Resource allocation in next generation cellular networks

Wang, Xiaofan

2014

Wang, X. (2013). Resource allocation in next generation cellular networks. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/59536>

<https://doi.org/10.32657/10356/59536>

RESOURCE ALLOCATION IN NEXT GENERATION CELLULAR NETWORKS

WANG XIAOFAN

**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

2013

RESOURCE ALLOCATION IN NEXT GENERATION CELLULAR NETWORKS

WANG XIAOFAN

G1002791G

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University in
fulfilment of the requirement for the degree of Master of Engineering

2013

Acknowledgement

The author would like to express her sincere gratitude to all who have extended their help, guidance and encouragement throughout the entire course of this research project.

Special thanks go to her supervisor, Associate Professor Chong Han Joo Peter, for his continuous support, patience and valuable guidance during the period of her research.

The author would like to express her gratitude to Dr. Li Xue Jun and Associate Professor Ting See Ho for their support and valuable advices. She would also thank all fellow research students and technicians in Network Technology Research Centre and INFINITUS Infocomm Centre of Excellence for establishing such a helpful group and making her research experience a pleasant journey.

The author would also like to express her gratitude to Nanyang Technological University for offering this research opportunity.

Last but not least, the author would like to acknowledge her family and friends for their unconditional support during this research project.

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Abstract

As cellular services become deeply rooted in people's daily life and more multimedia services are offered to larger audience, the access demand for high data rate is growing more rapidly than ever. Such demands are to be met with new wireless network technologies.

This thesis explored resource allocation schemes under the scope of two different network structures, Time-Division Duplex Code-Division Multiple Access (TDD-CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA).

First phase of this thesis studied Multi-hop Cellular Networks (MCNs) under the structure of TDD-CDMA in measurements of both system performance and energy consumption. Two new resource allocation schemes, Multi-Medium MAC with Retransmission (mmMAC/RT) and Opportunistic MAC (OMAC), were proposed and showed significant improvement over traditional Packet Reservation Multiple Access (PRMA) and baseline protocol Multi-hop Multiple Access Control (mMAC). Then the energy consumption of different single and multi-hop time slot allocation schemes was examined. Furthermore, an Opportunistic Relay Station (ORS) selection scheme was proposed and studied. The analysis led to a new half-fixed RS selection protocol and simulation proved the new protocol's ability to minimize energy consumption under various traffic conditions.

Second phase of this project focused on OFDMA networks as it has been selected for future release of 3GPP Long Term Evolution (LTE). The channel characteristics of frequency selective Rayleigh fading channels in OFDMA networks were first studied

and a simulation channel model was proposed. An Ordered Interference-Aware Resource (OIAR) allocation scheme was then proposed to take advantage of frequency and user diversity in such networks. Simulation results proved its ability to outperform the random resource allocation scheme. Device-to-Device (D2D) communication was also introduced to cellular networks for higher utilization of radio spectrum. An improved OIAR protocol was adapted for D2D users and different settings have been discussed. The D2D communication underlying cellular network was proved by simulation to provide higher capacity with such interference-aware resource allocation scheme.

Acronyms

BS	Base Station
MCNs	Multi-hop Cellular Networks
SCNs	Single Hop Cellular Networks
TDD	Time-Division Duplex
CDMA	Code-Division Multiple Access
mMAC	Multi-hop Medium Access Control
PRMA	Packet-Reservation Multiple Access
MS	Mobile Station
RS	Relay Station
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
ISI	Inter-Symbol-Interference
DCA	Dynamic Channel Assignment
D2D	Device-To-Device
2G	Second Generation
3G	Third Generation
MANETs	Mobile Ad Hoc Networks
VCN	Virtual Cellular Network
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
MA	Margin Adaptive
RA	Rate Adaptive
SNR	Single-To-Noise Ratio
IP	Integer Programming
ARP	Autonomous Reuse Partitioning
CIR	Carrier-To-Interference Ratio
LIA	Least Interference Algorithm
LTA	Least Interference Below Threshold Algorithm
MIA	Marginal Interference Algorithm
LTE	Long Term Evolution
FFR	Fractional Frequency Reuse
mmMAC/RT	Multi-Medium MAC with Retransmission
OMAC	Opportunistic MAC
TS	Time Slot
CS	Code Slot

PRS	Pre-Defined Relay Station
FRS	Fixed Relay Station
RRS	Random Relay Station
ORS	Opportunistic Relay Station
FTSA	Fixed Time Slot Allocation
DTSA	Dynamic Time Slot Allocation
ML-FTSA	Multi-Link Fixed Time Slot Allocation
ML-DTSA	Multi-Link Dynamic Time Slot Allocation
UL	Uplink
DL	Downlink
QoS	Quality Of Service
rms	Root Mean Square
ICI	Inter-Carrier-Interference
PDP	Power Delay Profile
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
INR	Interference-To-Noise Ratio
OIAR	Ordered Interference-Aware Resource Allocation
OIAR w/ D2D	Ordered Interference-Aware Resource Allocation with Device-to-Device Communication

Symbols

p	Permission Probability
d_{max}	Maximum Acceptable Delay
T_f	Frame Duration
R	Cell Radius
R_{rs}	Distance Between RS and BS
R_{inner}	Inner Region Radius
P_{intf}	Interference Level
PL_A	Path Loss
$\Delta\delta_{decr}$	Power Control Decrease Step
$\Delta\delta_{incr}$	Power Control Increase Step
P_T/P_t	Transmit Power
t_{talk}	Talkspurt Duration
t_{sil}	Silence Gap Duration
P_{loss}	Packet Loss Probability
P_{outage}	Power Outage Probability
P_d	Packet Dropping Rate Due To Excess Delay
P_i	Packet Corruption Rate Due To Interference
R_{relay}	Relay Location Radius
n	Path Loss Exponent
P_H	Transmitter Processing Power
T	Transmission Time
t_{slot}	Time Slot Duration
ρ	Traffic Load
T_s	Symbol Period
N	Number of Subcarriers
L	Number of Paths

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Chapter 1 Introduction

When the first ever wireless communication signal was successfully sent across the Bristol Channel by Marconi in 1897 [1], the age of modern wireless communication has begun. Various wireless communication technologies and applications have been developed and become an important part of people's daily life. The idea to divide service area into separate cells with a base station (BS) in the centre was proposed by Bell Labs in 1960s, namely cellular networks [2]. This architecture has significantly increased the spectrum reuse efficiency and lowered the cost of wireless communications, which made wireless cellular systems so popular and commercialized today. The number of mobile subscribers worldwide is expected to continue rising dramatically, and Cisco has reposted that the volume of global cellular traffic has triples (year-over-year) for three years in a row [3].

The ever growing demand for higher data rate and larger system capacity made researchers worldwide explore for new technologies. Multi-hop cellular networks (MCNs) was proposed in [4] to incorporate the flexibility of ad hoc networking [5] into traditional single hop cellular networks (SCNs). More details can be found in the literature review in Chapter 2. As the concept of MCNs opened a new area of cellular network research, the resource allocation became a crucial topic. Since most of the mobile terminals operate on limited battery, it is also of great importance to study the power consumption of such networks.

The first phase of our research focused on the effective resource allocation for TDD-CDMA networks. We proposed and studied new algorithms with emphases on system performance as well as power consumption levels.

In Chapter 3 we used the multi-hop medium access control (mMAC) scheme which was proposed by Li and Chong in [6] as a benchmark and developed two algorithms to achieve better utilization and network performance. Previous simulation results have shown that mMAC is able to provide much better system performance over joint Code-Division Multiple Access/Packet-Reservation Multiple Access (CDMA/PRMA) of SCNs. However, it is noted that relays are sometimes unnecessarily involved under mMAC and the performance is not desirable for large cell radius. Our proposed algorithms solved the drawbacks of the mMAC scheme and showed significant improvement of system performance.

We focused our study on the energy efficiency rather than the network performance in Chapter 4. Since the single path between the mobile station (MS) and the BS for traditional cellular communication systems is divided into several shorter links in MCNs, transmission power is greatly reduced as a benefit of shorter links and so is interference. Therefore, the reduced interference, attenuation and power consumption will have great impact on the system capacity and total transmission power. We first proposed an opportunistic relay station (ORS) selection scheme in Chapter 4 for multi-hop TDD-CDMA networks using fixed RSs. We then built a more practical model including the inter-cell and intra-cell interferences for different service for TDD-CDMA systems to study the energy consumption including the hardware processing energy.

Orthogonal Frequency Division Multiplexing (OFDM) has shown its advantages and been considered to be one of the most appealing communication technologies for future-generation wireless networks ever since it was chosen for the IEEE 802.16a and DVB-RCT standards [7, 8]. With the ability to adaptively allocate power and transmission rate among subcarriers, such systems can achieve higher throughput and have the capability to cover longer transmission ranges [9]. By using parallel narrow sub-channels, Orthogonal Frequency Division Multiple Access (OFDMA) systems are able to significantly mitigate the inter-symbol-interference (ISI) due to the frequency selective nature of the channel. The new network configuration has opened up the possibilities of future cellular network technologies and become a hot research topic in both industry and academia.

In the second phase of our research, we started to look at the OFDMA systems with frequency selective fading and studied resource allocation schemes for the next generation cellular networks.

The centralized resource allocation methodology is no longer optimal in today's ubiquitous wireless communication environment as the propagation environment becomes extremely diverse. Dynamic channel assignment (DCA) schemes start to show promises in recent studies due to their ability to dynamically allocate radio resources according to surrounding environment and achieve time-varying frequency reuse efficiently [10].

With the rapidly growing demand for multimedia cellular services, there occurred a huge need for high data rate access. Direct device-to-device (D2D) communication

was proposed to be used underlying cellular networks in [11] to help handle local peer-to-peer traffic. The capacity of the network can be increased with the D2D communication with pre-existing infrastructure. However the D2D communication unavoidably introduces interference to existing cellular users, therefore the resource allocation has to be taken extreme care of.

In Chapter 5 we first studied the frequency selective multipath Rayleigh fading channels and our multipath channel model is described. The same channel model was also used in our performance simulation of proposed resource allocation schemes.

We presented our Ordered Interference-Aware Resource (OIAR) allocation schemes in OFDMA cellular networks and adapted direct D2D communications underlying cellular networks. The results showed the proposed scheme can significantly improve the network performance over the random allocation. By introducing D2D communication with adjustable transmit power, the network is able to support more number of users and provide a higher system throughput.

