the cellular system performance. The definition of q in (7-13) imposes that a careful selection of transmission characteristics (e.g., spatial spectrum reuse factor f) for the discovery transmissions could lead to a quite low value of factor q, and thus, to a limited degradation factor Q, for the cellular transmissions. Based on this conclusion, in the next section we propose a D2D coordination scheme for enabling discovery transmissions under controlled degradation of the cellular transmission performance.

7.2.3 The proposed D2D coordination scheme

The proposed D2D coordination scheme can be considered as an advanced FFR mechanism where additional transmissions are enabled in the spectrum used by UEs inside the cell-center area. It requires a D2D coordinator, which controls the radius of the cell-center area of each eNB in the area Ω and configures the characteristics of the discovery transmissions. The D2D coordinator is able to communicate with all the eNBs in the area Ω, while it can be located at a delegate eNB or at a core-network entity. No channel measurements are available before the discovery transmissions, so the coordinator operates under an interference-unaware approach.

7.2.3.1 Functionality at the D2D coordinator

The main objective of the D2D coordinator is to provide each eNB with: i) the radius of the cell-center area and ii) the discovery transmission characteristics that guarantee the transmission constraints of the cellular and the discovery systems, respectively. To this end, the analysis of section 4 and more specifically the results depicted in (7-4) and (7-14) are exploited. For the utilization of (7-4) the D2D coordinator has to make two fundamental estimations; one for the density of the UL cellular transmitters in the area Ω and one for the pathloss exponent factor that best describes the wireless environment in the network.

Estimation of cellular system density

Let V denote the available target RBs in the fully-reused band B_1 and $|eNB|$ the deployed eNBs in the area Ω. For each one of the available target RBs in an UL subframe, the expected number of cellular transmitting nodes in a spatial unit is denoted by $\lambda_c(v)$, where $v = 1,2..V$, and it is the product of the number of deployed eNBs in the area Ω and the traffic loading:

$$\lambda_c(v) = z(v) \cdot \frac{|eNB|}{\mathrm{a}(\Omega)} \quad (7\text{-}15)$$

where $\mathrm{a}(\Omega)$ indicates the magnitude of the area Ω, and $z(v)$, $z(v) = [0,1]$, indicates an estimation of the traffic loading in the cellular system for RB n. In the case that all the RBs are uniformly utilized:

$$\lambda_c(v) = z \cdot \frac{|eNB|}{\mathrm{a}(\Omega)} \quad (7\text{-}16)$$

for every RB v, $v = 1,2..V$. Thus, the D2D coordinator considers that the cellular system density is $\lambda_c = z \cdot \frac{|eNB|}{\mathrm{a}(\Omega)}$, for every RB of band B_1.

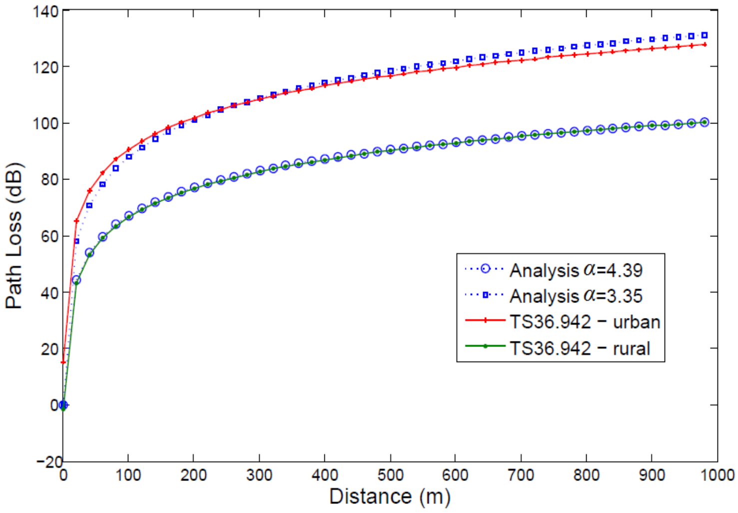

Figure 7-7: Attenuation factors that fit better to 3GPP urban and rural environments

Estimation of the attenuation factor

For the estimation of the attenuation factor a, the D2D coordinator decides on the value of the factor a that better fits to the wireless environment of the network. To this end, the

D2D coordinator can either i) try to find a realistic path loss model that describes the wireless environment and then select the factor a that gives the best matching with the simplified model, or ii) make a dynamic estimation based on measurement at eNBs. Here, we adopt the first approach and provide the value of the factor a that should be used in the case that the wireless environment matches with the urban or the rural environment defined by 3GPP in TS 36.942 [9]. In Fig. 7-7, we depict the performance of the pathloss models proposed by 3GPP. As can be observed the values $a = 4.39$ and $a = 3.35$, should be selected by the D2D coordinator for the urban and the rural environment, respectively.

