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Novel Concepts of Cooperative Wireless Networking

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Novel Concepts and Applications of Cooperative Wireless Networking

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Abstract

Although wireless networks have achieved great success in the lastest two decades, the current wireless networks have difficulties to fulfill users' ever-increasing expectations and needs. It is mainly due to available spectrum resource scarcity, limited battery capacity of wireless device, unreliable wireless radio link, etc. To tackle these issues, a new telecommunication paradigm has been proposed, referred to as cooperative wireless networking [1].

The basic idea of cooperative wireless networking is that wireless devices work together to achieve their individual goals or one common goal following a common strategy. Wireless devices share their resources (i.e. radio link, antenna, battery, processing unit, etc.) during cooperation using the short-range technology as the underlying communication platform. The amount of data exchanged over the short-range link differs from application to application. In some situations the short-range communication is not used at all in case all mobile devices have a predefined mutual understanding of their cooperativeness. The main reason of cooperation is threefold: first, the limit capability of wireless devices can be virtually enhanced by cooperation; secondly, the increasing density of the wireless devices makes cooperation possible; last, the cost of information exchange (i.e. transmission power, transmission time, spectrum, etc.) is very low if information exchange over short-range link is needed. Cooperation changes the way of information delivery and the concept of wireless device resource. It is promising to solve the crucial issues that cannot be easily tackled in conventional network architectures.

Different cooperative strategies or schemes according to cooperation concept are proposed in the thesis to solve crucial issues in different wireless networks. An energy saving cooperative strategy for DVB-H networks is designed as a primary attempt to illustrate the potential of cooperation application for multicast services. Furthermore, a cooperative retransmission scheme is proposed for reliable multicast service in wireless network. These two cooperative schemes are used for downlink traffic. In addition to that, cooperation is also applied to uplink access. *One4all* cooperative uplink access strategy is proposed for WLAN to reduce the collision probability to save energy. Cooperation concept is also applied in spectrum sensing for a cognitive radio MAC protocol. Finally, a novel modulation, hierarchical modulation, is used to facilitate the uplink transmission in cooperative networks. Simulation and analytical analysis has been conducted. Great potentials of cooperation are shown in improving the energy efficiency, spectrum efficiency, quality of service, and so on.

Resumé

Selv om trådløse kommunikationsnetværk gennem de seneste to årtier har vundet stor udbredelse, så er det svært for de nuværende netværk at opfylde brugernes stadigt voksende forventninger og behov. Dette skyldes især det begrænsede radio spektrum, de trådløse terminalers begrænsede batterilevetid og upålidelige støjfyldte radiokanaler. Til løsning af disse problemer foreslår afhandlingen et nyt telekommunikations paradigme, kooperative telekommunikations netværk [1].

Den grundlæggende idé i kooperative telekommunikationsnetværk er, at de trådløse terminaler kan opnå individuelle og fælles mål ved i samarbejde at følge en fælles strategi. Under samarbejdet deler de trådløse terminaler deres ressourcer (radiokanaler, antenner, batterier, processorer osv.) ved at bruge kortdistance radioforbindelser som den underliggende kommunikations platform. Den mængde data, der udveksles over kortdistance forbindelsen, varierer fra anvendelse til anvendelse. I nogle tilfælde bruges kortdistance forbindelsen slet ikke, hvis der er en på forhånd veldefineret samarbejdsform mellem de trådløse terminaler. Der er tre hovedbegrundelser for samarbejde: (i) for det første kan de begrænsede muligheder i den enkelt trådløse terminals udvides virtuelt ved samarbejde; (ii) for det andet muliggøres samarbejdet af den voksende terminaltæthed; (iii) endelig er omkostningen ved udveksling af data (forbrug af energi, tid, radiospektrum osv.) meget lavere, hvis informationsudvekslingen sker over kortdistance forbindelser. Ved kooperation ændres både ressource-begreberne i trådløse terminaler og den måde, informationsudveksling sker på. Kooperation er en lovende metode til løsning af kritiske problemer, der vanskeligt kan løses i konventionelle netværksarkitekturer.

Alt afhængigt af samarbejdsprincippet foreslår afhandlingen forskellige strategier og arrangementer til løsning af kritiske problemer i forskellige trådløse netværk. Som et primært forsøg på illustration af potentialet i kooperative strategier designes en energibesparende strategi for anvendelse af DVB-H netværk til multikast tjenester. Endvidere foreslås en kooperativ retransmissions protokol for pålidelige multikast tjenester i trådløse netværk. Disse to kooperative strategier anvendes på indkommende trafik til terminaler (downlink). Derudover anvendes kooperative metoder i afhandlingens senere kapitler også til udgående (uplink) trafik. "One4all" er en kooperativ tilgangs strategi for udgående trafik i trådløse lokalnet (WLAN) til reduktion af sandsynligheden for kollision og reduktion af energiforbrug. Kooperationsprincippet anvendes også til detektering af spektrum i en kognitiv radio tilgangs (MAC) protokol. Endelig anvendes en ny form for modulation, hierarkisk modulation, til at forbedre datatransmissionen i kooperative netværk. Undersøgelser er gennemført med simuleringer og analytiske metoder. De viser, at der er ved kooperation er et betydeligt potentiale for forbedring af bl.a. energi effektiviteten, spektrum udnyttelsen og service kvaliteten.

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Ph.D. Publications

The following publications have been achieved throughout this Ph.D. project.

Conference Publications:

[1] Q. Zhang, F. H. P. Fitzek, and V. B. Iversen, "Cognitive radio mac protocol for wlan," in *The 19th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC08)*, September 2008

[2] Q. Zhang, F. H. P. Fitzek, and V. B. Iversen, "Asymmetrical modulation for uplink communication in cooperative networks," *ICC Workshops - 2008 IEEE International Conference on Communications Workshops*, pp. 85–90, 2008

[3] Q. Zhang and H. Dam, "Wimax network performance monitoring & optimization," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, pp. 574–586, April 2008

[4] Q. Zhang, F. H. P. Fitzek, and V. B. Iversen, "One4all cooperative media access strategy in infrastructure based distributed wireless networks," in *IEEE Wireless Communication and Networking Conference (WCNC)*, pp. 1501–1506, April 2008

[5] Q. Zhang, V. B. Iversen, and F. H. P. Fitzek, "Throughput and delay performance analysis of packet aggregation scheme for prma," in *IEEE Wireless Communication and Networking Conference (WCNC)*, pp. 1380–1384, April 2008

[6] Q. Zhang, F. H. P. Fitzek, and V. B. Iversen, "Design and performance evaluation of cooperative retransmission scheme for reliable multicast services in cellular controlled p2p networks," in *The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC07)*, pp. 1–5, September 2007

[7] T. K. Madsen, Q. Zhang, and F. H. P. Fitzek, "Design and evaluation of ip header compression for cellular-controlled p2p networks," in *IEEE International Conference on Communication (ICC)*, pp. 4046–4051, June 2007

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[11] Q. Zhang and F. H. P. Fitzek, "Designing Rules for Self-Organizing Protocols for a Cooperative Communication Architecture," extended abstract for iwsos'06 poster section, University of Passau, Sep 2006

Journal publication list:

[1] G. P. Perrucci, F. H. Fitzek, Q. Zhang, and M. Katz, "Cooperative

mobile web browsing," *EURASIP Journal on Wireless Communications and Networking*, 2009

[2] F. H. P. Fitzek, M. Katz, and Q. Zhang, "Cellular controlled short-range communication for cooperative p2p networking," *Wireless Personal Communications*, 2008

[3] Z. He, Q. Zhang, and V. B. Iversen, "Trunk reservation in multi-service networks with bpp traffic," *Springer Lecture Notes in Computer Science*, vol. 4396, pp. 200–212, 2007

Book Chapters:

[1] Q. Zhang, F. H. P. Fitzek, and M. Katz, *WiMAX Evolution: Emerging Technologies and Applications*, ch. Cooperative Principles in WiMAX. John Wiley & Sons. Ltd, 2008

[2] Q. Zhang, F. H. P. Fitzek, and M. Katz, *Cognitive Wireless Networks: Concepts, Methodologies and Visions Inspring the Age of Enlightenment of Wireless Communications*, ch. On the Energy Saving Potential in DVB-H Networks Exploiting Cooperation among Mobile Devices. Springer, 2007

[3] Q. Zhang and F. H. P. Fitzek, *Cognitive Wireless Networks: Concepts, Methodologies and Visions Inspring the Age of Enlightenment of Wireless Communications*, ch. Cooperative Retransmission for Reliable Wireless Multicast Services. Springer, 2007

[4] Q. Zhang, F. H. P. Fitzek, and V. B. Iversen, *Cognitive Wireless Networks: Concepts, Methodologies and Visions Inspring the Age of Enlightenment of Wireless Communications*, ch. Cluster based Cooperative Uplink Access in Centralized Wireless Networks. Springer, 2007

[5] T. K. Madsen and Q. Zhang, *Cognitive Wireless Networks: Concepts, Methodologies and Visions Inspring the Age of Enlightenment*

of Wireless Communications, ch. IP Header Compression for Cellular - Controlled P2P Networks. Springer, 2007

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Chapter 1

Introduction

1.1 Motivation: Challenges of 4G

In the latest two decades 2G cellular networks have achieved an unprecedented success because of the revolutionary communication manner and a variety of new services. Since the early 21st century, 3G networks have been launched in Japan, South Korea, US, Europe, and so on. However, the transition of the commercial cellular networks from 2G to 3G was not as successful as researchers expected. Besides the reasons of the worldwide downturn in economy, the delayed technology development, spectrum usage right issues, etc. [26], the reasons lie in the limited data rates over the 3G air interface and the lack of novel and appealing services motivating the customers to shift their 2G mobile devices to 3G devices [26, 27]. Because of the limitations of 3G, researchers and industries are trying to define 4G in the research and development plans envisioning the future wireless and mobile networks.

What are the envisioned 4G networks? Opinions converge and diverge. So far there has not been any common, clear and widespread understanding of its meaning [21]. On one side many researchers see 4G as a simple linear extension of the existing cellular network [28–30], namely they regard 4G as the synonymous of high data rate wireless communication system. Such understandings are unilateral because high data rate is just one of the goals. On the other side, some other researchers have had first attempts to break the conventional design paradigm. They predict that 4G will not be a linear extension of 3G [31, 32]. Among the latter, one of the 4G definitions is given in [32]: 4G will be a convergence platform that will provide clear advantages in terms of bandwidth[1], coverage, power consumption and spectrum usage, and also offering a variety of new rich content services.

From the technical point of view, to implement 4G as defined above we should improve the key performances such as data rate, coverage, energy efficiency and spectrum efficiency as well as reduce hardware complexity. It is a multi-object optimization problem. There is a trade-off between different performances and it is hard to improve all of them simultaneously. For instance, all current available network technologies are not able to break through the limitation of the coverage and data rate trade-off defined by the Shannon law. It means that to achieve reliable transmission the signal to noise ratio (SNR) of each received bit should be above a certain threshold. At given transmission power, the higher data rate results in less energy at each bit. Therefore, the increased data rate reduces the coverage range, which results in more base stations (access points) to cover the same area. The other approaches to obtain reliable transmission at a target distance with certain data rate are often at the expense of high transmission power. However, the ever-increasing power consumption of mobile device has become a crucial issue in new generation networks, since the development rate of battery capacity cannot meet the mobile process power needs [27]. Besides those, to host all functionalities, the hardware complexity of a mobile device will inevitably be increased. Consequently, it is challenging to achieve large market penetration of such new mobile devices. In a nutshell, the relation of all the key factors of 4G can be expressed by Figure 1.1. It indicates that the key factors of 4G (i.e. energy efficiency, spectrum efficiency, QoS, hardware complexity) all relate with the cost in money.

Besides technical perspectives, novel and appealing services are indispensable to implement 4G; otherwise, 4G has a big risk to repeat the same path as 3G. As pointed out in [26], since users are the main actors playing on the stage of the wireless world; users' requirements should not be secondary with respect to the technological issues.

Therefore, a question comes up whether 4G can be realized by just inventing a new air-interface with all the expected features by techniques

[1] According to telecommunication fundamental, it would be more proper to use "peak data rate" instead of "bandwidth".

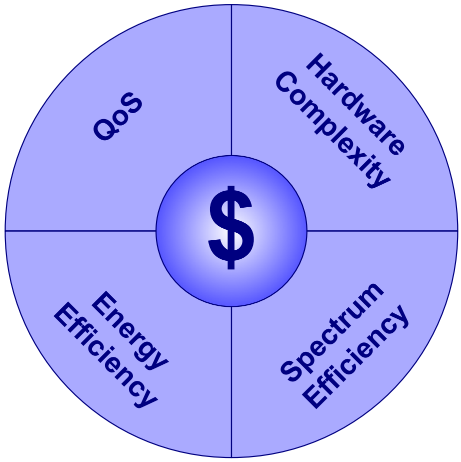


Figure 1.1: Relations among key factors of 4G.

such as advanced signal processing, MIMO, advanced modulation and coding schemes and other. In my point of view 4G is far more beyond that, since 4G will not be a simple linear extension following the paradigm of conventional generation upgrade.

1.2 A Possible Solution: Cooperative Networking

1.2.1 State-of-the-Art of Wireless and Mobile Networks

Before proposing a possible solution, let us take a look at the state-of-the-art of the current wireless and mobile networks. From the service coverage (range) point of view, wireless communication networks can be shown by Figure 1.2 [21].

Figure 1.2 clearly distinguishes the networks as two main components, i.e. *wide area network* and *short-range networks* [21]. Wide area networks usually work on licensed spectrum; moveover, it has relatively higher power consumption and lower data rates. Wide area networks are the most common commercial wireless networks dominated by centralized network architecture within which wireless handsets all work stand

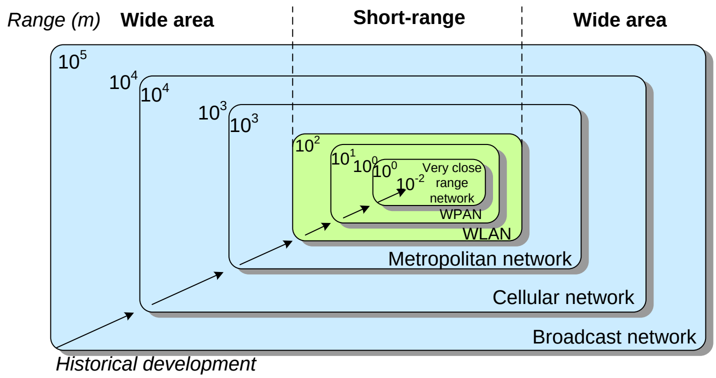


Figure 1.2: Overview of wireless communication networks in terms of service coverage [21].

alone, as illustrated in Figure 1.3. The development of short-range networks has shown the great potential of utilizing unlicensed spectrum and lower power consumption to support higher data rate in a distributed network architecture. The two components of networks are developed independently of each other and try to coexist. The relationship of the two components of networks is often seen as complementary.

Additionally, in current wireless communication world the density of wireless devices is continuously increasing. According to the Wireless World Research Forum (WWRF), *seven trillion ($7 \cdot 10^{12}$) wireless devices will serve seven billion ($7 \cdot 10^{9}$) people by year 2017* [33]. Therefore, on the average about 1000 wireless devices serve one person. The proliferation of wireless devices results in the increasing density of wireless devices. It means that the distance between wireless devices is getting shorter, namely one wireless devices can seldom be isolated from others. Consequently, it creates a good environment for the wireless devices close to each other to form a cluster for interaction. Furthermore, it should be mentioned that the wireless devices have heterogeneous characteristics with regards to display size, weight, performance (processing power, memory, storage space, battery life), supported network, and so on (Figure 1.4). Since in the future heterogeneity of wireless devices will exist more widely, how to take advantages of wireless devices surrounding a person to tackle the crucial issues would be a feasible design trend of 4G.

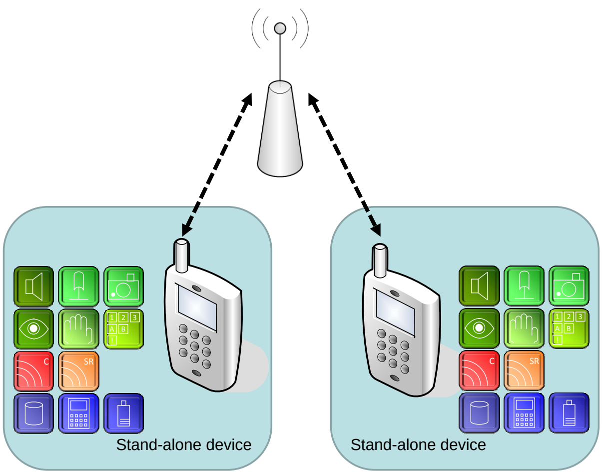


Figure 1.3: Communication manner of stand-alone mobile devices in centralized network [16].

Figure 1.4: Heterogeneous wireless devices.

In previous observations, wireless devices are often assumed to belong to the same person. Besides that, wireless devices belonging to different persons are also close to each other. Some recent measurement results show that a measured device can always see about six neighboring wireless devices through Bluetooth air interface in a scenario of a bar environment [22] (Figure 1.5). It actually reveals a common social phenomenon that is often overlooked by researchers: users of wireless device are not stand alone in daily life.

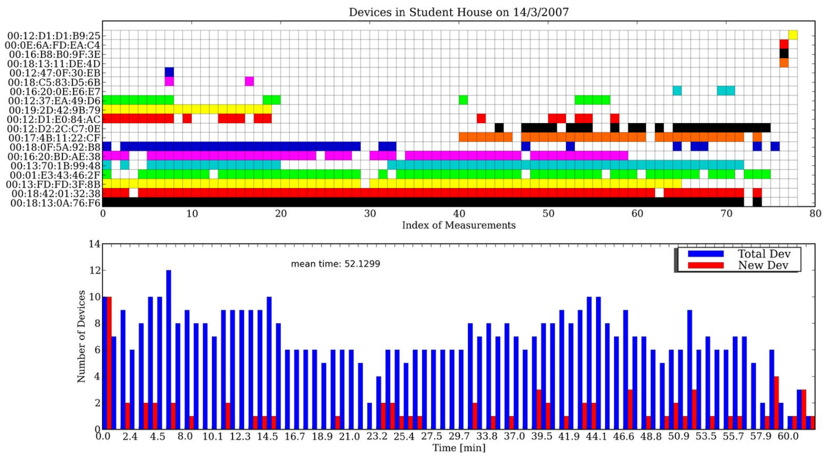


Figure 1.5: Measurement of number of neighboring devices in intercommunication coverage of a wireless device in a bar [22].

1.2.2 A Cooperative Network Architecture: CCP2P (Cellular Controlled Peer To Peer Networks)

With the trend of the existence of heterogeneous wireless devices and the increasing density of wireless devices, we believe that it will influence the way of information exchange and delivery as well as the evaluation of a wireless device resource. A simple case is that a wireless device can communicate directly with its neighbors if it needs, instead of always via a base station (or access point). Furthermore, a wireless device is composed of several entities or functionalities grouped into user interfaces (camera, keyboard, sensors, etc.), communication interfaces (cellular and short-range)[2], and a number of built-in resources as given in Figure 1.6. The resources of a wireless device should not be evaluated in isolation by counting only its physical resources, but the potential resources from the neighboring devices should be taken into account as well.

[2]The air-interface of a wireless device by which it communicates with the base station (or access point) is referred to as *cellular air-interface*. Therefore, the link between a wireless device and a base station (or an access point) is referred to as *cellular link*. Correspondingly, the air-interface for communication between neighboring wireless devices is referred to as *short-range air-interface*. Therefore, the link between neighboring wireless devices is referred to as *short-range link*.

Figure 1.6: Available entities on a wireless device grouped into user interfaces, communication interfaces, and built-in resources [16].

Therefore, the conventional centralized architecture is expected to be enriched by communication among wireless devices. By allowing communication links among wireless devices in proximity to each other, wireless devices can form a cooperative cluster to share their essential resources such as battery, CPU, wireless links, etc. By aggregating those resources into a virtual entity, it can be more efficiently utilized in a cooperative manner than in any stand alone mode. In a nutshell, there is a potential synergy between cellular network[3] and short-range networks.

Based on the anticipated potentials and the available heterogeneous network techniques, instead of researching the dominating centralized network architecture, a complete new telecommunication paradigm, *cooperative networking*, emerges. It is an innovative way of starting 4G research by a non-linear extension of the conventional existing networks.

Word *cooperate* derives from the Latin words *co-* (with, together, jointly) + *operate* (to work); therefore, it means "working together". Cooperation is a strategy of a group of entities working or acting together towards a common or individual goal [34]. Correspondingly, the connotation of cooperative networking is that within a network the wire-

[3]Here the concept of cellular network is wider than that of the conventional cellular network.

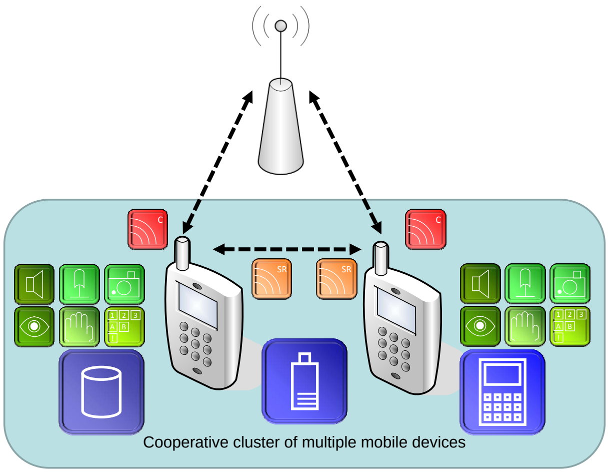


Figure 1.7: CCP2P–Cellular Controlled Peer to Peer Network [16].

less devices work together to achieve a goal. The cooperative network is often realized in the form of a composite access network which is composed of heterogenous networks (cellular and short-range networks) and can take good advantages of both. The predesigned cooperation strategies can be tailored towards different goals and applied within and across the layers in OSI (Open Systems Interconnection) model among the wireless devices. Considering the available network techniques, a cooperative network architecture, referred to as *Cellular Controlled Peer to Peer* (CCP2P) network (Figure 1.7), is proposed in [27].

CCP2P is a dynamic approach to bridge cellular and peer-to-peer network architecture [27] and it is a promising composite access network architecture. In CCP2P networks, a wireless device does not only have connection with outside world through *cellular link* but also can communicate with neighboring wireless devices within its proximity by *short-range link*. The great advantage of the proposed cooperative network architecture is that it efficiently exploits the synergy of two complementary networks, such as licensed and license-extempt spectrum usage, high power/wide area/low data rate/high EpBR (Energy per Bit Ratio) and with low power/short-range/high data rate/low EpBR. It can effectively tackle the critical trade-off issues among energy efficiency, spectrum efficiency, hardware complexity of wireless devices and service quality.

Furthermore, as Fitzek and Katz point out in [27], the CCP2P network architecture can bring the two current main component networks and future wireless communication systems into a closer and amicable relationship, rather than regarding them just as coexistent networks or even competing ones in the worst case. Consequently, in CCP2P network architecture the relation among the heterogeneous networks evolves from coexisting to cooperating as shown in Figure 1.8.

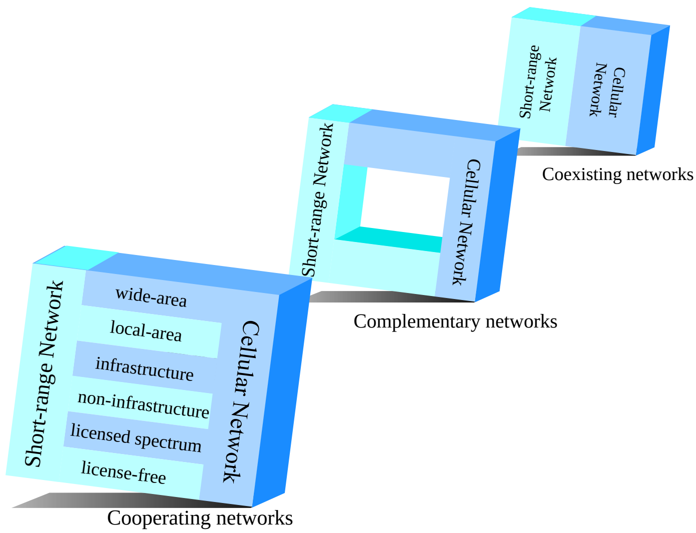


Figure 1.8: An evolving view of future heterogeneous wireless networks [11].

It should be noted that the so-called cellular link here is not limited as the radio link in the traditional cellular network, but that it can be generically understood as the main access link to the service. For example, a CCP2P network can use DVB-H radio link as cellular link and Bluetooth as short-range link, or it can use GPRS as cellular link and WiFi as short-range link, etc. The concept of cellular link and short-range link is relative. In other words, which network technique serves as cellular link or short-range link is very flexible and depends on the cooperation scenarios. Especially, the access networks which support both infrastructure based and infrastructure free topology (e.g. WiFi) might serve as cellular link in one cooperative scenario and as short-range link in another scenario.

The cooperative relationship between/among wireless devices can basically be summarized into four classes in the following.

S–S a single user cooperates with the other.

S–M a single user helps the others (i.e. multiple ones) in a cooperative cluster.

M–S the rest of users in a cooperative cluster together help a single one.

M–M two groups of peers in the same cooperative cluster, one group helps the other, i.e. multiple users cooperate with multiple ones.

According to w/o (with/without) incentives in cooperative partners, cooperation is divided into egoistic and altruistic cooperation. Cooperation in this thesis only denotes egoistic cooperation. Egoistic cooperation is a joint action for mutual benefits and it follows reciprocity principle which will be mentioned in Section 1.4. Therefore, the cooperative relationship in egoistic cooperation is not unilateral and there is often a cooperation cycle in which the partners contribute their efforts as well as gain benefits. For instance, in S–M cooperation case the peers in a cooperative cluster alternately take the role as the contributing node.

Considering the heterogeneity of wireless devices, the cooperative cluster in CCP2P network architecture (Figure 1.7) can more generically be interpreted as a wireless grid. Namely, the wireless grid communicates with a base station (access point) through cellular link, and the heterogeneous wireless devices are grouped together over short-range link within the wireless grid (Figure 1.9).

1.2.3 Interrelation between Cooperative Networking and Potential Services

To take 4G into a successful path, we should, as mentioned above, not only solve technical issues to improve the quality of service (QoS) of existing services, but also devise novel and appealing services. The cooperative network architecture has tremendous potential to design numerous services that otherwise would not be available, because cooperation can

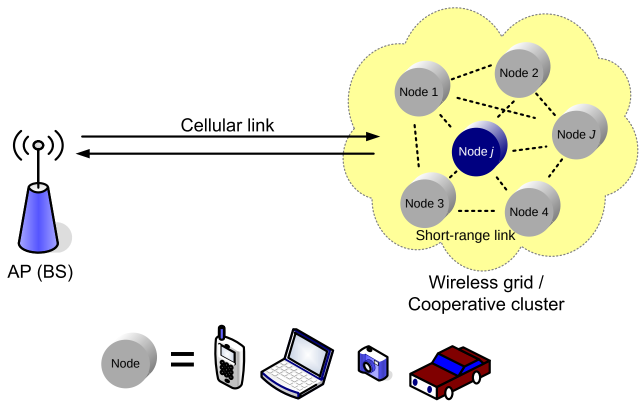


Figure 1.9: Wireless grids network architecture [16].

enable an ordinary wireless device to virtually extend or aggregate its capabilities[4]. For instance, people can show their pictures stored in the mobile phone through available big screen in public places. For instance, a mobile phone can automatically update the clock of a camera when it has synchronized with the local base station during traveling. For instance, two mobile phones can aggregate their cellular link to accelerate downloading.

Moreover, from cultural and social perspectives cooperation is seen as a mean to enhance one's social capital or to improve one's reputation record in a reputation-based system [26]. As we know, each user is a social individual and they are seldom in isolation. A cooperative cluster can be formed not only according to their physical location but also according to their social characteristics. Namely, a group of users can be formed by having certain characteristics in common (e.g. hobbies, ethnicity, interests, musical preferences, etc.) or belonging to the same social group, such as family, friends, and colleagues [26]. Based on cooperative network architecture and diverse social groups, a variety of social networking services will emerge to meet needs of different groups.

[4]By cooperation with other heterogeneous wireless devices, the wireless device can obtain capabilities extension; on the other hand, a wireless device can obtain aggregated capabilities (e.g. increased data rate, prolonged battery life, etc.) by cooperation with other homogeneous wireless devices.

Furthermore, it is promising that socio-technological possibilities can attract the users in a group to get closer to each other. The closer the users locate, the better performance cooperative networking can be obtained. Additionally, we can also expect that the more people join the cooperative group; the better and more interesting services will be devised, vice versa. In brief, cooperative networking provide a wide platform to create numerous novel services and increasingly enable social networking, while the novel services and social networking in turn shape the way in which wireless networks operate, namely leveraging the development of the cooperative networking.

1.3 Cooperation Examples in Nature and Human Society

Numerous examples of cooperation widely exist in nature from microbes to humankind. The mutual cooperation can take place between similar and dissimilar species:

- Cooperation between different species: it takes the advantages of different species. For instance, on the plain of Africa, ostriches, which have keen eyesight, cooperate with Zebras, which have acute hearing.

- Cooperation between the same species: since a single individual has very limited capability, cooperation can aggregate the contributions of all the individuals to achieve a common or individual goal beyond the single individual capability:

  – for an individual goal: it exists between a pair of peers or among a group of partners. A good case in point of cooperation between two individuals is the cooperation between vampire bats given in [34]. Vampire bats live in a large group. Vampire bats have the characteristic that they need blood at least every sixty hours; otherwise, most of them will starve to death. To have enough blood in time, they need cooperation. When they find a blood source, they will sip blood as much as possible. Those vampire bats full of harvesting blood can often help out the others which have not yet got enough blood. The interesting thing is that vampire bats have such a remarkable memory. A vampire bat can remember all the helpers who have ever donated blood to it; furthermore, it can detect and remember all the cheaters who have enough blood but refuse to donate. Later on, the vampire bat will help those who cooperated when they are in need; however, it will punish the cheaters by refusing their request for blood. It is a typical *tit-for-tat* strategy. In this example, the mutual cooperation is not completed at one time, i.e. the cooperative vampire bat uses its life time as a cooperative cycle.

– for a common goal: a group of individuals work together to achieve a goal which can hardly-obtained be by any single individual. One of the representative examples is the famous Tour de France[5]. Although the racers compete with each other trying to win the race, during most time of the race they have to form a big group to cooperate which is referred to as *peloton*. No one can afford if alienating themselves from the group. The reason lies in that wind resistance is a huge factor in energy use, and the *Peloton* can efficiently reduce the resistance and save energy. To form a *peloton*, the leading cyclist has to spend much more energy than the rest of people in the group. Therefore, people in the group alternately take the lead role to be fair. The cooperative relation in Tour de France at each cooperation instance is S-M cooperation. Besides that, M–M cooperation is also a very popular cooperation relationship to achieve a common goal. For instance, many ants often drag objects that are much larger than themselves, or primitive groups hunt together for food.