Chapter 6 concluded this thesis and recommend directions for future research.

Chapter 2 Literature Review

2.1 MULTI-HOP CELLULAR NETWORKS

The success of the second generation (2G) and third generation (3G) cellular networks have demonstrated the popularity and reliability of traditional single-hop cellular systems where all mobile stations (MS) communicate directly with a BS [12]. During the last few decades, the technologies of cellular communications have matured and provided reliable and satisfying performance to numerous users. The cellular communication is playing an important role in today's public telecommunication services. The increasing numbers of subscribers and the demand for high-speed multimedia services have made the cellular system design of great research interest.

Another paradigm of mobile communications is mobile ad hoc networks (MANETs), which is a group of wireless mobile nodes that have the ability to self-configure and form a network without any infrastructure [5]. In a MANET, every node can serve as an intermediary station and help relaying packets of other nodes towards their destinations. Due to the shorter transmission distance, MANETs can improve the system throughput and power efficiency.

Both traditional single-hop cellular networks (SCNs) and MANETs have advantages and drawbacks. The SCNs have mature technology as well as reliable performance. However it suffers from dead spots due to bad channel conditions or hot spots due to high traffic during peak hours [13]. Any problem related to the management and

allocation of limited capacity in traditional SCNs is exacerbated by unbalance traffic distribution [13, 14]. On the other hand, it is much cheaper to deploy MANETs and the performance under situations such as dead spots or hot spots can be significantly improved. However, the performance of MANETs is not as reliable as SCNs because it is more difficult to predict or control the channel contention and interference levels due to the nature of such networks. The limitations of each networking paradigm made it well worthy to investigate and create a hybrid system that benefits from the advantages of both networks, while avoiding their respective drawbacks [15].

Fig. 1 Multi-hop routing vs single hop routing [4]

The combination of traditional SCNs and MANETs appears to be a logical solution to the next generation cellular systems and various architectures have been proposed in recent years. To meet the increasing demand on wireless access services, Hsu and Lin proposed the concept of multi-hop cellular networks (MCNs) [4] to incorporate the flexibility of ad hoc networking [5] into traditional SCNs. The fundamental idea of MCNs communication is to break an original communication link into two or more shorter links, therefore the required transmission power of each node can be

reduced [13]. In a MCN, the physical layer of mobile nodes needs to be modified so that they can transmit data not only to the base stations but also to other mobile terminals [16]. In this case, MCN provides the possibility of direct peer-to-peer communications as well as relayed communication through other fixed and/or mobile nodes.

The BS coverage in MCNs becomes smaller with reduced transmit power as compared to that in SCNs, therefore the interference is also reduced. In this way the spectra can be reused more frequently and the capacity of the system can be increased [17]. The available transmission rate can also be increased [14] because in MCNs terminals closer to the BS can help other terminals further away from the BS gain access to high data rate services by relaying [13]. In MCNs, the blocking probability of the network can be reduced because MCNs have the ability to divert the traffic between the congested and neighbouring non-congested cells. Since the MSs in dead-spots can establish connections through multi-hopping, the system coverage can also be increased. Furthermore, the reliability of the system can also be improved with proper routing protocols.

In [18] authors proposed a virtual cellular network (VCN) and investigated the effect of multi-hop relaying on transmission power. The losses considered in the system included the Rayleigh fading, shadowing loss and path loss. It was noticed that the average transmission power decreases with the increase of the maximum multiple hops.

However, as stated in [19], the whole transmission power includes both energy for transmission itself and the hardware consumption. Therefore, a more accurate model taking the transmitter and receiver processing energy into account should be considered. For the multi-hop system, the total energy consumed is possible to be higher than the direct transmission [20]. However studies have shown that energy can be saved using two-hop links instead of the single hop transmission under proper circumstances, and the reduction in energy is more obvious for larger path loss.

In [21], the energy consumed by every bit of MCN system is analysed and it has been proven that the energy consumed per bit in a multi-hop system is much lower than in a single hop network. It is also noticed that multi-hop systems are more effective in reducing the transmission power considering path loss.

2.2 ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS NETWORKS

In an Orthogonal Frequency Division Multiple Access (OFDMA) network, based on OFDM technology, the system can adaptively and optimally allocate power and transmission rate among subcarriers to achieve high throughput and use multiple parallel channels to transmit data in order to enhance the transmission range [9]. Also, the drawbacks caused by ISI due to the frequency selective nature of channels are greatly mitigated by using several parallel narrower sub-channels instead of the wide-band channel.

The first OFDM scheme was proposed by Chang in 1966 [22] for dispersive fading channels and it has been a hot research topic ever since. Orthogonality is ensured in the OFDM scheme by converting incoming data stream into N parallel data streams

and using fast Fourier transforms (FFT) to modulate on separate carriers. Furthermore, the equalizer is not needed any more since N narrow bandwidth channels, broken down from the wide bandwidth, only experience flat fading. The channel diversity among various users is also taken advantage of therefore the system resources can be used more efficiently.

Fig. 2 Frequency domain of an OFDM system

The optimal subcarrier, power and bit allocation problems of multiuser OFDM have been formulated in [23, 24], i.e. to minimize the overall transmission power under a data rate constraint or to maximize the total data rate under a power constraint. These nonlinear optimization problems are extremely mathematically complicated and difficult to solve.

Under the scope of margin adaptive (MA) and rate adaptive (RA) optimizations with certain limited assumptions, various suboptimal algorithms have been proposed to reduce the computational complexity, such as in [25-27]. For example, [25] assumes all users have identical average signal-to-noise ratios (SNRs) and [27] considers only the case when all subcarriers equally share the total transmission power. In [28] Kim transformed the allocation problem in [23] into an integer programming (IP) problem

and proposed a heuristic and LP-based suboptimal algorithm. In [29] the authors combined iterative improvement schemes with the algorithm by Zhang [27] to obtain better performance.

In mobile radio communications the line-of-sight path is often blocked by obstacles, therefore the transmitted electromagnetic signals are not able to reach the destination antenna directly. The received signal is usually a superposition of signals resulting from diffraction, reflection and scattering, commonly known as multipath propagation. Such multipath propagation causes small scale (microscopic) fading, where a sum of attenuated, delayed, and phase-shifted replicas forms the received signal. It spreads in different dimensions due to multipath propagation and the mobility of the receiver, and there are mainly delay spread in time due to resolvable multipath components and Doppler spread in frequency due to the mobility of the terminals [30].

2.3 DYNAMIC RESOURCE ALLOCATION

While wireless communications become more and more ubiquitous, the conventional centralized resource allocation methodology is no longer a suitable solution as the propagation environment becomes too diverse to predict and mutual interference is extremely inaccurate. Under such circumstances, dynamic channel assignment (DCA) schemes start to show promises as they are able to dynamically minimize mutual interference among active calls and achieve time-varying frequency reuse patterns [10].

Autonomous Reuse Partitioning (ARP), a simple measurement-based DCA scheme, was proposed in [31]. In ARP, every BS scans all channels in the same order and selects the first channel which meets the requirement of a certain carrier-to-interference ratio (CIR). This algorithm has proven to achieve an effective allocation of network radio resources with minimum CIR margin and at the same time provide ‘reuse partitioning’ in a way that the lower numbered channels are reused at shorter distances.

Various DCA schemes have been discussed and compared in [32] including Least Interference Algorithm (LIA), Least Interference below Threshold algorithm (LTA), Marginal Interference Algorithm (MIA), etc. However studies have shown that performance of all threshold-based algorithms are very sensitive to the setting of such thresholds, while the optimal values are greatly affected by the environments [32]. Therefore the adaptability of the simple aggressive LIA is a great advantage and it appears to be one of the best DCA algorithms in local wireless communication environment. In the second stage of our study, we adapted the concept of measurement-based resource allocation to fully take advantage of frequency diversity and user diversity in OFDMA systems.

2.4 DEVICE-TO-DEVICE COMMUNICATIONS

As the public develops higher and higher expectations of multimedia mobile services, the demand for higher data rate is increasing more rapidly than ever. New technologies, such as 3GPP Long Term Evolution (LTE) and WiMAX, are of great research interest to accommodate such capacity and traffic of multimedia cellular networks.

Fig. 3 Illustration of D2D communication underlaying cellular network [33]

It was proposed in [11] to enable direct device-to-device communication to handle the local traffic as an underlay to the cellular networks. The D2D communication is able to offload the traffic transmitted through BSs in a reliable yet cost-efficient way, at the same time the end-to-end delay is reduced since MSs can exchange data directly without intervention of BSs [33]. The capacity of the network therefore can be increased with the help of D2D communication while maintaining pre-existing infrastructure of the cellular networks.

However, the introduction of D2D communication underlaying conventional cellular systems can lead to interference between BS relaying MSs and D2D users if they use the same frequency band. It is very important to guarantee that the D2D communication causes minimum disruption the cellular operations since the cellular network operates on licensed bands [34].

Authors in [11] used a simple admission control of limiting one D2D pair in each sub-band in every cell and proved it is a feasible idea to let D2D communications to reuse the same resources as the cellular users are using.

Similar to [11], two transmissions, one mobile link and one D2D link, are allowed in every sub-band in each cell in [34]. Such access control effectively guarantees a certain level of network performance for the original cellular network.

Another fractional frequency reuse (FFR) approach was proposed in [33] and enabled D2D users to selectively use subcarriers according to their locations.

Chapter 3

Improved Medium Access Control Schemes for TDD-CDMA Multi-Hop Cellular Networks

The growing popularity of multimedia technology has attracted designers to develop new technologies in order to increase the capacity of cellular networks as well as to improve the network performance. The multi-hop medium access control (mMAC) scheme proposed by Li and Chong in [6] has shown significant improvement of the system performance over CDMA/PRMA for SCNs. However, it is noticed that the mMAC protocol does not provide satisfying performance when the cell radius is large and RSs are sometimes unnecessarily involved especially because all mobile stations in the outer region adopt two-hop transmissions.

In this chapter, we proposed two new medium access control protocols, multi-medium MAC with Retransmission (mmMAC/RT) and opportunistic MAC (OMAC), to improve the performance of uplink voice transmissions for TDD-CDMA multi-hop cellular networks.