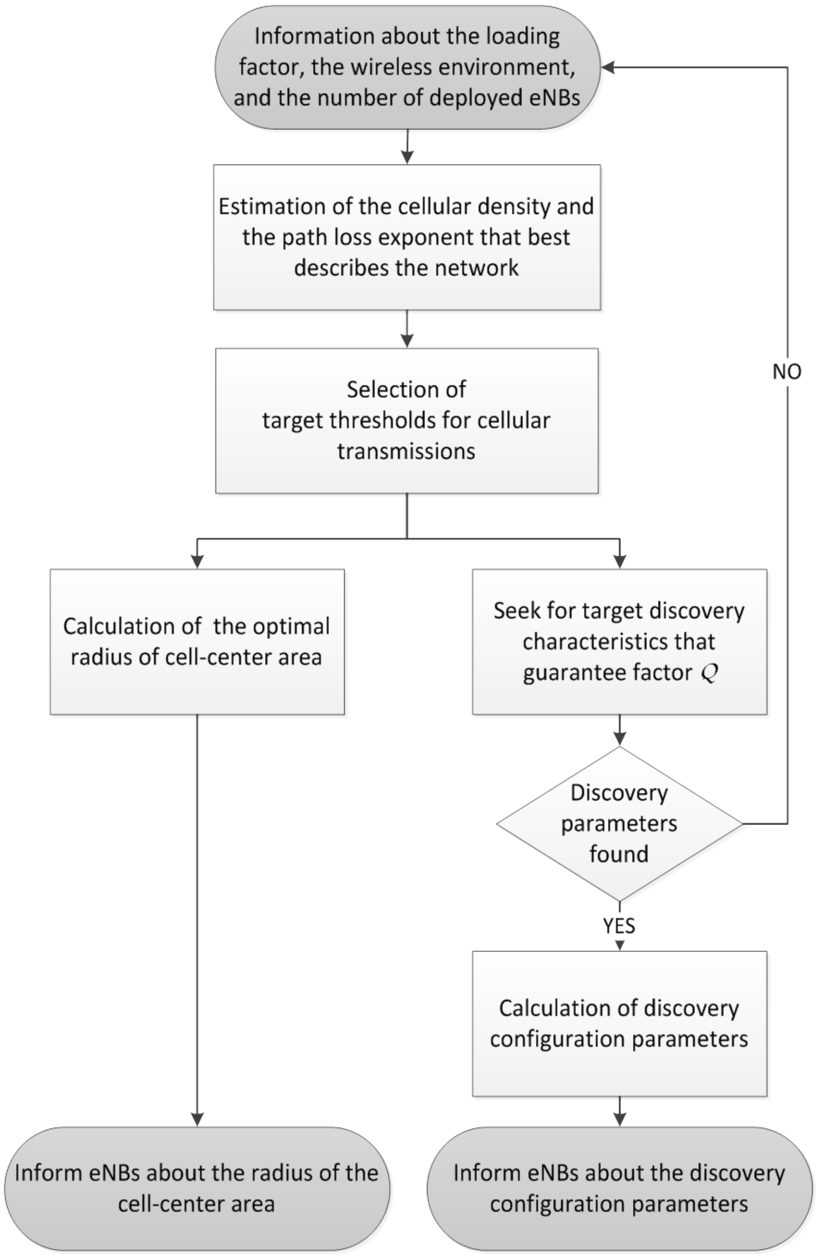

Figure 7-8: Flow chart of the functionality at the D2D coordinator

Sequentially, the D2D coordinator selects target thresholds for SIR, and outage probability for the cellular transmissions. Note that these thresholds refer to potential signals received at an eNB if all the cellular transmitters were located at the cell-center area edges (i.e., to the worst case scenario). The estimations of λ_c and a and these thresholds are used for the calculation of the optimal radius of the cell-center area, considering no additional discovery transmissions, as defined in (7-4). This functionality is represented by the left branch of the flow chart depicted in Fig. 4. In parallel, the D2D coordinator selects a degradation factor Q, and examines whether there are discovery transmission parameters, i.e., target spatial spectrum reuse factor f, target discovery transmission range, and target SIR and outage probability thresholds that can guarantee the selected factor. In the case that a set of discovery transmission parameters are found, the D2D coordinator sends its decision to eNBs together with the $\lambda_d^{opt'}$ and γ_{dc} parameters, which are used to configure the discovery transmission, as explained in the following subsection. In the case that a set of discovery transmission parameters are not found, i.e., the factor Q cannot be guaranteed, the discovery transmissions are not enabled and the D2D coordinator waits for a network offloading i.e., a lower cellular transmission density. Both of the cases are represented by the right branch of the flow chart depicted in Fig. 7-8.

7.2.3.2 Functionality at eNBs

In each cell, the serving eNB calculates the maximum number of eUEs that can utilize a target RB in band B_1, and the maximum acceptable transmit power for each one of them. Note that the interference-free coexistence of cellular and discovery transmissions in the target RB is guaranteed if these bounds are hold, independently of the resource allocation scheme that selects which specific eUEs will transmit. For the calculation of these bounds each eNB utilizes the $\lambda_d^{opt'}$ and γ_{dc} values sent by the D2D coordinator and Lemma 1.

> **Lemma 1.** *Assume that the eUEs are distributed inside the area Ω according to a PPP. Let N(S) denote the number of eUEs in the set S. Then for cell area W, where W is a subset of Ω, it holds that*
>
> $$Pr(N(W) = m \mid N(\Omega) = M) = \binom{M}{m} \cdot p^m \cdot (1-p)^{M-m}$$
>
> *where* $p = a(W)/a(\Omega),\ 0 \le m \le M$.

The proof is straightforward and can be found in [10] and in Appendix IV. Lemma 1 states that, given that the number of eUEs in Ω is M, the conditional distribution of the number of eUEs inside a specific cell area W, subset of Ω, is binomial with parameters M and $p = \mathrm{a}(W)/\mathrm{a}(\Omega)$.

The acceptable population of eUEs in area Ω for the optimal spatial density is

$$M = \mathrm{a}(\Omega) \cdot \lambda_{\mathrm{d}}^{\mathrm{opt}'} \tag{7-17}$$

Thus, according to Lemma 1, in a specific cell area W, the expected number of concurrent device discovery transmissions that can utilize the spectrum of a single UE transmitter is

$$M_W = p \cdot \mathrm{a}(\Omega) \cdot \lambda_d^{opt'} = \mathrm{a}(W) \cdot \lambda_d^{opt'} \tag{7-18}$$

For each one of the M_W transmissions, the eNB of the cell area W uses the power ratio $\gamma_{dc} = \frac{\varepsilon_c}{\varepsilon_d}$ provided by the coordinator to estimate the required transmission power.

Since $\gamma_{dc} = \left(\frac{P_{ic}}{P_d}\right)^{2/a}$, the transmit power, P_d, of each device discovery transmission is

$$P_d = P_{ic} \cdot \left(\frac{\varepsilon_d}{\varepsilon_c}\right)^{-a/2} \tag{7-19}$$

where P_{ic} is the transmit power allocated to UE i in the cell-center area.

Practically, when an eNB receives the $\lambda_d^{opt'}$ and γ_{dc} parameters, it utilizes (7-18) to define the number of discovery transmissions which will be enabled in each RB of the fully reused spectrum. Sequentially, for each subframe and for each one of the RBs in band B_1, utilizes (7-19) to define the transmission power of the discovery transmissions. The flow chart of the functionality at each eNB is depicted in Fig. 7-9.

The functionalities at the D2D coordinator and the eNBs realize the idea of enabling a limited number of discovery transmissions in spectrum used by UL cellular transmissions. The main characteristic of the proposed approach is that no interference information is needed, while it can operate as an optimized FFR scheme when the enabling of the discovery transmissions is expected to burden the cellular transmissions more than a bearable value represented by factor Q.