1.4 Cooperation Incentives and Rules

Wireless devices, controlled ultimately by human, can be considered as selfish, without any incentive to cooperate by nature. The reason is that a wireless device is always interested in maximizing its own benefit.

[5] Tour de France is the world's main cycle race and the route is around most of France.

Cooperation indeed costs (in terms of consuming its own resources), reducing the overall benefits to some extent. However, in any cooperation network the communication ultimately depends on the willingness of the peers to cooperate. Such cooperation can only be established and maintained if fairness is guaranteed among these peers; otherwise, the well known "tragedy of the commons" phenomenon will occur. Therefore, to avoid a cooperation to collapse, robust cooperation rules and good incentives are desirable.

To understand the incentives and basic rules for cooperation, we can learn from cooperation in nature. Inspired by these cooperative rules developed and optimized over millions of years, analogous principles can be developed and employed for wireless communication system. We summarize the main cooperation rules here [14]:

- Cooperators should have reciprocal behavior.
- Cooperator should be capable to effectively detect cheaters.
- Timely payoff should exist among cooperators, i.e. the payoff by cooperation should be received within a possible shortest delay.
- Group membership can affect the tolerance in payoff delay. In other words, the better one knows a partner entity, the longer one may accept to wait for getting revenue back. This implies that for different cooperative clusters, the social relations between users should be taken into account.

To analyze, design and implement the above mentioned cooperation rules in wireless communication system, game theory is a promising and appropriate tool and some work has been done in [35–40]. It can quantize the metric of the cooperation rules, and then it can be built into the decision maker. Thus it can help wireless devices to take a quick cooperative decision (i.e. whether to cooperate or not) and to have rational behavior in the cooperative networks. It can also re-enforce the cooperation among the cooperators, making cooperation more robust.

1.5 Related Work

1.5.1 Related Work on Cooperative Networking

Cooperative networking researches in addition to those on CCP2P network architecture or wireless grids, has many other interpretations and various extensions. Other main research on cooperative networking is on relay based cooperative networks exploiting the broadcast nature of the radio channel to form virtual antenna arrays, as in [41–46], which is referred to as cooperative communication in the following. In fact the concept of cooperative communication originates from relay wireless networks which are not new and can be traced back to [47, 48]. The work in [47,48] analyzes the information theoretic properties of the relay channel in the network composed of three nodes, a source, a destination and a relay node. The difference is that Van der Meulen discovered upper and lower bounds on the capacity of the relay channel [47]. Later on Cover and El Gamal [48] significantly improved the capacity bound given by Van der Meulen. The work by Cover and El Gamal [48] has the largest influence.

In recent years, cooperative communication based on the relay channel has gained tremendous attention and interests which started by the work of Sendonaris et al., [23, 49]. They generalize the conventional relay channel to multiple sources with information to transmit. These sources can also serve as relays for each other. The basic motivation of Sendonaris et al.'s work is that severe variations of the radio signal fading have great impact upon mobile user's data rate and upon the achievable quality of service (QoS) [23]. To improve the performance, besides the research work on advance signal processing, tailoring system components (such as coding, modulation, and detection), diversity is of primary importance due to the nature of the wireless environment [23]. To attain the diversity, it is indispensable to have multiple antennas; however, it is impractical for a small mobile to have multiple antennas. Therefore, to overcome the limitation yet still emulate the transmit antenna diversity, a new form of spacial diversity was proposed in [23]. The diversity gain is achieved by cooperation between the mobile users in a cell. The basic idea of user cooperation is that each user has a partner to cooperate with. Each user does not only transmit its own information but also forwards the information of its partner that it overhears due to the broadcast nature of wireless media. It generates spacial diversity by using of the partner's antenna, as given in Figure 1.10. The conclusion in [23] is that user cooperation is beneficial and can result in substantial gains over a non-cooperative strategy: it achieves higher data rates and decreased sensitivity to channel variations. Furthermore, [23] also indicates that the increased data rate with cooperation can be translated into reduced power for the users, as it can extend the battery life of a mobile device. According to Shannon's law, the cooperation gain can alternatively be used to increase cell coverage.

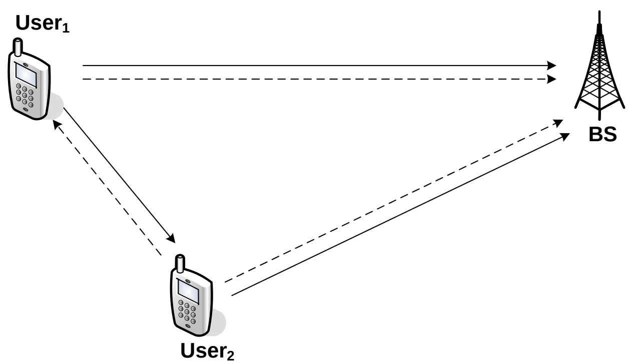


Figure 1.10: The basic network topology that used in the user cooperation study in [23]: both users work as a source and a relay.

Besides the works [23,49], remarkable contributions studying the performance of different relaying protocols in a fading environment is done in [42, 50, 51]. The main motivation in these work is to improve the reliability of communication in terms of, for example, outage probability, or symbol & bit error probabilities, for a given transmission rate [52]. More and more relaying algorithms or protocol variations are appearing in the literature and we summarize some of the basic and the most representative ones in the following, since the remaining protocols are variations of the basic ones. The classification is according to different types of processing by the relay node and different types of signal combination in the destination node.

- Fixed relaying

  - Amplify-and-Forward: The relay simply forward signals received from the source without data regeneration. Amplifying means a linear transformation at the relay. The amplification factor is decided by the relative strength of the source-relay and source-destination links [53]. This algorithm is often used in scenarios where source-relay and source-destination channels are comparable, and the relay-destination channel is good. Hence, in this scenario, the relay may not be able to decode the source signal, but nonetheless it has an independent observation of the source signal that can aid in decoding at the destination [53].
  - Decode-and-Forward: The relay uses apply some form of detection and/or decoding algorithm to the received signals and re-encode(s) the information for the transmit signals. The decoding and en-coding processes are often non-linear transformations of the received signals [52]. The decode-and-forward protocol is close to optimal when the source-relay channel is excellent, which often is the case where source and relay are physically near each other [53].
  - Coded Cooperation: In the previous two schemes users repeat their partner's detected symbols [49] or analog signals [50]. Different from those two, Hunter and Nosratinia proposed a new method that can be incorporated within the framework of existing channel codes. The users share their antennas such that a portion of each user's code bits arrive at the base station through a different, independent fading channel [43]. The basic idea is that each user tries to transmit incremental redundancy to its partner. Whenever that is not possible, the users automatically revert to a non-cooperative mode. The key to the efficiency of coded cooperation is that all this is managed automatically through code design, with no feedback between the users [24]. An illustration of the coded cooperation scheme is shown in Figure 1.11.

- Selection and dynamic relaying: The channel quality between source and relay limits the performance of fixed decode-and-forward protocol. Furthermore, the accurate fading coefficient between the source and relay, $\alpha_{r,s}$, can be measured by the cooperative nodes. Therefore, the transmission can be adjusted dynamically according to the fading coefficient $\alpha_{r,s}$.

Generally speaking, the selection relaying algorithm is that if the measured $\alpha_{r,s}$ is below a certain threshold, the source simply continues its transmission to the destination, in the form of repetition or more powerful codes. If the measured $\alpha_{r,s}$ is above certain threshold, the relay forwards the received signal from the source, by using either amplify-and-forward or decode-and-forward [42,52].

- Incremental relaying: Since the relaying requires extra radio resource; the fixed and selection relaying will result in inefficient spectrum use. The incremental relaying is an idea that exploits the limited feedback from the destination about the signal reception, i.e. success or failure. If the destination receives the signal successfully, the relay does no forwarding; otherwise, the relay does incremental forwarding.

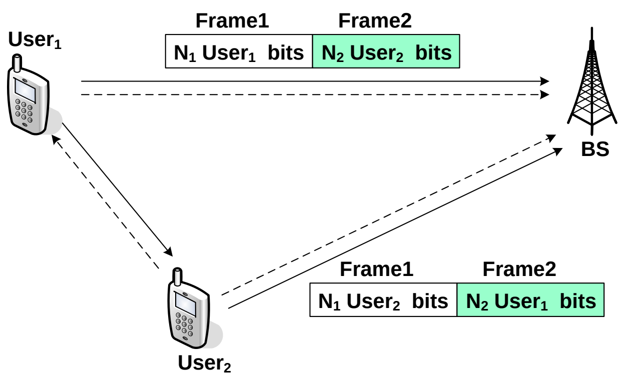


Figure 1.11: Illustration of coded cooperation [24].

From the previous description of the traditional relay channel and different schemes in current cooperative communication, we can summarize the differences as followings:

- The capacity studied by Van der Meulen, Cover and El Gammal [47,48] is based on an additive white Gaussian noise (AWGN) channel. However, the current research on cooperative communication is focusing on the diversity in a fading channel.

- In a relay channel, the relay is dedicated to assist the on-going communication in the main channel, whereas in cooperative communication users act both as information source as well as relays. In conventional relay networks, the relay cooperates altruistically with source. Such relays are often installed by network operator and they do not need any cooperation incentives. By contrast, in cooperative communication the cooperation between the two partners is egoistic. The roles of the partners are equal and they need cooperation incentives.

1.5.2 Comparison with the Related Work

The aforementioned works on cooperative communication only exploits the partners' antenna to form virtual antenna arrays (or virtual MIMO) to obtain cooperative diversity gain. The most of researches focus on the information theory perspectives. Therefore, generally speaking, the cooperation occurs mostly in the physical layer. The elements involved into the cooperation entities are signal, symbol, coded block, etc. The design of cooperative strategies is mostly independent of the network access technology. Besides that, some works on resource allocation for user cooperation have been done, such as [54–56] and some partner selection protocols are proposed in [57, 58].

Cooperative networking research based on CCP2P network architecture (or wireless grids) has a wider perspective. The cooperative strategies can take place in any OSI (Open Systems Interconnection) layer and any wireless access network, exploiting any functional block and resources. The elements involved into cooperation entities can be, among others, portions of a packet/frame, a set of packets in a packet flow, or some auxiliary information (e.g. additional information container (AIC) in head compression algorithm). Design of cooperative strategies takes into account the characteristics of specific applications, algorithms, wireless access technologies, and others.

Based on the CCP2P cooperative network architecture, various cooperative strategies have been applied at or across different layers in OSI model of different networks according to the defined goal [2,3,7–9,59–64].

A snapshot of some research examples on cooperative networking is illustrated in the OSI model as given in Figure 1.12. Other's work are presented in blocks with dashed edge in Figure 1.12. For example, [59] discussed the energy-efficient cooperative techniques in the multimedia services using multiple description coding; a cooperative web browsing mechanism is proposed in [60]; with a similar idea a more generic scheme of cooperative downloading for multi-homed wireless devices (i.e. multimodality devices that have multiple air interfaces) is proposed in [61]; in [62] a cooperation strategy is used for accurate mobile location estimation by combining long- and short-range location information; a cooperative roaming mechanism is proposed in [64] for L2 and L3 handoffs in WLAN.

My contributions are presented in blocks with solid edge in Figure 1.12. They are mostly at the three lower layers in the OSI model, i.e. network layer, data link layer, and physical layer. The potential of applying cooperation principle to tackle challenging issues has been studied, such as energy saving, spectrum efficiency, QoS, etc. by effectively balancing the trade-off among the 4G key factors (Figure 1.1).

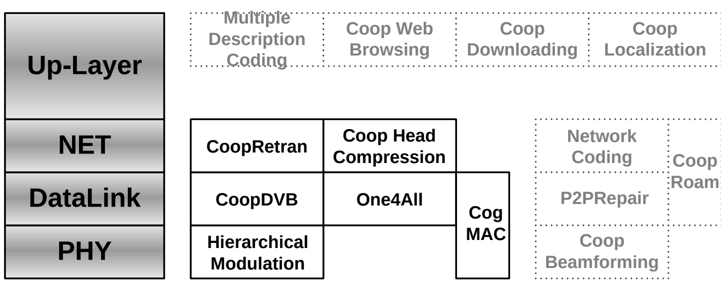


Figure 1.12: Snapshot of cooperative networking research examples in the OSI model (my contributions are the blocks with solid-line).

1.6 Structure of the Thesis

Among all the work done in the Ph.D. project, some representative papers are collected in the thesis as listed in the following.

- Chapter II: cooperative strategy for energy saving in DVB-H [9,17].

- Chapter III: cooperative retransmission for reliable multicast in wireless networks [7, 16, 18].
- Chapter IV: cooperative uplink access i.e. One4all strategy [5, 19].
- Chapter V: a cognitive radio MAC protocol with cooperative sensing mechanism [2].
- Chapter VI: hierarchical modulation for uplink communication in cooperative networks [3].

Chapter II

Energy saving is one of the crucial issues in DVB-H due to the battery driven mobile devices. In DVB-H standard time-slicing technique is introduced to save energy. The basic idea of time-slicing is to covey the data in bursts with idle period in between instead of sending data stream with lower rate constantly. It is clear that a mobile device can save energy during idle periods. The longer idle period is, the more energy is saved; however, the longer idle period results in longer zipping time (i.e. program/channel switching time). The shorter the burst is, the more energy is saved; however, the shorter the burst requires higher receiver sensitivity. Specially, in high data rate DVB-H network, multiple bursts are often bundled into one burst called parallel elementary stream (PES) to balance the receiver sensitivity and bandwidth utilization. Therefore, there is a clear trade-off between the energy saving, and the service performance and hardware complexity.

A cooperative strategy is designed to save more energy in DVB-H on top of time-slicing techniques. The basic idea is that if DVB-H mobile devices are close to each other they can form cooperative cluster to alternately receive the burst and then distribute the burst within the cluster over the short-range link. In this way, the idle time between the bursts is virtually increased at each mobile device. We use Bluetooth as the candidate for the cooperative short-range communication and three topology based cooperative algorithms are proposed. Furthermore, a cross–platform design approach is introduced to optimize the signalling communication in the Bluetooth system. The numeric results show the potential of the cooperative strategy in energy saving.

Chapter III

The motivation of design cooperative strategy to reliable multicast in wireless network is that: i). Multicast service has been regarded as an important revenue driver and is promising to bring huge revenue to the network and service operators in the future wireless network. Especially the reliable multicast service has tremendous potential to provide unique opportunities for the services beyond the conventional multicast services. ii). Although in the wired networks multicast services are widely and successfully used, to transplant multicast service to wireless network is challenging due to the unreliability of radio link in the wireless networks and the heterogeneity of radio link at the different receivers. iii). For normal multicast services in wireless network, it is challenge to figure out the optimized transmission data rate for a multicast group considering the trade-off between the overall network throughput and the user perceived QoS. For reliable multicast service, the error/loss recovery is more challenging in the unreliable and heterogeneous wireless environment. The traditional error/loss recovery schemes are not efficient due to *implosion*[6] and *exposure*[7] issues. Furthermore, wireless channel has time correlation characteristics [66]. Namely, when a radio link suffers from the bad channel condition, it cannot effectively help itself out by requesting retransmission.

Aiming at solving these crucial issues of the reliable multicast in wireless network, we propose cooperative retransmission scheme. The basic idea is that it is feasible and more efficient to exploit the short-range link among the mobile devices in each others' proximity and recover the lost packets locally instead of requesting retransmission only from the base station (or access point). It compares the cooperative retransmission scheme with the traditional error/loss recovery schemes such as ARQ, HARQ, and so on. Energy consumption at mobile device is used as comparison criteria and the cooperative scheme outperforms the traditional ones. Based on the cooperative retransmission scheme, network coding

[6]Implosion is a result from duplicated NACKs (or retransmission request) from many receivers. Additionally, in order to avoid loss of NACK, the receiver often continuously sends NACKs to the sender until it receives confirmation from the sender. Duplicated NACKs might swamp the sender and the network, even the other receivers.

[7]Exposure occurs when the retransmitted packets are delivered to those receivers who did not lose the packets [65].

is used to further improve the performance in terms of the number of retransmitted packets.

Chapter IV

Contention and collision is one of the main causes of the performance degradation in infrastructure based wireless network with distributed uplink access. Significant amount of energy of mobile devices and transmission opportunities are wasted due to contention and collision. To solve this issue a cooperative strategy called *One4all* is proposed. The basic idea is that mobile devices form a cooperative clusters and one mobile device represents a cluster to contend a channel. The rest mobile device of the cluster can access the channel free of contention. The task of channel contention is taken alternately by the members of the cluster. The relation among the mobile devices in the same cluster become cooperating instead of competing. It can highly reduce the collision probability thereby it results in energy saving and channel access delay reduction.

Chapter V

A cognitive radio MAC is proposed for BSS (Basic Service Set) based WLAN in this chapter. The motivation of using cognitive radio techniques is two-fold: on one hand the severe performance degradation in WLAN due to the ever-increasing density of wireless devices in WLAN spectrum; on the other hand, the spectrum utilization is very low in other licensed spectrum. The basic idea of the proposed MAC protocol is that cognitive radio techniques are employed on top of CSMA/CA (carrier sensing multiple access/collision avoidance) so that the WLAN devices cannot only access the legacy WLAN unlicensed spectrum but opportunistically access any other under-utilized licensed spectrum without a license.

The proposed cognitive radio MAC is referred to as C-CSMA/CA (Cognitive radio CSMA/CA). C-CSMA/CA efficiently exploits the inherent characteristics of CSMA/CA to design *distributed cooperative outband sensing* to explore spectrum hole; moreover, it designs *dual inband sensing* scheme to detect primary user appearance. Additionally, C-CSMA/CA has the advantage to effectively solve the cognitive radio self-coexistence issues in the overlapping cognitive radio BSSs scenario. It also realizes station-based dynamic resource selection and utilization.

Chapter VI

In CCP2P network architecture, the current transmission on cellular link and short-range link is separated by orthogonal channels such as different frequencies, time slots, codes, etc. Beyond the state-of-the-art, we exploit a method, referred to as hierarchical modulation, where a mobile device is generating signals that are conveyed towards the base station and the neighboring devices in the same frequency and even at the same time. The signal is composed in such a way that it has different meanings for the neighboring devices than the base station. While the base station is getting the coarse information, the neighboring devices are getting the fine grained information. The analytical analysis and simulation results show that hierarchical modulation can improve spectrum efficiency and reduce data queuing delay with neither degrading the symbol error rate performance nor increasing the average energy per bit. Therefore, hierarchical modulation is promising to be a good transmission scheme facilitating CCP2P network architecture.

The Relation Between The Chapters

The content of the selected five chapters are independent as well as correlated. Chapter II and Chapter III apply cooperative strategy in the downlink. The application scenario is multicast service or unicast service transmitted in a multicast fashion[8]. The cooperative strategy is used either for multicast data reception or multicast data recovery. For multicast service without strict reliability constraint such as multicast video services, cooperative strategy can exploit the potential of the common sharable data among cooperative partners to save energy by sharing the reception task, i.e. partners alternatively receiving multicast packets. It is worth mentioning that the energy per bit ratio on the short-range link is much lower than that of the cellular link. The cooperative strategy applied in DVB-H is just an illustration, which makes a good use of the

[8]In parallel elementary stream of DVB-H, a couple of unicast services are bundled in the same burst which is multicasted to the receivers.

burst traffic characteristics. For multicast service requiring high reliability, cooperative strategy exploits heterogeneity of the perceived wireless channel quality to efficiently use the resource of network and device to improve multicast service performance.

Chapter IV and Chapter V apply cooperative strategy in uplink access to improve MAC efficiency. In Chapter IV *One4all* strategy intends to solve the contention and collision issue by forming cooperative cluster to reduce the collision probability. However, the network performance will be eventually limited by the spectrum resource of the network with the ever-growing density of the wireless devices. To break through it, an upcoming technology cognitive radio is introduced to tackle the issues caused by over-crowded network. In Chapter V, cognitive radio is applied to WLAN as an example to illustrate a feasible solution to solve performance degradation in the network due to spectrum scarcity. To design effectively cognitive radio MAC, cooperative principle is employed. The motivation is that to sense and detect the free spectrum individually has many pitfalls: first, it is not accurate enough and results in high probability of miss detecting primary user; secondly, it wastes secondary users' transmission time. The basic idea of C-CSMA/CA is that instead of sensing and detecting the spectrum hole stand alone, mobile devices can cooperatively sense the potential spectrum during their idle time (i.e. NAV (network allocation vector) duration).

Chapter VI is a generic transmission mechanism with the novel modulation. It is proposed for uplink transmission in CCP2P network. It exploits the better channel quality in the short-range link to fundamentally change the transmission mechanism that is currently used in CCP2P network. It illustrates a feasible transmission mechanism to further facilitate the CCP2P based cooperative networking.

The cooperative strategies discussed in Chapter II–VI improve the key factors of 4G from different aspects. The impacts of the cooperative strategies are summarized in Table. 1.1. Chapter II (CoopDVB), Chapter III (CoopRetran) and Chapter IV (*One4all*) focus on improving energy efficiency and QoS with neither losing spectrum efficiency nor increasing hardware complexity. Since in Chapter III the cellular link and short-range link is distinguished by different time slots, spectrum efficiency is higher during the short-range link time slots. Chapter V (CogMAC) and Chapter VI (HMOD) improves the spectrum efficiency

Table 1.1: The impacts of different cooperative strategies on 4G key factors.

	Energy Efficiency	**Spectrum Efficiency**	**QoS**	**Hardware Complexity**
CoopDVB	+		+	
CoopRetran	+	+	+	
One4All	+		+	
CogMAC		+	+	−
HMOD		+	+	−

and QoS with less hardware complexity.

The possible cooperative relationships between/among wireless devices have been given in Subsection 1.2.2. Here we clarify the cooperative relationship in the studied scenarios. The summary is given in Table 1.2. In DVB-H when cooperation occurs between two DVB-H mobile devices it is S–S cooperation. When the cooperation is among multiple devices, the cooperation relation at each time is S–M and the relation becomes M–M seen from each cooperative cycle perspective. In cooperative retransmission strategy, the primary mobile devices (in worst case plus auxiliary mobile devices) help the members in the entire group recover the missed packets. We assume the number of primary mobile devices more than or equal to one and the group size is more than one; therefore, the cooperative relation can be regarded as multiple nodes cooperating multiple peers, i.e. M–M. In *One4all* strategy one representative mobile device contends the channel access for the cooperative cluster, so the other partners can access the channel free of contention. Cooperation relation is similar as that in Tour de France. Therefore, the cooperative relation in *One4all* strategy at each cooperation instance is S–M and from long-term perspective it is a kind of M-M cooperation. In C-CSMA/CA multiple idle mobile devices sense potential spectrum to explore new usable spectrum for the group to use. Since the newly discovered spectrum can be used by multiple users, the cooperation relation is M–M cooperation.

Table 1.2: The overview of the cooperative relation between (or among) the cooperative entities in the studied cases.

	S–S	**S–M**	**M–S**	**M–M**
CoopDVB	$\surd$	$\surd$		$\surd$
CoopRetran				$\surd$
One4all		$\surd$		$\surd$
CogMAC				$\surd$

Chapter 2

On the Energy Saving Potential in DVB-H Networks Exploiting Cooperation among Mobile Devices

In this chapter a cooperative strategy is proposed on energy saving in DVB-H networks. It demonstrates the potential of non-altruistic cooperation between mobile devices. The envisioned cooperation is based on cellular reception of DVB-H data, which is then shared among mobile devices within each others' proximity over short–range links. The short–range communication is realized by Bluetooth, where a cross–platform design approach is introduced to optimize the signalling communication in the Bluetooth system. Three different cooperative algorithms are designed for the short–range link (Bluetooth) communication. Numerical results show that an energy saving of over 50% can be achieved by cooperative networking of three mobile devices in fully cooperating mode.

2.1 Introduction

The aim of Digital Video Broadcasting on Handheld (DVB-H) standard is to deliver audio and video content to mobile handheld devices. As those devices are battery driven, energy is always a crucial issue for mobile application. Therefore, time slicing [67, 68] has been introduced into DVB-H to save energy. The basic idea behind time slicing is to convey data in bursts with long pause periods instead to send a low data rate stream constantly. The energy consumption with time slicing depends on the burst duration and the pause period referred to as OFF-time period. From an energy saving perspective, more energy can be saved by shortening the burst duration. However, because of receiver sensitivity performance constraint, the burst duration is often kept as certain length to alleviate the receiver sensitivity issue. Thus, the remaining factor to work on is the OFF-time period. Obviously, the longer OFF-time period results in the more energy saving. Unfortunately the OFF-time period cannot be excessively long because of quality of service aspects such as the access time and zapping time[1]. Therefore, there is a clear trade-off between burst duration and OFF-time to have optimum service access time and energy consumption.

IP-services over DVB-H can be transmitted in sequential elementary streams (SESs) or parallel elementary streams (PESs) [67]. Both types of streams are transmitted in either multicast or broadcast fashion. The difference is that SESs carry one service in one burst, while PESs can carry multiple services in one burst. The reason that multiple services are bundled and transported within the same burst is that the burst needs to meet a minimum burst duration length to fit the receiver sensitivity and at the same time DVB-H system tries to get the maximal utilization of DVB-H bandwidth. The use of parallel elementary streams brings many benefits, for instance, zapping time reduction, bandwidth optimization, the possibility of sending message type services in parallel to the main services, etc. However, when implementing PESs, the energy leak becomes an issue because a mobile device receives parallel elementary streams of several services encapsulated in the same burst. Indeed, it only keeps the desired elementary streams, discarding the remaining ones. From the entire system or network standpoint, the elementary

[1] Zapping time refers to the program or channel switching time.

streams discarded by a given mobile device could be used by other devices. It is clear that discarding unwanted elementary streams leads to inefficient use of resources, particularly energy. To my knowledge, this issue has not been addressed before. Furthermore as pointed out in [69], more research is needed in terms of novel techniques aiming at reducing energy consumption. In this direction, time slicing technique has been recently introduced. End users generally expect more and more hours of streaming audio on one battery charge; however, improvements in battery capacity develop slowly (typically 10% per year); hence, the requirements are difficult to meet. Energy saving techniques like those considered here are promising options to extend considerably the service time of mobile devices.

In this chapter a cooperative energy saving strategy is proposed for IP-services over DVB-H. The considered cooperative strategy focuses on reducing energy consumption in the PESs case, even though it can be as well applied to SESs to obtain further energy savings. The cooperative architecture is set up between mobile devices that are capable to communicate not only with a central base station but also among each other using short-range wireless technology. The essential reason of the proposed approach achieving energy saving is that by cooperative reception of data over cellular link, the OFF-time period is virtually increased. Furthermore, as the energy per bit ratio (EpBR) is much lower on a short–range link than in a cellular one, the energy consumption overhead over the former is significantly lower than over the latter.

A first attempt to save energy for DVB-H mobile device is introduced in [70]. The approach saves energy by leaving out some FEC columns in the Multi-Protocol Encapsulation-Forward Error Correction (MPE-FEC) frame once the receivers have received all the error–free data packets instead of getting the full block always. The maximum energy saving for this approach is 25%. The proposed cooperative energy saving strategy has larger energy saving potential than the one in [70]; furthermore, both approaches can also be combined.

2.2 Cooperative Strategy for IP-services over DVB-H

Cooperation is the strategy of a group of entities working together to achieve a common and/or an individual goal [1]. The proposed cooperative mechanism requires that the devices have two air interfaces: a cellular link (CL) for DVB-H packets reception and a short–range link (SRL) for exchanging packets locally. The basic idea of the cooperative mechanism is that devices cooperatively receive the DVB-H bursts. Each cooperative mobile device receives only partially the data over CL. In case of PESs, the mobile device does not discard the unwanted packets anymore, but forwards those packets to its neighboring devices. Based on reciprocity, the device gets the missing packets from those neighboring devices. As for services carried by SESs case, mobile devices simply exchange the missed packets using SRL. This scheme is beneficial to reduce energy consumption since the energy per bit ratio (EpBR) is much less in the short–range communication system. Furthermore, it guarantees very short service access time and zapping time. It does not require any modification in current DVB-H standard.

For multi-services transmitted by PESs scenario, the cooperative strategy works as following. Let us assume that there are three mobile devices which are interested in three different services with the same data rate transmitted by PESs, respectively[2]. The DVB-H base station transmits DVB-H bursts as usual, without being aware of any devices' cooperation. But the mobile devices can autonomously receive DVB-H bursts alternately, if they are willing to cooperate after their negotiation. For instance, after MD_1 finishes reception of the first burst containing the three services, it goes into sleep on its CL. And it transmits the related packets to MD_2 and MD_3 on SRL, respectively. Then MD_2 and MD_3 wake up at the start of the second and the third DVB-H burst, respectively. They deal with the packets in a similar way as MD_1 does. After a cyclic period, MD_1 wakes up again to receive the forth burst, and so forth. Therefore, MD_1 always wakes up at the start of the $(3n + 1)th$ burst. Figure 2.1 illustrates how this cooperative mechanism works. The ON/OFF reception characteristic of DVB-H makes it suitable for devices to cooperate, which is an inherent benefit of DVB-H. The proposed coop-

[2]Mobile devices (MD_1, MD_2, MD_3) are interested in service 1, 2, 3, respectively.

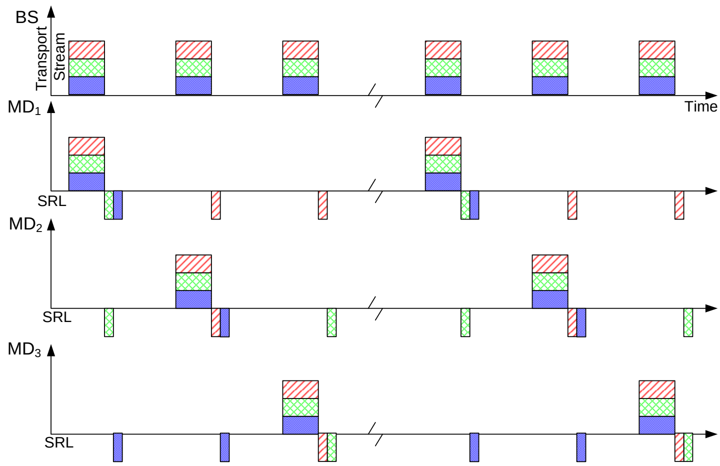


Figure 2.1: Burst flow mechanism in a cooperative scenario exploiting the Parallel Elementary Streams technique.

erative strategy exploits the inherent characteristic of DVB-H to achieve energy saving by allowing longer idle time on DVB-H link. Furthermore, it also saves the energy consumption that is spent on decoding the received MPE-FEC frame[3].

In the above example, the three different services have the same data rate so each device receives one DVB-H burst every three bursts. In reality the different services can have different data rates. So the frequency of mobile device waking up can be adjusted. This could be typically negotiated among the mobile devices before cooperation starts. Thus the energy consumption of all mobile devices is balanced.