3.1 PRMA BASED MULTI-HOP MEDIUM ACCESS CONTROL FOR TDD-CDMA MCNS WITH FIXED RELAYS

A. Packet Reservation Multiple Access (PRMA)

Joint code-division multiple access/packet-reservation multiple access is one well-cited MAC scheme among the researches on TDD-CDMA SCNs [35]. Each time slot (TS) is divided into a fixed number of code slots (CSs) and each CS can be used by a MS. As illustrated in Fig. 4, the BS broadcasts status of each CS during the downlink transmission, whether the CS is ‘available’, *C* slot, or ‘reserved’, *I* slot. The broadcast also includes information on interference level and acknowledgments, etc.

Fig. 4. CDMA/PRMA for TDD-CDMA [35]

A MS contends to access *C* slots with permission probability p , using Bayesian Broadcast Algorithm with TDD operation [35, 36]. The value of p is an important system parameter and has a significant effect on the system performance. A low value of p can reduce the collision probability but it also increases the waiting time, which results in increased number of dropped packets. On the contrary, if p is too

high, it increases the collision probability and will result in an increased number of dropped packets due to the excessive delay from the contention procedure.

If there are multiple C slots in one TS, the MS randomly selects one of them with equal probability. However the MS can only send one contention packet in each TS. Power control applies to the contention transmission and the contention packet is transmitted using the required transmit power estimated based on the interference and path loss between the MS and the BS.

If no other MS contends for the same C slot, the reservation is successful, and the MS will be acknowledged of the successful contention. Other MSs will also be informed during downlink broadcast that the CS becomes reserved. If the BS receives duplicated reservation from a same MS, only the first one will be acknowledged [35]. In this way, other MSs have no access to this slot and the successful MS can continue sending packets in its ‘reserved’ slot. When the MS finishes its talkspurt, it will release the slot and it becomes ‘available’ for contention again.

If the contention is unsuccessful, the MS will start over the contention procedure in the next frame. However, speech packets will be dropped after waiting more than the maximum acceptable delay. The value of the maximum acceptable delay, d_{max} , is usually set to be twice the frame time.

B. PRMA based mMAC with fixed RSs

The mMAC scheme based on joint CSMA/PRMA protocol was proposed in [6], and it includes BCH code selection, power control and multi-hop relaying.

Under TDD-CDMA, each frame has a duration of $T_f=10\text{ms}$, which is further split into 15 TSs. As shown in Fig. 5, six fixed RSs are placed symmetrically on the perimeter of a circle for each cell [35]. The cell radius is R and the distance between RS and its BS is R_{rs} . The inner region is defined with radius R_{inner} .

Under mMAC, MSs inside the inner region are defined as one-hop MSs and communicate directly with BS using the same PRMA approach as described above. The contention occurs at the BS, the permission p is adapted based on the Bayesian Broadcast Algorithm and power control are executed accordingly [35].

Fig. 5. TDD-CDMA MCNs with Fixed RSs [35]

For two-hop MSs, located in the outer region, multi-hop transmission is used with the help of a RS. The selection of RS is based only on path loss condition. And the geometrical position of RSs is designed in such a way that two-hop transmissions can efficiently cover the entire cell area.

The contention process of two-hop calls can be divided into two phases: the MS→RS phase and the RS→BS phase. It is noted that to avoid self-interference, two different TSs for MS→RS and RS→BS transmissions are required [6]. The contention process of MS→RS is the same as TDD-CDMA SCNs only that the contention occurs at RS. If MS_B succeeds in the MS→RS contention, RS_0 will start the RS→BS contention phase on behalf of MS_B . However, RS_0 would prefer to give higher priority to MSs and avoid using idle TSs, therefore it will try to contend for a C slot in a uplink TS which is currently used by itself for RS→BS transmission [35]. Upon completing transmission of the current talkspurt, MS_B and RS_0 are responsible to inform RS_0 and BS, respectively, to release the corresponding CSs.

3.2 PROPOSED MULTI-MEDIUM MAC WITH RETRANSMISSIONS FOR TDD-CDMA MCNs WITH FIXED RELAYS

A. Proposed mmMAC with RT

As the two-tier division is used in mMAC, all MSs in the outer region use two-hop transmissions with RSs involved no matter how good the channel condition is. However, some of those two-hop MSs are in fact able to communicate directly with the BS, thus the unnecessary involvement of relay results in waste of channel resources and increase of interference. On the contrary, MSs within the inner region may fail to transmit data packets due to high interference levels and RSs can

certainly offer great help in this situation. Therefore, we propose this Multi-Medium MAC with Retransmission (mmMAC/RT) scheme in which all MSs try to communicate directly with the BS, and RSs are only used to resend data packets when transmitted packets are corrupted at the BS.

Fig. 6. Illustration of Each Step of mmMAC/RT Scheme.

Same as in the mMAC protocol, six fixed RSs are symmetrically located for each cell and the distance between RS and its BS is R_{rs} while the cell radius is R . However, the cell is no longer divided into inner and outer regions; instead, all MSs follow the same protocol in Fig. 6 as described below.

- (1) During the $(n+1)^{th}$ downlink subframe, MS_A listens to the downlink broadcast by the BS. The downlink broadcast contains the following three types of information: (i) the status of each CS in a TS, whether it is currently available, C slot, or reserved for transmission, I slot; (ii) the interference levels at BS for the TSs in the n^{th} uplink frame; (iii) the acknowledgement on the contention results happened in the n^{th} uplink frame.
- (2) From the downlink broadcast information, MS_A selects a C slot in a TS, TS 1, for contention. In the $(n+1)^{th}$ uplink subframe, MS_A sends the contention packet based on p . MS_A can continue sending contention packets in other TSs in the current $(n+1)^{th}$ uplink subframe, but at most one contention packet per TS. If the BS receives duplicated reservations from MS_A , it will only acknowledge the first one. The required transmit power MS_A uses is estimated based on the interference level, P_{inf} , and estimated path loss, PL_A , between the MS_A and the BS.

$$P_{req} = (\delta_{cont} + \Delta\delta_{cont}) + P_{inf} + PL_A \quad (1)$$

where δ_{cont} and $\Delta\delta_{cont}$ are E_b/N_0 target and E_b/N_0 margin in dB for contention packets, respectively.

- (3) During the $(n+2)^{th}$ downlink subframe, MS_A listens to the downlink broadcast for the acknowledgement of its contention. If the contention packet is successfully received, it will lead to a reservation of a CS for MS_A in the $(n+2)^{th}$ uplink subframe. However, if MS_A fails to obtain a contention, it will start over the contention process in the $(n+2)^{th}$ uplink subframe exactly like in Step (2). The contention process is repeated until either when MS_A successfully contends a CS, or when the packet is dropped due to exceeding maximum acceptable delay d_{max} .
- (4) After successfully contending, MS_A will transmit its data packet to BS in its reserved I slot with δ_A at the BS. If the $\delta_A > \delta_{upper}$, the BS will inform MS_A to reduce its power by $\Delta\delta_{decr}$. On the contrary, if the $\delta_A < \delta_{lower}$, the BS will inform MS_A to increase its power by $\Delta\delta_{incr}$. The power control commands are included in the $(n+2)^{th}$ downlink broadcast by the BS so that MS_A will adapt its transmit power accordingly in the $(n+2)^{th}$ uplink transmission.
- (5) When the BS receives the data packet sent by MS_A in the $(n+2)^{th}$ uplink subframe, it checks the SIR to decide whether the packet is corrupted due to interference. If the data packet is successfully received, the transmission is considered successful and MS_A continues sending following packets of the same talkspurt. On completion of the talkspurt, the reserved I slot will be released.

However, if the data packet is not received successfully, the BS will inform a particular RS to resend the packet in the $(n+3)^{th}$ downlink subframe. The

selection of the RS is based on path loss condition. When the talkspurt is generated, MS_A estimates the path losses to all six RSs based on the received pilot signals from them and chooses the RS, RS_0 , with the minimum path loss. The chosen RS_0 checks the *SIR* of the data packet it overhears in the $(n+2)^{th}$ uplink subframe, which is transmitted from MS_A to BS. If the packet is successfully captured, the RS_0 will forward it on behalf of MS_A when requested by BS.

- (6) If RS_0 has successfully captured the data packet and receives request from the BS to forward the data, it will forward the data packet to the BS in the $(n+3)^{th}$ uplink subframe. Otherwise, the data packet is considered corrupted due to interference.

All the overheard data packets will be stored in RSs for only one time frame, i.e. if the RS_0 has successfully received data packet from MS_A during the $(n+2)^{th}$ uplink subframe but BS did not request it to resend, the data packet will be discarded.

In our mmMAC/RT scheme, the contention procedure is not applied to the RSs. As shown in Fig. 7, the last TS in an uplink subframe is exclusively reserved for RSs and no MS is permitted to contend for this TS. Each RS has reservation of one specific CS in the last TS. Therefore, when the RS_0 receives request from the BS in the $(n+3)^{th}$ downlink subframe, it can transmit the packet during the same frame without wasting time on the

contention phase. And since the last TS is only reserved for RSs, no self-interference issue arises here.

Fig. 7. Time Slots in One Time Frame.

B. Simulation Models

A cellular environment of 19 cells is used in the simulation, and we evaluate and study the performance of our new protocol for uplink voice transmission as compared to the original CDMA/PRMA SCNs and mMAC scheme. Statistics are collected from the central seven cells and only the average value is used. We use the same system configuration as in [6], except that the two-tier division is no longer needed.

In the simulation model, we consider a set of limited transmit power levels. The maximum and minimum power levels for a MS/RS are $P_{t, max} = 20\text{dBm}$ and $P_{t, min} = -40\text{dBm}$, respectively. The estimated minimum E_b/N_0 requirements for contention packet using BCH (255, 63, 30) and information packet using BCH (255, 147, 14) are 1.75dB and 0.72dB, for $P_E \leq 1\%$ [6]. According to [6], we also set δ_{cont} and $\Delta\delta_{cont}$ to -1.75dB and 1.75dB; and the power control upper limit and lower limit, δ_{upper} and

δ_{lower} , are set to 2dB and 1dB, respectively. As the uplink power control step size for TDD-CDMA system is 1~3dB [37], $\Delta\delta_{decr}$ and $\Delta\delta_{incr}$ are set to 1dB and 2dB, respectively. Other parameters are summarized in TABLE I.