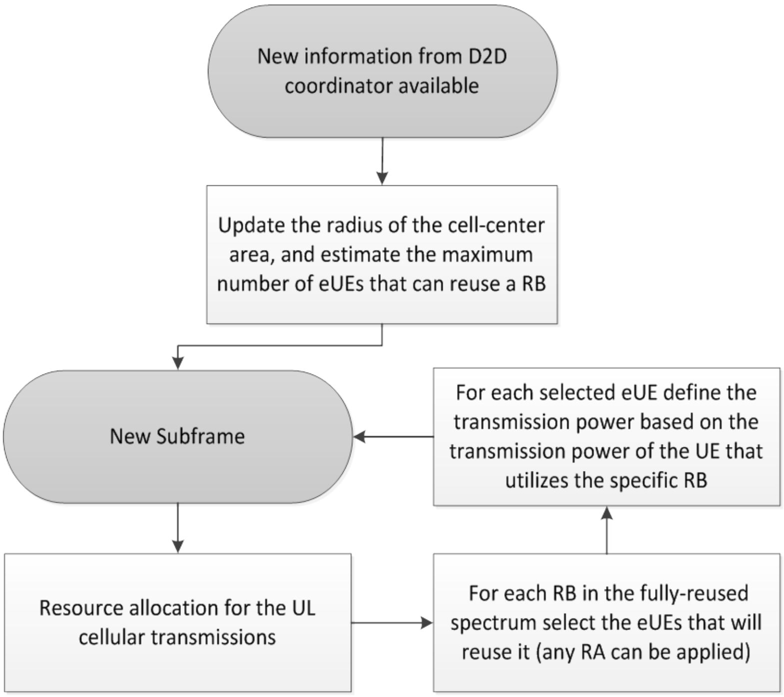

Figure 7-9: Flow chart of the functionality at eNB

7.2.4 Performance Evaluation

In this section, we use LTE-compliant parameters to quantify the discovery transmission opportunities, and we validate the efficiency of the proposed scheme using simulations.

7.2.4.1 Analytical Results

In Fig. 7-10, we calculate the optimal radius of the cell-center area for the approach where no additional transmissions are allowed, considering that 7 eNBs are deployed in an area of $10 \cdot 10^6 m^2$. The optimal radius of the cell-center area is estimated for different loading factors and pathloss exponents, considering SIR threshold for the transmissions from the edge of the cell-center area $u_c = 2$. As can be observed in Fig. 7-10a, a decreased loading factor leads to an increased optimal radius for the cell-center area, due to the thinning of the density of the cellular transmissions. Also, the impact of the selected cellular outage probability on the optimal radius of the cell-center area is stronger for low loading factors. For instance in Fig. 7-10a, the almost vertical curve that represents the loading factor $z = 0.8$ implies a slight impact of a potential outage probability increment on the optimal radius of the cell-center area. In Fig. 7-10b, we investigate the optimal radius of the cell-center area under different pathloss exponents. The results are proportional to that provided in Fig. 6a. Higher pathloss exponents represent worse wireless environments, where the attenuation of the transmitting signals is more rapid, and thus, larger cell-center areas can be used.

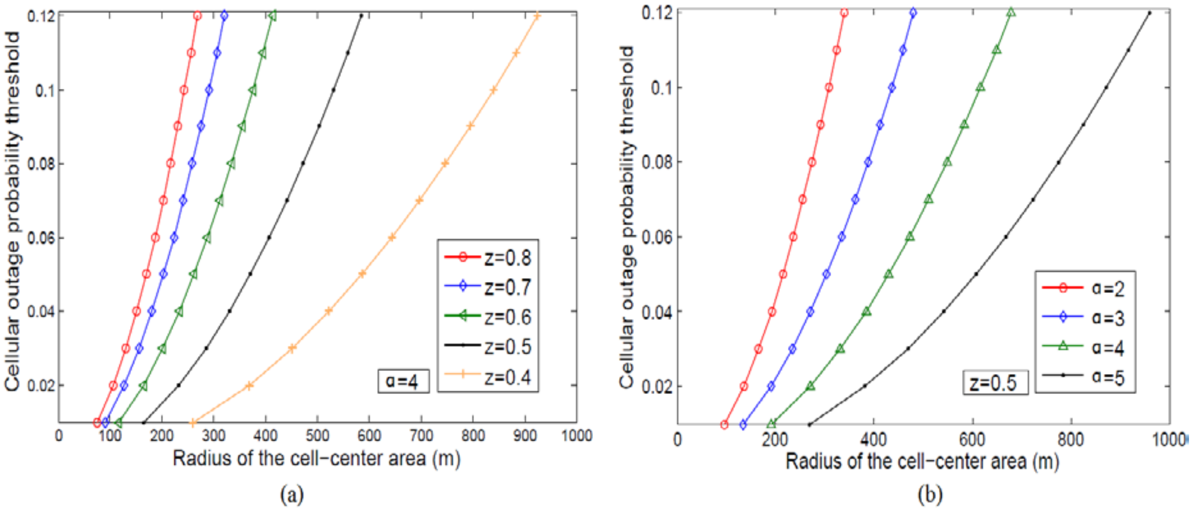

Figure 7-10: Impact of loading factor (a) and pathloss exponent (b) on the optimal radius of cell-center area for different outage probability thresholds

In Fig. 7-11, we consider again that 7 eNBs are deployed in an area of $10^7 m^2$, where z=0.5, and a=4.39. We calculate the factor Q in the case that additional discovery transmissions are enabled, under the following thresholds: $u_c = 2$, $u_d = 0.2$, $r_d = 50m$. The factor Q is depicted for different target discovery outage probability thresholds and spatial spectrum reuse factors. As can be observed in Fig. 7-11, factor Q is quite close to one, when the target outage probability is above the 0.1 value (i.e., 1% of the discovery transmissions will fail if all the potential receivers are located at the edge of the discovery range). Form Fig. 7-11 shows that the discovery transmissions can be enabled with very low impact on the cellular ones when the target spatial spectrum reuse factor is lower than 2 and the outage probability threshold is above 0.1.