SESs can be regarded as the simplest case of PESs. It is obvious that the cooperative strategy can easily be adapted to the case of services transmitted by SESs. Whether to cooperate or not should be evaluated by each mobile device independently. The decision depends on the cooperative strategy and the neighboring devices. In short, cooperation should be established as soon as the individual mobile device sees it own advantages [1]. This means that the establishment and termination of

[3]The decoded packets are exchanged directly between mobile devices without multiprotocol encapsulation and Reed-Solomon coding.

cooperation between mobile devices depends on the goal of the involved mobile devices, the cooperative strategy in use, and the prevailing relationship among mobile devices. The relationships among mobile devices change with time as devices move, terminate the ongoing service, join the network, and also the associated channels change, etc. For instance, in the above scenario, they will cooperate if they are close enough to each other to get mutual energy saving. However, if a device cannot attain energy saving anymore because of mobile devices movement and the increasing energy overhead on the short-range link, it will stop cooperation right away.

2.3 Cooperative Short–Range Communication

According to the above description of the cooperative communication mechanism, the short-range link is required to be very flexible and transparent to the end users. It works without any infrastructure in an autonomous mode. Namely, the short–range connection is a sort of ad hoc connection. The short-range link air interface and associated communication mechanism can be designed and implemented by many different approaches, only if it meets the cooperative strategy principles. Bluetooth technology (Bluetooth 2.0 EDR) is used as an example to illustrate how it supports cooperation strategies in the short–range link, though any other short–range communication technology can be also used.

Cooperation range is defined as the range within which the mobile devices can achieve energy saving. Each mobile device has its own cooperation range. A mobile device is capable of service discovery and has possibility to cooperate with the discovered devices within its cooperation range. When the mobile devices cooperate, they form a cooperative piconet. In the cooperative piconet, which role (Master/Slave) to take or which cooperative approach (centralized or distributed approach) to use is dependent on the topology of the formed piconet or scatternet.

2.3.1 Topology Based Cooperative Algorithm

The cooperative algorithms in the Bluetooth based short–range link can be summarized into the following three basic approaches according to the topologies.

Piconet Based Centralized Cooperative Approach

This approach is used for Topology I (see Figure 2.2(a)). In this topology all mobile devices form one piconet. The slaves within the piconet are out of each others' cooperation range. In this topology, the master controls the slaves' states and transmission slots as typical Bluetooth piconet. But the slaves all stay in PARK state in most of time. When the master wishes to transmit the received DVB-H packets to its cooperative slaves, it will unpark slaves by a master-initiated unparking method (using dedicated link manager protocol unpark command with slaves PM_ADDR or its BD_ADDR). A slave can also unpark itself when it needs to transmit the received DVB-H packets to the master by a slave-initiated unparking method (sending access request message with AR_ADDR).

Piconet Based Distributed Cooperative Approach

This approach is used for Topology II (see Figure 2.2(b)). In Topology II the mobile devices form one piconet and all the mobile devices are within each others' cooperation range. Namely, they can have fully meshed connections. In such case, all the mobile devices within the piconet are capable to work as a master and they alternately take master role in the piconet. Therefore, all the mobile devices periodically switch role (Master/Slave) and only master mobile device transmits in its turn. When the first master establishes the cooperative piconet, it decides the master role switching sequence and broadcasts it to its slaves. The key technical issue here is the effective role switching which can be initiated by either slave or master. The master initiated role switching method is preferred, because it can implicitly check if the slave (i.e. the successor master) is still in the piconet or not. If the slave (i.e. the successor master) has gone, the master can timely update the master role switching sequence. Then it will switch role with another successor in the new role switching sequence list.

Scatternet Based Cooperative Approach

This approach is employed for Topology III (see Figure 2.2(c)). In Topology III the mobile devices form a scatternet, i.e. some mobile devices stay in more than one piconet. Considering signalling complexity and exchanging load, the mobile device is assumed to work at the most in two piconets. In Figure 2.2(c) MD_3 can work as slave in both Piconet A and B or it can work as slave in the Piconet A and master in the Piconet B. MD_3 should be able to harmonize its operation in both piconets. For instance, MD_3 works as master in the Piconet B during its PARK state interval in Piconet A. It requires MD_3 to have an accurate synchronization in Piconet A, otherwise it might miss the unpark message from master of Piconet A. This issue can be effectively resolved by synchronization knowledge from DVB-H system.

2.3.2 Signalling on Short-Range Link

In the cooperative short-range link implementation, Bluetooth–supporting mobile devices will be involved into frequent role switching, SYMMETRICAL service discovery (INQUIRY/INQUIRY SCAN), connection establishment (PAGE/PAGE SCAN), connection validity check, and so on. These procedures will eventually result in frequent signalling exchange load and random short-range link connection establishment delay[4]. No doubt, it is a real challenge to design an efficient and feasible short–range communication scheme supporting a cooperative strategy.

It is very difficult to resolve all these critical issues in an independent Bluetooth system because of the limitations of Bluetooth's frequency hopping physical layer. Although many researchers have explored on similar issues such as neighboring Bluetooth devices discovery, autonomous link establishment, piconet or scatternet formation [71, 72], a good engineering solution solving all these issues has not been proposed yet. However, these issues can be tackled in the cooperative system considered here. The essential reason is that the mobile device in the system exploits *air interfaces diversity* (i.e. DVB-H and Bluetooth). The main obstacle in resolving those issues in Bluetooth is due to the unawareness of neighboring mobile devices' INQUIRY or INQUIRY SCAN information. It is a sort of complete autonomy. However, in a DVB-H system the mobile device has accurate synchronized time information

[4] The random connection delay issue is due to the symmetrical link mode in the connection establishment [71, 72], i.e. any mobile device can start Inquiry or Inquiry Scan in service discovery. In the asymmetrical link mode Inquiry or Inquiry Scan duty is predefined between mobile devices.

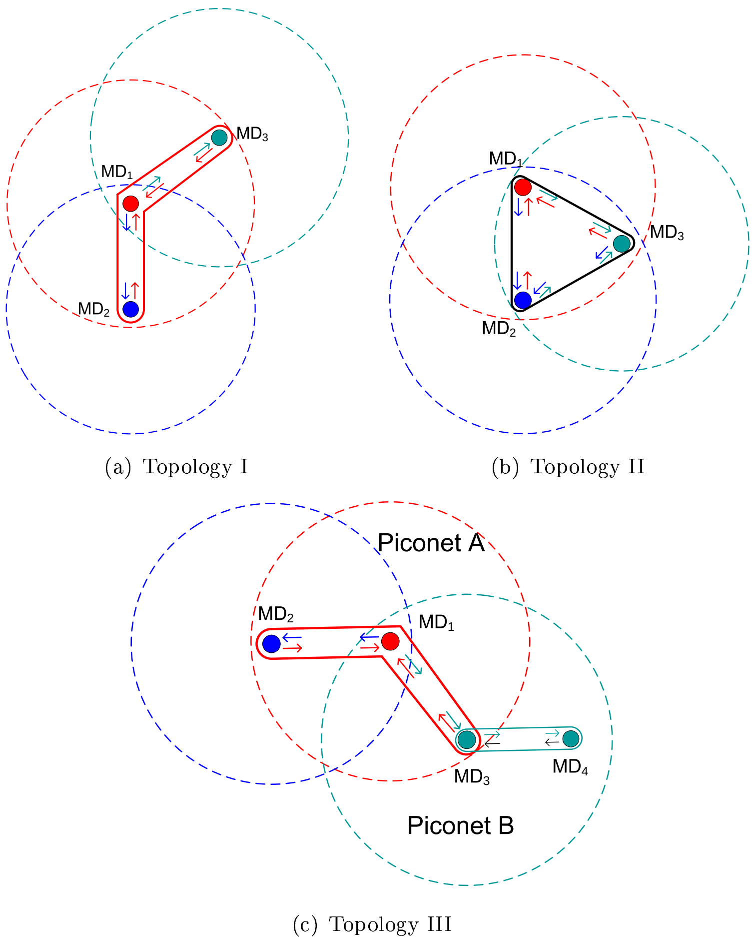


Figure 2.2: Cooperative Topologies.

of the DVB-H system to receive the burst at a right time. Mobile stations also have the knowledge of their target services. So in short-range link, a mobile device can exploit the known cross–platform information (e.g. burst starting time and end time) from DVB-H system to effectively resolve all these issues. A good case in point is that the random service discovery delay [71] can be eliminated by mobile devices starting INQUIRY/INQUIRY SCAN state at the right time with predefined inquiry length. At the same time, mobile devices can effectively differentiate their INQUIRY/INQUIRY SCAN states to facilitate the service discovery procedure based on the different service information in the burst block. The detailed cross–platform optimization implementation is out of the scope of this chapter.

2.4 Numerical Examples for Energy Consumption Analysis

This section will present two numerical examples to illustrate energy saving by cooperation over short-range link.

The average energy consumption per burst without cooperation and with cooperation are expressed in Equation 2.1 and Equation 2.2, respectively. The notation of parameter expressions are summarized in Table 2.1.

$$\begin{aligned} E_{nocoop} &= t_{c,cyc}^{nocoop}\left(\frac{(t_{c,Bd}+t_{c,syn}+\frac{t_{c,Dj}}{2})P_{c,on}+t_{c,off}P_{c,off}+t_{c,i}P_{c,i}}{t_{c,cyc}^{nocoop}}\right) \\ &= t_{c,cyc}^{nocoop}\overline{P_c^{nocoop}} \end{aligned} \tag{2.1}$$

where $t_{c,cyc}^{nocoop} = t_{c,Bd} + t_{c,syn} + t_{c,Dj}/2 + t_{c,off} + t_{c,i}$

$$E_{coop} = \frac{t_{cyc}^{coop}}{N_{burst}}\left(\overline{P_c^{coop}} + \overline{P_{sr}^{coop}}\right) \tag{2.2}$$

where

$$\overline{P_c^{coop}} = \frac{t_{c,on}P_{c,on} + t_{c,off}P_{c,off} + t_{c,i}P_{c,i}}{t_{c,cyc}^{coop}}$$

and

$$\overline{P_{sr}^{coop}} = \frac{t_{sr,tx}P_{sr,tx}+t_{sr,rc}P_{sr,rc}+t_{sr,i}P_{sr,i}}{t_{sr,cyc}^{coop}}$$

where N_{burst} denotes the number of bursts transmitted by the DVB-H networks in one cooperative cyclic period

$$\begin{aligned} t_{c,on} &= t_{c,Bd} + t_{c,syn} + t_{c,Dj}/2 \\ t_{c,cyc}^{coop} &= t_{c,on} + t_{c,off} + t_{c,i} \\ t_{sr,cyc}^{coop} &= t_{sr,tx} + t_{sr,rc} + t_{sr,i} \\ t_{c,cyc}^{coop} &= t_{sr,cyc}^{coop} = t_{cyc}^{coop} . \end{aligned}$$

In Equation 2.2, $t_{c,i}$ is much longer than that in Equation 2.1. Consequently $t_{c,cyc}^{coop}$ is much longer than the cyclic period of non-cooperative case $t_{c,cyc}^{nocoop}$.

Example I: This example corresponds to fully connected mobile devices as given by Topology II in Section 2.3. In this example the short-range link is assumed to have power control. Transmission power is a function of the distance between transmitter and receiver. Due to the complexity of the power control mechanism, the exact expression for the transmission power is unknown. Here transmission power is assumed to be approximately proportional to the distance between mobile devices. The short-range link can also be assumed to have very short synchronization time. The transmission data rate on the short-range link for the master is 1.3Mbps (with 3-DH5 packet symmetrical maximum rate[5]) [73]. The reception power consumption and idle power consumption is set to constant values as 10mW (10dBm) and 1mW (0dBm) [73], respectively. Transmission power consumption is varying between range of 10mW – 100mW (10dBm – 20dBm) on short-range link. The values of the parameters for the cellular link are taken from [67] and listed in Table 2.1. With all these assumptions, the relation of average energy saving $(1 - E_{coop}/E_{nocoop})$ and transmission power is shown in Figure 2.3. It can be seen from Figure 2.3 that the achievable energy saving can be over 50% with three cooperating mobile devices, if the transmission power on the short-range link is less than about 16 dBm.

Example II: This example considers a scenario with three mobile devices (MDs) which are individually receiving three different services with the same data rate. The power consumptions of transmission, reception and idle state are assumed to be constant. The positions of

[5] 3-DH5 packet type is newly defined in Enhanced Date operation. 3-DH5 has maximum payload of 1021 Bytes, occupying five time slots.

Table 2.1: Parameter list for cellular and short–range air interfaces.

Cellular link		
Notation	Mean	Value
$P_{c,on}$	power consumption when RF is on	400mW
$P_{c,off}$	RF is shutdown, but MPE-FEC is ongoing	50mW
$P_{c,i}$	DVB-H receiver waiting for next burst	10mW
$\overline{P_c^{coop}}$,$\overline{P_c^{nocoop}}$	average power consumption on DVB-H interface w/o cooperation	
$t_{c,syn}$	synchronization time	120ms
$t_{c,Bd}$	burst duration	236ms
$t_{c,Dj}$	delta-t jitter	10ms
$t_{c,off}$	duration when receiver is at RF_OFF1 state	500ms
$t_{c,i}$	idle time	-
$t_{c,cyc}^{nocoop}$	frame cyclic period without cooperation	2.7165s
$t_{c,cyc}^{coop}$	frame cyclic period with cooperation	-
Short–Range Link		
Notation	Mean	Value
$P_{sr,tx}$	transmission power	-
$P_{sr,rc}$	reception power	10mW
$P_{sr,i}$	power consumption for idle state	1mW
$\overline{P_{sr}^{coop}}$	average power consumption on Bluetooth interface	
$t_{sr,tx}$	transmission time	-
$t_{sr,rc}$	reception time	-
$t_{sr,i}$	idle time	-
$t_{sr,cyc}^{coop}$	cyclic period	-

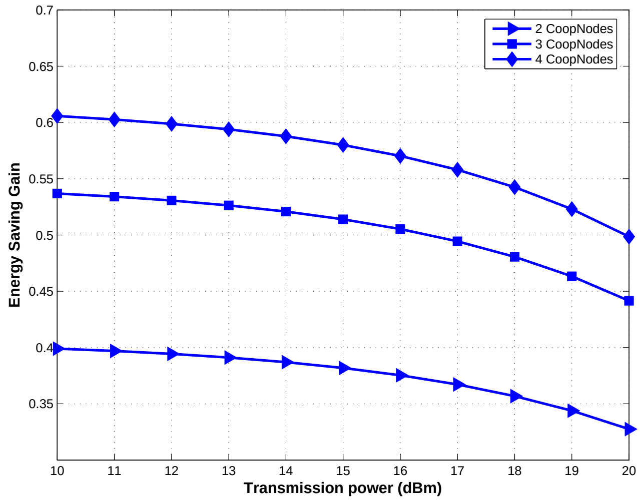


Figure 2.3: Energy saving by cooperation.

Table 2.2: Parameters of example II.

Parameter	Velocity of MD_3	$P_{sr,tx}$	$P_{sr,rx}$	$P_{sr,i}$	Time
Value	1m/s	10mW	10mW	1mW	180s

two mobile devices (MD_1 and MD_2) are fixed and they form a piconet. Another mobile device (MD_3) is moving from far away towards the two mobile devices, then it moves away. Figure 2.4 illustrates the topology of the scenario and MD_3's trace of this example. The parameters used in this example is listed in Table 2.2.

The calculation results of this example is shown in Figure 2.5. Two different cooperative strategies are implemented for the Topology I scenario (Figure 2.2(a)). Figure 2.5(a) is generated by *Cooperative Strategy I* which considers the selfish characteristics of mobile devices and the fairness requirement of the system. So it is based on the principle that the exchanged packets between mobile devices must be equal. In Topology I scenario, when MD_1 works as master with MD_2 and MD_3 as slavers, MD_1 can have about 54% energy saving while MD_2 and MD_3 only get about 26% energy saving (MD_1 is the final winner because its optimal location).

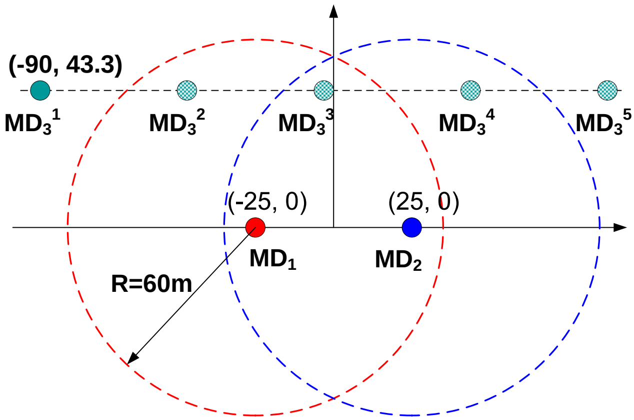
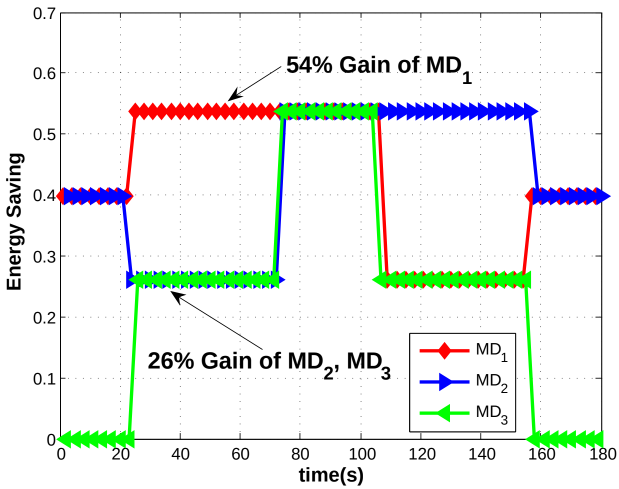


Figure 2.4: Cooperative scenario of example II.

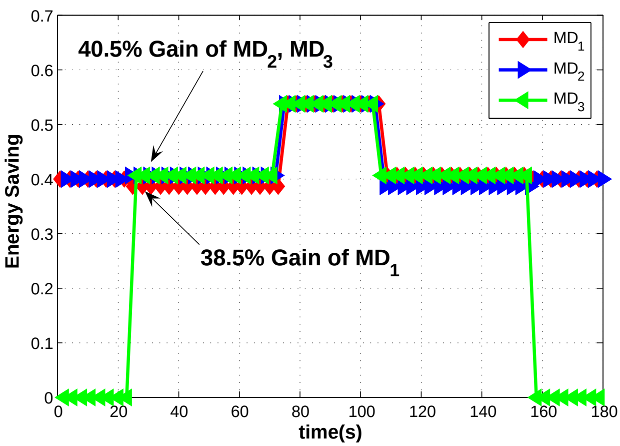
At this situation, mobile devices get unequally pay-offs by cooperation and the gain difference between different mobile devices is about 28%. It is obvious that with *Cooperative Strategy I* the gain achieved by a mobile device depends on its relative position in a cooperative group.

Figure 2.5(b) is based on *Cooperative Strategy II*. This strategy tries to balance the energy saving of the mobile devices, while it is not dependent on the mobile devices' relative location any more. Here the energy consumption on the short-range link is assumed to be very low. Hence, if the master receives half of all DVB-H burst packets and each slave receives the remaining packets, it is very close to the optimum value to balance the energy saving of the mobile devices. By this strategy in the same Topology I scenario, MD_1 gets 38.5% energy saving; and MD_2 and MD_3 achieve 40.5% energy saving. Note that it obtains a very good balance of energy savings for all mobile devices at a little expense of the MD_1's energy saving. Furthermore, in this case *Cooperative Strategy II* saves 7% more energy from the standpoint of the cooperative system (10% without considering the overhead on the short-range link[6]). If one master cooperates with more slaves it can save even more energy by *Cooperative Strategy II* than that of *Strategy I*. Theoretically, it can save 20%, 26.47%, 30.77% more energy respectively, when one master

[6] $\frac{\textit{Energy Saving of Strategy II} - \textit{Energy Saving of Strategy I}}{\textit{Engergy Consumption of Strategy I}} = \frac{(\frac{1}{2}+\frac{1}{2}+\frac{1}{2})-(\frac{2}{3}+\frac{1}{3}+\frac{1}{3})}{(\frac{1}{3}+\frac{2}{3}+\frac{2}{3})} = 10\%$



(a) Equal exchanged packets.



(b) Balanced energy consumption.

Figure 2.5: Energy Saving in example II.

cooperates with 3, 4, 5 slaves[7] in one piconet.

Figure 2.5(a) and Figure 2.5(b) also clearly show the corresponding

[7]In such case, the maximum cooperative slaves can only reach 5, because when more than 5 slaves are in the same piconet, two or more slaves must be in each others' cooperation range.

energy saving changing with the movement of MD_3 because the different topology based cooperative algorithms are used. It is evident that all mobile devices achieve the maximum energy saving when they are fully-connected. It is up to 54% in this example scenario.

2.5 Conclusion

The proposed cooperative mechanisms are used for multi-interface DVB-H mobile devices (i.e. Multi-modality device). Multi-modality devices are already commercially available. Results show the strength of non-altruistic cooperation between mobile devices in DVB-H to save energy. The numerical energy consumption analysis examples show the achievable energy by cooperative strategies using the state-of-the-art technology. The energy saving depends on the number of cooperative mobile devices and the energy consumption on the short-range link. It is expected that data rates supported by short-range link will increase significantly while energy consumption in such systems will continue to decrease. Such short-range systems include UWB (Ultra Wide Band), UWB Bluetooth , wireless USB (Universal Serial Bus) and others. The development of advanced short-range air interfaces will accentuate the advantages of the proposed cooperative techniques. Therefore, with energy per bit ratio on short-range link decreasing, more energy saving is expected to be achieved.

Chapter 3

Cooperative Retransmission for Reliable Wireless Multicast Services

Multicast services have been identified as an important key technology to increase the network and service providers' revenue. Many data dissemination applications require even reliable multicast. Error/loss recovery for reliable multicast is different from conventional schemes taking into consideration the unreliable wireless channel, the battery driven mobile device, and the limited wireless bandwidth. To have an efficient error/loss recovery scheme for reliable multicast in wireless networks, a new communication architecture is advocated. It is referred to as cooperative wireless networking, where the mobile devices can communicate directly with each other to perform retransmissions using their short-range communication capabilities in addition to their cellular links. Based on the cooperative architecture a novel retransmission scheme is proposed exploiting the short-range retransmission in this chapter. The cooperative retransmission strategy is compared with the non-cooperative error recovery strategies in terms of mobile device energy consumption to show the benefit of the newly introduced scheme. Based on cooperative retransmission strategy, network coding is applied in the local retransmission. By exploiting the heterogeneity of the packet loss, network coding can significantly improve the local retransmission efficiency which is proved by simulation.

3.1 Introduction

Multicast communication has been identified as an effective way to disseminate information to a potential group of receivers [74] sharing the same service interest. Many data dissemination applications such as software distribution, distributed information (e.g. stock market data, sports scores, business inventory data, world news updates [75]), and mailing list delivery, etc. [76] require reliable multicast. Due to its increasing importance, it has received many researchers' interests and attentions in the previous years [74, 76–80].

Another fact is that various new wireless networks are deployed and more sophisticated mobile devices are available. So it is an emerging trend that more multicast applications and services will converge into wireless networks. Comparing with the wired network, reliable multicast in wireless networks becomes more challenging because of unreliable wireless links and mobile device's limitations.

Reliability requirements vary depending on different applications. It includes error/loss recovery, ordered delivery, no duplicates, and isolation of independent failures aspects. Among these aspects, error/loss recovery is the most concerned designing issue. The main reasons are: first, the packet error/loss rate is higher in wireless networks; and secondly, the error/loss recovery schemes have significant influences on the multicast application's quality of service and wireless network performance, for instance, error/loss recovery latency, bandwidth utilization, mobile device energy consumption efficiency, and others.

Two well-known techniques are usually used for error/loss recovery: automatic repeat request (ARQ), in which the transmitter retransmits the lost packets on requests from the receivers; and forward error correction (FEC), in which the transmitter transmits the redundant parity packets with data packets therefore the error/loss can be recovered directly at the receiver [79]. Pure ARQ has scalability issues such as implosion and exposure [65]. And pure FEC cannot provide full reliability [79]. Better performance for reliable transmission can be achieved by combining both of them (i.e. Hybrid ARQ) [81–84]. Hybrid ARQ is usually classified into two categories, namely type I and type II schemes [85]. HARQ I scheme is used for communication systems with relatively stationary channel conditions. HARQ II is an adaptive scheme for non-stationary channels. HARQ II *cannot* always outperform ARQ and FEC schemes, especially in wireless networks as proved by [79]. It shows that HARQ II schemes usually outperform ARQ and layered FEC for homogeneous packet loss probability in the receivers [79]. However, for the receivers with different packet loss probabilities, the performance is almost solely determined by the receivers with high loss rate. This is true even though if the fraction of high-loss receivers among all receivers is very small.

The essential reason of HARQ II performance degradation in wireless networks is due to the number of parity packets depending on the worst receivers. So the channel heterogeneity in wireless networks limits the achievable performance. Moreover, considering the wireless channel time correlation [66], when a radio path between a base station (BS) and a mobile device is greatly deteriorated, the mobile device cannot effectively help itself out by requesting retransmissions. The other devices in the multicast group consume extra energy because of receiving many useless parity packets. Additionally, the recovery latency is increased and bandwidth is wasted consequently. Some modified strategies [79] proposed that the receiver can stop receiving the parities when it has received enough parities. However, network bandwidth is wasted anyway, which results in low channel efficiency.

Therefore, it is worth investigating a more efficient and scalable error/loss recovery solution for reliable multicast in wireless networks taken into account the power consumption constraints, latency, and available bandwidth resources. One feasible solution called *cooperative retransmission strategy* is proposed. In this strategy, the wireless devices can recover error by local retransmission with devices in each others' proximity over the short-range link. Local retransmission is not a new idea in general for reliable multicast. However, the previous work of local retransmission (e.g. in Pragmatic general multicast (PGM) protocol) [86], implements the local retransmission only on the network element side. It comes up one design issue of how to locate the re-transmitter and evaluate their efficiency relative to other available sources. The main contribution of this chapter is that a host-side based local retransmission is designed and it is implemented by a novel and simple cooperative retransmission scheme. It should be noted that packet error/loss happening in the multicast tree is not considered here. Only packet error/loss in the last-hop (i.e. in wireless access networks) is considered, because most of the packet errors/losses occur here.

The proposed solution can efficiently save energy consumption at mobile devices, because it essentially reduces the average number of transmissions required to receive a packet reliably at all the receivers. Consequently, it can reduce retransmission delay and improve bandwidth utilization. Energy consumption is used as metric to compare the proposed cooperative retransmission scheme with the non-cooperative schemes. The corresponding delay reduction and bandwidth utilization improvements are obvious due to the average number of retransmission decreasing.

3.2 Non–Cooperative Error Recovery Strategies

Traditionally to recover packet error/loss, mobile devices have to either request packet retransmission or request a repairing packet from base station (BS), as BS is the only reference for mobile device in non-cooperative networks. In the following two subsections, energy consumption of the representative error recovery schemes, namely ARQ and FEC/HARQ will be introduced.

3.2.1 ARQ Scheme

ARQ scheme has been widely used in several multicast protocols such as MTP (Multicast Transport Protocols) [87], AFDP (Adaptive File Distribution Protocol) [88], PGM (Pragmatic general multicast protocol) [86], and SRM (Scalable Reliable Multicast protocol) [89, 90]. In MTP and AFDP the receiver unicasts the NACKs (Negative Acknowledgements) to request retransmission and the sender retransmits the requested packets [91]. In PGM and SRM the sender can suppress the NACKs from the different receivers that lost the same packets [91]. All these protocols have implosion and exposure issues. Implosion results from duplicated NACKs (or retransmission request) from many receivers. Furthermore, to avoid loss of NACK, the receiver often continuously sends NACKs to the sender until it receives confirmation from the sender. Duplicated NACKs might swamp the sender and the network, even the other receivers. Exposure occurs when the retransmitted packets are delivered to those receivers who did not lose the packets [65]. Both implosion and exposure are fatal impediments for multicasting in wireless networks.

In this subsection, SRM (Scalable Reliable Multicast) protocol [89,90] is used as one example of ARQ scheme and derive the corresponding energy consumption as following.

I define:

- $P_{c,rx}$, $P_{c,tx}$, $P_{c,i}$ as the power consumed in the reception process, the transmission process and the idle state for the cellular communication facility on a mobile device, respectively.

- $t_{c,rx}$, $t_{c,tx}$, $t_{c,i}$ as the corresponding time spent on the reception, transmission and idle state on the cellular link, respectively.

The total energy consumption of a mobile device is

$$E_{NoCoop} = t_{c,rx}P_{c,rx} + t_{c,tx}P_{c,tx} + t_{c,i}P_{c,i}\,. \tag{3.1}$$

Packet size is assumed to be constant. Additionally, the reception time of one packet on the cellular link is assumed to one time unit.

Average energy consumption of one valid packet reception is given in the following:

$$E_{ARQ} = \underbrace{(1+fN\gamma\alpha)}_{t_{c,rx}} P_{c,rx} + \underbrace{f\gamma\beta\alpha}_{t_{c,tx}} P_{c,tx} + \underbrace{f\gamma\beta\alpha(N-1)}_{t_{c,i}} P_{c,i}\,, \tag{3.2}$$

where

- N is the number of mobile devices in the multicast group.

- α is packet loss rate.

- γ equal to $\frac{1}{1-\alpha}$, considering retransmitted packet loss possibility.

- β is the ratio of NACK size to data packet size.

- f is defined as the *uncorrelated factor*[1].

- $t_{c,rx}$ consists of two parts: the time for an original packet reception, i.e. one time unit, and the time for the retransmitted packet reception which depends on the number of devices losing this packet (i.e. $N\alpha$), the probability of retransmitted packet loss and the uncorrelated factor.

[1]The detailed definition refers to the next paragraph

- $t_{c,tx}$ is the time of a mobile device transmitting NACK, which depends on a NACK message size, probability of a mobile device fails to receive the original packet and the retransmitted packet, and also the uncorrelated factor.
- $t_{c,i}$ is the time during which other devices send NACK.

The concept of the *uncorrelated factor* comes from the suppression NACKs scheme from loss recovery algorithm of SRM. In SRM, the mobile device that detects packet loss waits for a random backoff time before requesting retransmission. When a base station retransmits the requested packets in a multicast fashion, some wireless devices will receive the missed packets which they have not requested retransmission yet. The reason lies in that the lost packets of each mobile device are correlated to some extend. The random backoff time delay is not included in the energy consumption formula, i.e. the real energy consumption and delay performance of the ARQ strategy is even worse than the calculation result from the given formula.

3.2.2 FEC/HARQ Schemes

In this section, the energy consumption is derived for layered FEC and HARQ II based on the average number of transmissions required to transmit a packet reliably to all receivers which is denoted by $E[M]$. $E[M]$ of different mechanisms has been derived in [79]. For layered FEC $E[M]$ is given in Equation 4 in [79]; for integrated FEC II, i.e. HARQ II, $E[M]$ can be obtained from Equation 5,6,7 in [79]; Equation 8,9 in [79] is used at the condition of heterogenous reception. The detailed derivation of $E[M]$ for different mechanisms can refer to [79]. To calculate the energy consumption for layered FEC and HARQ II, the same energy calculation methodology described in Subsection 3.2.1 is used. Hence, the energy consumption of layered FEC or HARQ II[2] scheme can be expressed as

$$E_{FEC} = \underbrace{E[M]}_{t_{c,rx}} P_{c,rx} + \underbrace{(E[M]-1)\beta}_{t_{c,tx}} P_{c,tx} + \underbrace{(N-1)(E[M]-1)\beta}_{t_{c,i}} P_{c,i} \,. \qquad (3.3)$$

[2]The $E[M]$ of the HARQ II calculated by the formula given in [79] is the ideal lowest value. So in fact the energy consumption of the HARQ II scheme is underestimated.