TABLE I. SYSTEM PARAMETERS FOR TDD-CDMA SYSTEMS

Definition	Units	Values
TDD-CDMA Frame Duration	ms	10
Time Slots per Frame		15
Time Slots per Uplink Subframe		8
Codes per Time Slot		8
CDMA Channel Rate	Mbps	3.825
PRMA Channel Rate after Coding	Kbps	382.5
PRMA Channel Rate before Coding	Kbps	220.5
Voice Source Rate	Kbps	8
Information Bits per Packet	b	80
Overhead form Information Packets	b	67
Maximum Delay	ms	20
Shadowing Parameters	dB	(0, 8)
Path Loss Constant	dB	137
Path Loss Exponent		3.52
Permission Probability		variable
Number of Simultaneous Users		variable
Inner Region Radius (for mMAC)	m	0.4R
Number of Relay Stations		6
Cell Radius	m	variable

The Markov two-state machine is used to model the voice traffic, and the talkspurts and silence gaps are set to be exponentially distributed with mean durations of $t_{talk}=1$ and $t_{sil}=1.35$ seconds, respectively Voice packets will be dropped after waiting longer than d_{max} in order to guarantee the instant communication nature of voice traffic.

C. Simulation Results

Fig. 8. Packet Loss Probability for mmMAC/RT.

Fig. 8 shows the packet loss probability P_{loss} against the number of users for mmMAC/RT with different R .

The proposed mmMAC/RT scheme works well for $R \leq 750\text{m}$. We can see a significant improvement of P_{loss} for $R=750\text{m}$ as compared to mMAC. This is mainly because at this radius, some of the outer region MSs are in fact able to communicate directly with BS; while the mMAC uses one unnecessary relaying hop. However, the performance is not desirable for larger cell radius, e.g. $R=1\text{km}$, the reason will be discussed in the following section.

TABLE II. SYSTEM CAPACITY AT PLOSS=1%

Cell Radius R	CDMA/PRMA	mMAC	mmMAC/RT
500m	60	40	55
750m	42	40	52
1km	0	30	0

As for the power outage probability P_{outage} , the results are similar for mmMAC/RT and CDMA/PRMA since in both schemes the MSs try to communicate directly with the BS.

Fig. 9. Power Outage Probability for mmMAC/RT.

D. Problems with the mmMAC/RT scheme

It is noted in the previous discussion that the mmMAC/RT scheme does not provide satisfying results for large cell radius. The scheme shows significant improvement

for $R=750\text{m}$, however the P_{loss} is much higher than the original mMAC protocol for $R=1\text{km}$.

Since the packet loss probability, P_{loss} , is defined as the sum of the packet dropping rate due to excessive delay, P_d , and the packet corruption rate at the BS due to interference, P_i . We look at the simulation results of P_d and P_i separately to investigate the reason why mmMAC/RT scheme leads to high P_{loss} for large R .

Fig. 10. Packet Dropping Probability for mmMAC/RT.

Fig. 11. Packet Corruption Probability for mmMAC/RT.

The comparison of Fig. 10 and Fig. 11 shows that the poor performance at $R=1\text{km}$ is mainly caused by the increase of P_d . In Section 2.2 C, we've shown that similar to CDMA/PRMA, mmMAC/RT suffers from a high P_{outage} for large R . When $R>750\text{m}$, MSs are not able to contend due to the limited power, which results in high P_d and thus high P_{loss} .

3.3 PROPOSED PRMA BASED OPPORTUNISTIC MAC FOR TDD-CDMA MCNS WITH FIXED RELAYS

According to the simulation performance and analysis of mmMAC/RT, we further proposed another enhanced scheme, named Opportunistic Medium Access Control (OMAC), which is also based on PRMA protocol but overcomes the disadvantages of mmMAC/RT for large cell radius.

Same as in mmMAC/RT, during the $(n+1)^{th}$ downlink subframe, MS_A listens to the downlink broadcast by BS. It then starts to contend during the $(n+1)^{th}$ uplink subframe. As mentioned earlier, the problem for large cell radius occurs when MS_A is not able to send the contention packet using the required transmit power, leading to the high dropping probability, P_d .

In order to resolve this problem, when the contention process fails due to power outage, the MS_A will switch to a two-hop mode in our new OMAC and contend to send its packet to its corresponding RS, same as in the mMAC scheme. Otherwise, it will send the data packets directly to BS following the mmMAC/RT protocol, and only use RS to resend packets corrupted due to interference.

Since the two-hop transmission procedure is adopted here, more medium resources are needed and the probability of retransmissions from RS to BS is expected to be much lower. Hence, the last TS is no longer reserved for RSs to resend data packets. When a RS receives the request from BS to resend the data packets, it will contend for a CS in the same way as when it is involved in a two-hop transmission, provided that it has successfully overheard the data packet during the $MS \rightarrow BS$ transmission.

Fig. 12. Packet Loss Probability for OMAC.

As shown in Fig. 12, OMAC outperforms CDMA/PRMA and mMAC significantly. Not only does it provide much lower P_{loss} for $R=1\text{km}$, it can also work well for even larger cell radius, e.g. $R=1.5\text{km}$.

TABLE III. SYSTEM CAPACITY AT PLOSS=1%

Cell Radius (R)	CDMA/PRMA	mMAC	mmMAC/RT	OMAC
500m	60	40	55	65
750m	42	40	52	55
1km	0	30	0	50
1.5km	0	0	0	18

In the proposed OMAC, when a MS cannot contend directly to BS due to power outage, it switches back to two-hop mode as in the mMAC scheme. This solves the drawbacks of mmMAC/RT for large radius. On the other hand, since the new scheme no longer divides the cell into outer and inner regions, the medium resources

will not be wasted by unnecessary hopping if the MSs are able to communicate directly with the BS.

The P_{outage} is also reduced as compared to mmMAC/RT because the transmission distance is shorter when RSs are used for relaying.

Fig. 13. Power Outage Probability for OMAC.

3.4 SUMMARY

In this chapter the performance of CDMA/PRMA was studied with power control algorithm for uplink voice packet transmission in TDD-CDMA SCNs and MCNs. We proposed a Multi-Medium MAC with Retransmissions (mmMAC/RT) scheme with fixed RSs based on CDMA/PRMA. Simulation results have shown that mmMAC/RT outperforms both CDMA/PRMA and mMAC for $R=750\text{m}$ but it cannot provide desirable performance for large radius. The reasons have been

investigated and a further modified scheme, OMAC, was proposed. Simulation results prove that the proposed OMAC outperforms CDMA/PRMA for SCNs and mmMAC for MCNs. Furthermore, it is able to work well in large cell radius such as $R=1.5\text{km}$.

The two-tier division is no longer needed in either of our proposed schemes. In this way, we can avoid the unnecessary hopping which result in waste of channel resources and increase of interference levels.

The performance of mmMAC/RT and OMAC schemes investigated in this chapter is only for voice communications. Future research can be done to analyse the performance of proposed MAC schemes when data and video traffic are taken into account for multimedia services.

Chapter 4

Opportunistic Relay Selection in Future Green Multi-Hop Cellular Networks

Continuous expand of cellular subscribers and fast growing demand for high-speed multimedia services are making researchers worldwide explore for new technologies to increase system capacity and data rate. With the increasing data rate provided by new systems, the energy consumption increases rapidly at the same time. Therefore, designing an efficient resources allocation scheme and architecture to improve the network performance and reduce energy consumption is also a necessary focus of future research.

In this chapter, we proposed an opportunistic relay selection technique to save energy consumption for future green multi-hop cellular networks. A comprehensive simulation model with consideration of path loss, shadowing, inter-cell and intra-cell interference and other service requests for both single hop and multi-hop TDD-CDMA based cellular system was used to conduct an exhaustive investigation of energy consumption including the hardware energy for different RS selection under various time slot allocation schemes.

4.1 RELAY SELECTION TECHNIQUES

Firstly two relay station architectures, pre-defined relay stations (PRSs) and random relay stations (RRSs), are presented in this section. Then we proposed our RS

A. Fixed RS (FRS) Selection in PRS Architecture

B. ORS Selection in RRS Architecture

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For ORS selection in RRS architecture, the distance between MS and BS as well as the positions of RSs are used to determine whether a RS should be used. This is different from the FRS selection where the RS is always used when the distance between the MS and BS is greater than R_{relay} . The proposed ORS selection is as follows.

The distance between the MS and the BS is used as a diameter to form a circle through MS and BS as shown in Fig. 15 (a). If there is any RS inside the circle, a two-hop connection will be used. Otherwise, the MS will directly send the data to the BS. This is because when the RS is outside the circle range, i.e.

$$d_{1c}^2 + d_{2c}^2 > d^2 \quad (2)$$

the total transmission energy used in two-hop connection will be larger than that used in a single-hop connection since the transmission power is proportional to the transmission distance with the power of n where n is the path-loss exponent.

If two or more RSs are inside the circle, the RS with shortest distance to the circle centre will be chosen because it requires minimum transmission power. As shown in Fig. 15 (b), RS₁ locates further away from the centre as compared to RS₂ therefore the total transmission energy will be lower if RS₂ is used as RS.

Fig. 15. Opportunistic Relay Station Selection.

4.2 SYSTEM AND SIMULATION MODEL

A. System Model

A cluster of 19 cells with two-tier configuration is used in our model. Each frame of 10ms is divided into 15 time slots. The maximum spreading factor is 16 and the maximum data rate supported is 256 kbps. The propagation model for micro-cellular has been well studied in [38]. And we assumed a log-normal fading model to simplify the simulation.

When a new call is generated based on Poisson process, it is randomly assigned to a cell with exponentially distributed duration. We assumed the system to be under perfectly power control and the user to be stationary after establishing the connection.

TABLE IV. SYSTEM PARAMETERS

Number of cells	19
Cell Radius, R	1 km
R_{relay}	$0.45 \cdot R$
Max. MS/RS Power, $P_{\text{MS}}/P_{\text{RS}}$	20 dBm
Max. BS/ Power, P_{BS}	43 dBm
Pathloss Exponent, l	3.25
Pathloss Constant, k	137 dB
Background Noise, η	-103 dBm
Log-normal Shadowing	Mean: 0dB δ : 4 dB

B. Energy Consumption Model

We developed a model with hardware energy taken into account to analyse and compare the energy consumption for different time slot allocation schemes for TDD-CDMA. One commonly used model [39] is to assume the transceiver power is proportional to the transmission power. However, when the data rate is lower than 100 kbps, the power consumption of the hardware is almost constant [39]. Therefore, we calculated the total energy consumption including the transmission power and transmitter hardware power based on [40] as follows:

$$E = (P_T + P_H) \cdot T \quad (3)$$

where P_T is the transmission power; P_H is the transmitter processing power, which changes with the data rate; T is the transmission time. In a TDD-CDMA system, each

user only occupies certain time slots hence the data transmission is not continuous, therefore, T can be derived as

$$T = \frac{\Delta t}{t_{frame}} * t_{slot} \quad (4)$$

where Δt is call duration; $t_{frame} = 10\text{ms}$ is frame duration and $t_{slot} = 667\mu\text{s}$ is time slot duration. Note that only uplink energy consumption is studied in this simulation.