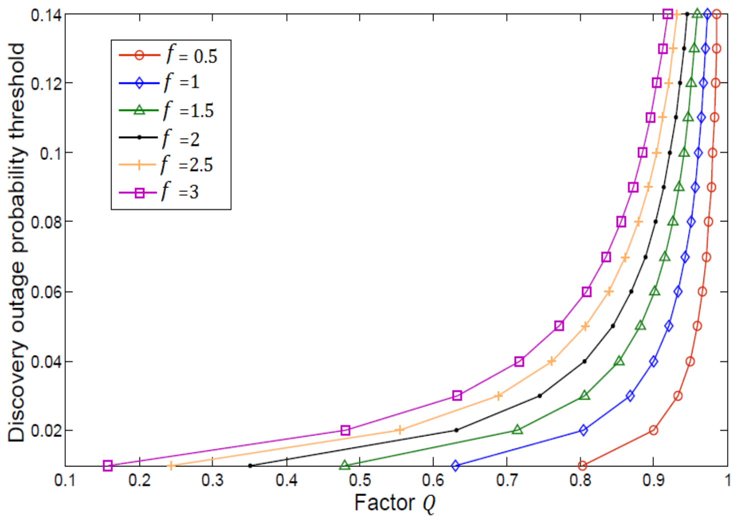

Figure 7-11: Quantification of factor Q for different discovery outage probabilities and target spatial spectrum reuse factors

In Fig. 7-12, we adopt the same scenario as in Fig.7-11 and we investigate the impact on the achievable cellular SIR value from the enabling of discovery transmissions under the following thresholds for the cellular and discovery transmissions: $u_c = 2$, $\theta_c = 0{,}09$, $f = 2$, $\theta_d = 0{,}1$. The results vary for different target discovery ranges and discovery SIR values. Fig. 8 shows that if discovery transmissions with transmission range from 40m to 80m and target SIR from 0.05 to 0.2, the achievable SIR value of the cellular transmissions decreases from 1% to 18%, respectively.

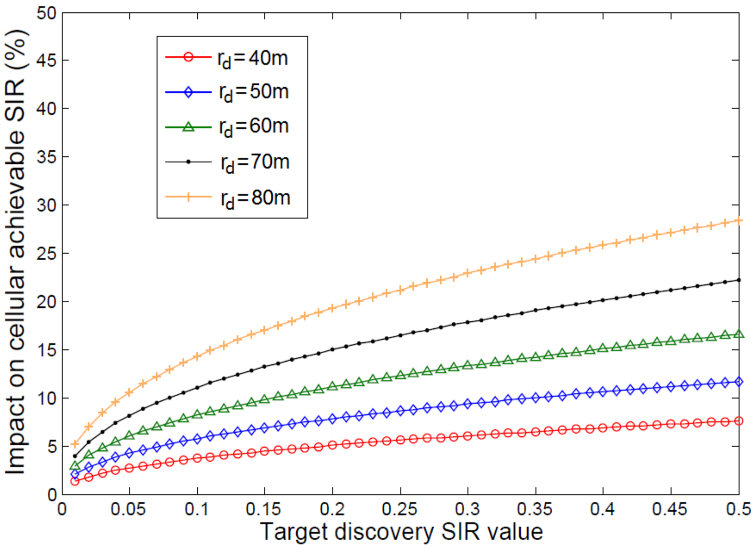

Figure 7-12: Impact of device discovery range on the cellular outage probability threshold

7.2.4.2 Simulation Results

To validate the efficiency of the proposed scheme, we simulated a specific scenario using the system level LTE simulator described in [11] with the appropriate extensions for direct transmissions, and the parameters depicted in Table 7-1.

Table 7-1: Evaluation parameters – Spectrum access for discovery

Parameter	Value
Number of eNBs ($\|eNB\|$)	7
Magnitude of the area (a(Ω))	$10^7 \mathrm{m}^2$
loading factor (z)	0.5
Distribution of UE transmitters	Poisson
Distribution of eUE transmitters	Poisson
Path loss model	3GPP 36.942
Channel type	Rayleigh Fading (unit mean)
Environment	urban
Thermal Noise Density	-174 dBm/Hz
Noise figure	5 dB
UE/eUE antenna type	Omni-directional
UL Cellular Resource allocation in fully reused spectrum B_1	Proportional fair
UL power control for UEs	Minimum transmission power to achieve the target SIR threshold
Resource allocation for discovery transmissions	RBs in band B_1 are allocated in Round Robin fashion. One RB can be allocated to multiple discovery transmitters

At the D2D coordinator, the following target parameters were used: $a = 4.39$, $f = 2$, , $\theta_c = 0.09$, $u_c = 1.85$ (at the edge of the cell-center area). The bearable degradation is set to $Q = 0.93$ (i.e., 7% lower SIR when all the cellular transmitters are located at the cell-center area edge – worst case scenario) which is translated to the following characteristics for the discovery transmissions: $\theta_d = 0.1$, $u_d = 0.18$ and $r_d = 50m$.