3.3 Cooperative Retransmission Strategy

The idea of cooperative retransmission strategy is based on the topology shown in Figure 3.1. Multiple mobile devices located in proximity of each other form a cooperative cluster. The mobile devices within the same cluster can communicate directly with each other using short-range link (SRL). In contrast to SRL, link between mobile devices and a base station is referred to as cellular link (CL). Data rate of SRL is much higher than that of CL. Furthermore, power consumption on SRL is much lower, because of the shorter distance between transmitter and receiver, which also contributes positively to the reliability of SRL.

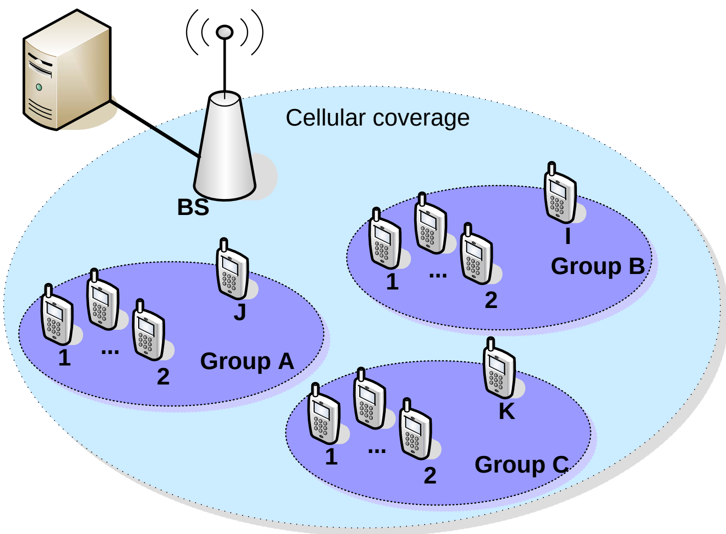


Figure 3.1: Topology of cooperative groups within one central base station [1].

Exploiting the characteristics of short-range link, the wireless devices in one cluster can exchange (retransmit) the missed packets in a very short time over the short-range link. This does not only save energy but also reduces the recovery latency. It consequently increases the total throughput on cellular link. In case that there is unrecoverable packet error/loss in a cooperative cluster after local retransmission, the cluster is able to send NACKs to the base station to trigger cellular retransmissions. In the following subsections, how to implement coop-

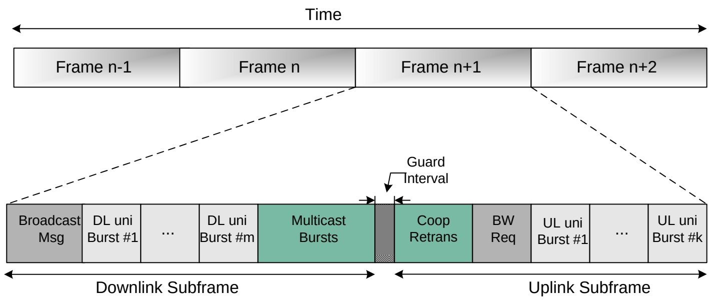


Figure 3.2: Frame structure in the cooperative protocol.

erative retransmission on both cellular link and short-range link will be explained.

3.3.1 Frame Structure Design on Cellular Link with TDD Mode

In the investigated system a mobile device is assumed to have one air interface. Mobile device communicates either over cellular link with a base station or over short-range link with its neighboring mobile devices. The base station controls the mobile devices to communicate alternatively over cellular link or over short-range link. All the mobile devices are synchronized to the clock of the base station, and thus all mobile devices within one cluster are synchronized.

The investigated system uses TDD (Time Division Duplex) for downlink and uplink transmission. The designed frame structure on cellular link is shown in Figure 3.2. A frame consists of a downlink subframe, an uplink subframe and a guard interval. The information in downlink subframe consists of signalling and data. The signalling is conveyed in broadcast fashion. It includes description of the downlink/uplink physical layer parameters and downlink/uplink usage assignment information. The data packets are transmitted as unicast or multicast bursts. The time slot allocation for unicast or multicast is very flexible, which depends on the current services and packet scheduling algorithm in the BS. In one downlink subframe, it can contain only unicast bursts or multicast burst or both.

Cooperative retransmission slots are assigned by BS, according to the number of mulitcast service subscribers and the number of mobile devices involved in cooperation. If mobile devices are sparsely distributed in the coverage and are unable to form cooperative clusters, there is simply no need for BS to reserve cooperative retransmission slots. In such case, mobile device should be capable to recover error/loss stand alone. Hence, cooperative retransmission is optional for mobile devices. In stand alone mode, mobile devices deal with packet loss by conventional ARQ schemes, sending NACKs individually in uplink unicast slots. Then BS retransmits requested packets to individual user in downlink unicast burst slots.

Cooperative retransmission is usually executed once for a batch of packets. As for stand alone mobile device, it can send a NACK message when it has lost packets. The design is very generic and flexible for base station and mobile devices.

3.3.2 Design Cooperative Retransmission Scheme on Short–Range Link

Cooperative retransmission is done among cooperative devices during the cooperative retransmission slots which are reserved by a base station. A novel scheme design is advocated for the cooperative retransmission implementation.

First of all, the cooperative retransmission is assumed to be done once every M multicast packets and there are N mobile devices in one cluster. All the devices within a cluster have short-range links to each other and all the short-range links have the same data rate. The cluster membership is maintained by a *Common Connectivity Table*. All the devices in the cluster host a local copy of the *Common Connectivity Table* which is updated periodically.

The proposed cooperative retransmission protocol is based on a logical token ring topology. The signalling among the devices in a cluster is carried by a token packet. The devices use the token packet to collect the lost packet information and to share the retransmission duty. Usually all the losses/errors can be recovered by K ($K = 2 \sim 4$) devices called *primary* devices, due to packet error/loss diversities in different devices. The remaining devices, called *auxiliary* devices, can help to complete recovery in case the K primary devices are not able to recover all the losses. This is implemented by an additional bit called *Complete Reception Bit* (CRB) and an optional field in the token packets.

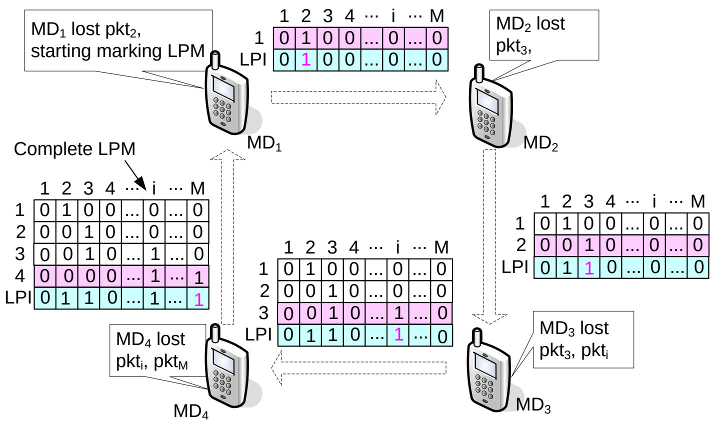


Figure 3.3: Marking Lost Packet Matrix procedure.

The cooperative retransmission can basically be divided into two procedures. The first procedure is to count all the lost packets within a cluster by marking the *Lost Packet Matrix* (LPM). Each mobile device generates one packet loss report vector with M elements and inserts it into LPM. The final completed matrix is composed of $(N+1)$ rows and M columns. If mobile device i loses the jth packet, it marks the bit $LPM(i,j)$ as bit "1", otherwise it sets the bit as "0". The last additional row is called *Lost Packet Information* (LPI) vector which indicates all of the lost packets within the cluster. A concrete example is given here: there are four devices in a cluster and two of them work as *primary* devices (i.e. MD_1 and MD_2 in Figure 3.3 and Figure 3.4). The marking LPM procedure is illustrated in Figure 3.3.

Followed by the first primary mobile device (i.e. MD_1 in this example) receiving the token packet, the second procedure starts: local retransmission. The illustration diagram is shown in Figure 3.4. Assuming there are L induplicated lost packets within the cluster. The first primary mobile device scans the LPI vector and knows which L packets are lost. Then it scans the first K rows and chooses the packets which are lost by the other $K-1$ primary devices but are correctly received by itself. Then it retransmits such packets first. If the number of such

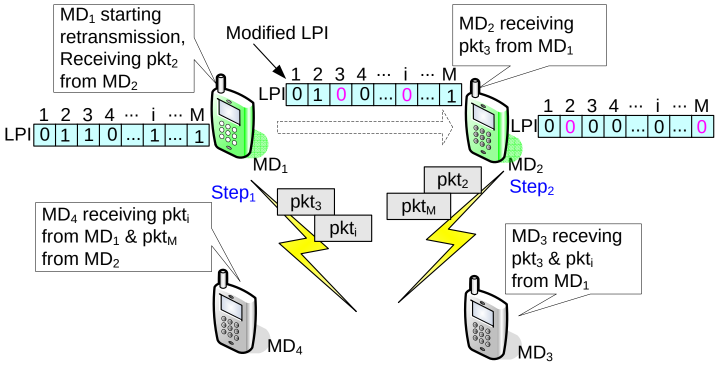


Figure 3.4: Local retransmission procedure (MD_1 and MD_2 are *retransmitters*).

packets is less than $\lceil L/K \rceil$, it continues to retransmit some lost packets until the number of packets that it has transmitted is equal to $\lceil L/K \rceil$. After finishing its retransmission duty, the first primary mobile device resets the index bits of the retransmitted packets as "0" in the LPI vector (MD_1 retransmits pkt_3 and pkt_i in the example). Then it passes the token to its successor. The second primary mobile device executes the same procedure as its predecessor, and so forth. The last primary mobile device will check the Complete Reception Bit (CRB) and the optional field, when it finishes its retransmission duty. If the CRB indicates there are unrecoverable packets in the cluster, the last primary mobile device will send a NACK to the BS requesting the missed packets over cellular link. If it knows who can complete the rest recovery task from the optional field, it will pass the token packet directly to that auxiliary mobile device. The last case is that the last primary mobile device knows all the lost packets have been recovered and it sends an ACK to the BS.

To reduce the latency of passing the *Lost Packet Matrix* (LPM) and the overhead load due to it, the LPM can be compressed from $N+1$ rows to $K+1$ rows. The compressed LPM of the aforementioned example is shown in Figure 3.5. The idea is that the auxiliary devices can mark a lost packet on a random row but with a specific column index, instead of having individual rows to indicate their lost packets. For instance, in the case of $N = 128$ and $K = 3$, the compressed LPM reduces by 95% latency. So it is a very efficient way to control latency bound in a big cluster.

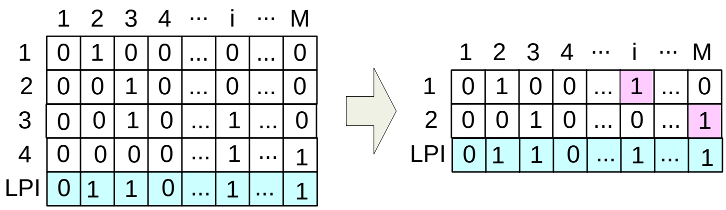


Figure 3.5: Compressed Lost Packet Matrix for the example.

The pseudo-code of the marking a compressed LPM and setting CRB procedure are listed as algorithm 1.

This cooperative retransmission scheme is very fair for all the devices to cooperate in the cluster. Furthermore, such task sharing cooperation highly meets the timely reciprocity requirements of the designing principle for cooperative wireless networks. As mentioned in [1], cooperative interaction should payoff in a timely fashion. Every cooperating party should see its benefits in doing so within the shortest possible delay. The delay of the feedback benefit in the proposed cooperative protocol is only at the order of seconds, which can be regarded as nearly instantaneous reciprocity.

3.3.3 Energy Consumption of Cooperative Retransmission Protocol

The probability that a packet loss cannot be recovered by local retransmission is very low. Therefore, the following energy calculation only considers local retransmission within the cluster. Moreover, the short-range link can reasonably be assumed to be very reliable and no retransmitted packet loss over it. I define:

- $P_{sr,rx}$, $P_{sr,tx}$ and $P_{sr,i}$ as the power consumed in reception, transmission process and idle state on short-range link of a mobile device, respectively.

- $t_{sr,rx}$, $t_{sr,tx}$ and $t_{sr,i}$ is the corresponding time spent on reception, transmission and idle state on short-range link, respectively.

```
/* initialization                                              */
LPI = zeros(1, M) ;
crb = 0;
for i ← 1 to N do
    LPV_i = zeros(1, M);
    for j ← 1 to M do
        if node i lost packet j then
            LPV_i(j) ← 1;
        end
    end
    if i ≤ K then
        LPM(i, ·) ← LPV_i;
        LPI ← Or(LPI, LPM(i, ·));
        if i == K then
            crb ← all(Or(∼ LPM(:, ·)));
        end
        /* check if pkts are all received by the K nodes     */
    end
    else
        if crb == 0 then
            crb ← all(∼ And(LPV_i, And(LPM(:, ·)));
            /* check if the ith node has the missed pkts      */
            if crb==1 then
                OptionField ← itsID;
            end
        end
        unLPktIdx ← find(LPI == 0);
        /* return index of any element whose value is equal
            to 0 in vector LPI                                */
        LPktIdx ← find(LPV_i == 1);
        /* return index of any element whose value is equal
            to 1 in vector LPV_i                              */
        UnMarkedLPktIdx ←
        LPktIdx(ismember(LPktIdx, unLPktIdx));
        /* return unmarked lost packets' indices              */
        for p ← 1 to length(UnMarkedLPktIdx) do
            randomly select an integer r between [1, K];
            LPM(r, UnmarkedLPktIdx(p)) ← 1;
        end
    end
end
```

Algorithm 1: Algorithm of marking Compressed *Lost Packet Matrix* and *Complete Reception Bit*.

The total energy consumption of a mobile device is

$$E_{Coop} = \underbrace{t_{c,rx} P_{c,rx}}_{E_c} + \underbrace{t_{sr,rx} P_{sr,rx} + t_{sr,tx} P_{sr,tx} + t_{sr,i} P_{sr,i}}_{E_{sr}}, \tag{3.4}$$

where E_c, E_{sr} are the average energy consumption on the cellular link and the short-range link, respectively.

E_{sr} includes two parts: the energy consumption used for marking *Lost Packet Matrix* LPM and local retransmission. Marking LPM period is defined as the time of the first mobile device starting marking LPM until it receiving the complete LPM. During one marking LPM period, each mobile device receives and transmits the LPM once. A mobile device can stay in idle state during the remaining time of marking LPM period. So the average energy overhead for marking LPM on every packet, δ, is given by

$$\delta = \frac{1}{M} \left(\frac{\rho}{\omega} (P_{sr,tx} + P_{sr,rx}) + \frac{\rho(N-2)}{\omega} P_{sr,i} \right),$$

where

- ρ is the ratio of the average token packet size to data packet size.
- ω is the data rate ratio of short-range link to cellular link.

The average energy overhead for each packet on each mobile device induced by local retransmission is derived below. As there are K primary devices in one local retransmission, each mobile device takes retransmission task every N/K local retransmissions. Hence, one mobile device's energy consumption can be summed up on the short-range interface during the consecutive N/K local retransmissions. Then the sum is averaged by N/K and M. So E_{sr} can be expressed by

$$E_{sr} = \frac{E_{pri} + (\frac{N}{K} - 1) E_{aux}}{\frac{N}{K} M} + \delta, \tag{3.5}$$

where E_{pri} and E_{aux} is the energy consumption of a mobile device working as *primary* mobile device or *auxiliary* mobile device in one local retransmission. Their expressions are given by

$$E_{pri} = \frac{L/K}{\omega} P_{sr,tx} + \frac{L/K}{\omega} (K-1) P_{sr,rx}$$

Table 3.1: Parameters assumption for Analysis.

Notation	α	β	ρ	R_c	R_{sr}	ω
Value	2% or 5%	0.2	0.1	6 Mbit/s	54Mbit/s	9
Notation	$P_{c,rx}$	$P_{c,tx}$	$P_{c,i}$	$P_{sr,rx}$	$P_{sr,tx}$	$P_{sr,i}$
Value	0.9W	2W	0.04W	0.4W	1W	0.04W

$$E_{aux} = \frac{L}{\omega} P_{sr,rx} \,,$$

where L is the number of the unduplicated lost packets within a cluster, $L = fNM\alpha$.

The explanation of E_{pri} and E_{aux} expression is: after the BS transmits M multicast packets, the number of packets lost at one mobile device is equal to $M\alpha$; the sum of lost packets at all devices in one cluster is $NM\alpha$; considering correlation of the lost packets, the number of the unduplicated lost packets within one cluster is $L = fNM\alpha$. The time that a primary device spends on packet transmission is $\frac{L/K}{\omega}$ and the time of a primary device receiving the packets transmitted by other primary devices is $\frac{L/K}{\omega}(K-1)$.

3.4 Comparison of Energy Consumption

Based on the cooperative retransmission protocol, this section compares energy consumption of the cooperative retransmission strategy with the non-cooperative ones. Table 3.1 summarizes the variables and notations that are used in the following energy analysis. The parameter values are taken from [1].

Figure 3.6 and Figure 3.7 compare energy consumption of the non-cooperative ones with the cooperative strategy under the condition of homogeneous and heterogeneous packet loss rate at receivers, respectively. Fig, 3.6 and Figure 3.7 shows the energy consumption comparison based on energy units. It clearly shows that energy consumption of the cooperative strategy is quite stable with an increasing number of devices in the multicast group for both homogeneous and heterogeneous packet loss situations. However the energy consumptions of the layered FEC and the ARQ (SRM) schemes increase dramatically when the number of the devices increases. Hence, the achievable energy saving gain by coop-

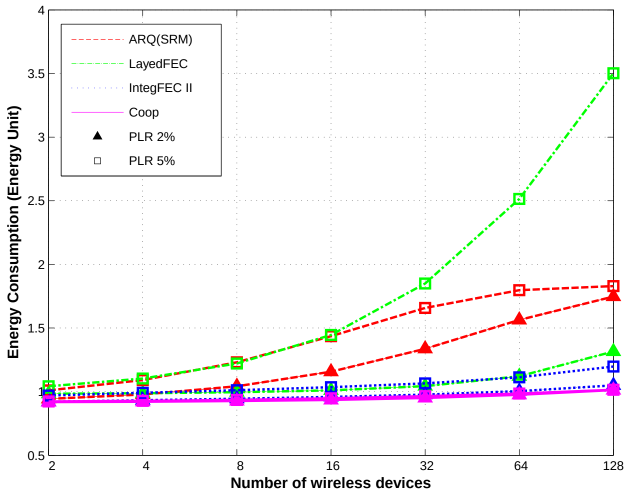


Figure 3.6: Energy consumption comparison of different error recovery schemes in homogeneous packet loss rate scenario.

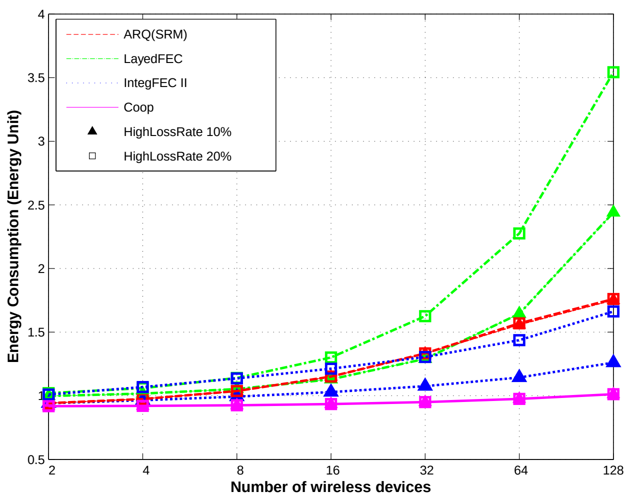


Figure 3.7: Energy consumption comparison of different error recovery schemes in heterogeneous packet loss rate scenario (The high packet loss is 10% or 20%. There are 5% high packet loss devices in the cluster. The rest of devices has 2% packet loss rate).

erative retransmission becomes significant when there are many devices in the multicast group. It can be seen clearly that higher packet loss rates lead directly to a more energy saving. In the two figures the effect of ARQ (SRM) suppression scheme can also be seen. For example, due to uncorrelated factor deceasing with the number of the mobile devices increasing, the increasing trend of energy consumption of ARQ (SRM) decreases. Moreover, in Figure 3.7, the two ARQ (SRM) curves are overlapped because the packets lost by high loss rate devices are overlapped with the packets lost by normal devices and the suppression scheme in SRM highly avoids the duplicated retransmission.

The HARQ II (IntegFEC II) has as good energy consumption as the cooperative retransmission scheme when the receivers have the homogeneous packet loss. But the cooperative retransmission scheme outperforms the HARQ II under the heterogeneous packet loss rate assumption. For instance, it can be seen in Figure 3.7 that for 128 devices in one cluster the cooperative scheme achieves energy saving up to 40% at the high packet loss rate equal to 10%.

All the above calculation results are based on the scenario that all devices in the system form one cluster. However, considering real usage scenario, mobile devices scatter within the coverage of a base station. It is possible for mobile devices to form small clusters. Different groups can do local cooperative retransmission concurrently by grouping, assuming that the distance between groups are far away enough to ensure no interference among groups. For example, there are 128 devices in the system and for simplicity they are assumed to be split into 2, 4, 8, 16, 64 groups. The energy saving with grouping is shown in Figure 3.8. The energy saving range is between 40% and 48% at packet loss rate of 5%, when the number of groups varies between 1 and 64. It means that the average cooperative energy saving is within the range of [40% $\sim$ 48%] when there are 128 devices in the system. Furthermore, it indicates that the smaller cluster results in the higher energy saving. The reason is less energy overhead on short-range link in a smaller cluster.

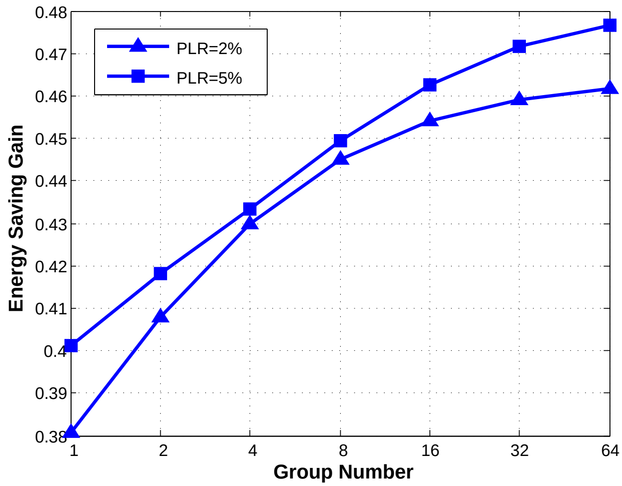


Figure 3.8: Cooperative energy saving gain with grouping.

3.5 Network Coding Applied in Cooperative Retransmission

Although the great potential of the cooperative local retransmission scheme has been illustrated above, the retransmission procedure can be further improved by encoding the retransmitted packets with network coding. The reason lies in the coding mechanism of network coding and the error/loss heterogeneity. By network coding, a mobile device can make linear combination of the packets that it receives to generate new packets. When other mobile devices receive the new coded packets, they can use their known packets to decode the missed packets which are encoded in the retransmitted packets. The advantage of network coding is that although different mobile devices miss the different packets, it is possible for them to use the same coded packets to recover the different missed packets. The detailed encoding and decoding algorithm of network coding can refer to [92]. With network coding the number of local retransmission packets can be significantly reduced; specially, when the missed packets at each mobile device are heterogeneous. In other words, higher cooperation gain can be obtained by network coding.

A simple case in point is that assuming there are N mobile devices in a cluster and the cooperation retransmission is done every M packets ($M > N$). Assuming each mobile device miss one packet but different ones, then the cluster can complete the recovery by $1 + 1 = 2$ coded retransmission packets instead of retransmitting N packets.

The theoretical analysis is given in the following. The set of the missed packets of a cluster can be expressed by

$$\hat{L} = L_1 \cup L_2 \ldots \cup L_n \,, \tag{3.6}$$

where $L_1, L_2, \ldots, L_n$ are the sets of the missed packets of mobile device 1, 2,. . . , n, respectively.

Therefore, the number of the retransmission packets N_{lr} is

$$N_{lr} = |\hat{L}| \,, \tag{3.7}$$

where $|\hat{L}|$ is the cardinality of set $\hat{L}$, i.e. the number of the total lost packets in the cluster. With network coding, the number of the retransmission packets is N_{nc}, which is given by

$$N_{nc} = \begin{cases} max\{|L_1|, |L_2|, \ldots, |L_n|\} + min\{|L_1|, |L_2|, \ldots, |L_n|\} & \Lambda = \phi \\ max\{|L_1|, |L_2|, \ldots, |L_n|\} + min\{|L_1|, |L_2|, \ldots, |L_n|\} - |\Lambda| & \Lambda \neq \phi \end{cases} , \tag{3.8}$$

where $|L_1|, |L_2|, \ldots, |L_n|$ represent the cardinality of set $L_1, L_2, \ldots, L_n$. Λ is the intersection of set L_1, L_2, $\ldots$, L_n, i.e. $\Lambda = L_1 \cap L_2 \ldots \cap L_n$. When $\Lambda = \phi$, it means that all the missed packets can be recovered within the cluster. In case $\Lambda \neq \phi$ the cluster needs to request $|\Lambda|$ packets from the BS. Note that the expression of N_{nc} here does not consider the error/loss of the retransmitted packets.

A simulation is conducted to show the potential of network coding in cooperative retransmission. The assumptions are given in the following. The cooperative retransmission is done every M sequent packets with M=20 or 40. There are 5 to 100 mobile devices in a cluster. The packet loss rate (PLR) is 2% or 5%. The comparison of cooperative retransmission w/o (with/without) network coding is shown in Figure 3.9. It is clear that with network coding, the number of retransmitted packets is much less than that of the conventional cooperative retransmission. For instance, when the number of packets in one packet flow is 20 and

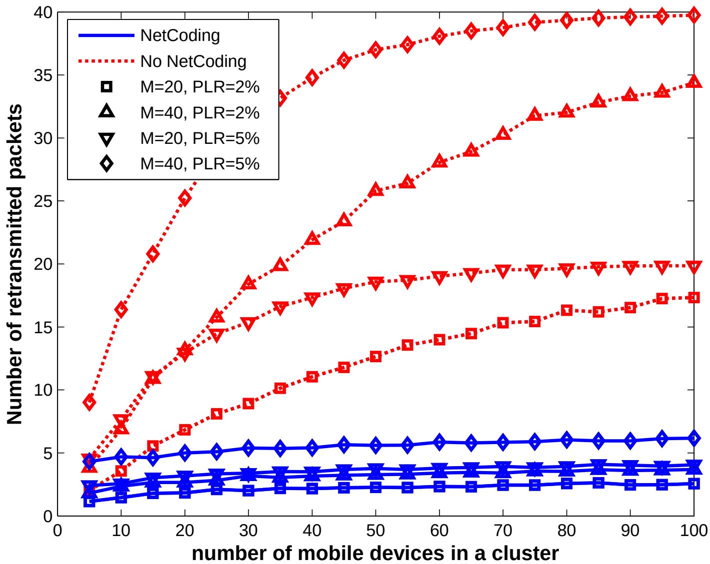


Figure 3.9: Number of retransmitted packets within a cluster by cooperative retransmission w/o network coding.

the packet loss rate is 2%, under the condition that there are 100 mobile devices in the multicast group the number of retransmitted packets w/o network coding is 2 and 16, respectively. With the same number of mobile devices in one multicast group, when the number of packets in one packet flow is increased to 40 and the packet loss rate is increased to 5%; the number of retransmitted packets without network coding increases to 40. However, the number of retransmissions increases to only 6 with network coding. It indicates that with increasing packet loss rate or number of packets in one packet flow, the variation of number of the retransmitted packets is much smaller using network coding. Furthermore, it should be noted, that with network coding number of the retransmitted packets is quite stable with varying size of a cluster.

The advantage of applying network coding for cooperative retransmission is threefold:

- Network coding shortens the retransmission time and it further improves the overall network throughput performance.

- Network coding reduces the times of transmission and reception within a cluster; therefore, it has great potential to save more energy on mobile devices.
- With the characteristics of stable retransmission times, it is easier for BS to reserve certain number of time slots for cooperative retransmission beforehand.

3.6 Conclusion

In this chapter, a novel and generic cooperative retransmission scheme is proposed for reliable wireless mulitcast services to reduce energy consumption, to minimize packet loss recovery latency and to improve the network throughput. It exploits the higher data rate, better reliability and low power consumption characteristics of short-range link and can recover almost all packet errors/losses locally in a very short time. It is robust to not only homogeneous but also to heterogeneous channel conditions. Comprehensive comparison and analysis of energy consumption between the cooperative and the non-cooperative strategies has been given. The analysis results show that the proposed cooperative retransmission scheme is more efficient and suitable for the reliable multicast services than the non-cooperative ones. Moreover, network coding is applied in the retransmission to further improve the retransmission efficiency. The simulation results prove that network coding can significantly reduce the number of retransmitted packets because of heterogeneity of lost packets at each mobile device.

Chapter 4

One4all Cooperative Media Access Strategy in WLAN

In this chapter *one4all* cooperative access strategy is proposed to introduce a more efficient uplink access strategy for infrastructure based WLAN. The *one4all* scheme is based on *Cellular Controlled Peer-to-Peer* network architecture. The basic idea is that mobile devices form a cooperative cluster using their short–range air interface and one device contends the channel for itself and also for all neighboring devices within the cluster. This strategy reduces the number of mobile devices involved in the contention process for wireless medium resulting in larger throughput, smaller access delay, and less energy consumption. Based on an analytical model, the proposed strategy is compared with the two existing strategies i.e. basic RTS/CTS (request to send/ clear to send) scheme and packet aggregation scheme. The results show that the proposed cooperative scheme has better throughput performance than packet aggregation and has much higher throughput than the conventional RTS/CTS scheme. Furthermore, the newly introduced scheme outperforms packet aggregation and RTS/CTS schemes in terms of channel access delay and energy consumption.

4.1 Introduction

Current wireless local area networks (WLANs) suffer from an inefficient wireless access strategy. For example, IEEE 802.11 WLAN standard product can provide up to 54Mbps transmission rate at physical layer. The recent IEEE 802.11n proposals aim at providing physical layer transmission rates up to 600Mbps. However, theoretical throughput limits exist [93, 94] due to the overhead at medium access control (MAC) and the physical layer (PHY), the backoff time in case of contention, the inter-frame space (IFSs) and others. Therefore, to achieve high throughput values at network layer, research should focus not only on higher physical layer data rates but also on more efficient MAC strategies to reduce the aforementioned overhead. So far the most popular and effective strategy to enhance WLAN throughput is packet aggregation [95–99]. But packet aggregation has inevitable drawbacks, for instance, throughput gain is highly dependent on arrival traffic pattern. Packet aggregation does improve throughput of bursty traffic such as video streaming, but it would not improve throughput so much for non–bursty traffic such as VoIP traffic. Furthermore, it also may cause longer channel access time which in turns leads to higher energy consumption and unfair channel usage between mobile devices. The performance of packet aggregation is sensitive to channel error.