C. Time Slot Allocation Schemes

Four different time slot allocation schemes are studied in this chapter and the details can be found in [41]. For the single hop scenarios, there are Fixed Time Slot Allocation (FTSA) and Dynamic Time Slot Allocation (DTSA). The other two schemes, Multi-link Fixed Time Slot Allocation (ML-FTSA) and Multi-link Dynamic Time Slot Allocation (ML-DTSA), are used for multi-hop scenarios.

1) Fixed Time Slot Allocation (FTSA)

Under FTSA, the frame is divided into uplink (UL) and downlink (DL) subframes, TS 1 to TS 7 for UL transmission and the rest for DL transmission. When a new call arrives, the algorithm first searches for a free TS to establish the uplink connection. If the call admission is not successful in any of the UL TSs, the new call will be blocked. After the uplink TS is selected, a searching for DL TS starts from the rightmost TS, TS 15, to choose a free TS between TS 8 and TS 15 for DL connection.

A new call is only accepted when TSs can be successfully allocated for both UL and DL transmissions.

2) Dynamic Time Slot Allocation (DTSA)

When a new call is generated, this algorithm searches from TS 1 to TS15 to allocate the UL connection. The same procedure is carried out for downlink TS selection, except that the searching for DL connection starts from TS 15.

The removal of the switching point enables the protocol to fully utilize all free TSs and increases the possibility of accepting new-coming users. However, since each cell independently allocates TSs for uplink and downlink, cross-time slot interference may appear between adjacent cells.

3) Multi-Link Fixed Time Slot Allocation (ML-FTSA)

A switching point between TS 7 and TS 8 is defined for ML-FTSA as in FTSA. In order to reduce self-interference, RSs are not allowed to transmit and receive data in the same TS simultaneously. For ML-FTSA, a 2-hop call is accepted if TSs can be allocated successfully for UL, MS-to-RS and RS-to-BS, and DL, BS-to-RS and RS-to-MS.

4) Multi-Link Dynamic Time Slot Allocation (ML-DTSA)

There is no switching point to separate the UL and DL transmissions in this scheme. All TSs can be allocated for any connection. The network offers its full ability to accept more users and most utilized system capacity.

D. Traffic Model

We consider two types of traffic in our simulation model. One is defined as low traffic, Class A, for voice service and the other is defined as high traffic, Class B, for low-quality video service. The parameters for each traffic model is shown at TABLE V [40].

TABLE V. TRAFFIC CLASSES

Service	UL Data Rate	DL Data Rate	Target E_b/N_0	Duty Factor (α)	Ave. Holding Time
Class A	16 kbps	32 kbps	5.0 dB	0.4	120 sec
Class B	32 kbps	64 kbps	7.0 dB	1.0	120sec

4.3 RESULTS AND DISCUSSION

Since extra hardware energy is consumed by RSs in a multi-hop scenario, the question arises as whether multi-hop is better in terms of the total transmission power. In this section of the thesis, we examined the differences of RS selection between PRS and RRS and investigated which is the best architecture for relaying network systems.

A. Energy Comparison for Single Hop and Multi-hop PRS Networks with 6 RSs

This Section studied the energy consumption for both SCNs and MCNs. The multi-hop network is based on PRS architecture with 6 RSs using FRS selection. Firstly the performance of energy consumption was studied without consideration of the hardware power, $P_H = 0$. TABLE VI lists the energy consumption for different time slot allocation schemes. It is shown that the energy consumption is almost identical for the two single hop schemes even with different traffic and data load. This is

because the mobile users are uniformly distributed in the system hence the average transmission distance for both single hop schemes is the same. However, when the traffic load ρ increases, the interference also increases. In order to maintain the quality of service (QoS), a higher transmission power is required.

TABLE VI. CONSUMED ENERGY (MJ) OF FOUR SCHEMES WITH $PH = 0$.

Type	Traffic/cell	FTSA	DTSA	ML-FTSA		ML-DTSA	
				Per MS	Per link	Per MS	Per link
Class A	2 E	208	211	26	82	23	77
	6 E	269	271	47	140	27	122
Class B	0.5 E	334	365	90	283	67	337
	2 E	365	367	160	394	92	335

For low data rate (voice) traffic, the multi-hop schemes consume much lower energy as compared to single-hop schemes. The energy per MS can be reduced by as much as 80%. Similarly, the energy consumption increases as the traffic increases because more interference is generated and higher transmission power is required to maintain the QoS. Multi-hop schemes have proven to be a very good solution to reduce the transmission power for low data rate traffic.

For high data rate traffic, the multi-hop schemes still consume less energy when the traffic load is low. Although the energy per MS can still be reduced when the traffic load becomes high, the total transmission energy is similar to the single hop schemes. This is due to the increased interference caused by the increased number of users supported by multi-hop systems with high data rate requests. Therefore, in terms of total energy consumption, multi-hop transmission performs relatively the same as single hop but it is able to support more users with higher data rates.

In order to understand the whole picture of the energy consumption, we add the hardware processing power $P_H = 12$ mW for comparison as in [40].

Fig. 16. Energy consumption (mJ) for Class A and Class B traffic with $P_H = 12$ mW at $\rho = 2$ Erlang/cell.

At low data rate, the energy reduction of multi-hop systems is obvious even though more hardware power is consumed by the RSs. At high data rate, the interference generated by the RSs will have a significant impact on the total energy consumption and multi-hop schemes end up with a little higher total energy than single hop cases. However, with the benefits of lower blocking, dropping probabilities and higher system throughput, the approach of multi-hop transmission is still a better choice.

B. Energy Comparison among Different RS Selection Schemes

In this section the performance of two RS selection schemes, FRS and ORS, was studied in terms of energy consumption for the multi-hop transmissions. Only the

performance with ML-FSTA is shown here and no hardware energy consumption is included.

Fig. 17 shows the energy consumption per MS with FRS and ORS selections using 6 RSs. The label of ‘fixed’ in x-axis refers to FRS selection and ‘0.4-0.6’ indicates ORS selection within the region from $0.4 \cdot R_{cell}$ to $0.6 \cdot R_{cell}$. It is observed that the energy consumption per MS for ORS selection is higher than FRS selection. Since ORS uses RRS architecture, and RSs are randomly placed, it is possible that a MS cannot find a suitable RS and single-hop transmission is adopted to reach the BS. As the region for RSs allocation increases in RRS, the energy consumption per MS also increases because the RSs are more widely spread and it is more difficult for MSs to find a suitable RS.

It can be seen in Fig. 18 that both RS selections have similar energy consumption per link. Even though higher energy per MS is consumed in ORS selection due to more single hop transmissions, the energy saved with multi-hop transmissions in ORS selection is more substantial. Therefore, ORS has similar performance to FRS in terms of the total energy consumption per link.

Fig. 17. Energy (mJ) per MS in ML-FTSA with 6 RSs.

Fig. 18. Energy (mJ) per link in ML-FTSA with 6 RSs.

The energy consumption per MS with FRS and ORS using 12 RSs is presented in Fig. 19. Even with 12 RSs, ORS still has higher energy consumption per MS.

Similarly, energy consumption per MS increases as the area for RSs selection becomes larger in RRS architecture. Fig. 20 shows the energy consumption per link with FRS and ORS using 12 RSs. The total energy consumption per link of ORS is lower than FRS when the system has smaller area for RS allocation, e.g., between $0.4 * R_{cell}$ and $0.6 * R_{cell}$. This is because the RSs are distributed more uniformly over the area when the number of RSs increases, therefore it is easier for the MS to find an optimal RS. However, when the RSs are placed over the whole cell, a MS might use single hop transmission because there is no nearby RS, and it leads to higher energy consumption.

Fig. 19. Energy (mJ) per MS in ML-FTSA with 12 RSs.

Fig. 20. Energy (mJ) per link in ML-FTSA with 12 RSs with different RS selection schemes.

Fig. 21. Energy consumption (mJ) per link for different RS selections at $\rho = 2$ Erlang/cell.

We then compare the energy consumption among different RS selection schemes including the combination of FRS and ORS selection, namely half-fixed RS selection. The FRS uses 12 RSs located at $0.45 \cdot R_{cell}$ while the half-fixed RS selection uses 6 RSs at $0.45 \cdot R_{cell}$ and another 6 RSs randomly located at the range from $0.4 \cdot R_{cell}$ to $0.6 \cdot R_{cell}$. As shown in Fig. 21, half-fixed RS selection provides the lowest energy consumption per link. The combination of FRS and ORS selection is proven to be an optimal solution to reduce energy consumption while keeping a reasonable blocking and dropping probability.

4.4 SUMMARY

In this chapter we first studied energy consumption for various time slot allocation schemes of TDD-CDMA cellular networks by comparing the performance of two conventional single-hop schemes, FTSA and DTSA, with two multi-hop schemes, ML-FTSA and ML-DTSA. We then proposed an ORS selection scheme to examine its energy consumption and compared to traditional FRS selection. The comparison of energy consumption was held under two traffic scenarios: low-data rate traffic and high-data rate traffic.

The results have shown that energy consumption can be decreased significantly for multi-hop links when the data rate is low. When the data rate is high, the energy consumptions of multi-hop and single hop are very similar. For ORS selection, the energy consumption is higher than FRS selection when the number of RSs is small; but less transmission energy is required with the increases number of RSs. Therefore, by increasing the number of RSs, we can build a system with low transmission power and high system capacity using ORS selection. Finally, we combined the

technique of FRS and ORS selection and the half-fixed RS selection scheme has the best performance over all.

Chapter 5

Ordered Interference-Aware Resource Allocation with Device-to-Device Communication in Cellular Networks

Since cellular networks are operated on licensed bands, it becomes extremely important to guarantee that cellular users are not affected by any harmful interference generated by the device-to-device (D2D) radios. Similar problems of interference management are often encountered in the context of cognitive radios, where the solutions usually consider cellular usage as the primary service [42, 43].

In order to control how the D2D communication uses cellular network resources and achieve an effective cooperation with primary users of the cellular network, we decided to adapt a measurement based technique [31] which is able to provide an efficient and easy management of interference.