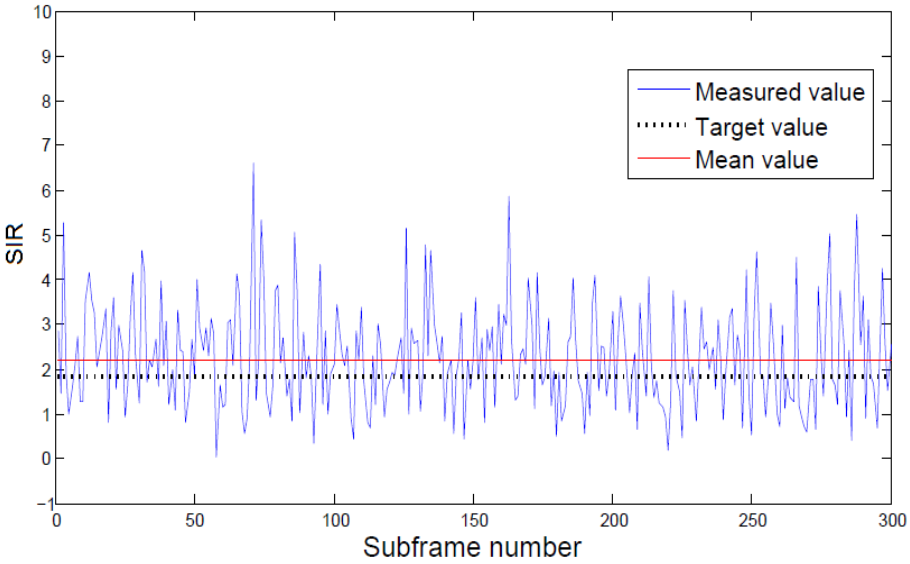

Figure 7-13: SIR values at a target eNB without discovery transmissions

First, we considered the FFR technique without the additional discovery transmissions and we monitored the network for 300 UL subframes. Fig. 7-13 depicts the SIR values at a target eNB, and as can be observed, the measured values are close to the target one, while their mean value is slightly above the target. This result validates the efficiency of the proposed coordinator when it is used for inter-cell interference protection. This is an interesting result, considering that no interference information was used, while the power control for each UE transmission ignored the potential interference from neighboring cells. Moving one step further, in Fig. 7-14 the measured u_c'/u_c ratio and the threshold set by the coordinator, i.e., the $Q = 0.93$ value, are compared towards quantifying the impact of the additional discovery transmissions on the SIR value received at a target eNB. As can be observed in Fig. 7-14, the measured degradation respects the target constraint, i.e., the measured u_c'/u_c value is above the Q threshold, and, thus, the analytical results are validated.

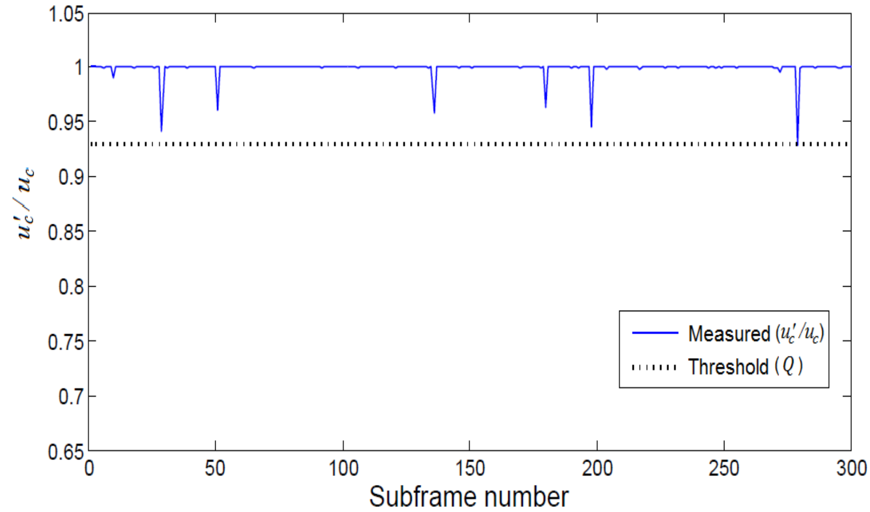

Figure 7-14: Measured u_c'/u_c ratio and comparison with the threshold Q

In Fig. 7-15, we repeat the simulation with the parameters used in Fig. 7-13; however, this time we measure the SIR at a potential discovery receiver located at the edge of the discovery range. As can be observed in Fig. 7-15 due to the Rayleigh fading effect the measured SIR values vary around the target value $u_d = 0.18$, while the mean value of the measured SIR values is almost the same with the target one. This result, in combination with the result depicted in Fig. 7-13, implies that under the proposed scheme bidirectional interference protection is provided, while the introduced interference is quite limited, both at the eNBs and the potential discovery receivers.

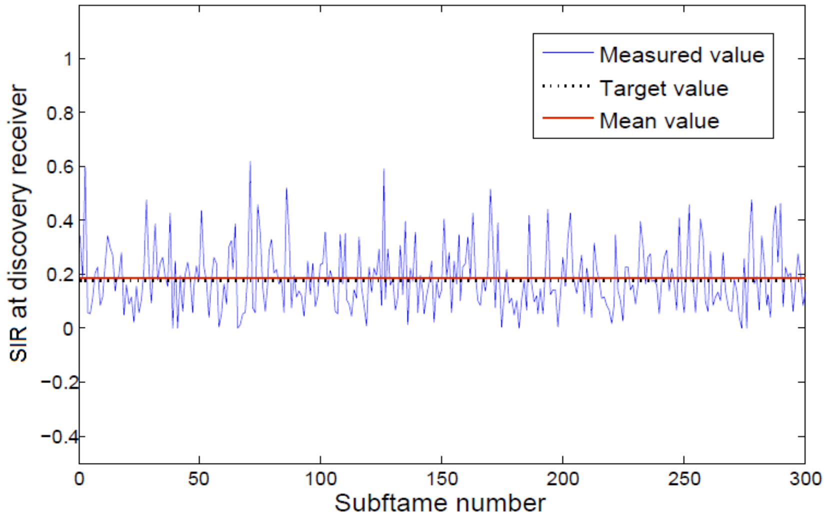

Figure 7-15: SIR values at a target discovery receiver

7.3 Conclusions

In this chapter, the device discovery problem has been faced from two different perspectives. First a set of enhancements applied on the conventional resource request/allocation procedure of an LTE-A access network has been proposed to enable discovery transmissions, and second a centralized interference-unaware D2D coordination scheme has been proposed towards finding spatial spectrum opportunities for device discovery transmissions.

For the first approach, the main advantages are the following:

- The recent directions by the 3GPP on integrating ProSe communications in future LTE releases are adopted.
- Spectrum resources are ensured at the discovery peers (discovery peers are tuned at the same spectrum region.
- The proposed scheme can be easily integrated to the current LTE release (Rel.10) to enable one-to-one (or one-to-many) discovery transmissions.

For the second one, the main conclusions are the following:

- The proposed scheme can be used as an advanced FFR scheme for inter-cell interference coordination in LTE networks, where in addition to the inter-cell interference protection, discovery transmissions are enabled in part of the cellular spectrum.
- Under certain conditions for network density and discovery transmission characteristics, a number of discovery transmissions can be enabled in a multi-cellular network even if no interference information is available.
- The device discovery transmissions are more suitable for spatial reuse of the cellular spectrum than other type of transmissions, since QoS and reliability requirements in such transmissions are relaxed.