In this chapter, a new cooperative uplink access strategy named *one4all* is proposed. It is based on Cellular Controlled Peer to Peer network architecture described in Chapter 1. The basic idea of the proposed strategy is that every mobile device within a communication cell is not contending for the channels for itself anymore, but benefit from cooperation among neighboring mobile devices.

Before explaining the *one4all* strategy more in detail, the two existing channel access strategies in WLANs will be explained.

4.2 CSMA/CA based MAC Strategies

This section presents two existing MAC strategies based on carrier sense multiple access with collision avoidance (CSMA/CA), namely the conventional RTS/CTS strategy and the packet aggregation strategy. According to the analytical model of CSMA/CA in [25, 100], the throughput, channel access delay and energy consumption of conventional RTS/CTS strategies is first analyzed. Afterwards the existing analytical model is extended and it is applied to a system with packet aggregation. The corresponding performances of packet aggregation scheme are analyzed.

4.2.1 RTS/CTS Strategy

An analytical model for CSMA/CA to analyze throughput and delay performance in case of saturation is developed in [25, 100]. The model in [100] is built on top of [25] with more accurate results. Therefore, some derived results from [100] are used here. In this model, it is assumed that the network consists of n contending mobile devices and each device has an arrival packet for transmission immediately after its completion of a successful packet transmission. In [100] it has already shown that CSMA/CA with RTS/CTS outperforms the basic CSMA/CA under given packet size assumption. Therefore only the RTS/CTS case is addressed in this chapter. The RTS/CTS access mechanism illustration diagram is shown in Figure 4.1. The detailed description of RTS/CTS mechanism can refer to [101].

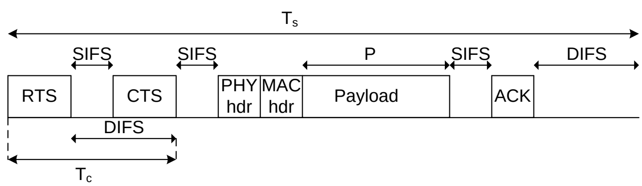


Figure 4.1: The RTS/CTS access mechanism [25].

In the following throughput, channel access delay and energy consumption are analyzed; and their mathematical expression are derived. The notations in the equations are listed in Table 6.1.

Throughput Analysis

For the model presented in [25,100], it is assumed that each transmission is a renewal process, no matter whether it is successful or not. Therefore, the saturation throughput η can be calculated according to the payload

Table 4.1: Parameter list.

Notation	Meaning
n	the number of contending mobile devices
W	min (initial) contention window
m	backoff stage ($W_{max} = 2^m W$)
p_b	the channel busy probability
p	collision probability of a transmitted frame
P_s	the probability that a transmission is successful
τ	the probability that a mobile device transmits during a slot time
Ψ	The number of consecutive idle slot times before a transmission takes place
N_c	the number of collisions of a frame until its successful transmission
D_b	the backoff delay
σ	one unit slot time
C_{bk}	the value of the backoff counter
F	the duration that a counter is in freezing state before a counter reaching zero
N_{fr}	the number of times that a counter freezes before a counter reaching zero
T_s	transmission time of a single successful frame transmission
T_c	the average transmission time of transmission with collision
T_o	the time that a mobile device has to wait when its frame transmission collides, before sensing the channel again.
T_p	the time used for successful transmission of a payload
T_{int}	the time interval between two consecutive transmissions
η	throughput
D_c	the channel access delay
RTS/RTS_t	size of a RTS frame / transmission time of a RTS frame
CTS/CTS_t	size of a CTS frame/ transmission time of a CTS frame

Notation	**Meaning**
P/P_t	size of the PDU payload/ transmission time of a payload
PHY_h/PHY_{ht}	size of a physical layer header/ transmission time of a PHY header
MAC_h/MAC_{ht}	size of a physical layer header/ transmission time of a MAC header
ACK/ACK_t	size of a block ACK frame/ transmission time of a block ACK frame
δ	propagation delay
$SIFS$	short interframe space
$DIFS$	distributed interframe space
R	channel data rate

transmitted during a single renewal interval between two consecutive transmissions. The expression of saturation throughput η is given in [100] as following:

$$\begin{aligned} \eta &= \frac{E[T_p]}{E[T_{int}]} \\ &= \frac{P_s E[P_t]}{E[\Psi]\sigma + P_s T_s + (1-P_s)T_c}\,. \end{aligned} \tag{4.1}$$

Based on the model in [25, 100], the unknown variables in Equation 4.1 are obtained by using the equations given in [100] which defines three new variables p, p_b and τ (see Table 6.1). The detailed derivation of τ can refer to [100]. The relations of these three variables are given in the following:

$$p = 1 - (1-\tau)^{n-1} \tag{4.2}$$

$$p_b = 1 - (1-\tau)^{n} \tag{4.3}$$

$$\tau = \frac{2p_i(1-2p)}{2p_i^2(1-2p)(1-p) + (p_b+pp_i)(1-2p)(W+1) + pW(p_b+pp_i)(1-(2p)^m)}\,, \tag{4.4}$$

where the channel idle probability $p_i = 1 - p_b$.

Substituting Equation 4.2 and 4.3 to Equation 4.4, the probability τ is obtained. Afterwards p and p_b are calculated.

The probability of a successful transmission P_s is given by [100]

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}\,. \tag{4.5}$$

The average number of consecutive idle slots before a transmission takes place $E[\Psi]$ is given by [100]

$$E[\Psi] = \frac{1}{P_b} - 1\,. \tag{4.6}$$

Then based on the RTS/CTS mechanism (see Figure 4.1), the transmission time of a single successful frame transmission T_s and T_c can be calculated as following:

$$T_s = RTS_t{+}\delta{+}SIFS{+}CTS_t{+}\delta{+}SIFS{+}H_t{+}P_t{+}\delta{+}SIFS{+}ACK_t{+}\delta{+}DIFS\,, \tag{4.7}$$

where $H_t = PHY_{ht} + MAC_{ht}$.

$$T_c = RTS_t + \delta + DIFS\,. \tag{4.8}$$

After getting all these unknown variables in Equation 4.1, throughput η can be easily obtained.

Channel Access Delay Analysis

Channel access delay, D_c, is defined as the time duration starting when a mobile device contends a channel to transmit a packet for the first time until the instant where it can start to transmit the packet successfully. It includes backoff delay (D_b), which is the time a mobile device chooses to wait before accessing the channel under busy channel condition; the time (T_c) during which the channel is captured by mobile devices and collision happens; the time (T_o) that a mobile device has to wait if the transmitted frame collides [100]. The channel access delay also depends on the number of collisions before it finally access the channel successfully. In a nutshell, to calculate the average channel access delay $E[D_c]$, the following time duration should be included: a). before a mobile device can transmit packet successfully, it has collided with others for $E[N_c]$ times; b). before each contention try, it has waited for time $E[D_b]$; c). if there is a collision, it knows after time T_c; d). after a collision occurs, it has to wait for time T_o before sensing the channel again. Hence, the average channel access delay, $E[D_c]$, can be expressed as

$$E[D_c] = E[N_c](E[D_b] + T_c + T_o) + E[D_b]\,, \tag{4.9}$$

where the average number of collision before a mobile device finally access the channel is taken from [100]

$$E[N_c] = \frac{1}{P_s} - 1\,. \tag{4.10}$$

The backoff delay depends on the product of C_{bk} (the value of the backoff counter) and the slot time, and the time duration F during which each mobile device freezes the counter before the counter reaching zero. The average of the backoff counter is a random variable depending on the initial contention window and the backoff stages. The total duration of the counter in freezing state depends on the number of times that a mobile device freezes the counter and also on the duration of each freezing. So the average backoff delay is given by [100]

$$\begin{aligned} E[D_b] &= E[C_{bk}]\sigma + E[F] \\ &= E[C_{bk}]\sigma + E[N_{fr}](P_sT_s + (1 - P_s)T_c)\,, \end{aligned} \tag{4.11}$$

where

$$E[N_{fr}] = \frac{E[C_{bk}]}{max(E[\Psi], 1)} - 1\,.$$

The time T_o can be calculated according to the standard as

$$T_o = SIFS + CTS_{timeout}\,. \tag{4.12}$$

Thus, the average channel access delay can be calculated by substituting Equation 4.8, 4.10, 4.11, 4.12 into Equation 4.9.

Energy Consumption Analysis

Energy consumption depends on the energy consumed in different communication phases of a mobile device and the time that the mobile device staying at the corresponding state. There are four different possible states that a device can stay: transmission state, reception state, listening state and idle state. Their corresponding power consumptions are denoted by P_{tx}, P_{rx}, P_{li}, P_i, respectively.

Mobile device is in transmission state only when it sends RTS messages or data frames. It is in reception state when it receives CTS messages or ACK messages from an access point or receives RTS message from other mobile devices. During DIFS and SIFS mobile device is in listening state. The mobile device is assumed to perform a smart energy saving strategy, i.e. mobile device can switch to idle state when it sets its network allocation vector (NAV) timer. Energy consumption of each packet is calculated by summing up all the energy consumption from a mobile device starting to contend until it has finished sending the packet. Hence, energy consumption for each packet can be expressed by

$$Eng = P_{tx}T_{tx} + P_{rx}T_{rx} + P_{li}T_{li} + P_iT_i \,, \tag{4.13}$$

where

- T_{tx} consists of two parts: $T_{tx,1}$, the successful transmission time which includes transmission time of RTS, physical header, MAC header and the payload; and $T_{tx,2}$, the time that the transmitted RTS collides which is the product of the average collisions and the transmission time of RTS.

$$\begin{aligned} T_{tx,1} &= RTS_t + PHY_{ht} + MAC_{ht} + P_t \\ T_{tx,2} &= E[N_c]RTS_t \,, \end{aligned}$$

- T_{rx} also consists of two parts: $T_{rx,1}$, the time that a mobile device receives other's RTS&CTS during backoff duration; and $T_{rx,2}$, the mobile device receives its own CTS and ACK when its RTS is successfully transmitted.

$$\begin{aligned} T_{rx,1} &= (E[N_c]+1)E[N_{fr}](P_s(RTS_t+CTS_t)+(1-P_s)RTS_t) \\ T_{rx,2} &= CTS_t + ACK_t \,, \end{aligned}$$

- T^a_{li} consists of three parts: the listening time during all backoff durations within channel access delay, the listening time when the transmitted RTS collides, and the listening time during a successful transmission.

$$T^a_{li} = (E[N_c] + 1)T^{bk}_{li} + E[N_c](\delta + DIFS) + (3\delta + 3SIFS + DIFS) \,,$$

where T_{li}^{bk} is a mobile device's listening time during a backoff duration. It includes the time spending on backoff counter and the listening duration when the counter freezes. T_{li}^{bk} is given by

$$T_{li}^{bk} = E[C_{bk}]\sigma + E[N_{fr}]\left(P_s(2\delta + 2SIFS + DIFS) + (1-P_s)(\delta + \mathrm{DIFS})\right),$$

- T_i^a includes two parts: all the time durations of waiting for NAV timer out in the channel access delay and the idle time induced by T_o.

  $$T_i^a = (E[N_c]+1)E[N_{fr}]P_s T_{nav} + E[N_c]T_o\,,$$

  where T_{nav} is one NAV timer duration:

  $$T_{nav} = PHY_{ht} + MAC_{ht} + P_t + \delta + SIFS + ACK_t + \delta\,.$$

4.2.2 Packet Aggregation Strategy

Packet aggregation is a popular strategy to improve throughput in wireless networks based on CSMA/CA. It has been addressed in many research works [95–99] and it will be included in IEEE 802.11n standard. Aggregation can be performed on different sub-layers. There are two main categories of packet aggregation [101–106]: Aggregation of multiple MAC Protocol Data Units (A-MPDU) and aggregation of multiple MAC Service Data Units (A-MSDU). A-MPDU is also called packet concatenation [106]. The idea of A-MPDU is to concatenate multiple MAC PDUs into a single physical PDU. MAC PDUs can be concatenated if they are available and have the same physical source and destination address. The length of concatenation should not exceed a given threshold. The A-MSDU is also referred to as packet packing in the document [106]. The idea is to combine multiple MAC SDUs from a higher layer into a big MAC PDU. The MAC SDUs have the same MAC address. The detailed description of these two aggregation schemes can be seen in proposals from TGnSync or WWiSE [102,103]. A comprehensive performance comparison of A-MPDU and A-MSDU considering channel error rate and the number of packets in an aggregated frame is given in [105]. Since there is FCS (frame check sequence) for each packet in an aggregated frame by A-MPDU, A-MPDU is more robust against channel error impact than A-MSDU, which is also proofed in [105]. Although channel error impact on network performance is not considered, to compare with

Table 4.2: Parameter list.

Notation	Meaning
T_s^{Agg}	transmission time of an aggregated frame transmission
N_a	the number of packets in an aggregated frame
$\hat{N}_a$	the threshold of the number of packets in an aggregated frame
T_a	the duration of the previous aggregated frame starting to contend until its sucessful completion transmission
η^a	throughput with packet aggregation
$MD/\ MD_t$	size of a MPDU delimiter/ transmission time of a MPDU delimiter
λ	packet arrival rate

other schemes it is more fair to use A-MPDU strategy as a representative packet aggregation method. Additionally, block ACK is also used in the A-MPDU strategy. The A-MPDU frame structure diagram is shown in Figure 4.2.

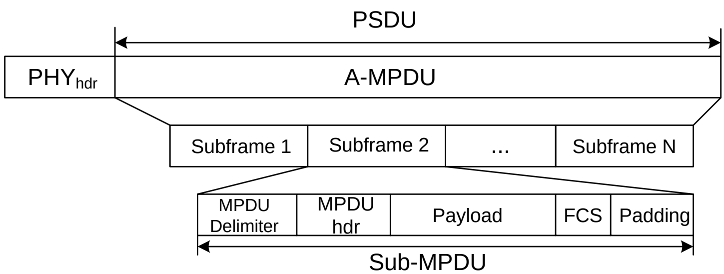


Figure 4.2: Frame structure in A-MPDU packet aggregation scheme.

Throughput & Channel Access Delay Analysis

To calculate throughput and channel access delay in CSMA/CA with packet aggregation, the model developed by [100] can be extended.

First of all, when the A-MPDU packet aggregation strategy is used in RTS/CTS mechanism, T_s has to be calculated in a different way. Based on the frame structure of A-MPDU (Figure 4.2), average transmission time of an aggregated frame transmission T_s^{Agg} is a function of $E[N_a]$. $E[N_a]$ is the average number of packets in an aggregated frame. $E[N_a]$ depends on the number of available packets in the buffer when a mobile device just finishes transmitting an aggregated frame. Hence, similarly as the expression of T_s, T_s^{Agg} is given as

$$T_s^{Agg} = RTS_t + \delta + SIFS + CTS_t + \delta + SIFS + PHY_{ht} + E[N_a]U_t + \delta + SIFS + ACK_t + \delta + DIFS\,, \tag{4.14}$$

where $U_t = MD_t + MAC_{ht} + P_t$.

The model in [100] assumes that each mobile device has an arrival packet for transmission immediately after its completion of a successful packet transmission. This assumption has to be extended considering the packet aggregation strategy. Packet aggregation is performed under the condition that the packets are available in the buffer and the number of packets in one aggregated frame must be smaller than the threshold, which means the number of packets in one aggregated frame is not fixed. Furthermore, to calculate the saturation throughput, the arrival traffic should meet the condition that there is at least one arrival packet in the buffer immediately after the mobile device completes an aggregated frame transmission. such arrival traffic is generated by a poisson process with additional constraints. The arrival rate with poisson process has to meet that the probability of no arrival packet during time T_a is close to zero, denoted by ε (e.g. $\varepsilon = 10^{-4}$). Under this condition, there will be at least one packet in the buffer.

Hence, the assumed poisson arrival process $P(i,t)$ with constraints is expressed by

$$P(0, T_a) = e^{-\lambda T_a} = \varepsilon \tag{4.15}$$

then

$$\lambda T_a = -ln\varepsilon\,. \tag{4.16}$$

The time T_a is composed of the channel access delay and the transmission time of the aggregated frame. The channel access delay $E[D_c]$ is calculated as Equation 4.9. Hence, T_a can be given by

$$\begin{aligned} T_a &= E[D_c] + T_s^{Agg} \\ &= E[N_c](E[D_b] + T_c + T_o) + E[D_b] + T_s^{Agg}\,, \end{aligned} \tag{4.17}$$

where the backoff delay can be calculated as Equation 4.11.

$$E[D_b] = E[C_{bk}]\sigma + E[N_{fr}](P_s^a T_s^{Agg} + (1 - P_s^a)T_c)\,, \tag{4.18}$$

where

$$P_s^a = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}\,.$$

According to the packet aggregation mechanism, the average number of the packets in an aggregated frame can be given by

$$\begin{aligned} E[N_a] &= \sum_{i=1}^{\hat{N}_a} i\frac{(\lambda T_a)^i}{i!}e^{-\lambda T_a} + \sum_{i=\hat{N}_a+1}^{\infty} \hat{N}_a\frac{(\lambda T_a)^i}{i!}e^{-\lambda T_a} \\ &= \varepsilon\left(\sum_{i=1}^{\hat{N}_a} i\frac{(-ln\varepsilon)^i}{i!} + \sum_{i=\hat{N}_a+1}^{\infty} \hat{N}_a\frac{(-ln\varepsilon)^i}{i!}\right)\,. \end{aligned} \tag{4.19}$$

So the throughput of CSMA/CA with the packet aggregation strategy similarly as Equation 4.1, can be expressed as

$$\eta^a = \frac{P_s^a E[N_a]E[P_t]}{E[\Psi]\sigma + P_s^a T_s^{Agg} + (1-P_s^a)T_c}\,. \tag{4.20}$$

By Equation 4.14, 4.17 and 4.19, $E[N_a]$ and T_s^{Agg} can be solved. Then the throughput η^a can be calculated by Equation 4.20. The average channel access delay of each mobile device can be calculated by substituting Equation 4.18 into Equation 4.9. So the average channel access delay for each packet is the average channel access delay experienced by each mobile device divided by $E[N_a]$.

From Equation 4.20, it is also clear that the achieved throughput gain depends on $E[N_a]$ which is a function of $\hat{N}_a$ and the arrival rate of poisson process. So when the arrival rate is low, the packet aggregation scheme cannot highly enhance throughput.

Another drawback of packet aggregation is its longer backoff delay (see Equation 4.18) which causes longer channel access delay. Longer channel access delay results in larger energy consumption of mobile devices.

Energy Consumption Analysis

Energy consumption of packet aggregation scheme is calculated by the same methodology described in Subsection 4.2.1. According to the packet aggregation strategy, the power level changes as shown in Figure 4.3.

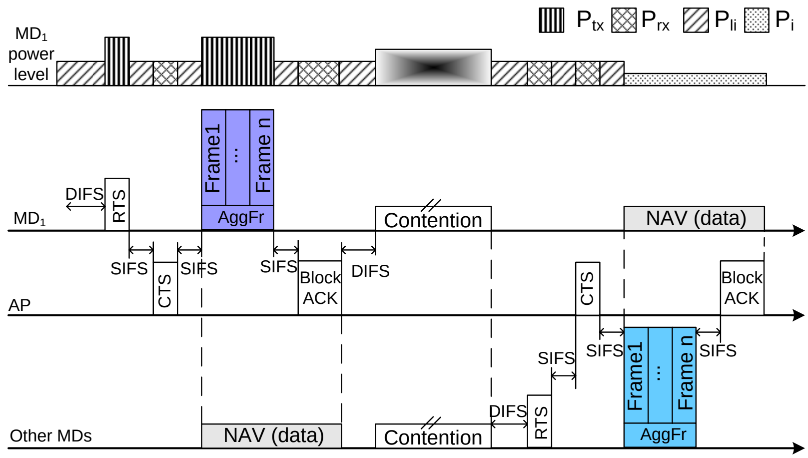


Figure 4.3: The power level changing of mobile device 1 diagram.

Based on Figure 4.3, energy consumption of each packet can be calculated by summing up all the energy consumption of a mobile device from it starting to contend until it finishing sending the aggregated frame; then the sum is averaged by the number of packets in one aggregated frame. Hence, energy consumption for each packet can be expressed by

$$Eng^a = \frac{1}{E[N_a]} \left(P_{tx} T_{tx}^a + P_{rx} T_{rx}^a + P_{li} T_{li}^a + P_i T_i^a \right) , \tag{4.21}$$

where

- T_{tx}^a consists of two parts: $T_{tx,1}^a$, the successful transmission time which includes transmission time of RTS, the physical header and the PSDU with $\overline{N_a}$ subframes; and $T_{tx,2}^a$, the time that a transmitted RTS collides which is the product of the average collisions and the transmission time of RTS.

$$\begin{aligned} T^a_{tx,1} &= RTS_t + PHY_{ht} + E[N_a](MD_t + MAC_{ht} + P_t) \\ T^a_{tx,2} &= E[N_c]RTS_t \,. \end{aligned}$$

- The expression of T^a_{rx} and T^a_{li} is same as T_{rx} and T_{li} just needing to replace the item P_s in T_{rx} and T_{li} by P^a_s.
- T^a_i includes two parts: the duration of all the NAV timers in the channel access delay and the idle time induced by T_o.

$$T^a_i = (E[N_c] + 1)E[N_{fr}]P_s T_{nav} + E[N_c]T_o \,,$$

where T_{nav} is one NAV timer duration (see Figure 4.3):

$$T_{nav} = PHY_{ht} + E[N_a]\,(MD_t + MAC_{ht} + P_t) + \delta + SIFS + ACK_t + \delta \,.$$

4.3 *One4all* Strategy

As described above, packet aggregation has three drawbacks. (i) the achievable throughput depends on the arrival traffic pattern. It is good for bursty traffic but not for light smooth traffic. (ii) long channel access delay in packet aggregation might lead to unfair media usage between mobile devices. (iii) longer channel access delay also causes higher energy consumption in mobile devices. To overcome these drawbacks of packet aggregation, *one4all* strategy is proposed.

The proposed strategy is based on the cellular controlled peer-to-peer (CCP2P) network architecture in Chapter 1. The mobile devices in the network are assumed to have two air-interfaces: one for cellular link and the other for short–range link. A mobile device is capable to form a cluster with the mobile devices in its proximity by the short-range link. The idea of *one4all* strategy is that a mobile device cooperates with the other devices in its clusters and only one device in a cluster contends to access a channel instead of all of them contending to access the channel. The contending device also receives the block ACK and distributes the block ACK over the short–range link. The advantage of the proposed strategy is that: first, the collision probability of the transmitted frames by the contending mobile devices is reduced; secondly, the remaining devices in

Table 4.3: Parameter list.

Notation	Meaning
c_m	the number of the mobile devices in a cluster
T_s^c	transmission time of a cooperative cluster
η^c	throughput with *one4all* strategy
p_b^c	the channel busy probability with *one4all* strategy
p^c	collision probability of a transmitted frame with *one4all* strategy
P_s^c	the probability of a success transmission with *one4all* strategy

a cluster can access the channel free of contention. The contention duty and transmission sequence in a cluster can be maintained by a logical token ring topology. The signalling between the devices in a cluster is exchanged over the short–range link.

The proposed strategy also has its drawback because the achievable throughput gain depends on the number of the cooperative mobile devices in one cluster; however, it can be integrated with packet aggregation strategy to exploit the advantages of both strategies. Figure 4.4 shows the integrating of *one4all* scheme and packet aggregation.

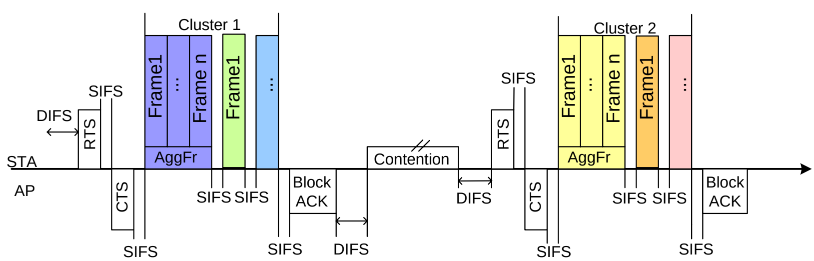


Figure 4.4: Contention and transmission procedure in *one4all* scheme.

The throughput, channel access delay and energy consumption of the proposed strategy are analyzed in the following subsection. The additional notations are given in Table 4.3.

4.3.1 Throughput & Channel Access Delay Analysis

Throughput of *one4all* strategy can be calculated by extending the model described in Subsection 4.2.1. One contention and transmission period is defined as the duration that the representative mobile device starts to contend until the available packets in the clusters being transmitted. In the period each mobile device sends one packet and mobile device also has one packet available in the buffer immediately after the period. So the throughput is expressed by

$$\eta^c = \frac{c_m E[P_t] P_s^c}{E[\Psi]\sigma + P_s^c T_s^c + (1 - P_s^c) T_c} \,. \tag{4.22}$$

The related variables in the model can be given as following:

$$p^c = 1 - (1 - \tau)^{\frac{n}{c_m} - 1} \tag{4.23}$$

$$p_b^c = 1 - (1 - \tau)^{\frac{n}{c_m}} \tag{4.24}$$

$$P_s^c = \frac{\frac{n}{c_m}\tau(1 - \tau)^{\frac{n}{c_m} - 1}}{1 - (1 - \tau)^{\frac{n}{c_m}}} \tag{4.25}$$

$$T_s^c = RTS_t + \delta + SIFS + CTS_t + \delta + SIFS + c_m U_t + \delta + SIFS + ACK_t + \delta + DIFS \,, \tag{4.26}$$

where $U_t = PHY_{ht} + MAC_{ht} + P_t$.

In the proposed strategy, only one device contends to access the channel in one contention and transmission period; and the remaining mobile devices access the channel free of contention. The mobile devices in a cluster alternately take the role as the contending mobile device. So the average channel access delay per device is the channel access delay experienced by the contending mobile device averaged by c_m. It is given by

$$E[D_c] = \frac{1}{c_m}\left(E[N_c](E[D_b] + T_c + T_o) + E[D_b]\right) \,, \tag{4.27}$$

where

$$E[N_c] = \frac{1}{P_s^c} - 1$$

$$E[D_b] = E[C_{bk}]\sigma + E[N_{fr}](P_s^c T_s^c + (1 - P_s^c) T_c) \,.$$

4.3.2 Energy Consumption Analysis

Like device working with other strategies, with *one4all* scheme the device also has four power levels. The difference is that when one representative mobile device contends a channel (i.e. sending RTS, receiving CTS, listening the channel status, backoff, etc.), the other mobile devices in the cluster are all in idle state. After the representative has caught the channel successfully, the remaining mobile devices alternately wake up to transmit their own frames. They switch to idle mode right away after completion of transmission. So the average energy consumption per packet is calculated by summing up all the energy consumption of the mobile devices in one cluster in one contention and transmission period; and then the sum is averaged by c_m. Hence, energy consumption for each packet can be given by

$$Eng^c = \frac{1}{c_m}\left(P_{tx}T^c_{tx} + P_{rx}T^c_{rx} + P_{li}T^c_{li} + P_iT^c_i\right) . \tag{4.28}$$

The derivation of T^c_{tx}, T^c_{rx}, T^c_{li} and T^c_i is similar as those in the other two schemes. where

- T^c_{tx} consists of: $T^c_{tx,1}$, all the successful transmission time; and $T^c_{tx,2}$, the time that the transmitted RTS collides.

$$\begin{aligned} T^c_{tx,1} &= RTS_t + c_m(H_t + P_t) \\ T^c_{tx,2} &= E[N_c]RTS_t\,. \end{aligned}$$

- The expression of T^c_{rx} and T^c_{li} is same as T_{rx} and T_{li} just needing to replace the item P_s in T_{rx} and T_{li} by P^c_s.

- T^c_i is the idle time of all the mobile devices in a cluster during one contention and transmission period. The contending mobile device has different idle time than the other devices in a cluster. So they are calculated separately.

  The idle time of the contending device, T^{cnd}_i, consists of: $T^{cnd}_{i,1}$, the total NAV time due to the transmission of other clusters; $T^{cnd}_{i,2}$, all the time T_o because of its transmitted RTSs collision; and $T^{cnd}_{i,3}$, its idle time during all the transmission time of the other devices in its cluster.

$$
\begin{aligned}
T_{i,1}^{cnd} &= (E[N_c]+1)E[N_{fr}]P_s^c(c_m(H_t+P_t+\delta+SIFS)+ACK_t+\delta) \\
T_{i,2}^{cnd} &= E[N_c]T_o \\
T_{i,3}^{cnd} &= (c_m-1)(H_t+P_t)+c_m(SIFS+\delta)\,.
\end{aligned}
$$

The idle time of one non-contending device, $T_{i,0}^{nocnd}$, consists of the transmission time of the other mobile devices within the cluster and channel access delay during which the contending device is contending the channel.

$$T_{i,0}^{nocnd} = ((c_m-1)(H_t+P_t)+c_m(SIFS+\delta)+ACK_t)+E[D_c]\,.$$

Hence, the total idle time of all the non-contending mobile devices in a cluster T_i^{nocnd} can be given as

$$T_i^{nocnd} = (c_m-1)T_{i,0}^{nocnd}\,. \tag{4.29}$$

In summary T_{tx}^c includes the time of the representative sending RTSs, its own packet and the time of the remaining mobile devices sending their packets. T_{rx}^c includes the time of the representative receiving CTS and block ACK for the cluster, the RTSs and CTSs of the other clusters. T_{li}^c is the time of the representative listening the channel. T_i^c is the sum of the time that all mobile devices are in idle states during one contention and transmission period. Figure 4.5 makes it easy to understand the way to calculate T_i^c.

4.4 Numerical Results

To illustrate the proposed cooperative access strategy outperforming other existing MAC strategies, some numerical results are presented in this section. The assumption of the parameters is listed in Table 4.4.

In this section the performance of three different MAC strategies (i.e. *one4all* strategy, packet aggregation strategy and the conventional RTS/CTS strategy) based on CSMA/CA is compared. The performance of throughput, channel access delay and energy consumption is focused.

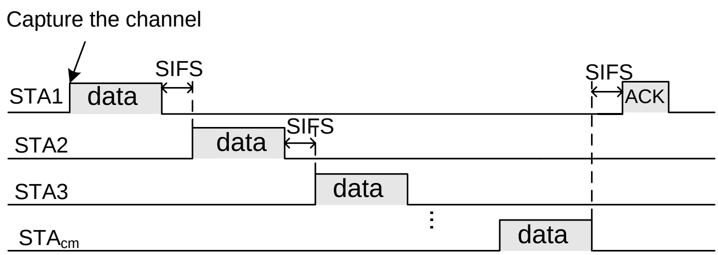


Figure 4.5: Active and idle switching diagram of the mobile devices in one cluster.