5.1 DISTRIBUTED MEASUREMENT BASED DYNAMIC CHANNEL ASSIGNMENT

Autonomous Reuse Partitioning (ARP), a simple adaptive cellular resource allocation scheme, was proposed in [31]. All base stations simply scan all channels in a certain order and select the first channel which meets the threshold requirement of Carrier-to-Interference-Ratio (CIR). The algorithm has proven itself able to avoid interference

effectively and have better capability of handling traffic. ‘Reuse partitioning’ is also achieved in such a way that the lower numbered channels are reused at shorter distances.

Fig. 22. Autonomous Reuse Partitioning [31]

Since the entire ARP protocol depends solely on the uplink interference measurement, the downlink usually has much poorer performance than the uplink. Authors in [44] showed that it is feasible to achieve a balanced two-way performance when BS and MS jointly make the allocation selection. In such schemes, the BS first makes the measurement and forms a candidate list of channels with low uplink interference. The MS is informed of the list and then scans all channels in it. After measuring channels in the candidate list, it selects the channel with lowest downlink interference for its transmission.

Another class of distributed algorithms use the approach of selecting the worst channel above a certain threshold [45] and they are able to more compactly utilize the frequency spectrum. The simulation also showed very promising results if the threshold is properly set.

However the simple aggressive LIA appears to be one of the best choices in local wireless communication networks according to the comparison and study in [32]. It outperforms all the other algorithms, yet without the need of any threshold or constraint. Although the threshold-based algorithms can have better performance if SIR is accurately estimated as such algorithms are very sensitive to the surrounding environment. On the other hand, the adaptability of LIA proves the introductory of a threshold/constraint as an admission control mechanism is not necessary.

5.2 STUDY OF FREQUENCY SELECTIVE MULTIPATH RAYLEIGH FADING ENVIRONMENT IN LTE OFDMA NETWORKS

A. Channel Impulse Response

Many channel parameters can be derived from the multipath power delay profile, which represents the received power with respect to a fixed time delay reference [46]. The power delay profile is usually described either using a L-path tapped delay line fading model or a statistical model with the rms delay spread.

A typical example is shown as below [47], where the power delay profile is represented by a L-path tapped delay model. Each tap describes the power strength received at a particular time from a different path.

TABLE VII. AN EXAMPLE OF POWER DELAY PROFILE

Power Profile	0dB	-3dB	-6dB	-9dB
Delay Profile	0ns	260ns	521ns	781ns

Fig. 23. Tapped Power Delay Profile

For the latter case, an exponentially decaying Rayleigh fading channel is often used as a baseline channel model [48]. The impulse response is a composition of complex samples with uniformly distributed random phase and Rayleigh distributed magnitude with average power decaying exponentially.

$$h_i = N\left(0, \frac{1}{2}\sigma_k^2\right) + jN\left(0, \frac{1}{2}\sigma_k^2\right) \quad (5)$$

$$\sigma_k^2 = \sigma_0^2 e^{-kT_s/T_{RMS}}$$

$$\sigma_0^2 = 1 - e^{-T_s/T_{RMS}}$$

Where $N\left(0, \frac{1}{2}\sigma_k^2\right)$ is a zero mean Gaussian random variable and $\sum \sigma_k^2 = 1$ is satisfied to ensure same received power.

B. N-Point FFT From Time Domain To Frequency Domain

The P-point channel impulse response can be made into a N-point vector by zero-padding. After applying FFT to the N-point vector, the unsampled frequency channel response is generated [49]. When the number of FFT points increases, the resolution of the spectrum obtained becomes higher [50]. Although the zero-padding can give better resolution, it does not in fact provide any extra information. As a DFT has constraints on the sampling number, FFT can only work with sample numbers of powers of 2, such as 16, 32, 64 etc.

Fig. 24. Example of a Power Delay Profile

The symbol period time T_s in the time domain decides the bandwidth of each beam in the frequency domain, and the number of FFT points decides the number of beams. For example, a delay profile is given in Fig. 24.

If the symbol period is $10\mu\text{s}$ and the power delay profile is zero-padded into 128 points, where each tap period is $0.15625\mu\text{s}$, a zero-padded delay profile is generated as below for the FFT transfer. The value of channel gain is also converted into numerical value in power.

Fig. 25. Zero-Tapped Power Delay Profile

A 128-point FFT generates a frequency spectrum consisting of 128 beams and each beam has a bandwidth of 100kHz. However because the gain of each beam generated in the FFT is a complex number, the magnitude is used. Fig. 26 shows the channel gains of

128 channels in frequency domain after the FFT and Fig. 27 presents the normalized channel gains.

Fig. 26. Channel Gain of 128 Channels in Frequency Domain

Fig. 27. Normalized Channel Gain of 128 Channels in Frequency Domain

1) Independent Rayleigh frequency channels

If the channel gains are assumed to be independent of each other and Rayleigh distributed [51], the frequency selective channel can be generated in the following manner.

Step1: Channel delay profile is used and various impulse responses are generated for different users. The voltage value of each tap follows a Rayleigh distribution.

Step2: Each impulse response is padded with zeros and N-point FFT is taken.

Step3: For each user, the gain of each subcarrier is used as a mean and channel characteristics are obtained by Rayleigh distribution for every symbol transmitted.

2) Correlated Rayleigh frequency channels

In order to maintain the correlation between subcarriers, the Rayleigh variation should be feed into the time domain.

Step1: Various impulse responses are generated for different users by Rayleigh distribution using channel delay profile as the mean.

Step2: For each user, the CIR varies with time according to the Rayleigh distribution.

Step3: Update CIR with time and pad with zeros. Then the N-point FFT is taken to obtain channel gain for each subcarrier.

C. Common Assumptions

Although OFDM uses cyclic guard interval to provide strong tolerance against timing offset, the tightly packed subcarriers result in increased sensitivity with respect to ICI and carrier frequency errors.

The frequency fluctuation of oscillators causes a random process, phase noise, and it leads to three major problems, i.e. phase shift, effective power degradation and inter-carrier interference (ICI). These problems often have a big impact on the bit error rate (BER) analysis [52]. The difference of carrier frequency between transmitter and receiver as well as the Doppler shift, on the other hand, leads to another problem called frequency offset. The subcarrier spacing, number of subcarriers, and modulation scheme commonly result in the degradation caused by frequency offset [53].

Assuming a Gaussian distribution of ICI is inappropriate due to the correlation between different subcarriers' frequency channel responses.

Only when a frequency selective channel has uniform power delay profile (PDP) and N independent paths, it can be considered to be frequency independent fading [52]. Since usually the path number L is much smaller than the subcarrier number N , this assumption is impractical. However it gives the upper bound of BER range in a frequency selective channel. Since the channel gain of each subcarrier is i.i.d. distributed, an assumption can be made that ICI is approximately Gaussian distribution similar to the case in AWGN channel.

In reality the CIRs of different users do not have a pure Rayleigh distribution because they are correlated to the distance between the users. However it is often assumed that CIR distribution is approximated to be a Rayleigh curve.

D. BER Analysis Simulation

With reference to [47] a SNR vs BER analysis is conducted to verify the validation of our frequency selective multipath Rayleigh channel model.

A modified multipath fading channel model is used in the simulation.

TABLE VIII. POWER DELAY PROFILE FOR SIMULATION

Power Profile	0dB	-3dB	-5.05dB	-12dB
Delay Profile	0ns	260ns	521ns	781ns

And some of the system configurations are shown as below.

TABLE IX. SYSTEM CONFIGURATIONS FOR SIMULATION

Number of subbands	12
Number of slots	8 slots/radio frame
Total number of subcarriers	1024
Number of data-carrying subcarriers	768
OFDM symbol period	10 μ s
Cyclic prefix period	2 μ s
Radio frame period	2ms
Signal constellation	QPSK

A group of 64 adjacent subcarriers, a subband, is allocated to each user. A random subband allocation scheme is used for the simulation and the allocation is reapplied for

every time slot, which is 25 OFDM symbol periods. On the other hand, a new CIR is generated for each symbol time to simulate the channel characteristics.

The transmitted SNR and subcarrier gain in the frequency domain are used to calculate the received SNR for every transmitted symbol. Then E_b/N_0 is calculated based on received SNR, beam bandwidth and bit duration.

$$\frac{E_b}{N_0} = SNR * BW * T_b \quad (6)$$

And the BER is calculated using the QPSK equation.

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad (7)$$

Fig. 28. Average BER Performance vs. Transmitted SNR

A network of 4 users is simulated using random subband allocation and the result of average BER vs transmitted SNR obtained in Fig. 28 is very similar to [47].

5.3 DEVICE-TO-DEVICE COMMUNICATION IN CELLULAR NETWORKS

With the increasing population of mobile users and popularity of multimedia services, a huge multimedia traffic demand is expected to be met in the near future. However cellular networks have very limited radio resources and the installation of BSs is extremely expensive. The current systems cannot provide sufficient data rate to the MSs when the network is crowded therefore congestions may easily occur [33]. Radio resources are not efficiently utilized in today's cellular networks because every MS's data is routed through BSs even though they are located within communication coverage with each other. Hence how to improve the cellular networks capacity with pre-existing infrastructure has become a very hot research topic in recent years. By enabling direct communication between two cellular MSs, this problem can be solved by local ad-hoc networking services.

Authors in [34] proposed an interference-aware resource allocation for this scenario and used an interference-to-noise (INR) target to control the transmit power of D2D nodes. But they assumed in every cell and subband there are always two transmissions, one in D2D link and one in BS→MS link, taking place simultaneously. The simulation showed a 10% improvement over random allocation but their assumption is very unrealistic and limited. A similar approach was also used in [11] with same assumptions. In [33] a fractional frequency reuse (FFR) was proposed therefore cellular and D2D users make

use of different resource bands depending on their locations. In such a scheme there is no need of interference coordination therefore the network is more effective in terms of signalling overhead.

5.4 PROPOSED ORDERED INTERFERENCE-AWARE RESOURCE ALLOCATION SCHEME WITH D2D COMMUNICATION (OIAR w/ D2D)

When a source generates its traffic, it will categorize whether it is cellular communication or D2D communication. The source of cellular communication sends its traffic to a destination outside its transmission range via the BS while the source of D2D communication sends its traffic to a destination within its transmission range.

Fig. 29. Illustration of Cellular Network with D2D users.