7.4 References

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8. SUMMARIZED RESULTS AND CONCLUSIONS

The introduction of femtocells and D2D communications in 3GPP cellular networks (LTE/LTE-A) shifts the conventional spatial spectrum reuse paradigm, to a more dynamic, flexible and distributed one, where the design of more efficient radio resource management, interference management and spectrum access schemes is required.

3GPP has already defined the specifications for the femtocells in Release 8, while the most recent enhancements can be found in Release 12. A lot of effort has also been allocated by 3GPP to the standardization of the D2D communications in Release 12 and beyond. D2D communications define an emerging technology which, in 4G networks, is expected to play an important role under the public safety concept, while in 5G networks will totally change the current cellular communication landscape.

This thesis dealt with challenges arising from the introduction of femtocells and D2D communications in 3GPP cellular networks, and especially in LTE/LTE-A networks. The focus was on the following challenges:

- **Interference management in femtocell-overlaid networks**
  This problem refers to femtocells that reuse the cellular spectrum under the co-channel deployment, raising new types of interference. The problem is more severe when femtocells operate under the closed subscriber group mode, and, thus, deny the access to non-subscribed users. In this case, the interference perceived during the downlink by unsubscribed users in femtocell proximity needs more investigation. Special investigation is needed for the interference in control channels, which carry vital information for the connection maintenance.
- **Spectrum access and management for D2D communications**
  This problem refers to the management of the radio resources used for the direct transmissions in a cellular area. The main issue is how the available radio resources will be shared between cellular and direct communications, and also how the radio resources that are used for direct transmissions will be allocated to the D2D transmitters. The target is to guarantee interference-free conditions to cellular and D2D users.
- **Spectrum access and management for device discovery**
  This problem is quite similar to the previous one. However, it referred to discovery transmissions, i.e., frequent, low range direct transmissions with no QoS requirements that are used by a device in order to discover another device in its vicinity. Device discovery is an important procedure and is required prior the establishment of a D2D communication. The nature of these transmissions calls for designing different spectrum access and management schemes, than that used for the D2D communications.

A comprehensive study of the above mentioned problems has been provided, while some innovative solutions and working directions were proposed. The main achievements and results are listed below:

Interference management in femtocell-overlaid networks

- The interference protection of control channels is a severe problem which poses the design of interference management schemes tailored to these channels. A thorough study on LTE-A standardized tools used for control channel protection has been provided, while qualitative and quantitative comparison revealed the special characteristics of each scheme.
  - o The carrier aggregation with cross carrier scheduling and the almost blank subframes, requires hard coordination among femtocells and between

femtocells and macrocells. It was shown that due to this requirement the above mentioned interference protection schemes cannot follow the dynamic nature of femtocell deployment posing for fast, reliable, and efficient coordination algorithms.
    - Extensive performance evaluation process showed that in dense femtocell-overlaid networks, the control channel protection through distributed uncoordinated interference protection schemes is preferable.
    - The power control approach was proved to be one of the most efficient uncoordinated interference protection schemes. The drawback of this scheme is that the interferences at the victim users cannot be reduced further than a bound defined by the required signal strength/quality at the serving users.
- The involvement of QoE in network management was studied, and a QoE-driven power control scheme for interference management was proposed. Simulation results shown that the involvement of QoE criteria in interference management procedures is beneficial. More specifically, the proposed QoE-driven power control scheme decreases the transmission power of the femtocell base stations in lower levels that that achieved by QoS-based power control, reducing altruistically the interference at macrocell users and guaranteeing the QoE at serving users.

Spectrum access and management for D2D communications

- It was shown that, under a full knowledge of the interference map in a network, graph coloring theory can be used for allocating radio resources to D2D communicating pairs, achieving high spatial spectrum reuse factors.
- Simulation results shown that gathering and processing interference information at the base station is a very complex problem which also burdens the network with extra signaling. This result raises the investigation for schemes where unreliable interference information or part of the interference information is available.
- Performance analysis has been provided in terms of normalized throughput, access delay and energy consumption, of a contention-based scheme for D2D communications, where the D2D pairs compete to access the spectrum with no need for interference information collection and processing in a central node. The performance of a contention-based scheme is highly correlated with the number of competing D2D pairs, and also the access and discovery probability
- The use of Euclidian geometry provided us with upper bounds for access and discovery probabilities (i.e., the probability a D2D transmitter to be outside the interfering area of a cellular transmitter and the probability the target D2D receiver to be located in transmitter’s range) in an interference isolated cell.

Spectrum access and management for device discovery

- Thorough study of the LTE/LTE-A standardized access procedures showed that an application layer identity can be used for enabling resource allocation signaling for reactive device discovery transmissions. To this end, empty records allocated for future use in standardized RRC connection request and BSR messages, can be utilized to communicate the new identities to the serving base station.
- It was proved that, under certain conditions for the network density and the wireless environment, the FFR (fractional frequency reuse) technique can be exploited both as an inter-cell interference protector and an enabler of additional discovery transmissions.

- o Analytical results shown that, for LTE/LTE-A network parameters, interference-unaware spatial spectrum reuse is suitable only for low-range low-demand transmissions, such as the discovery transmissions.
- o Simulations proved that the theoretical bounds found through the analysis can be used in a realistic environment. More specifically, monitoring of the cellular transmission performance showed that the measured degradation is below the analytically calculated degradation threshold.

To conclude, this thesis focuses only on a subset of the numerous challenges that have currently arisen towards designing the mobile communications of the future. However, some solid and efficient solutions have been proposed, which abide by the most recent specifications defined by 3GPP. The main focus was on mitigating the interference in femtocell-overlaid networks and enabling D2D communications in LTE/LTE-A networks. Three general outcomes highlight the future research directions: first, the use of QoE promises a completely new network management and service provisioning model, second, a sharp change in the current spectrum management is required to accomplish a successful integration of cellular and D2D communications, and third, the solution of device discovery problem will launch a series of new proximity services, providing user devices with an augmented sense of their vicinity.