Table 4.4: Parameter list.

Notation	**Value**	**Unit**
W	32	
m	3	
n	[4 – 60]	
P	1023	byte
MAC_h (incl. FCS)	34	bytes
PHY_h	16	bytes
RTS (incl. PHY_h)	20	bytes
CTS (incl. PHY_h)	14	bytes
P_t ... CTS_t	P/R ... CTS/R	us
$SIFS$	10	us
$DIFS$	50	us
δ	1	us
$\hat{N}_a$	4	
c_m	4	
σ	20	us
R	11, 54	Mbps
P_{tx}	2	W
P_{rx}	0.9	W
P_{li}	0.9	W
P_i	0.04	W

It should be mentioned here that these three strategies are not completely independent. For instance, cooperative access strategy and packet aggregation strategy are both built on RTS/CTS scheme. More generically, cooperative access strategy can also be built on top of packet aggregation scheme, but in the example they are implemented independently.

The throughput comparison of three different MAC strategies in CSMA/CA is shown in Figure 4.6. It is similar as the conclusion in [100] that with RTS/CTS scheme the saturation throughput is insensitive to the number of the mobile devices in the network. The difference is that when packet aggregation and *one4all* strategies are employed in CSMA/CA, both of them can greatly enhance throughput. Furthermore, the more throughput gain can be achieved under the condition of the higher channel data rate. For example, one4all scheme can have about 11% throughput gain at data rate of 11Mbps and the throughput gain can reach about 20% at data rate of 54%.

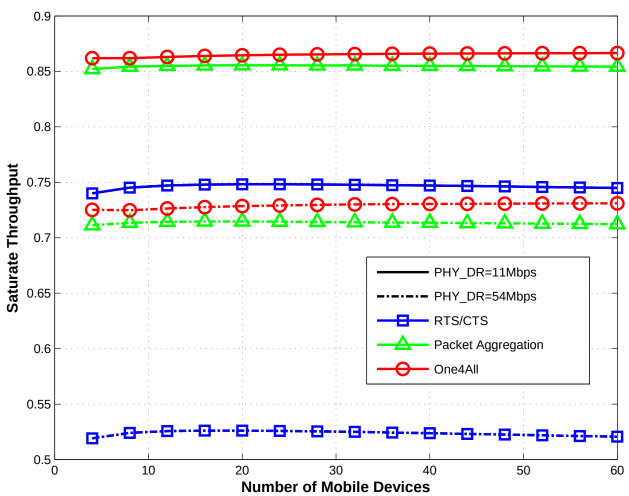


Figure 4.6: Throughput comparison of different MAC strategies in CSMA/CA.

As for the performance of channel access delay, the average channel access delay per device is defined, which means the delay experienced by a mobile device starting to contend until it successfully catching the channel. The average channel access delay per packet is also defined, which is the channel access delay per device averaged by the number of PDUs transmitted by the mobile device(s) after the channel is obtained. So in the conventional RTS/CTS and *one4all* strategies, the average channel access delay per packet is same as channel access delay per device. The average channel access delay per device comparison is shown in Figure 4.7, from which we can see the average channel access delay per device of the packet aggregation scheme is much larger than the other two schemes. The reason is that it takes longer time for a device to transmit a big aggregated frame, which prolongs all the other devices' channel access delay. Figure 4.8 shows the average channel access delay per packet comparison. It shows that the average channel access delay per packet of packet aggregation scheme is a little shorter than the conventional RTS/CTS scheme, but it is much longer than *one4all* scheme. Furthermore, the channel access delay increases with an increasing number of devices. The longer channel access delay has a great impact on fairness of media usage between different mobile devices, if they have different types applications.

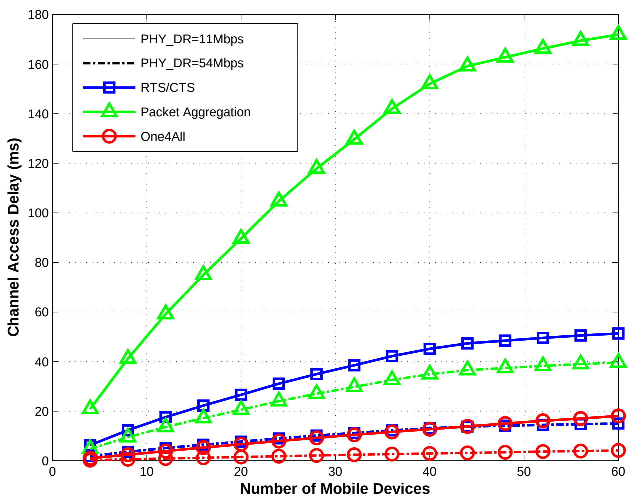


Figure 4.7: Comparison of average channel access delay per mobile device.

The comparison of energy consumption performance of the three strategies is shown in Figure 4.9. Because the conventional RTS/CTS

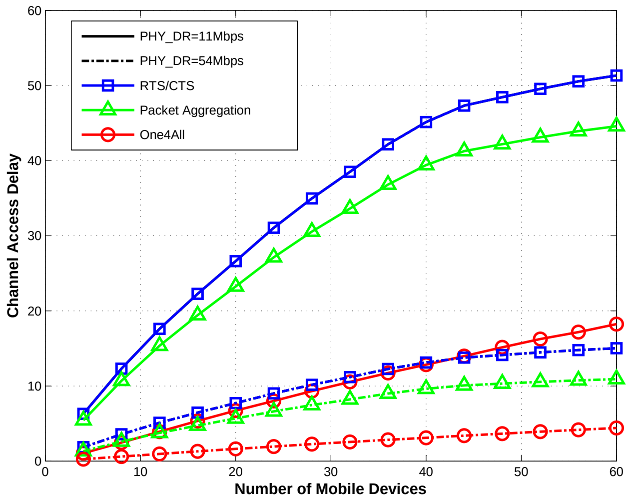


Figure 4.8: Comparison of average channel access delay per packet.

and packet aggregation strategies have much longer channel access delay, more energy is wasted in channel contention duration, even though both of these two schemes are assumed to have smart energy saving scheme. The energy comparison clearly shows that in case the number of mobile devices in the network exceeds 30, the conventional RTS/CTS consumes as over three times energy as *one4all* scheme does. Packet aggregation strategy uses approximately double the energy as *one4all* scheme.

4.5 Conclusions

Based on the CCP2P network architecture, *one4all* strategy is proposed for MAC protocol design in WLANs. The proposed scheme significantly enhances throughput compared with the conventional RTS/CTS scheme and packet aggregation scheme. It overcomes the drawback of packet aggregation where the throughput performance is sensitive to the arrival traffic pattern. Furthermore, it outperforms the packet aggregation scheme in terms of channel access delay and energy consumption. *One4all* strategy is a good illustration underlining the great potential of cooperation among mobile devices to solve the low uplink throughput

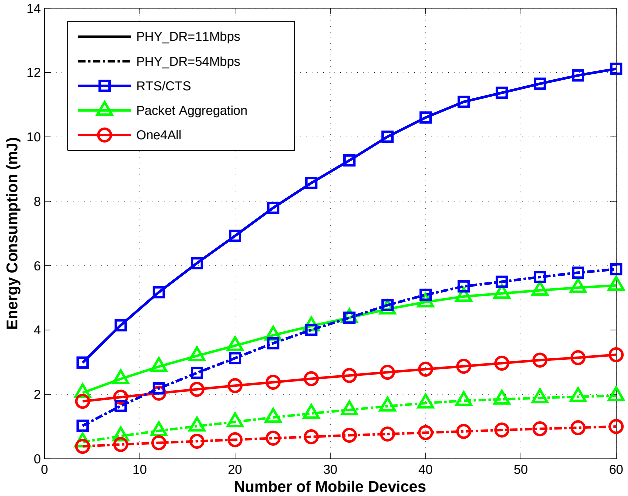


Figure 4.9: Average energy consumption for one packet successful transmission.

issue in wireless network.

Chapter 5

A Novel Cognitive Radio MAC Protocol for Enhancing WLAN Performance

To solve the performance degradation issue in current WLAN caused by the crowded unlicensed spectrum, a cognitive radio media access protocol, C-CSMA/CA, is proposed. The basic idea is that with cognitive radio techniques WLAN devices cannot only access the legacy WLAN unlicensed spectrum but opportunistically access any other under-utilized licensed spectrum without a license. The application scenario of C-CSMA/CA is infrastructure BSS (Basic Service Set). C-CSMA/CA efficiently exploits the inherent characteristics of CSMA/CA to design *distributed cooperative outband sensing* to explore spectrum hole; moreover, it designs *dual inband sensing* scheme to detect primary user appearance. Additionally, C-CSMA/CA has the advantage to effectively solve the cognitive radio self-coexistence issues in the overlapping cognitive radio BSSs scenario. It can also realize station-based dynamic resource selection and utilization. It is compatible with legacy WLAN (BSS) system. The simulation of C-CSMA/CA is developed and implemented by OPNET. The simulation results show that C-CSMA/CA highly enhances throughput and reduces the queuing delay and media access delay.

5.1 Introduction

WLAN has achieved a tremendous success in recent years because of using the unlicensed spectrum. Public WLAN hotspots have been widely deployed [107]. For example, according to the reports by *DataMonitor*, at the end of 2003, there were approximately 31,700 such hotspots in operation globally and this number will grow at a CAGR (Compound Annual Growth Rate) of 47% to approach 146,100 by year-end 2007 [108]. However, the popularity of WLAN also gets a lot of concerns for the reason that densely spaced WLAN devices and other technology users in the unlicensed spectrum make it too crowded.

There are several research works on network congestion relief in hotspots [109, 110]. The performance of these works is limited by the available spectrum for WLAN. Therefore, to fundamentally relieve network congestion in WLAN we intend to solve spectrum scarcity issues. Cognitive radios [111–114] have emerged as a promising and key technology to solve spectrum scarcity issue for wireless applications [115]. One of the important motivation of cognitive radio is the under-utilization of licensed spectrum. That is why FCC recommended that significant spectral efficiency is expected by deploying wireless devices coexisting with the licensed users but introducing minimal interference to the licensed users [116].

Mandayam also points out one of the motivations for cognitive radio techniques is WLAN spectrum congestion and continuing density increase of wireless devices [117]. In this chapter COGNITIVE RADIO techniques is applied in WLAN to solve the performance degradation issue. It should be noted that the proposed scheme is different from 802.11h which is single channel solution for dynamic frequency access in 5 GHz.

Knowing the aforementioned issues, this chapter proposes a generic Cognitive Radio MAC protocol based on CSMA/CA, referred to as C-CSMA/CA (Cognitive radio Carrier Sensing Multiple Access / Collision Avoidance). C-CSMA/CA is designed for infrastructure BSS (Basic Service Set), namely one access point associated with a set of WLAN stations. Infrastructure BSS is the most popular network architecture of hotspots. In C-CSMA/CA, the AP can have multiple *MAC_modules* which can work in parallel on multiple channels and one *MAC_module* can only work on one channel at one time. The station is assumed to work on a single channel at one time.

In cognitive radio, the user with license is defined as primary user (PU) and the user access the licensed spectrum opportunistically is defined as secondary user (SU). In this chapter, PU represents legacy user in the licensed spectrum and SU is the WLAN devices using cognitive radio techniques. From coexistence with primary user perspective C-CSMA/CA attacks two main issues: i). how to detect transmission opportunities in the unknown cognitive radio spectra; ii). how to track the usability of the known cognitive radio spectra. The first issue is solved by *outband sensing*. The idea of *outband sensing* is that the idle stations exploit the duration of network allocation vector (NAV) to cooperatively sense an unknown potential spectrum as a way to explore a new available spectrum. For the second issue, dual *inband sensing* (i.e. implicit and explicit) is employed. C-CSMA/CA exploits the inherent characteristics of CSMA/CA, "listen before talk", to implicitly sense PU. Besides that, specific time slots[1] are reserved for the stations to explicitly sense primary user. By inband and outband sensing, the AP *MAC_controller* collects, manages and distributes all the unknown, unaccessible and accessible spectrum information through the AP *MAC_modules*. The AP *MAC_controller* is also responsible to allocate the accessible spectra to the AP *MAC_modules*. The stations update all the available spectrum information preparing for the seamless channel switch. The channel switch decision is either made independently by the station (according to the station's experience or observation of the current channel status) or triggered by channel vacation request from the AP *MAC_module* in case of primary user appearance.

Besides coexistence issues with primary user, C-CSMA/CA can also deal with the issues of coexistence with the other cognitive radio users in the multiple overlapping BSSs. This is achieved by the inherent collision avoidance capability and implicit synchronization of inband sensing periods.

In brief, with cognitive radio techniques C-CSMA/CA has significant potential to improve the performance of conventional WLAN. Furthermore, seamless primary user detection recovery, minimum interference to primary user, station-based dynamic resource selection and load balance

[1]The length of the time slot depends on sensing techniques on physical layer.

can be realized in C-CSMA/CA.

5.2 C-CSMA/CA Protocol Description

Generally speaking, the major difference between cognitive radio MAC and conventional MAC is that cognitive radio MAC should not only consider media share among cognitive radio users but also deal with primary user (PU) detection and protection.

The C-CSMA/CA protocol reference architecture at access point is shown in Figure 5.1. In C-CSMA/CA the media access function is based on the traditional CSMA/CA scheme with RTS/CTS. The key difference is that C-CSMA/CA introduces cognitive radio functions such as spectrum sensing, spectrum management and channel vacation and so on. Furthermore, with multiple *MAC_modules* an AP can communicate with different stations on multiple channels simultaneously. In summary C-CSMA/CA inherits the distributed media access but utilizes the centralized sensing scheduling and spectrum management. In the following, the main functions in C-CSMA/CA will be presented.

5.2.1 Primary User Detection

Protecting primary user service not to be harmed by the interference from secondary user is the prerequisite of cognitive radio. To fulfil with this requirement, spectrum sensing is mandatory for primary user detection purpose.

Spectrum sensing can be divided into *inband sensing* and *outband sensing* in terms of whether the sensed channel is the current channel in use.

In C-CSMA/CA the AP and its associated stations use the conventional unlicensed band to establish network during the network initialization. Then it starts to exploit the traditional CSMA/CA characteristics to explore new usable spectrum by *outband sensing*. The basic idea is as following: in CSMA/CA RTS/CTS is used for media reservation. All the other devices which overhear the RTS/CTS should set the NAV timer. They will not contend media until the NAV timer expires. In other words, the devices which do not win the media are doing nothing when waiting for the NAV timer expiration. By contrast, in C-CSMA/CA the

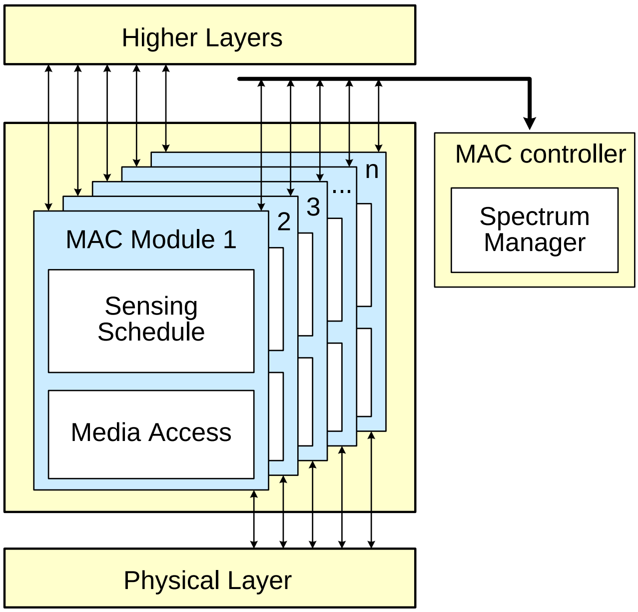


Figure 5.1: C-CSMA/CA MAC protocol reference architecture of access point.

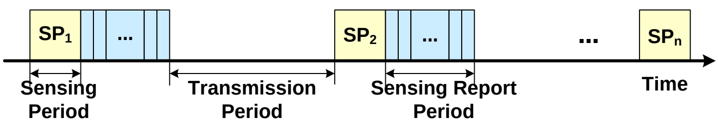


Figure 5.2: Inband sensing period and transmission period.

AP *MAC_module* sends CTS carrying the *outband sensing* request to require the idle stations to perform cooperative *outband sensing* during the NAV duration. The *outband sensing* request includes the spectrum to sense and the sensing report minislots allocation. All the idle stations switch to the designated outband channel and sense the spectrum until the NAV expires. Then they switch back to the inband channel and send their sensing report beacon in the report minislots. Transmission of beacons is based on the slotted ALOHA protocol. By means of *outband sensing*, the AP obtains the channel status of an unknown channel without any additional cost in time. According to the received sensing reports, the AP will update the spectrum status which will be described in detail in Subsection 5.2.3. *Outband sensing* provides the feasibility of seamless channel vacation and channel renewal.

As for *inband sensing*, dual *inband sensing* (i.e. implicit and explicit) is used in C-CSMA/CA. It employs the inherent characteristic of the traditional CSMA/CA, "listen before talk", as implicit *inband sensing*. The basic idea is that if media is detected as busy, there are two possibilities: another secondary user activity or appearance of primary user. Different from CSMA/CA, in C-CSMA/CA the stations can immediately start various primary user detection process[2], instead of just listening and waiting for the media becoming free. If primary user is detected, secondary user can immediately vacate the channel. Therefore, implicit *inband sensing* increases the sensing frequency so that primary user can be detected within the maximum interfered duration as only one packet transmission time. This is a significant advantage of C-CSMA/CA comparing with the other cognitive radio MACs such as IEEE 802.22. Besides implicit *inband sensing*, explicit *inband sensing* is also designed. The purpose of reserving specific time for periodic sensing is threefold. First, when there are only sporadic cognitive radio transmission activities, it is necessary to have explicit *inband sensing* to update the channel usability status. Secondly, the short implicit *inband sensing* cannot insure high precision of primary user detection; furthermore, there could be interference from the secondary users of another AP. Therefore, the explicit primary user detection is in need.

5.2.2 Uplink and Downlink Media Access

In conventional CSMA/CA there is no difference between uplink and downlink media access. In C-CSMA/CA the uplink media access is similar as CSMA/CA. It will not be explained in this chapter. The readers who are not familiar with CSMA/CA can refer to [101]. As for downlink, since different stations can communicate with different AP *MAC_modules* and stations have independent channel switch capabil-

[2]There are many primary user detection techniques such as matched filter detection, energy detection and cyclostationary feature detection, which will not be discussed in the chapter.

ity, the access point sometimes loses track of which channel a station is located. In other words, the AP does not know which *MAC_modules* should deliver the packet to the station. How C-CSMA/CA effectively solving this issue is explained in the following.

Inspired by the operation approach in 802.11 with station sleep mode, the downlink media access is designed in a similar way. The idea is that when there are data frames for stations in an access point, the access point will broadcast a Traffic Indication MAP (TIM) message through all the active AP *MAC_modules* to indicate which stations have buffered traffic waiting for being picked up. The TIM message is a virtual bitmap following a logical structure composed of N bits. Each bit is tied to a station ID. If there is traffic buffered for that station ID, the bit is set to 1, otherwise, the bit is set to 0. Once a station sees its associated bit in TIM is 1, it will sends a POLL message to retrieve its data packets from its AP *MAC_module*. Once the AP *MAC_module* receives the POLL message, it uses conventional CSMA/CA to complete the packet transmission.

5.2.3 Spectrum Management

The usability status of all the channels is varying over time due to primary user activities. To efficiently utilize the available transmission opportunities in cognitive radio spectrum, it is of significant importance to decide when to sense which spectrum. This is realized by sensing scheduling function and will be discussed in the next subsection. To design intelligent sensing scheduling, it is necessary to track the status of all the spectra. Here it is worth mentioning that although primary user activity is dynamic, it is feasible to utilize the statistical characteristics of primary user activity to reasonably estimate the mean active and idle time of primary user. The detailed study of primary user traffic statistics is out of the scope of this chapter. Based on this assumption the AP *MAC_controller* can track spectrum status.

The AP *MAC_controller* regards the potential cognitive radio spectra as a channel pool and categorizes them into three classes: accessible channel (ACH), unaccessible channel (UACH), unknown channel (UnCH). ACH is the channel in which no primary user is detected for the time being. UACH is the channel in which primary user was detected just now. UnCH is the channel whose status is unknown to the AP or whose status in the AP has outdated. To track the channel status, each channel is associated with a timer according to its category. A TTS (Time to Sense) timer is set for periodic inband sensing for an ACH. An UACH has a blocking timer, i.e. the AP would not ask for sensing the UACH before the blocking timer expires. For UnCH, AP *MAC_controller* has a *defer_UnCH_update_timer* which is designed for distributed outband sensing and will be explained in the next subsection.

Here are the cases that the AP *MAC_controller* updates the channel lists:

- if primary user is detected during *inband sensing*, the ACH will be moved from the ACH list to the UACH list.
- if no primary user is detected during *outband sensing*, the UnCH will be moved the UnCH list to the ACH list; otherwise, the UnCH will be inserted into the UACH list;
- if an UACH blocking timer expires, the UACH will be moved from the UACH list to the UnCH list.

The spectrum management chart is shown in Figure 5.3.

5.2.4 Sensing Scheduling

Sensing scheduling is one of the main additional functions in cognitive radio MAC comparing with conventional MAC. Sensing scheduling aims at answering the question of when to sense which spectrum. With spectrum status tracking, AP *MAC_module* can perform sensing scheduling.

Distributed Cooperative Outband Sensing

As mentioned above, C-CSMA/CA uses cooperative outband sensing to explore an unknown channel. An outband sensing request is always piggybacked in CTS from an AP *MAC_module*. What I would like to emphasize here is the distributed characteristics of the cooperative outband sensing. Based on the access point C-CSMA/CA protocol reference architecture (Figure 5.1), an AP can have parallel communications

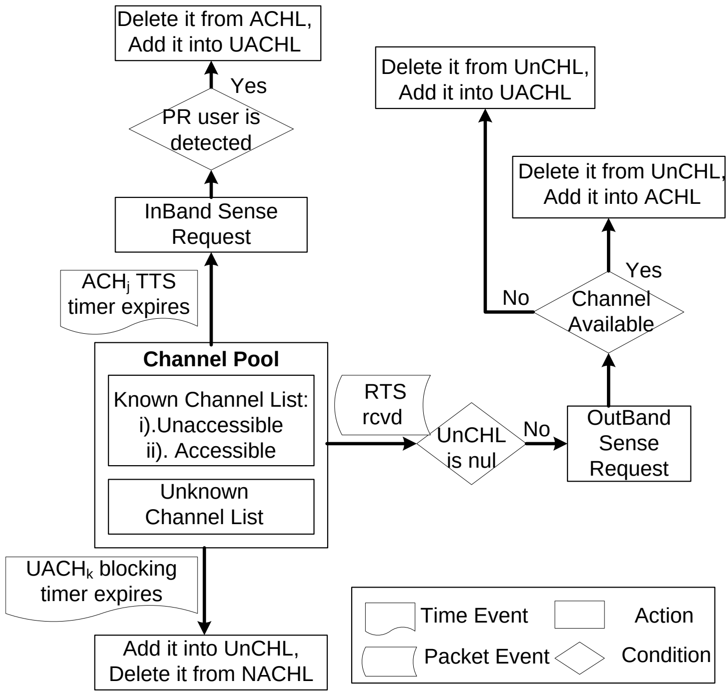


Figure 5.3: Spectrum management chart.

with different stations through different AP *MAC_modules*. Moreover, there is no synchronization among different communication pairs. It means that different AP *MAC_modules* receive RTSs from different stations at asynchronously. If an AP *MAC_module* requests sensing an UnCH, it always takes the UnCH which has stayed in the UnCH list longest. Namely, different AP *MAC_modules* select the same UnCH to sense unless the UnCH list has been updated. Thus the stations associated with different AP *MAC_modules* perform cooperative *outband sensing* and report the sensing results distributedly. Therefore, when the *MAC_controller* receives the first sensing result of an UnCH from an AP *MAC_module*, instead of updating the channel status immediately, it records the sensing result and starts the *defer_UnCH_update_timer*. The *MAC_controller* collects and compares the sensing results from the different AP *MAC_modules* until the *defer_UnCH_update_timer* expires. Then the *MAC_controller* makes a final decision for the UnCH update.

An illustration of distributed cooperative outband sensing is shown in Figure 5.4. Three AP *MAC_modules* are in active state. Each AP *MAC_module* associates with four stations. The AP *MAC_modules* work on channel 1, 2 and 3, respectively. When AP *MAC_module* 1 receives a RTS from STA_4^1, *MAC_module* 1 requests the group of stations (STA_i^1, $i = 1, 2, 3$) to cooperatively sense an unknown channel K. After the NAV timer duration, the stations (STA_i^1) send short beacons in the minislots to report the sensing results by contention[3]. The AP *MAC_module* 1 sends the collected sensing report to *MAC_controller* at the end of the sensing reporting period (i.e. t_1). The moment *MAC_controller* receives the report from AP *MAC_module* 1, it starts the *defer_UnCH_update_timer* which will expire at time t_u. AP *MAC_module* 2, 3 and their associated stations have the same procedure asynchronously. AP *MAC_module* 2, 3 send their report to *MAC_controller* at time t_2 and t_3, respectively. Finally the *MAC_controller* makes an UnCH update decision at t_u according to all the received reports.

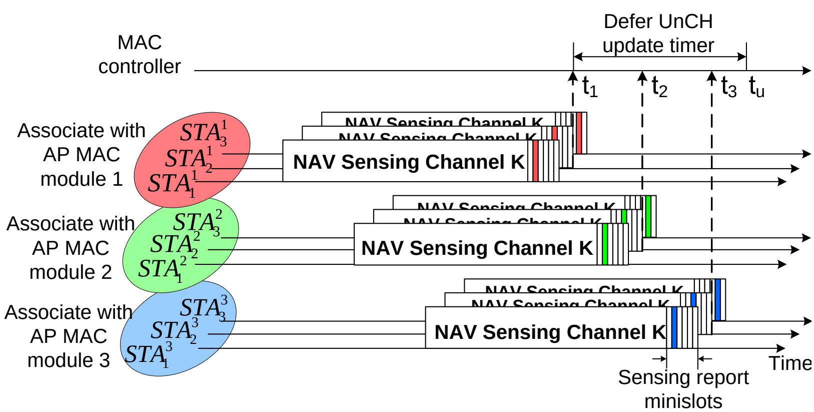


Figure 5.4: Distributed outband sensing diagram.

[3]Here simple algorithm can be designed to reduce collisions during the sensing reporting phase. For instance, the station can suppress its beacon if it hears a beacon from other station with the same sensing result.

The advantage of distributed cooperative outband sensing is that it highly reduces the probability of primary user miss detection. One of the reason is that the shorter NAV duration results in the higher probability of primary user miss detection; however, the distributed cooperative outband sensing virtually increases sensing time. Furthermore, more stations can join in sensing the same UnCH, which exploits spatial diversity to enhance accuracy of primary user detection.

Quasi-periodic Inband Sensing

Strict periodic inband sensing is not efficient because it often interrupts an on-going communication. C-CSMA/CA can slightly adjust the time to perform inband sensing according to the on-going communication schedule, which is referred to as quasi-periodic inband sensing. Consequently, an inband sensing request can often be piggybacked in the traditional control packets. The advantages of quasi-periodic inband sensing has threefold: i). long time synchronization can be avoided; ii). cost for sending the inband sensing request[4] is reduced; iii). it is easily to realize inband sensing synchronization among the overlapped BSSs, which is another important advantage of C-CMSA/CA comparing with the other cognitive radio MACs such as IEEE 802.22 and will be addressed detailed in the next subsection.

5.2.5 Self-coexistence

Self-coexistence means coexistence of multiple overlapping cognitive radio BSSs or cells, which is another challenge of cognitive radio MAC. Multiple APs may operate with the overlapping coverage area. Furthermore, since APs may belong to different operators, explicit coordination and frequency planning cannot be assumed in cognitive radio [118].

Self-coexistence tries to solve two main issues: avoiding interference among the overlapping cognitive radio BSSs and synchronization of the overlapping inband sensing periods. In IEEE 802.22 it is quite difficult to solve these two problems. The reason lies in that all the slots usage (either transmission, reception or sensing) are allocated at the beginning of a superframe by base station [118], however, base station has no

[4]Individual inband sensing request is sent only when there is no on-going communication and it is time to do inband sensing.

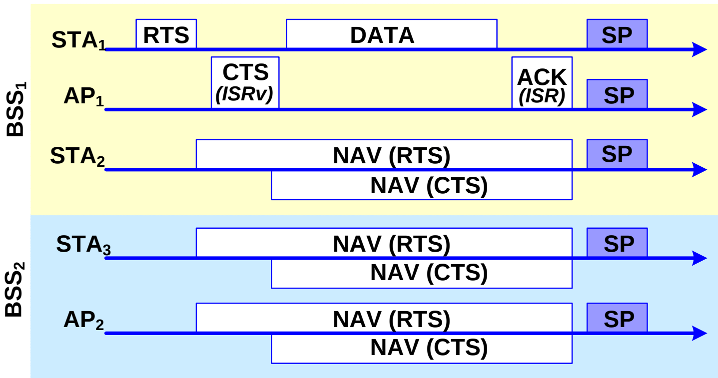


Figure 5.5: Implicit synchronization of the inband sensing periods in the overlapping BSSs.

idea of the slots allocation of the other overlapping base stations. To tackle these issues, 802.22 designs very complicated algorithms such as coexistence beacon protocol, inter-BS communication and so on which introduce big overhead and complexity (details can be referred to [118]). However, C-CSMA/CA can solve these issues effectively by its inherent characteristics and the quasi-periodic inband sensing function.

C-CSMA/CA inherits the CSMA/CA characteristics that is capable to avoid interference effectively by "listen before talk", namely the devices defer transmission as long as the media is busy, no matter the media is occupied by the transmission from its own BSS or from the other BSSs. Furthermore, in some partially overlapping BSSs, parallel transmissions in different BSSs are allowed as long as there is no interference between each other.

Another important issue is inband sensing synchronization within the overlapping BSSs, which directly affects primary user detection. In C-CSMA/CA, once the devices within the overlapping BSSs overhear the inband sensing request from an AP *MAC_module*, they can immediately adjust their inband sensing schedule to synchronize with the neighbor BSS. This is called as implicit synchronization of inband sensing periods whose illustration is shown in Figure 5.5. In the example, AP_1 makes an inband sensing reservation (ISRv) in a CTS. Any station that receives the CTS will sense the inband channel right after the NAV timer expires.

The inband sense request (ISR) in the ACK is for the devices who did not receive the CTS. Thus, all the devices within the overlapping area of BSS_2 can synchronize their inband sensing with BSS_1.

5.2.6 Channel Switch and Primary User Detection Recovery

In C-CSMA/CA, both AP and stations can make channel switch decision. An AP *MAC_module* switches channel only if primary user is detected in the current channel. In this case, the AP *MAC_module* will send an urgent channel vacation request to its associated stations. Then the AP *MAC_module* can switch to its backup channel or switches to the conventional WLAN spectrum or simply suspends itself. Stations have more flexible channel switch choices. They can switch to the backup channel or select any channel that another AP *MAC_module* is using. The channel switch procedure which is resulted from primary user appearance is often referred to as primary user detection recovery.