In most OFDMA systems, each subcarrier is considered equivalent to a flat fading channel with no interference from other subcarriers, therefore individual pilots can be used to estimate each subcarrier's channel gain [30]. We allocate the radio resources in a set of adjacent subcarriers, in other words, a subband. The BSs and/or MSs estimate the channel gain and measure the interference from surrounding cells for each subcarrier before resource allocation takes place. The averaged subband estimated BER will be used as a decision metric for resource allocation.

A. Ordered Interference-Aware Resource Allocation for Cellular Networks

Firstly we consider an OFDMA cellular network without D2D communication. The concept of measurement based allocation is adopted and we propose the following Ordered Interference-Aware Resource (OIAR) allocation scheme.

MS→BS Uplink Resource Allocation:

- (1) BS scans all subcarriers and gathers information of each subcarrier's channel gain and interference level.
- (2) BS calculates the estimated BER for each subcarrier and order the resource blocks based on the average estimated BER.
- (3) BS selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.

The allocation selection takes both channel gain and interference into account.

- (4) BS informs MS of the chosen resource block.

- (5) MS uses the selected resource blocks for uplink transmission.

BS→MS Downlink Resource Allocation:

- (1) BS broadcasts a list of idle resource blocks to MS.
- (2) MS scans the subcarriers in the idle list.
- (3) MS calculates the estimated BER of all idle resource blocks and order the resource blocks based on the average estimated BER.
- (4) MS selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.
- (5) MS informs BS of the selected resource blocks.
- (6) BS uses the chosen resource blocks for downlink transmission.

Unlike the traditional ARP, where the allocation solely depends on uplink measurement, our proposed scheme takes measurement of both uplink and downlink interference therefore it is possible to achieve a more balanced two-way performance. The allocation scheme uses an ordered mechanism therefore it can fully utilize the frequency and user diversity of such networks.

However, the uplink resource allocation depends on the BS's choice therefore the selection may cause severe interference to any D2D communication near the MS using the same resource block. This matter will be addressed to in our proposal for device-to-device communication underlying cellular networks.

*B. Ordered Interference-Aware Resource Allocation with Device-to-Device
Communication in Cellular Networks*

When D2D communication is introduced to a cellular network, the local awareness of the network environment becomes extremely critical to the system performance as the existing cellular users can be severely affected by the added D2D users. In order to utilize the radio spectrum and avoid interference as much as possible, we consider the cellular terminals as primary users in the network and the D2D communication is only introduced after all cellular users are accommodated. At the same time D2D terminals use a much lower transmit power to mitigate the effect of interference.

MS→BS Uplink Resource Allocation:

- (1) BS scans all subcarriers and gathers information of each subcarrier's channel gain and interference level.
- (2) BS estimates BER for each subcarrier and form a candidate list of resource blocks with low average estimated BER.
- (3) BS informs MS of the candidate list of resource blocks.
- (4) MS scans the candidate list and order the resource blocks based on the average estimated BER.
- (5) MS selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.
- (6) MS uses the selected resource blocks for uplink transmission.

BS→MS Downlink Resource Allocation:

- (1) BS broadcasts a list of idle resource blocks to MS.
- (2) MS scans the subcarriers in the idle list.
- (3) MS selects the resource blocks with low estimated BER to form a candidate list.
- (4) MS informs BS of the candidate list.
- (5) BS scans the candidate and order the resource blocks based on the average estimated BER.
- (6) BS selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.
- (7) BS uses the chosen resource blocks for downlink transmission.

In this scheme, both UL and DL allocations use a two-way scanned algorithm to ensure no severe interference is caused to existing D2D users nearby.

In a D2D pair, we consider the one who initiates the communication is the UL transmission.

MS1→MS2 Uplink Resource Allocation:

- (1) MS1 scans all subcarriers and measures the interference from surrounding cells.
- (2) MS1 calculates the estimated BER for each subcarrier and order the resource blocks based on the average estimated BER.

- (3) MS1 selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.
- (4) MS1 uses the selected resource blocks for transmission.

MS2→MS1 Downlink Resource Allocation:

- (1) MS2 scans all subcarriers and measures the interference from surrounding cells.
- (2) MS2 calculates the estimated BER for each subcarrier and order the resource blocks based on the average estimated BER.
- (3) MS2 selects the resource block with lowest estimated BER until the number of subbands needed for the link is fulfilled.
- (4) MS2 uses the selected resource block for transmission.

It is noted the D2D users do not use a two-way scanned algorithm as the cellular users. This is because MS1 and MS2 are within each other's transmission range, they are expected to be in a very similar environment and experience similar interference levels.

5.5 SIMULATION MODELS AND PARAMETERS

We performed snap-shot MATLAB simulations for a cellular system of 19 cells to evaluate the performance of proposed OIAR allocation with D2D communication under cellular networks. Results are only collected from the central cell, with two-tier interference. Only the downlink transmission of the cellular system is compared to one-way D2D communication in this simulation. For each realization of the simulation, mobile users are generated one by one with random positions in any of the cells until all

cells reach maximum number of users. Cellular users have priority of the network services and are allocated first. More configuration details of the simulation model are listed in the following table.

TABLE X. SIMULATION SYSTEM CONFIGURATIONS

Number of cells	19
Cell radius	0.5 km
Total number of sub-carriers	1024
Total number of used sub-carriers	900
Sub-carrier spacing	15kHz
OFDMA symbol duration	66.68 μ s
Number of RUs	75
Number of sub-carriers per RU	12
Downlink modulation	QPSK
Noise	-103.2057 dBm
Path loss exponent	3.5
Total DL transmit power	43dBm
Maximum DL transmit power	2W
D2D transmit power	variable
Delay profile	[0, -3, -5.05, -12] dB
Radio frame	2ms

5.6 RESULTS AND DISCUSSIONS

A. *Ordered Interference-Aware Resource Allocation without D2D Communication*

The simulation was first conducted without D2D users to evaluate the performance of our proposed ordered interference-aware resource allocation scheme. Random resource allocation scheme was used as a baseline for network performance comparison.

Fig. 30 Average BER of proposed OIAR allocation compared to random allocation

It is shown in Fig. 30 that the proposed OIAR allocation scheme achieves a significantly lower average BER than the random allocation scheme because the interference-aware scheme adaptively allocates resource blocks with surrounding interference levels and users' unique channel characterisers in consideration. It makes better use of the frequency diversity and user diversity nature of the OFDMA networks.

Fig. 31 shows the throughput of the network. The OIAR allocation scheme is able to improve the total system throughput but it is limited by the total number of resource blocks available in the network.

Although the improvement on system throughput is not so significant due to limited radio resources, the proposed algorithm can support more high data rate users as a result of its lower average BER.

Fig. 31 System throughput of proposed OIAR allocation compared to random allocation

If the network is required to maintain a minimum data rate of 1.4Mbps for each user, the blocking probability is as shown in Fig. 32. The proposed OIAR allocation scheme can reduce the blocking probability by half at full network capacity, i.e. more high data rate users are supported by the network.

Fig. 32 Blocking Probability of proposed OIAR allocation compared to random allocation at min 1.4Mbps per user

B. Ordered Interference-Aware Resource Allocation with D2D Communication

The previous simulation results proved that the proposed ordered interference-aware resource allocation scheme is able to reduce the average BER and provide high data rate service to more users. However the throughput is still limited by the number of resource units in the network system. Therefore D2D users are introduced into the cellular network to achieve a higher total network throughput.

Since the harmful interference caused by D2D users is unavoidable even with the measurement-based protocol, the transmit power and transmit distance of D2D users become very important design parameters of such networks.

TABLE XI. PARAMETERS OF D2D USER PAIRS IN CELLULAR NETWORK

	Transmit Power	Maximum Transmit Distance
Set 1	1W	100m
Set 2	1W	200m
Set 3	0.25W	100m
Set 4	0.25W	200m

The results of average BER of the same resource allocation scheme under different network scenarios are shown in Fig. 33. When D2D users are introduced into the network, the BER increases as a result of the increased interference. Four different sets of D2D users are simulated to investigate the effect of different D2D transmit power and distance.

Fig. 33 Average BER of proposed OIAR w/ D2D allocations scheme with different combinations of D2D communication

When the transmit power of D2D users is high, the distance between D2D pairs does not have much impact on the average BER of the network. A significant increase is noticed when the number of cellular users per cell goes over 10, this is caused by two reasons: Firstly, the network radio resource is not fully utilized for small number of users, therefore the cellular users do not have to share same resource blocks with D2D users. When the number of cellular users increases, the harmful interference caused by D2D communication operating on the same subbands increases dramatically; Secondly, the total transmit power is limited in each cell, so if there are more than 10 cellular users, the transmit power for each cellular user decreases which makes them more vulnerable against the interference caused by D2D communication.

When the transmit power of D2D users is low, the distance between D2D pairs has a more obvious impact on the average BER. When the D2D pairs are placed within 100m to each other, the performance of D2D communication is very promising. However the transmit power is insufficient for D2D users to communicate over long distance. Also the low transmit power scenarios do not have the abrupt increase because the interference introduced by D2D communication is low.

Fig. 34 Average BER of proposed OIAR w/ D2D allocations scheme with different combinations of D2D communication

The results of total system throughput are presented in Fig. 34. Although the network suffers from a higher BER with D2D communication, the total system throughput can be improved significantly as a benefit of using D2D communication underlying a cellular network. The spectrum can be efficiently reused by introducing the direct device-to-device communication and the network is able to support more users with its limited bandwidth.

When D2D users have a low transmit power, the system achieves a high throughput for small distance D2D pairs. However the performance is not as good for D2D pairs located further apart due to insufficient transmit power. When the transmit power of

D2D users is large, the throughput performance of different D2D distances does not show much difference. As the number of cellular users increases, the transmit power per cellular user decreases and more resource blocks have to be reused. Therefore a slower increasing trend is observed for larger number of cellular users as a result of the abrupt increase of average BER.

The results of different settings of D2D users in Fig. 33 and Fig. 34 showed that the both the transmit power and distance of D2D users are very critical parameters affecting the network performance of such hybrid systems.

A high transmit power of D2D users might cause more severe interference to existing cellular users but it is able to cover a longer transmit distance for D2D communication. While a low transmit power achieves better system performance if the D2D users are placed near to each other.