ABBREVIATIONS – ACRONYMS

3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframes
BSR	Buffer Status Report
CC	Component Carrier
CCDT	Control Channel Decoding Threshold
CP	Cyclic Prefix
C-RNTI	Cell Radio Network Temporary Identifier
CSG	Closed Subscriber Group
CTS	Clear-To-Send
D2D	Device-to-Device
DCF	Distributed Coordination Function
DL	Downlink
DMO-ID	Direct Mode Operation Identity
eNB	evolved NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FFR	Fractional frequency Reuse
FUE	Femtocell User Equipment
H-ARQ	Hybrid-Automatic Repeat Request
HeNB	Home eNB
HeNB-GW	HeNB - Gateway
HII	High Interference Indicator
IFA	Interference-Free Area
IM	Interference Management
ITU	International Telecommunication Union
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MAC	Media Access Control
MME	Mobility Management Entity
MOS	Mean Opinion Score
MUE	Macro User Equipment
NKUA	National and Kapodistrian University of Athens
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Overload Indicator
PAPR	Peak to Average power Ratio
PC	Power Control
PCFICH	Physical Control Format Indicator Channel
PCI	Physical Cell identity
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit

P-GW	Packet Data Network - Gateway
PHICH	Physical H-ARQ Indicator Channel
PRACH	physical random access channel
PRB	Physical Resource Block
ProSe	Proximity Services
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoE	Quality of Experience
QoS	Quality of Service
RA	Resource Allocation
RB	Resource Block
RE	Resource Element
RNTP	Relative Narrowband Transmit Power Indicator
RRC	Radio Resource Control
RTS	Ready To Send
SC-FDMA	Single Carrier –Frequency Division Multiple Access
S-GW	Serving Gateway
SINR	Signal to interference plus Noise Ratio
SRS	Sounding Reference Signal
TDD	Time Division Duplex
UE	User Equipment
UL	Uplink
UNIPI	University of Piraeus
VoIP	Voice over Internet Protocol
X2-GW	X2- Gateway

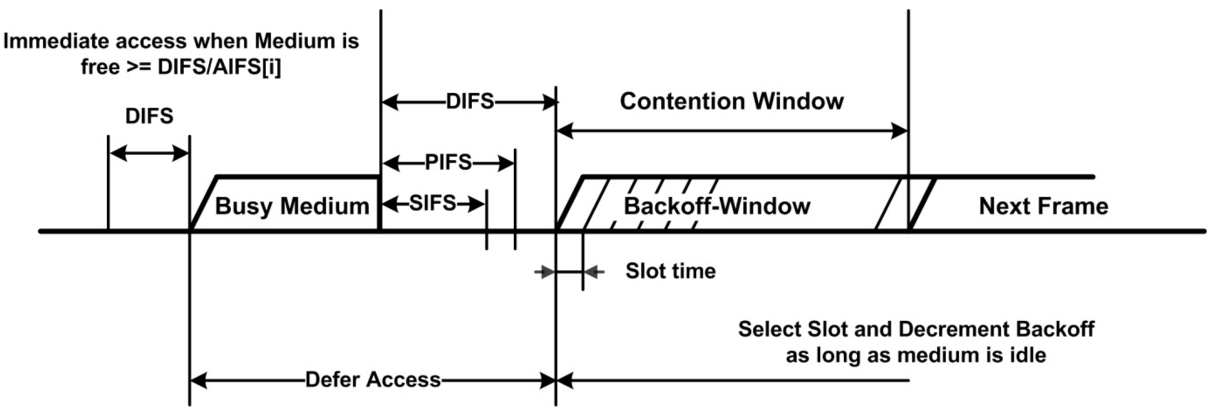
APPENDIX I

The fundamental access method of the IEEE 802.11 MAC is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The DCF is be implemented in each station belonging either in ad-hoc or infrastructure network configurations. Before a station attempts to perform a transmission, it will first sense the wireless medium in order to detect the possible presence of transmissions by other stations. If the wireless medium is idle, the station may perform its transmission. Carrier Sensing (CS) may be either *physical* or *virtual*. *Physical Carrier Sensing* is used for the detection of other WLAN users' presence. On the other hand, *Virtual Carrier Sensing* is performed through the exchange of the Request To Send / Clear To Send (RTS/CTS) frames before the transmission of the data frame in order to inform the other WLAN users of the upcoming transmission. The RTS and CTS frames contain a Duration field that defines the period of time that the medium is to be reserved to transmit the actual data frame and the returning ACK frame. Thus, all other stations within the reception range of both the sender and the receiver of the RTS/CTS frames are informed of the reservation of the wireless medium. The duration information contained in the RTS and CTS frames is used by each station to adjust their Network Allocation Vector (NAV) that maintains a prediction of future traffic on the medium based on duration information that is announced in RTS/CTS.

The time interval between frames is called the *Interframe Space (IFS)*. There are three basic IFSs that provide priority levels for access to the wireless media.

i. *Short Interframe Space (SIFS)*: It is used prior to transmission of an Acknowledgment (ACK) frame, a CTS frame, the second or subsequent MPDU of a fragment burst, and by a station responding to any polling by the PCF.
ii. *PCF Interframe Space (PIFS)*: It is used only by stations operating under the PCF to gain priority access to the medium at the start of the CFP.
iii. *DCF Interframe Space (DIFS)*: The DIFS shall be used by stations operating under the DCF to transmit data frames (MPDUs) and management frames (MMPDUs).

A station will perform carrier sensing in order to determine whether the wireless medium is idle or occupied. In case the medium is occupied by another transmission, the station will defer until the wireless medium is idle again, for a period of time that equals DIFS, in the case of correct reception of the last frame detected on the medium. After this DIFS medium idle time, the station shall then generate a random backoff period for an additional deferral time before transmitting. This process minimizes collisions during contention between multiple stations that have been deferring to the same event. The whole procedure is illustrated in figure below:

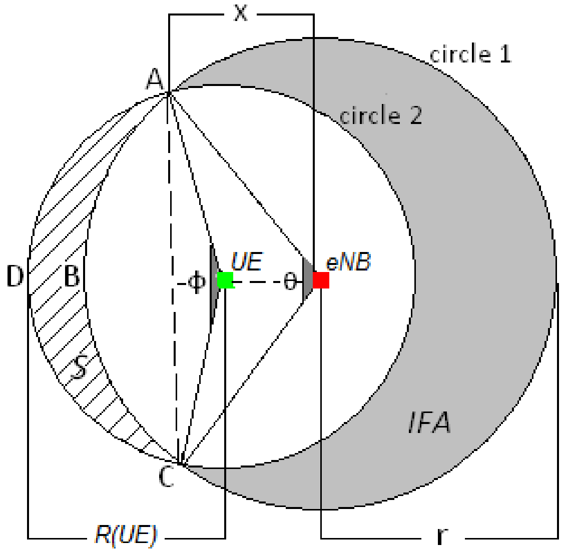


APPENDIX II

The interference free area (IFA) in the case that $R(UE) \leq \frac{r+R_{th}}{2}$ can be easily calculated using the difference between the cell area πr^2 and the PU transmition area $\pi R(UE)^2$,

$$IFA = \pi r^2 - \pi R(UE)^2$$

However, in the case where $R(UE) > \frac{r+R_{th}}{2}$ the calculation is more complex and includes the determination of the S area shown in the following figure.