Besides primary user detection recovery, a station can switch to another channel if it experiences or observes a bad channel state such as low SINR (signal to interference and noise ratio), deep fading, many collisions, and so on. Such channel switch is completely spontaneous from the viewpoint of a station. By independent channel switch, it can realize station-based dynamic spectrum selection and load balance.

5.3 Simulation and Performance Analysis

Based on the C-CSMA/CA protocol described above, the proposed protocol is developed and implemented in OPNET modeler 12.0. In the simulation, the AP has four *MAC_modules* and one overall *MAC_controller*. One of the AP *MAC_modules* works on the conventional WLAN unlicensed spectrum. The other three AP *MAC_modules* can work on cognitive radio spectra as long as they detect transmission opportunities. In the simulation scenario there are 16 stations communicate with the AP. The data rate between the AP and the stations is 5 Mbps on each channel. The explicit inband sensing is 1 ms and the transmission period

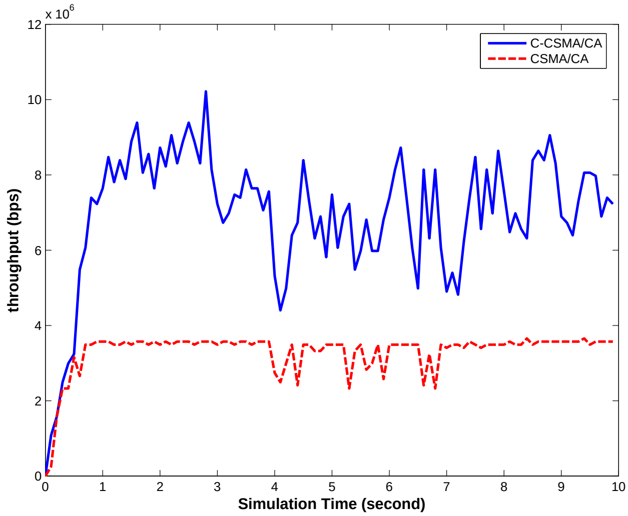


Figure 5.6: Throughput comparison of C-CSMA/CA with CSMA/CA.

in between is 4 ms[5]. Packet inter-arrival time at each station follows exponential distribution with mean value 10 ms. The packet size is also exponential distribution with mean value 1024 Bytes.

In the following the performance of C-CSMA/CA is compared with CSMA/CA in terms of throughput, queuing delay and media access delay. Figure 5.6 shows the comparison of throughput. It can be seen from the figure that under the assumed simulation inputs it reaches the saturation throughput using the conventional CSMA/CA. However by cognitive radio techniques C-CSMA/CA exploits the other spectrum hole to significantly enhance throughput. With the assumption of the example, it can achieve 10 Mbps throughput nearly as three times as that of CSMA/CA. In reality, achievable throughput depends on the number of *MAC_modules* and the available cognitive radio spectrum.

Figure 5.7 and Figure 5.8 shows the comparison of packet queuing delay and the corresponding CDF (cumulative distribution function). The definition of queuing delay is the time that from a packet arrival

[5]These data is taken from IEEE 802.22. In reality, the sensing period depends on the sensing techniques.

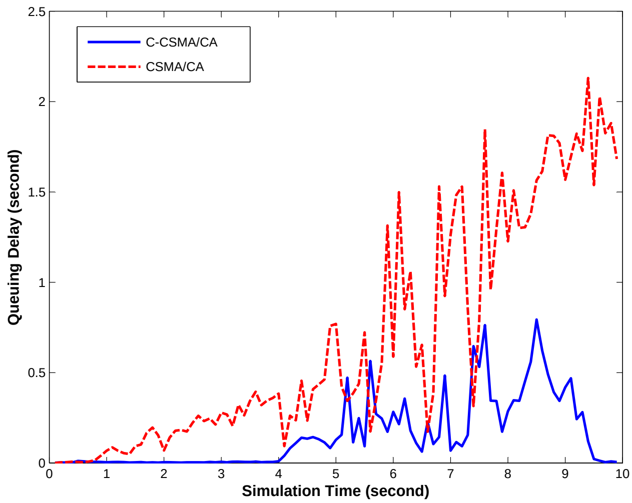


Figure 5.7: Queuing delay comparison of C-CSMA/CA with CSMA/CA.

until the beginning of a transmission attempt for the packet. It is very clear that in CSMA/CA when the throughput approaches the saturation throughput, the queuing delay increases dramatically (see Figure 5.7). It means that packets will be dropped if the buffer size is finite. Using C-CSMA/CA the queuing delay becomes much shorter. Figure 5.8 shows that 90% packet delay is less than 0.5s in C-CSMA/CA, however, it reaches about 1.75s in CSMA/CA. Similar comparison of media access delay is given in Figure 5.9 and Figure 5.10. The definition of media access delay is the time that from a transmission attempt for a packet until the packet can be successfully transmitted. The media access delay in CSMA/CA can even up to 0.16s, however, C-CSMA/CA can reduce the media access delay to less 0.02s. The media access delay of 90% packets is less than 5ms and 22ms in C-CSMA/CA and CSMA/CA, respectively.

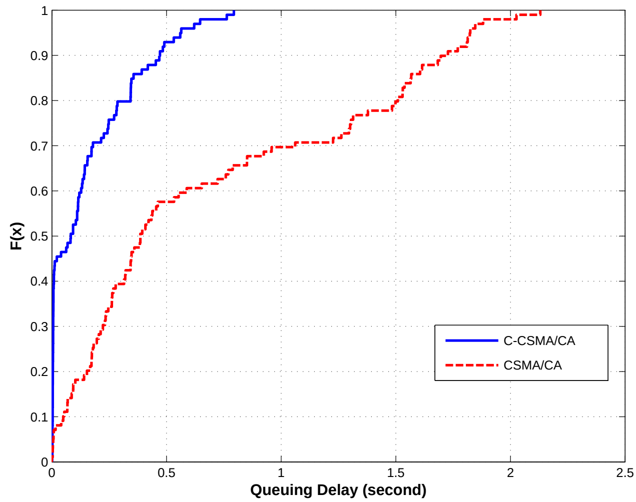


Figure 5.8: Queuing delay CDF comparison of C-CSMA/CA with CSMA/CA.

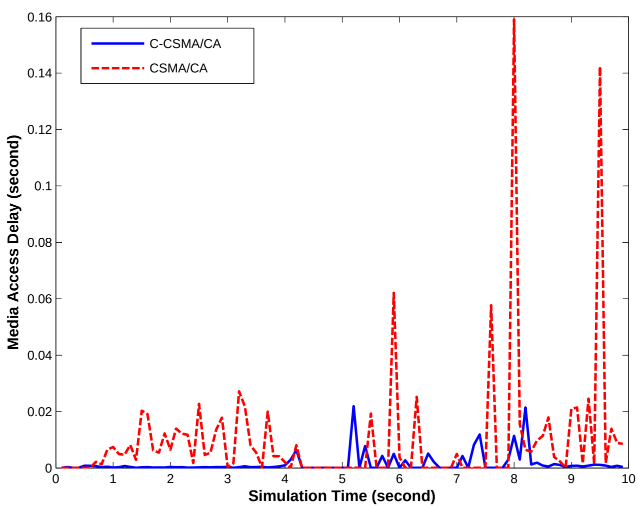


Figure 5.9: Media access delay comparison of C-CSMA/CA with CSMA/CA.

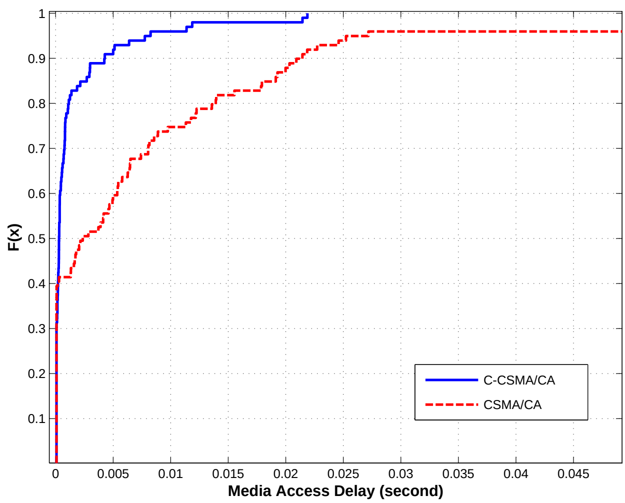


Figure 5.10: Media access delay CDF comparison of C-CSMA/CA with CSMA/CA.

5.4 Conclusion & Future Work

A cognitive radio MAC protocol (C-CSMA/CA) is proposed for WLAN to solve the performance degradation issues caused by spectrum scarcity. The proposed scheme effectively exploits the inherent characteristics of the conventional CSMA/CA to facilitate its cognitive radio capability. By dual *inband sensing* it achieves that primary user can be detected with the interfered duration upper bound of only one packet transmission time theoretically. It can detect spectrum hole in cognitive radio spectrum by distributed cooperative *outband sensing*. By simulation it has shown the great advantages of C-CSMA/CA in improving the performance of WLAN. It is quite promising to implement the proposed MAC protocol with current technology.

To maximize the performance of C-CSMA/CA, it is important to find out the optimal inband sensing period and transmission period in between according to the tolerable interference of different primary users. It is also worth taking a look into the correlation of channel management timer configuration and the traffic pattern of primary users.

Chapter 6

Hierarchical Modulation for Uplink Communication in Cooperative Networks

In this chapter a spectrum efficient uplink communication method for cooperative wireless networks is presented. In cellular controlled peer to peer (CCP2P) cooperative wireless networks a mobile device is logically connected over cellular links with a base station and simultaneously over short-range links with neighboring mobile devices to form cooperative clusters. So far the physical communication over cellular links and over short-range links is separated in time or in frequency. Beyond this state-of-the-art, a method is exploited, referred to as hierarchical modulation, where a mobile device is generating signals that are conveyed towards the base station and the neighboring devices in the same frequency and even at the same time. The signal is composed in such a way that it has different meanings for the neighboring devices than the base station. While the base station is getting the coarse information, the neighboring devices are getting the fine grained information. The analytical analysis and simulation results show that hierarchical modulation can improve spectrum efficiency and reduce data queuing delay with neither degrading symbol error rate performance nor increasing average energy per bit. Therefore, hierarchical modulation can be a good potential transmission scheme to facilitate CCP2P network architecture.

6.1 Introduction and State-of-the-Art

Recently cooperative wireless networks have gained more attention. Especially the so called cellular controlled peer to peer (CCP2P) communication architecture [1,119] has been proven to support higher data rates and at the same time reduces the energy consumption of a mobile device. In CCP2P, mobile devices are not only connected to the base station, but also with the neighboring mobile devices to form cooperative clusters. CCP2P combines the advantage of cellular networks, as the main access to services, and peer to peer networks exploiting wireless grid techniques for efficient usage of the build-in entities such as battery, memory, wireless data rate, etc. The cooperation is based on the communication capabilities between a base station and its connected mobile devices as well as the communication among mobile devices. So far the cellular and the short-range communication is realized in different frequencies or at different time slots. An example of separation in frequency is the multi-radio approach, where a mobile device can use 3G, WLAN or DVB-H links for the cellular link and Bluetooth or WLAN for the short-range link as introduced in [9,120,121]. When the short-range link (SRL) and the cellular link (CL) are using the same frequency, they are separated in time [7]. Whatever solution has been found so far is separating the cellular and short-range communication by orthogonal communication channels realized by separation in frequency, time, and code.

In contrast to that, a new approach is introduced in this chapter. It is clearly beyond this state-of-the-art, transmitting information from a dedicated mobile device to the base station and simultaneously to the neighboring mobile devices at the same time in the same frequency. In a nutshell, one dedicated mobile device is conveying an information signal such that it will be read by the different receiving entities in a different manner. Such an approach allows to make cooperative communication even more effective than it would be with orthogonal channels using different frequencies or time slots. The main focus of the following work is to investigate the error characteristic and energy consumption of the combined channels compared to the state-of-the-art approach.

As given in Figure 6.1, the integrated signal conveyed from the originating mobile device consists of two information parts, namely the *coarse* information part for base station and the *fine grained* information part for neighboring mobile devices, respectively. As the integrated signal reaching the base station is impacted more by path loss than the short-range connection, the fine grained information part, intended for the neighboring mobile devices is washed out. On the other hand, the neighboring devices can get both information parts in the integrated signal and will subtract the coarse information for the base station to retrieve their relevant information part. In summary, in the approach the wireless channel is exploited with its path loss nature as some kind of native filter to realize the novel communication method.

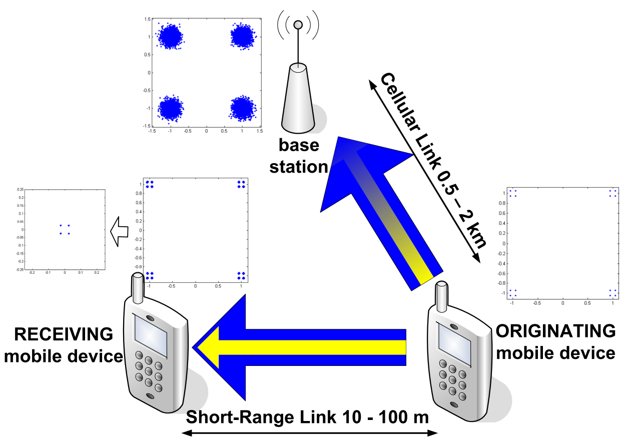


Figure 6.1: The applicable network architecture of hierarchical modulation.

The proposed approach is realized by using hierarchical modulation. Hierarchical modulation is also called asymmetrical modulation which is originally proposed as an unequal error protection technique for extending the service availability and obtaining graceful degradation characteristics [122–126]. It is mostly used for terrestrial broadcasting of television signals or image transmission, for example HDTV and DVB-H. Hierarchical modulation is well suited for video transmission over wireless channels, as video encoder outputs are not equally important [125]. It is also employed in multi-class data transmission, when different kinds of data services have different bit error rate requirements [124]. Generally speaking there are two main approaches to implement hierarchical modulation. The first approach is based on novel signal constellation with non-uniformly spaced signal points [125]. The second approach uses time division multiplexing of different conventional coded modulation schemes [125]. The first approach is used to implement hierarchical modulation in this chapter. All of the proposed hierarchical modulations, for example [122–125], are only used for the transmission from BS to mobile devices for unequal error protection purpose. However, in this work hierarchical modulation is applied for the transmission from a mobile device to a BS and the other mobile devices, i.e. two different types of recipients, with the same error protection.

The chapter is organized as following. The hierarchical modulation model and derive symbol error rate, energy per bit cost, spectrum efficiency and so on are described in the Section 6.2. The simulation procedure and results are given in Section 6.3. Implementation of the proposed communication method is introduced in Section 6.4. Finally a conclusion will be drawn.

6.2 Hierarchical Modulation Model & Performance Analysis

The design idea of hierarchical modulation (HMOD) for CCP2P is based on the fact that the cellular link (CL) suffers much more path loss than the short-range link (SRL). If the signals to neighboring mobile devices are integrated into the signals to a base station (BS), the path loss on the cellular link can easily filter out all the fine grained information for the neighboring mobile devices. On the other hand, due to the smaller path loss, the neighboring mobile device can easily extract its own information from the integrated signals. From illustration purpose, in the following example the mobile device is assumed to use 4QAM to communicate with both, the BS and neighboring mobile devices. It is worth mentioning that for other hierarchical modulation constellations the derivation can be done in a similar way as shown later.

Figure 6.2 illustrates the basic idea of the hierarchical modulation (HMOD) approach. The signal point position of HMOD depends on both the signal to the BS and the corresponding signal for the neighboring mobile device. The 4QAM signals to the neighboring mobile devices regard the corresponding signal point position for the BS as the *ori-*

gin of its own signal constellation plane (i.e. sub-constellation plane of HMOD). For example, 4QAM signals for BS is assumed as (00, 01, 10, 11) are mapped to the four big dashed points (N_0, N_1, N_2, N_3) in the traditional modulation. Therefore, when a signal to the BS is "10" and a signal to the neighboring mobile device is "00" (mapping to the relative Quadrant II in sub-constellation plane around point N_2), the HMOD signal (10 00) finally locates its position at the point M_0.

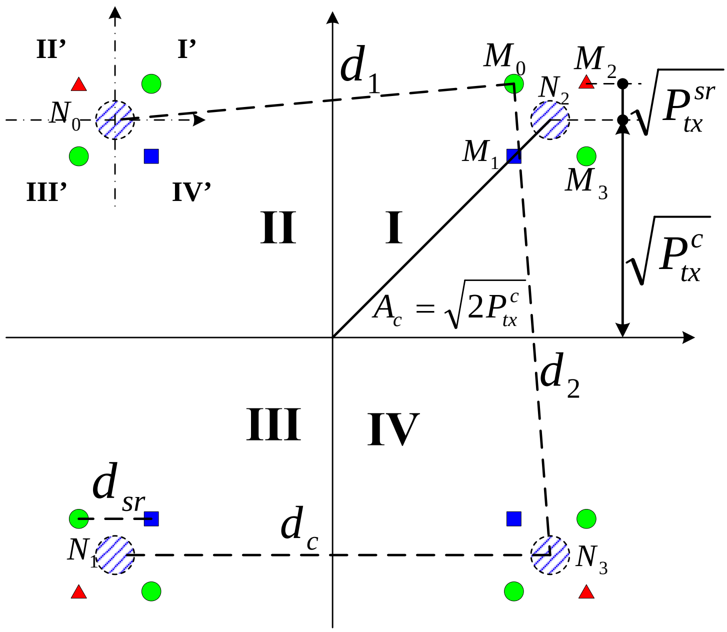


Figure 6.2: Hierarchical modulation constellation at mobile device transmitter.

MQAM (multiple quadrature amplitude modulation) signal is generically expressed by $S(t) = A \cdot g(t) \cdot e^{j2\pi f_c t}$. $g(t)$ is a signal pulse with unit amplitude. The average power of the signal is equal to $A^2/2$. Hence, the amplitude of the transmission signal can be assumed as that on the cellular link equal to $A_c = \sqrt{2P_{tx}^c}$ and that on the short-range link equal to $A_{sr} = \sqrt{2P_{tx}^{sr}}$, respectively. Obviously, using traditional 4QAM the decision regions are bounded by horizontal and vertical lines at zero for both cellular link and short-range link, which does not depends on the amplitude of the signal. However, in the case of hierarchical modula-

Table 6.1: Parameter list.

Notation	Meaning
d_{ij}	the Euclidean distance between two received signal points i and j
N_o	the one-sided spectral density of white Gaussian noise
M	the total number of signal points in a constellation
P^c_{tx}	the transmission power at mobile device on the cellular link in traditional modulation
P^{sr}_{tx}	the transmission power at mobile device on the short-range link in traditional modulation
P^{sr}_{rx}	the receiving power at mobile device on the short-range
P_i	the mobile device power consumption at idle mode
f_c	the attenuation factor on the CL because of path loss
f_{sr}	the attenuation factor on the SRL because of path loss

tion with 4QAM for both cellular link and short-range link, the decision regions are bounded by horizontal and vertical lines at zero for cellular link and at $\pm\sqrt{P^c_{tx}}$ for short-range link.

6.2.1 Symbol Error Probability

In the following first symbol error rate (SER) in the cellular link and short-range link is derived under AWGN (Additive White Gaussian Noise) channel assumption. Then the symbol error rate will be extended in Rayleigh fading channel. All of the notations used in the equations are listed in Table 6.1.

In AWGN channel symbol error probability that a transmitted signal as point i is received and demodulated as point j ($j \neq i$) can be expressed as following:

$$P_{e,ij} = Q\left(\frac{d_{ij}/2}{\sqrt{N_o/2}}\right). \tag{6.1}$$

Hence, an upper bound for the total symbol error probability may be obtained as

$$P_e \leq \frac{1}{M}\sum_i \sum_{j\neq i} Q\left(\frac{d_{ij}/2}{\sqrt{N_o/2}}\right). \tag{6.2}$$

Since Q function is a very fast decreasing function, it is possible to limit the second summation in Equation 6.2 to a smaller set of the nearest neighboring points around point i. Based on the parameters shown in Figure 6.2, the symbol error probability of the received signals at the BS using traditional modulation can be expressed as following,

$$P_{e,BS}^{old} \leq 2 \cdot Q\left(\frac{d_c^{rx}/2}{\sqrt{N_o/2}}\right) = 2 \cdot Q\left(f_c\sqrt{\frac{2P_{tx}^c}{N_o}}\right), \tag{6.3}$$

where the ideal Euclidean distance of two received signal points at BS, d_c^{rx}, has such relation that $d_c^{rx} = f_c d_c = 2f_c\sqrt{P_{tx}^c}$, which is clear from Figure 6.2.

Using hierarchical modulation in this specific example, there are 16 possible signal points which can be divided into three types (Figure 6.2): (i) $\square$ (ii) $\bigcirc$ and (iii) $\triangle$, according to their positions in the constellation. Signal points at different position have different probabilities to make an error to the nearest neighboring points. At the BS receiver the probability that point M_0 is demodulated as N_0 and N_3 is assumed as p_1 and p_2, respectively. Therefore, the error probability of M_0 is $p_1 + p_2$, which is same for all $\bigcirc$ type signal points. Note, in Figure 6.2 the BS always supposes that the signal points from a mobile device are at the big dashed points, although the real signal points are located at solid points.

$$p_1 \leq Q\left(\frac{d_1^{rx}/2}{\sqrt{N_o/2}}\right), \qquad p_2 \leq Q\left(\frac{d_2^{rx}/2}{\sqrt{N_o/2}}\right).$$

At the BS receiver the symbol error probability of point $\square$, such as M_1, is $2p_1$ and the error probability of point $\triangle$, such as M_2, is $2p_2$. So the average symbol error probability of received signals at the BS by hierarchical modulation can now be calculated by:

$$\begin{aligned} P_{e,BS}^{hmod} &\leq \frac{1}{16}\{4 \cdot 2p_1 + 8 \cdot (p_1 + p_2) + 4 \cdot 2p_2\} \\ &\leq Q\left(\frac{d_1^{rx}/2}{\sqrt{N_o/2}}\right) + Q\left(\frac{d_2^{rx}/2}{\sqrt{N_o/2}}\right), \end{aligned} \tag{6.4}$$

where according to Figure 6.2 and considering signal attenuation, the Euclidean distance of the received signals at the BS receiver d_1^{rx} and d_2^{rx}

can be derived as

$$\begin{aligned} d_1^{rx} &= f_c d_1 \\ &= f_c \sqrt{\left(\sqrt{2P_{tx}^c} - \sqrt{P_{tx}^{sr}}\right)^2 + \left(\sqrt{P_{tx}^{sr}}\right)^2} \\ &= f_c \sqrt{4P_{tx}^c - 4\sqrt{P_{tx}^c P_{tx}^{sr}} + 2P_{tx}^{sr}}\,. \end{aligned}$$

Assuming $\sqrt{P_{tx}^{sr}} = \sigma\sqrt{P_{tx}^c}$ $(\sigma \ll 1)$, then

$$d_1^{rx} = f_c \sqrt{2P_{tx}^c}\sqrt{2 - 2\sigma + \sigma^2}\,.$$

Likewise, the expression of d_2^{rx} can be obtained:

$$d_2^{rx} = f_c \sqrt{2P_{tx}^c}\sqrt{2 + 2\sigma + \sigma^2}\,.$$

For $x > 3$, the $Q(x)$ can be approximated as

$$Q(x) \approx \frac{1}{\sqrt{2\pi}x} e^{-\frac{x^2}{2}} \qquad x > 3\,. \tag{6.5}$$

Because of the relation $Q(x) = \frac{1}{2}erfc(x/\sqrt{2})$, it can be proven that in order to guarantee a SER below 10^{-3} in 4QAM case, x should be larger than 3. Therefore, according to Equation 6.5 $P_{e,BS}^{old}$ and $P_{e,BS}^{hmod}$ can be rewritten as following:

$$P_{e,BS}^{old} \approx \frac{1}{f_c}\sqrt{\frac{N_o}{\pi P_{tx}^c}} e^{-\frac{f_c^2 P_{tx}^c}{N_o}}$$

and

$$P_{e,BS}^{hmod} \approx \frac{1}{f_c}\sqrt{\frac{N_o}{2\pi P_{tx}^c}} \left(\frac{1}{\sqrt{\gamma_1}} e^{-\frac{f_c^2 P_{tx}^c \gamma_1}{2N_o}} + \frac{1}{\sqrt{\gamma_2}} e^{-\frac{f_c^2 P_{tx}^c \gamma_2}{2N_o}}\right) \tag{6.6}$$

with

$$\gamma_1 = 2 - 2\sigma + \sigma^2\ , \quad \gamma_2 = 2 + 2\sigma + \sigma^2\,.$$

When $\sigma \ll 1$, γ_1 and γ_2 are approximately equal to 2. By substituting the approximate values of γ_1 and γ_2 into Equation 6.6, Equation 6.7 is obtained. It can be seen from Equation 6.7 that the symbol error probability of hierarchical modulation is close to that of the traditional modulation on the cellular link.

$$P_{e,BS}^{hmod} \approx \frac{1}{f_c}\sqrt{\frac{N_o}{\pi P_{tx}^c}}e^{-\frac{f_c^2 P_{tx}^c}{N_o}} \approx P_{e,BS}^{old}\,. \tag{6.7}$$

In the above derivation the channel is assume to be AWGN channel so the symbol error rate is deterministic. If the channel has Rayleigh fading, then the symbol error rate should be calculated by [127]

$$P_e^f = \int_0^\infty P_e(x)p_\eta(x)dx\,, \tag{6.8}$$

where $P_e(x)$ is the symbol error rate in AWGN channel. $p_\eta(x)$ is the pdf (probability density function) of the received symbol signal to noise ratio.

$$p_\eta = \frac{1}{\widetilde{\eta}}e^{-x/\widetilde{\eta}}\,, \qquad x \geq 0 \tag{6.9}$$

where $\widetilde{\eta}$ is the average symbol signal to noise ratio.

So substituting Equation 6.7 and 6.9 into Equation 6.8, the symbol error rate at BS with hierarchical modulation in rayleigh fading channel can be obtained as following. Note the received signal to noise ratio is $\frac{f_c^2 P_{tx}^c}{N_o}$.

$$P_{e,BS}^{hmod,f} \approx \int_0^\infty \frac{1}{\widetilde{\eta}}\sqrt{\frac{2}{\pi x}}e^{-(\frac{1}{2}+\frac{1}{\widetilde{\eta}})x}dx \approx P_{e,BS}^{old}\,. \tag{6.10}$$

As for the symbol error probability on the short-range link, it is derived as following.

$$P_{e,sr}^{hmod} = 1-(1-P_{e,1})(1-P_{e,2})\,, \tag{6.11}$$

here $P_{e,1}$ is the symbol error probability of the signal for base station at the demodulator of the cooperative mobile device, and $P_{e,2}$ is the symbol error probability of the signal for the cooperative mobile device at the demodulator of the operative mobile device.

It is clear that $P_{e,sr}^{old}$ is equal to $P_{e,2}$

$$P_{e,sr}^{old} = P_{e,2} \leq 2Q\left(\frac{d_{sr}^{rx}/2}{\sqrt{N_o/2}}\right)\,, \tag{6.12}$$

where the Euclidean distance of the received signals at the neighboring mobile device receiver, d_{sr}^{rx}, is expressed by

$$d_{sr}^{rx} = f_{sr} d_{sr} = 2 f_{sr} \sqrt{P_{tx}^{sr}} \,. \tag{6.13}$$

Because $P_{e,1}$ in Equation 6.11 is close to zero in the application scenario described in this chapter, there is:

$$P_{e,sr}^{hmod} \approx P_{e,sr}^{old} \leq 2Q\left(f_{sr} \sqrt{\frac{2P_{tx}^{sr}}{N_o}} \right) . \tag{6.14}$$

If considering rayleigh fading in the short-range link, then the symbol error rate can be calculated in a similar way based on Equation 6.8.

6.2.2 Energy Consumption

In this subsection, the average energy per bit, E_b, and the average energy consumption is derived for the conventional modulation and hierarchical modulation schemes. Both the cellular link and the short-range link is assumed to use 4QAM; and there are same amount of data available to be transmitted over both links. The baud rate is $\frac{1}{T}$ symbol/s. Therefore, in the traditional modulation the average energy per bit at a transmitting mobile device can be expressed as

$$E_b^{old} = \frac{1}{2} \left(\frac{E_s^c + E_s^{sr}}{2} \right) ,$$

where E_s^c and E_s^{sr} is the energy per symbol on the cellular link and short-range link. They can be expressed by

$$\begin{aligned} E_s^c &= \int_0^T \left(A_c g(t) \cos(2\pi f_c t + \theta) \right)^2 dt \\ &= \int_0^T (\sqrt{2P_{tx}^c} \cos(2\pi f_c t + \theta))^2 dt \\ &= P_{tx}^c T \,, \end{aligned} \tag{6.15}$$

where assuming $g(t) = 1$ and $f_c \gg \frac{1}{T}$.

$$\begin{aligned} E_s^{sr} &= \int_0^T (A_{sr} g(t) \cos(2\pi f_c t + \theta))^2 dt \\ &= \int_0^T (\sqrt{2P_{tx}^{sr}} \cos(2\pi f_c t + \theta))^2 dt \\ &= P_{tx}^{sr} T , \end{aligned} \tag{6.16}$$

where assuming $g(t) = 1$ and $f_c \gg \frac{1}{T}$.

Therefore,

$$E_b^{old} = \frac{1}{4}(P_{tx}^c + P_{tx}^{sr})T . \tag{6.17}$$

The hierarchical modulation in this example becomes an hierarchical 16QAM. To transmit the same amount of data, the baud rate is the same with $\frac{1}{T}$ symbol/s. But each symbol has 4 bits. So the average energy per bit, E_b, can be expressed as following, considering the probability of different signals' position.

$$E_b^{hmod} = \frac{1}{4} E_s^{hmod} , \tag{6.18}$$

where E_s^{hmod} is the energy per symbol of the hierarchical modulation signal. Due to the instant energy per symbol depending on signal point position, the signal's amplitude can be categorized as A_0, A_1 and A_2 for signal point $\square$, $\bigcirc$ and $\triangle$, respectively. So the average energy per symbol E_s^{hmod} can be simply given by

$$\begin{aligned} E_s^{hmod} = & \frac{1}{16}\left(4\int_0^T (A_0 g(t) \cos(2\pi f_c t + \theta_0))^2 dt\right) + \\ & \frac{1}{16}\left(8\int_0^T (A_1 g(t) \cos(2\pi f_c t + \theta_1))^2 dt\right) + \\ & \frac{1}{16}\left(4\int_0^T (A_2 g(t) \cos(2\pi f_c t + \theta_2))^2 dt\right) , \end{aligned} \tag{6.19}$$

where letting $g(t) = 1$, furthermore, $\theta_0 = \theta_2 = \frac{\pi}{4}$, $\theta_1 = \tan^{-1} \frac{\sqrt{P_{tx}^c} - \sqrt{P_{tx}^{sr}}}{\sqrt{P_{tx}^c} + \sqrt{P_{tx}^{sr}}}$ and $f_c \gg \frac{1}{T}$, where

$$\begin{aligned}
A_0 &= \sqrt{2}\left(\sqrt{P_{tx}^c}-\sqrt{P_{tx}^{sr}}\right) \\
A_1 &= \sqrt{\left(\sqrt{P_{tx}^c}+\sqrt{P_{tx}^{sr}}\right)^2+\left(\sqrt{P_{tx}^c}-\sqrt{P_{tx}^{sr}}\right)^2} \\
A_2 &= \sqrt{2}\left(\sqrt{P_{tx}^c}+\sqrt{P_{tx}^{sr}}\right).
\end{aligned}$$

Substituting A_0, A_1 and A_2 into Equation 6.19, $E_s^{hmod} = (P_{tx}^c + P_{tx}^{sr})T$ is obtained. Therefore, there is

$$E_b^{hmod} = \frac{1}{4}(P_{tx}^c + P_{tx}^{sr})T\,. \tag{6.20}$$

From the results of Equation 6.17 and Equation 6.20, it is clear that the average energy per bit is the same for the traditional and hierarchical modulation schemes.