Although the setting of 0.25W transmit power and 100m D2D distance provides best overall performance, the scenario is very limited and the performance cannot be guaranteed as the D2D distance increases. However it is noticed the case of D2D transmit power of 1W can achieve comparable system performance when the number of cellular users is small, where the D2D pairs are in fact using idle resource blocks that are not used by cellular communication. Therefore it is feasible to use high transmit power for D2D communication in a network not so densely packed.

With the increased number of cellular users, more resource blocks have to be shared and transmit power per cellular user decreases. In such situations, D2D communication with lower transmit power is preferred so that the quality of cellular communication will not be downgraded.

Taken the above two points into consideration, we proposed to use an adjustable transmit power for D2D users such that the system can cover a longer D2D distance in a sparse network but does not suffer too much from the interference when the number of cellular users becomes large.

Fig. 35 Average BER of proposed OIAR w/ D2D allocation and OIAR allocation compared to random allocation scheme

From the above study of parameter settings of D2D communication, an adjustable power level is used for device-to-device users with maximum D2D distance of 200m. The D2D users will always use half of the transmit power as compared to cellular users, therefore the cellular users are provided necessary protection against the increased interference. The simulation results of network performance with this setting are compared to OIAR allocation without D2D communication and random allocation scheme in Fig. 35 and Fig. 36.

With adjustable D2D transmit power, the average BER is relatively the same as the scenario with high transmit power for small number of cellular users. But as the cellular user number increases, it benefits from using decreased D2D transmit power so that there is no longer an abrupt increase in BER.

The total system throughput increases significantly with the additional device-to-device communication enabled. The system is now able to support more users with its limited bandwidth and provide a much higher throughput.

Although the average BER is still higher than the cellular network without D2D communication as there are, after all, more users sharing the same radio resource. However the system throughput is much higher as a result of increased number of total users in the network. Therefore it is fair to say the hybrid system of D2D communication underlying cellular network is able to provide improvement on network performance.

Fig. 36 Average BER of proposed OIAR w/ D2D allocation and OIAR allocation compared to random allocation scheme

Furthermore, we studied the following scenarios with different users added to the cellular network. In each scenario, it begins with 10 cellular users in each cell using the resource allocation scheme accordingly. The D2D communication users are allocation with maximum distance of 200m and have an adjustable transmit power as stated in the previous text.

TABLE XII. PARAMETERS OF ADDED USERS IN CELLULAR NETWORK

	Added Users	Resource Allocation Scheme
Set 1	Cellular users	Random
Set 2	Cellular users	OIAR
Set 3	D2D users	OIAR w/ D2D

As each cell is able to accommodate 15 users on different subbands, the cellular network without D2D communication rejects more users to share the network. Therefore the average BER stays the same but the blocking probability increases dramatically when the total number per cell exceeds 15. However the added D2D users are still able to share the network resource with OIAR w/ D2D allocation scheme. Although the average BER keeps increasing, the blocking probability is kept at an acceptable level. The system throughput is therefore much higher for OIAR w/ D2D scenario as its network can accommodate more than 15 users per cell.

Fig. 37 Average BER of a cellular network with added users using different resource allocation schemes

Fig. 38 Blocking probability of a cellular network with added users using different resource allocation schemes

Fig. 39 System throughput of a cellular network with added users using different resource allocation schemes

5.7 SUMMARY

In this chapter we proposed an ordered interference-aware resource allocation scheme to fully adapt to the characteristic of the multipath Rayleigh fading channels in OFDMA networks and take advantage of the network diversity as well as the user diversity.

Simulation results have shown significant improvement on network performance over random resource allocation. The network can achieve higher capacity with lower BER using our dynamic interference-conscious approach. If a certain high data rate service is required by the network, the proposed scheme is able to achieve a lower blocking probability.

When D2D users are introduced to the cellular network, the shorter transmission distance enables a higher utilization of the network resources therefore a higher system throughput can be achieved. Although it introduces additional interference, but the disruption is relatively tolerable because of the lower transmit power and shorter transmit range of D2D terminals.

However, since the D2D transmissions take place on the same spectrum as the cellular users, the increase in interference level is not avoidable. And because the cellular users operate on licensed bands, the interference needs to be taken extreme care of. The effect of transmit power and transmit distance of D2D users were first studied and the network performance was presented and analysed. The study came to a conclusion that an adjustable transmit power should be used for D2D users.

Our protocol minimizes the effect of harmful interference by sensing surrounding interference levels to efficiently and intelligently reuse radio resources. The adjustable transmit power according to the network environment also provide maximum D2D coverage without disturbing the cellular communication. The simulation results showed a significant improvement on total network throughput with relatively comparable average BER level.

More interference mitigation techniques for D2D communication under cellular networks can be explored in the future. And it is also feasible to adapt a blocking mechanism of D2D users when necessary in order to guarantee the QoS of cellular users.

Chapter 6

Conclusion and Future Work

6.1 CONCLUSION

The rapidly increasing number of cellular subscribers and high demand for multimedia cellular services are calling researchers in both academia and industry to explore new technologies for next generation cellular communication systems. In conclusion, this thesis has mainly explored new resource allocation schemes for future cellular networks based on two network structures, TDD-CDMA and OFDMA. Simulations were carried out to evaluate the proposed algorithms in terms of network performance as well as energy consumption. The results proved the proposed schemes able to increase the radio spectrum utilization and use radio resources more efficiently. Therefore the overall system performance can be significantly improved.

In this thesis, two network structures, TDD-CDMA MCNs and OFDMA networks, were studied to explore resource allocation techniques for the next generation cellular networks.

Firstly the original CDMA/PRMA scheme was studied for uplink voice packet transmission in TDD-CDMA SCNs and MCNs and served as a comparison baseline. A Multi-Medium MAC with Retransmissions (mmMAC/RT) scheme with fixed RSs was proposed based on the CDMA/PRMA protocol and its simulation results outperform

both CDMA/PRMA and mMAC for $R=750\text{m}$. An investigation was conducted because this scheme cannot provide desirable performance for large radius.

Furthermore, a modified scheme, OMAC, was proposed and proved to outperform CDMA/PRMA for SCNs and mMAC for MCNs. The new algorithm is also able to reach a larger cell radius such as $R=1.5\text{km}$. Because the two-tier division is no longer needed in either of the two proposed schemes, the unnecessary hopping in mMAC which result in waste of channel resources and increase of interference levels can be efficiently avoided.

After investigating network performance for TDD-CDMA MCNs, the emphasis moved onto energy consumption. Various time slot allocation schemes were studied and compared to conventional single-hop schemes, using two multi-hop schemes, ML-FTSA and ML-DTSA. Then a new ORS selection scheme was proposed and examined in two traffic scenarios, low-data rate traffic and high-data rate traffic. The results of energy consumption were proved to be significantly lower compared to traditional FRS selection when the data rate is low. When the data rate is high, the multi-hop schemes have very similar performance to the single hop schemes in terms of energy consumptions. The ORS selection has higher energy consumption than FRS when the number of RSs is small, but requires less transmission energy with increased number of RSs. Finally, by taking advantages of both FRS and ORS, a half-fixed RS selection was proposed and outperformed the rest.

After studying the resource allocation and relay selection schemes for TDD-CDMA

networks, the focus of the research moved onto OFDMA networks as it is a very promising structure selected by LTE.

The frequency selective fading channel characteristics were studied in order to conduct the performance simulation of OFDMA networks. A channel generation model was proposed for frequency selective multipath Rayleigh fading channels from a L-path tapped delay model. The details were presented and the calculation of performance metrics was also discussed. The channel model was validated through simulation and showed very similar performance to previous studies. The same model was also used in the last part of this thesis for performance analysis of proposed resource allocation schemes in OFDMA networks.

In the last part of OFDMA resource allocation study, an ordered interference-aware resource allocation scheme was proposed to take advantage of the channel and user diversity of the network. The inference-conscious scheme has proven to be able to adaptively adjust to the multipath Rayleigh fading channels in OFDMA networks. Simulation results showed significant improvement on network performance over random resource allocation scheme. Thus a higher capacity can be offered by the network with lower BER and blocking probability.

Since direct D2D communication has a shorter transmission distance, it is able to achieve higher utilization of the network resources therefore provide a higher system throughput. However, by reusing the same spectrum as cellular users, the D2D communication causes an increase in interference level and may affect the performance

of cellular network. Different settings of D2D users were studied and the results proved using an adjustable transmit power for D2D users is one of the optimal solutions.

An order interference-aware resource allocation scheme with D2D communication under cellular network was proposed using adjustable transmit power according to the number of cellular users in the cell. The simulation results have proved its ability to efficiently and intelligently reuse radio resources and provide a significant improvement on total network throughput with relatively comparable average BER level.

6.2 FUTURE WORK

With the tremendously increasing popularity of smart phones, capability of data traffic volume and application access has become an important aspect of network design. It has become the greatest challenge in next generation cellular networks to support high-speed multimedia services. Data traffic should therefore be taken into serious consideration in developing future allocation schemes and network architecture design.

The performance of allocation schemes in TDD-CDMA MCNs simulated in this thesis is only limited to voice communications. But we believe the proposed algorithms also provide an idea for data traffic communications. More researches considering data and video traffic can be carried out to investigate new resource allocation schemes for multimedia services. Data traffic, unlike conventional voice traffic which is balanced between uplink and downlink communications, usually requires much more downlink data compared to uplink. Different traffic scenarios combining conventional voice traffic

and various biased data traffic demands should also be investigated to study new resource allocation schemes.

In order to mitigate the effect of added interference by multihop communication, a more efficient power control scheme is also worth conducting research on. At the same time, energy efficiency should always be kept in mind for network designers as it is an important aspect in cellular communications. With careful planning and suitable resource allocation schemes, multihopping can be a very appealing alternative to support affordable high-data-rate services to cellular users.

In a hybrid network with device-to-device communications underlaying cellular communication, interference management becomes a very critical issue for resource allocation design. The inter-system interference between the cellular and D2D transmission, as well as the inter-cell interference between adjacent cells, might prevent the overall system throughput from being further enhanced if they are not taken good care of.

More researches can be carried out to explore various interference control techniques for D2D communication in order to minimize its effect on existing cellular users. A feasible idea might be adopting a blocking mechanism of D2D users so that the priority services of cellular users can be guaranteed. Also a more dynamic power control with channel estimation can be considered to mitigate the effect of inter-system interference from D2D communication.

Although more exploration on the interference control is needed, the benefit of low transmission power and reliable communication helps D2D communication utilize spectrum resources more efficiently and provides a promising possibility to the future cellular networks.

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