The S area is the part of the interfering area (circle 2) that is not included in the cell area (circle 1) and it is determined via the difference between the circular segments ADC and ABC. Using Euclidean geometry for the circular segment ABC it holds that:

$$(circular\ segment\ ABC) = \frac{r^2}{2}(\theta - \sin(\theta))$$

where $\frac{\theta}{2} = argcos\left(\frac{x}{r}\right)$ and x is the distance between the center of the circle 1 and the line segment AC.

Also, for the circular segment ADC it holds:

$$(circular\ segment\ ADC) = \frac{R(UE)^2}{2}(\varphi - \sin(\varphi))$$

where $\frac{\varphi}{2} = argcos\left(\frac{x-d(eNB,UE)}{R(UE)}\right)$.

Thus, the S area is:

$$S = \frac{R(UE)^2}{2}(\varphi - \sin(\varphi)) - \frac{r^2}{2}(\theta - \sin(\theta))$$

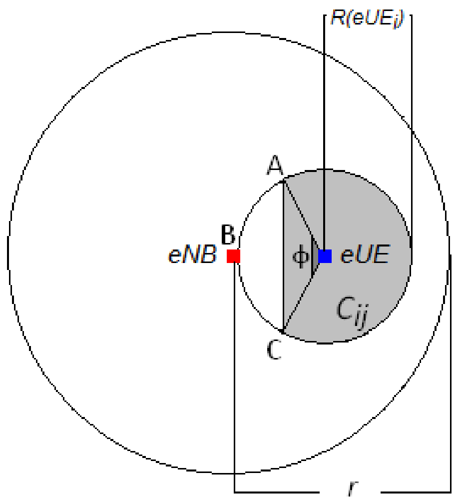
And

$$IFA = \pi r^2 - \pi R(UE)^2 + S$$

For a UE that is located in a specific place inside the cell, i.e., the $d(eNB, UE)$ is known, the probability for eUE_i to access the spectrum is: $P_{access}(eUE_i) = \frac{IFA}{\pi r^2}$.

APPENDIX III

The C_{ij} region in the case where $R(eUE_i) \leq r$ is calculated using the difference between the interfering area $\pi R(eUE_i)^2$ of eUE_i and the circular segment ABC as shown in the following figure.

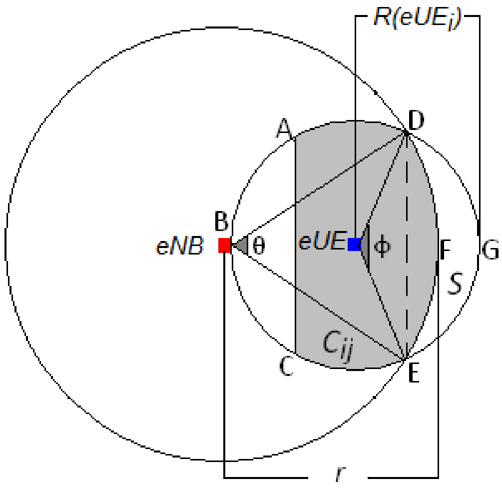


Using Euclidean geometry it holds that:

$$C_{ij} = \pi R(eUE_i)^2 - \frac{R(eUE_i)^2}{2}(\varphi - \sin(\varphi))$$

where $\varphi = \frac{3}{4}\pi$ due to the fact that the AC line is in the middle of the distance between eNB and *eUE*$_i$.

In the case that $R(eUE_i) > r$ the extra calculation of the S area (see figure bellow) is required.



Using Euclidian geometry it holds that

$$S = \frac{R(eUE_i)^2}{2}(\varphi - \sin(\varphi)) - \frac{r^2}{2}(\theta - \sin(\theta))$$

and

$$C_{ij} = R(eUE_i)^2 - \frac{R(eUE_i)^2}{2}(\varphi - \sin(\varphi)) - S$$

APPENDIX IV

Let $0 < m < M$, then:

$$Pr(N(W) = m \mid N(\Omega) = M) = \frac{Pr(N(W) = m\,,\ \ N(\Omega) = M)}{Pr(\,N(\Omega) = M)}$$

$$= \frac{Pr(N(W) = m\,,\ \ N(\Omega\backslash W) = M - m)}{Pr(\,N(\Omega) = M)}$$

As W and $\Omega\backslash W$ are disjoined areas $N(W)$ and $N(\Omega\backslash W)$ are independent. Thus, the numerator can be rewritten as follows:

$$= \frac{Pr(N(W) = m\,) \cdot Pr\,(\,N(\Omega\backslash W) = M - m)}{Pr(\,N(\Omega) = M)}$$

$$= \frac{e^{-\lambda_c \cdot \mathrm{a}(W)} \dfrac{(\lambda_c \cdot \mathrm{a}(W))^m}{m!} \cdot e^{-\lambda_c \cdot \mathrm{a}(\Omega\backslash W)} \dfrac{(\lambda_c \cdot \mathrm{a}(\Omega\backslash W))^{M-m}}{(M-m)!}}{e^{-\lambda_c \cdot \mathrm{a}(\Omega)} \dfrac{(\lambda_c \cdot \mathrm{a}(\Omega))^M}{M!}}$$

$$= \frac{M!}{m! \cdot (M-m)!} \cdot \left(\frac{\mathrm{a}(W)}{\mathrm{a}(\Omega)}\right)^m \cdot \left(\frac{\mathrm{a}(\Omega\backslash W)}{\mathrm{a}(\Omega)}\right)^{M-m}$$

$$= \binom{M}{m} \cdot p^m \cdot (1-p)^{M-m}$$

where $p = \mathrm{a}(W)/\mathrm{a}(\Omega)$.

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