To calculate the average energy consumption of a mobile device for both schemes, the energy consumption for receiving data from base station is not considered, because it is same for both schemes. A cooperation cluster is assumed to consist of N mobile devices. In the case of a traditional scheme differentiating cellular link (CL) and short-range link (SRL) by different time slots, each mobile transmits data for time T_s both on CL and SRL. When a mobile device is transmitting data to a BS, the other mobiles are all in idle mode. During short-range communication, when a mobile device is transmitting, the other mobiles in the cooperation cluster are all receiving. So the average energy consumption of the traditional scheme can be expressed as

$$E^{old} = \underbrace{P_{tx}^c T_s}_{\text{tx on CL}} + \underbrace{P_i(N-1)T_s}_{\text{idle on CL}} + \underbrace{P_{tx}^{sr} T_s}_{\text{tx on SRL}} + \underbrace{P_{rx}^{sr}(N-1)T_s}_{\text{rx on SRL}}\,. \tag{6.21}$$

With hierarchical modulation, when a mobile device is sending hierarchical modulation (HMOD) signal, all the other mobiles are all receiving the HMOD signal. After all the mobiles finish transmission data by HMOD, they all swift to idle mode. In other word, there is no need to assign a specific short-range communication duration for the cooperative mobiles. The energy consumption of the HMOD is given by

$$E^{hmod} = \underbrace{P_{tx}^{hmod} T_s}_{\text{tx on CL}} + \underbrace{P_{rx}^{sr}(N-1)T_s}_{\text{rx on SRL}} + \underbrace{P_i N T_s}_{\text{idle}}\,, \tag{6.22}$$

where as we know the average energy per symbol in HMOD $E_s^{hmod} = (P_{tx}^c + P_{tx}^{sr})T$, therefore, the average transmission power of HMOD can be expressed by $P_{tx}^{hmod} = P_{tx}^c + P_{tx}^{sr}$. Then the average energy consumption using HMOD is

$$E^{hmod} = \underbrace{(P_{tx}^c + P_{tx}^{sr})T_s}_{\text{tx on CL}} + \underbrace{P_{rx}^{sr}(N-1)T_s}_{\text{rx on SRL}} + \underbrace{P_i N T_s}_{\text{idle}} \,. \tag{6.23}$$

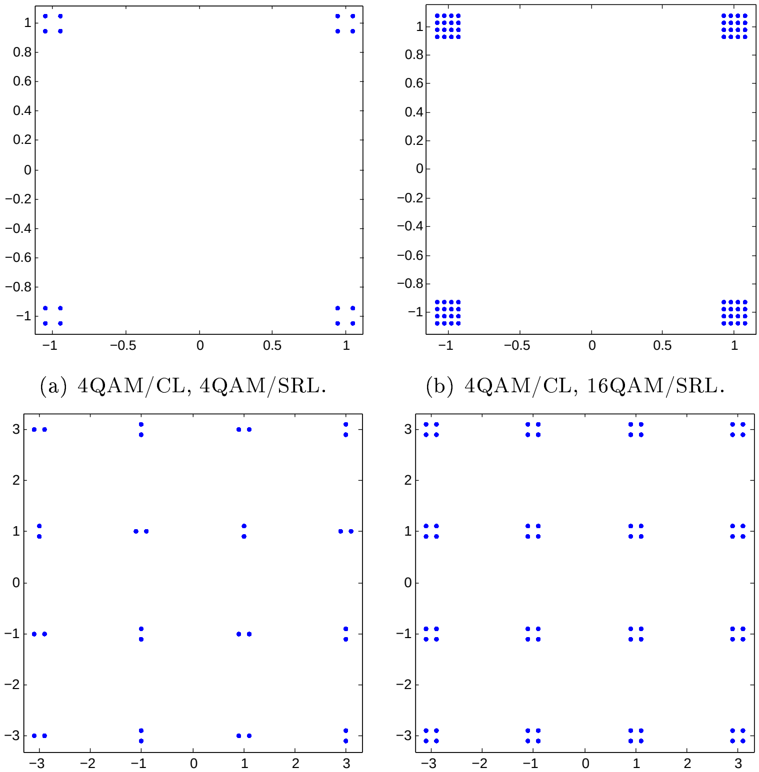
Comparing Equation 6.21 and 6.23, the energy consumption of using hierarchical modulation has $P_i T_s$ more in each transmission period. Due to the power consumption at idle mode is very low, it is almost negligible.

6.2.3 Spectrum Efficiency and Transmission Delay

From symbol error probability and power consumption performance analysis, it has been proven that hierarchical modulation can achieve the same performance as traditional modulation. The advantage of hierarchical modulation is that it increases spectrum efficiency and at the same time it reduces delay as shown throughout this section.

In the given example if the spectrum efficiency is 2ζ bits/s/Hz by traditional modulation then with hierarchical modualtion the spectrum efficiency is doubled i.e. 4ζ bits/s/Hz. The hierarchical modulation method presented here is very flexible. It can have many variations not only 4QAM on both cellular link (CL) and short-range link (SRL). It can be 4QAM on CL and 16QAM on SRL; or it can be 16QAM on CL and BPSK on SRL, 16QAM on CL and 4QAM on SRL, and so on. Which hierarchical modulation constellation to use depends on the amount of data flows towards base station and neighboring mobile devices. It also depends on the wireless link quality. So the achievable spectrum efficiency gain depends on the hierarchical modulation constellation. Figure 6.3 shows some examples of the applicable hierarchical modulation constellation.

The delay of the traditional and the hierarchical modulation case using TDD will be compared here. In the traditional case the BS would reserve time slots for uplink transmission and short-range communication. In the latter one the BS is not even involved by exchanging data, but in controlling the communication among cooperative peers. Using hierarchical modulation, while the short-range communication is ongoing,



(a) 4QAM/CL, 4QAM/SRL.

(b) 4QAM/CL, 16QAM/SRL.

(c) 16QAM/CL, BPSK/SRL.

(d) 16QAM/CL, 4QAM/SRL.

Figure 6.3: Examples of hierarchical modulation constellation (cellular link (CL), short-range link (SRL)).

now data can be sent towards the BS. The originating mobile device has two queues, namely one for the BS and one for the receiving neighboring mobiles. The queue can be emptied whenever time slots are assigned. In the traditional case only one of the queues is served at one time.

In the cooperative case presented in this work, both queues can be served at the same time. The rates depend only on the signal constellation. In case of 4QAM for both CL and SRL, the dequeuing rate is equal. In case 4QAM is used for CL and 16QAM for SRL, the short-range link is dequeued as two times fast as cellular link. Therefore, in the cooperative case the delay becomes shorter and the longer cellular link phase will not block the short-range link phases.

In summary, hierarchical modulation improves the spectrum efficiency and delay performance, with neither any system performance degradation nor additional costs.

6.3 Simulation & Results

To validate the analytical findings, simulative measurements were conducted. This section describes the simulation procedure and shows the simulation results. The basic simulation procedure is illustrated in Figure 6.4. The signals for the cellular link and short-range link are modulated separately by 4QAM modulation in two signal flows. Then the modulated short-range link signals are superimposed on the modulated cellular link signals. So two signal flows merge into one which is transmitted by a mobile device. The transmitted signals arrive at the base station and the cooperative mobile device through the cellular link channel and the short-range link channel, respectively. The transmitted signals suffer path loss and rayleigh fading in both the cellular link and the short-range link. The receiver will first equalize the received signals then demodulated the signals. It should be mentioned that the base station simply demodulates the received signal as normal 4QAM modulated signal. However, the cooperative mobile device performs successive interference cancelation: it decodes the cellular link signal and proceeds to subtract the decoded signal from the received signal and then decodes its own signal [128].

In the simulation, I am interested in the different effects of the cellular link and the short-range link on the received symbols. Generally, the received baseband signal $y(t)$ can be expressed as

$$y(t) = h(t)x(t) + w(t)\,, \tag{6.24}$$

where $h(t)$ represents the narrowband channel; $x(t)$ is the transmitted signal; $w(t)$ is the additive Gaussian noise.

Generally in wireless communications, channel model $h(t)$ consists of two component radio variables [129]:

$$h(t) = m(t) \cdot r_0(t)\,, \tag{6.25}$$

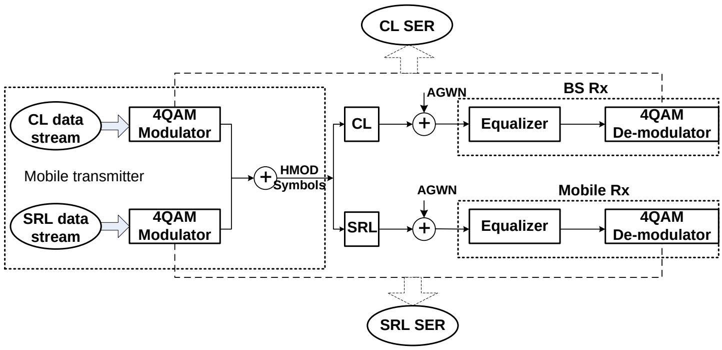


Figure 6.4: Simulation chart.

where $m(t)$ is called the large-scale-fading component which is composed of path loss and log-normal distributed variation caused by shadowing effects. $r_0(t)$ is small-scale-fading component which is represented by Rayleigh fading in this chapter.

Assuming the channel is block-fading channel with stationary and ergodic time-varying gain channel, channel transfer function $h(t)$ can be expressed as [130]

$$h = \sqrt{L(d)} \cdot \alpha e^{j\theta}\,, \tag{6.26}$$

where α is the fading coefficient between the transmitter and the receiver; θ is the phase shift because of mulitpath; $|\alpha e^{j\theta}|$ follows Rayleigh distribution; d is the distance between the transmitter and the receiver; $L(d)$ is the path loss between the transmitter and the receiver.

So substituting Equation 6.26 into Equation 6.24, there is

$$y(t) = \sqrt{L(d)}\alpha e^{j\theta} x(t) + w(t)\,. \tag{6.27}$$

In the simulation, not only path loss but also the effects of some other parameters on the received signal power, such as antenna gain, cable loss and so on should be considered. The values of the parameters for the assumption in the simulation are listed in Table 6.2 [131–133]. Generally the power of the received signal at the BS receiver and at the neighboring mobile device can be expressed as following:

$$\begin{aligned} P_{rx}^{c} &= P_{tx}^{c} + G_m - L_b - PL_c + G_{bs} - L_{cb} \\ P_{rx}^{sr} &= P_{tx}^{sr} + G_m - L_b - PL_{sr} + G_m\,. \end{aligned}$$

Table 6.2: Simulation parameter values.

Notation	**Meaning**	**Value**
f	Frequency	1950 MHz
B	Bandwidth	200 kHz
P_{tx}^{c}	Mobile transmission power on CL	30 dBm
P_{tx}^{sr}	Mobile transmission power on SRL	6.25e-4 dBm
G_m	Mobile antenna gain	0 dBi
L_b	Body loss	0 dB
$EIRP$	Equivalent Isotropic Radiated Power	30 dBm
n_d	Thermal noise density	-174.0 dBm/Hz
N_f	Receiver noise Figure	7.0 dB
n_{rx}	Receiver noise density	-167.0 dBm/Hz
N_{rx}	Receiver noise power	-114.5 dBm
I_m	Interference margin	3 dBm
NI	Total effective noise and interference	-111.5 dBm
G_{bs}	Base station antenna gain	18 dBi
L_{cb}	Cable loss in the base station	2dB
h_{bs}	Base station height	30m
h_m	Mobile device height	1.5m
PL_0	Intercept in SR path loss formula	38.2 dB / 42 dB
γ	Path loss exponent	2.8
X_{σ}^{c}	variation of the cellar link path loss with standard deviation σ	$\sigma = 4\ dB$
X_{σ}^{sr}	variation of the short-range link path loss with standard deviation σ	$\sigma = 4.4\ dB$
R_c	Antenna distance in CL	[0.5 - 2] km
R_{sr}	Antenna distance in SR	[0.01 - 1] km

The path loss is calculated based on proper propagation models. The propagation models of cellular link and short-range link used in the simulation are given as following.

6.3.1 Path Loss of Cellular Link

To calculate the path loss of cellular link, PL_c, the famous Okumura-Hata propagation model is used for an urban macro cell with the BS antenna height of 30 m and mobile antenna height 1.5 m with carrier frequency of 1950 MHz [134]:

$$PL_c = 137.4 + 35.2\log_{10}(R_c) + X_\sigma^c \quad (dB)\,,$$

where R_c is the range in km. X_σ^c is the log-normally distributed random variable (in dB) with standard deviation equal to $4dB$. For suburban areas the path loss is usually assumed an additional area correction factor of 8 dB [131].

6.3.2 Path Loss of Short-Range Link

It is quite challenging to calculate the path loss of the short-range link. The typical BS to mobile propagation model cannot be applied to mobile to mobile (M2M) model as: 1) one antenna is not in the far field of the other antenna [135]. 2) for low antenna height the effects of the close proximity between the Earth and the antenna produce a strong interaction between the antenna and the ground, and the antenna pattern performance is vastly different than if the antenna is in free space [135].

A comprehensive survey is performed in [135], which studied the available propagation models and measured data in the current 125 literature references to determine their applicability to the short-range M2M propagation model. However, unfortunately none of the models fits exactly the scenario in this work.

There are several channel models among which [132, 136, 137] are developed for the picocell in indoor environment at frequency 1700 MHz and 5 GHz; [133] is developed for outdoor environment with low antenna at 1.8 GHz. Generally speaking, all of these works use the power decay law $K + \gamma\log(d/d_{ref})$. The main difference between them is that [137] additionally considers an excess loss because of the floor or wall between the transmitter and the receiver [138]. Combining the previous work, in this chapter the path loss of the short-range link, PL_{sr}, is given as

$$PL_{sr} = [PL_0 + 10\gamma\log_{10}(R_{sr})] + X_\sigma^{sr} \qquad R_{sr} > R_0\,, \tag{6.28}$$

where $R_0 = 1\ m$. The distance between antennas, R_{sr}, is in meter; bracketed term is a least-squares fit to path loss. PL_0 is intercept and γ is path loss exponent. X_σ^{sr} is the variation of the short-range link path loss, assumed to be a zero-mean Gaussian variate with standard deviation σ

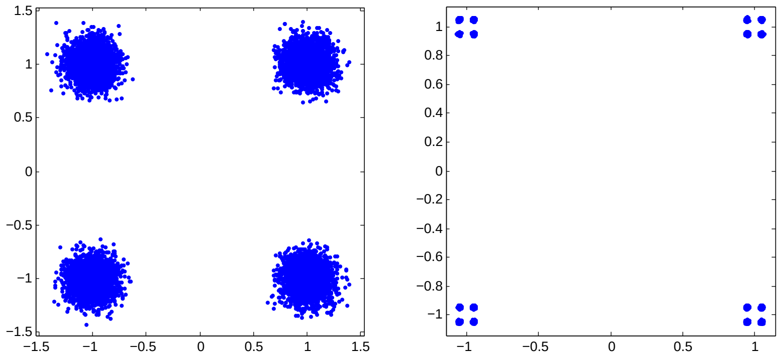
dB. The simulation assumes NLOS environment. The corresponding value of the parameters in the formula 6.28 are listed in Table 6.2.

6.3.3 Simulation Results Details

The case that 4QAM is used for both the cellular link (CL) and the short-range link (SRL) (Figure 6.3(a)) is simulated in AWGN channel and in Rayleigh fading channel.

The hierarchical modulation (HMOD) transmission signal gets attenuation and distortion when it passes the cellular link. At the receiver side, it includes additive white gaussian noise in the signal. The received signals at the BS after equalizer are shown in Figure 6.5(a). Because of the severe signal attenuation and distortion, the BS is only able to distinguish the 4QAM signals for itself. The symbol error rate of the 4QAM modulated signal for the BS is shown in Figure 6.6. In Figure 6.6 the simulation results of the hierarchical modulation is compared with that of the traditional modulation under the condition of AWGN channel and Rayleigh fading channel, respectively. Furthermore, the simulation results of two schemes in AWGN channel is also compared with the analytical results. We can see that in AWGN channel the analytical model can match very well with the simulation results. It shows that the SER of cellular link in AWGN channel is always less than 10^{-3} when the antenna distance is less than 1.9 km. In the case of Rayleigh fading channel, the SER of cellular link is less than 10^{-3} until the antenna distance reaches 1.3 km. It also shows that hierarchical modulation has almost the same SER performance as the traditional modulation on the cellular link. Comparing the SERs of hierarchical modulation in the different channel assumptions, it shows that to achieve at least 10^{-3} SER, the coverage performance difference is about 0.6 km coverage radius.

Figure 6.5(b) shows the constellation of the received signal at the neighboring mobile device side. Because of the less signal attenuation, the mobile is able to extract the fine grained information. Figure 6.7 compares the SERs on the short-range link under two channel assumptions. Furthermore, it also compares the simulation results of the two schemes in AWGN channel with the analytical results. It also shows in AWGN channel, the simulation results can have a good match with the analytical result. Furthermore, the SER is below 10^{-3} when the



(a) At the BS receiver. (b) At the neighboring mobile device receiver.

Figure 6.5: Hierarchical modulated signal constellation at the BS receiver and at the neighboring mobile device.

antenna distance is less about 78 m in the AWGN channel. To achieve the same performance, the antenna distance should be less than 50 m in the Rayleigh fading channel. Additionally, as theoretical analysis expects, the SER performance of hierarchical modulation is also same as the traditional modulation on the short-range link.

6.4 Implementation

In traditional communication system, there exists two duplex modes for the communication channel referred to as frequency division duplex (FDD) and time division duplex (TDD). The idea of FDD is to differentiate downlink and uplink by different frequencies, whereas TDD uses different time slots for that. The benefit of FDD over TDD is the fact that no synchronization between communicating devices is needed. On the other side TDD may be more flexible for capacity allocation on downlink and uplink for asymmetric traffic.

Considering an implementation of the proposed cooperative communication approach using hierarchical modulation, the classical view of downlink and uplink obviously does not hold anymore. E.g. if a mobile device is transmitting its information towards a base station, the neighboring devices should be in receiving mode. This is a clear change from

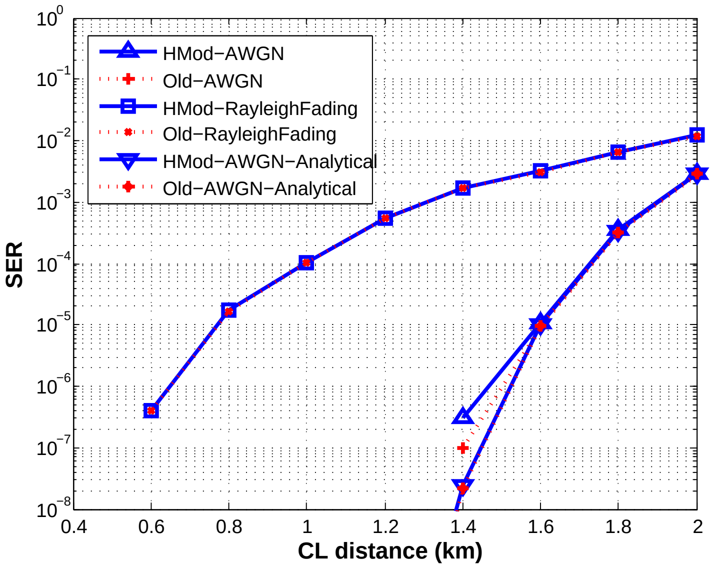


Figure 6.6: Symbol Error Rate comparison at the receiver of base station.

traditional communication systems.

In case of traditional TDD all mobile devices shift from receiving mode to transmitting mode at the same time. Sticking to the TDD mode example, a potential implementation is illustrated in Figure 6.8. The traditional superframe in TDD mode consists of downlink (DL) subframe, uplink (UL) subframe and the transmit/receive transition gap (TTG/RTG) between them. In the UL subframe, each mobile device is assigned specific transmission slots by the base station. Such assignment information is usually broadcasted in the beginning of each downlink phase. Between to uplink slots a small mobile device transaction gap (MDTG) is introduced. MDTGs separate the transmissions of the various mobile devices during the uplink subframe. The gap allows for ramping down of the previous burst, followed by a preamble allowing the BS and mobile devices to synchronize to the new mobile device. In the traditional system, the first mobile device MD_1, being in the uplink phase, transmits in the first time slot TS_1. After that transmission MD_1 can switch to idle until the next downlink phase starts. MD_2 started to

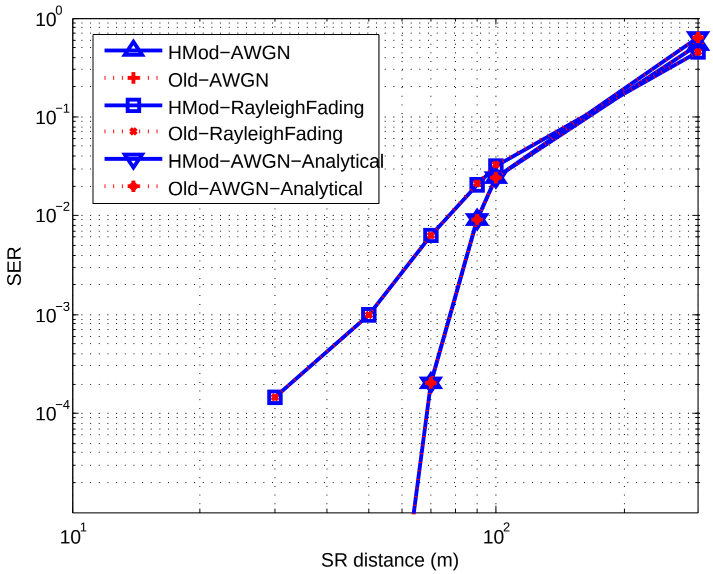


Figure 6.7: Symbol Error Rate comparison at the receiver of the neighboring mobile device.

be in idle state during the transmission of MD_1 and it transmits at time slot TS_2. After TS_2 finishes transmission it also switches to idle state.

In the cooperative communication scenario, at the end of downlink transmission phase, only $MD_1^{'}$ switches to uplink mode and transmits. The others mobiles still keep in downlink mode (i.e. listening and receiving state). After $MD_1^{'}$ finishes transmission at time slot TS_1, $MD_1^{'}$ switches to listening and receiving state. Meanwhile, the next transmitter $MD_2^{'}$ switches to uplink mode and transmits. The other neighboring mobiles are still in the downlink mode until their transmission slots are scheduled.

Comparing those two schemes in Figure 6.8, the cooperative schemes is not switching to idle state anymore, which could give the impression of higher energy consumptions. But it is worth mentioning that as analyzed in Subsection 6.2.2, hierarchical modulation scheme does not consume more energy than the traditional scheme. The reason lies that with hierarchical modulation there is no need to assign a specific short-range communication duration for the cooperative mobiles.

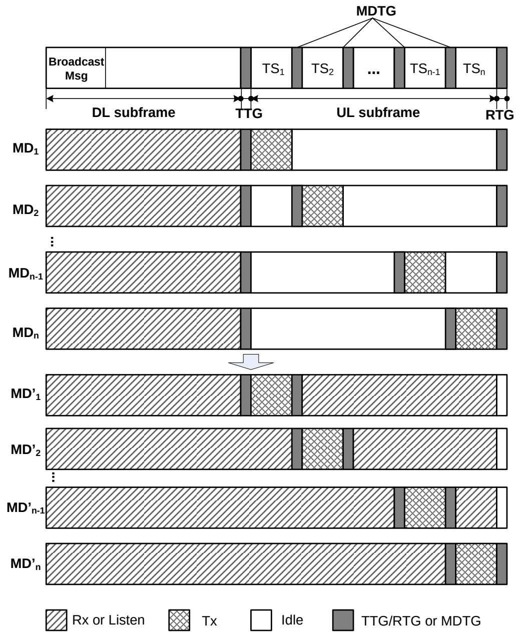


Figure 6.8: Transmission scheme (TTG: Transmit/Receive Transition Gap; RTG: Receive/Transmit Transition Gap; MDTG: Mobile Device Transaction Gap).

6.5 Conclusion

This chapter presents a novel method for a mobile device transmitting different signals towards the BS and the neighboring mobile devices in the same frequency and at the same time using hierarchical modulation. By analytical and simulation results it is proven that the proposed method significantly improves the uplink spectrum efficiency and reduces the data queuing delay with neither degrading the symbol error rate performance nor consuming extra energy. The proposed communication method is targeted to facilitate the signalling and data transmission in cellular controlled peer to peer (CCP2P) network architecture. Also one potential implementation for TDD based wireless communication systems is presented within the chapter.

Chapter 7

Conclusion

To tackle the challenges (i.e. energy saving, spectrum efficiency, QoS, etc.) faced by the current wireless networks, a novel concept, *cooperation*, is proposed [1]. Cooperation opens a new view of the exploitable resources (i.e. the resources from neighboring mobile devices) and changes the way of information exchange and delivery. Cooperative networking based on Cellular Controlled Peer to Peer (CCP2P) network architecture brings an additional dimension of communication (i.e. short-range communication) into the conventional cellular network, which introduces design diversity to solve the crucial issues in wireless networks.

Primary cooperative networking research based on CCP2P network architecture has been conducted in this thesis. Cooperation strategies are applied in different applications and networks to overcome specific problems.

- Cooperative strategy is applied in DVB-H network to save energy. It can save about 50% energy with three mobile devices in full cooperation scenario using Bluetooth as short-range link.

- For reliable multicast services in wireless networks, cooperation retransmission strategy exploits error/loss heterogeneity of different mobile devices to improve error/loss recovery efficiency in terms of energy consumption, as well as recovery latency and overall network throughput. The research results show that the cooperative retransmission strategy can outperform non-cooperative ones, specially when the mobile devices have heterogeneous packet loss rate.

For example, for a multicast group with 128 mobile devices among which 5% mobile devices have 10% packet loss rate, energy consumption of layered FEC, ARQ (SRM) and HARQII is as 2.5, 1.75, 1.25 times as that of cooperative one, respectively. Furthermore, higher gain can be expected in the performance of the cooperative retransmission strategy using network coding. For example, for a multicast group with 100 mobile devices at 5% homogeneous packet loss rate, if a Base Station transmits 40 packets each time, it needs up to 40 retransmitted packets within the cooperative group to recover all the lost packets. However, with network coding 5 coded packets can recover all the lost packets within the cooperative group.

- To solve low uplink access efficiency issue in WLAN, *One4all* cooperative strategy can effectively reduce collisions by reducing the number of contention mobile devices. Consequently, it can reduce channel access delay and energy consumption comparing with the conventional RTS/CTS and packet aggregation schemes. For example, at physical data rate 54 Mbps, the channel access delay per mobile device of RTS/CTS and packet aggregation scheme is about double and nearly five times of that of One4all, respectively. Regarding energy consumption per packet successful transmission, RTS/CTS and packet aggregation use about six times and double as One4all does, respectively.

- To solve the WLAN spectrum scarcity issue, a cognitive radio MAC protocol, C-CSMA/CA, exploits the indirect cooperation among mobile devices to detect spectrum hole. The simulation results show C-CSMA/CA can significantly improve throughput by utilizing unused spectrum opportunities; consequently, MAC access delay and queuing delay is highly reduced.

- To facilitate uplink communication on cellular link and short-range link in CCP2P cooperative networking, hierarchical modulation is applied as a novel communication method to realize two independent communications in the same frequency and at the same time slot without the expense of symbol error rate and energy. It is an important contribution for the development of cooperative networking.

As the accomplishment of the Ph.D. project, 17 publications on cooperative networking have been achieved in book chapters, journals, and conference proceedings. Furthermore, the work has been used to propose cooperative networking in the IEEE 802.11 VHT (Very High Throughput) standardizations group in Taipei in 2008 [139].

According to the achieved results, cooperative networking has shown a significant potential to bring numerous and unique opportunities to tackle multitude crucial issues in future wireless networks. Although the research conducted in the thesis is only from technical perspectives, we can expect that challenges in cooperative networking are multidisciplinary. It is important for us to understand users' individual and social behaviors and their impacts on wireless networks in terms of network operation and performance. Even though challenges do exist, various standardization bodies are considering including cooperation strategies in designing the forthcoming 4G, due to the large impact of cooperation technology [140]. Followed by other researchers, they also believe that cooperative strategies, both on the technical and the social level, will become an essential ingredient of the new generation of communication technologies [141].

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List of Acronyms

2G The 2nd Generation

3G The 3rd Generation

ACH Accessible Channel

ACK Acknowledgement

AP Access Point

AR_ADDR Access Request Address

ARQ Automatic Repeat Request

AWGN Additive White Gaussian Noise

BD_ADDR Bluetooth Device Address

BSS Basic Service Set

CCP2P Cellular Controlled Peer to Peer

CL Cellular Link

CSMA/CA Carrier Sensing Multiple Access/Collision Avoidance)

CTS Clear to Send

DCF Distributed Coordination Function

DIFS DCF Interframe Space

DVB-H Digital Video Broadcasting - Handheld

FCC Federal Communications Commission

FCS Frame Check Sequence

FEC Forward Error Correction

HDTV High-definition Television

HMOD Hierarchical Modulation

ISO Open Systems Interconnection

MAC Media Access Control

MIMO Multiple Input and Multiple Output

MPE-FEC Multiprotocol Encapsulation – Forward Error Correction

NACK Negative Acknowledgement

NAV Network Allocation Vector

PDU Protocol Data Unit

PES Parallel Elementary Stream

QoS Quality of Service

RTS Request to Send

PHY Physical Layer

PM_ADDR Parked Member Address

PU Primary User

SDU Service Data Unit

SER Symbol Error Rate

SES Sequential Elementary Stream

SIFS Short Interframe Space

SINR Signal to Interference Noise Ratio

SRL Short-range Link

SRM Scalable Reliable Multicast

SU Secondary User

TDD Time Division Duplex

TTS Time to Sense

UACH Unaccessible Channel

UnCH Unknown Channel

UWB Ultra-Wide Band

WLAN Wireless Local Area Network

WWRF Wireless World Research Forum