Cooperation in Wireless Grids

Master Thesis

An Energy Efficient MAC Protocol for Cooperative Network with Game Theory Model

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Abstract

Battery lifetime is a crucial factor of a wireless device to support its mobility and quality. The system can answer to this issue by implementing cooperating protocols that attempt to reduce energy consumption. In an ideal system where no Medium Access Control (MAC) is considered or no collision accurs, it has been proven that cooperation can reduce energy consumption. The existing MAC layer protocol might worsen the performance thus a new and improved scheme is needed for the scenario.

This work proposes a new MAC scheme to solve energy consumption problem in cooperative wireless networks. The proposed scheme is simulated under a cooperative network model and compared with ideal system and existing MAC system. The results show that the proposed scheme gives significant improvement to existing system. Later, it is also simulated under several varying parameters, namely number of mobile devices, cluster ranges, strategies, mobility, and cluster periods.

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Abbreviations

ACK	Acknowledgment
AP	Access Point
ATIM	Announcement Traffic Indication Message
BO	Back-off
BS	Base Station
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CTS	Clear-to-Send
DIFS	Distributed Inter-Frame Spacings
GPRS	General Packet Radio Service
ID	Identity
IFS	Inter-Frame Spacings
IPD	Iterative Prisoner's Dilemma
MAC	Medium Access Control
NE	Nash Equilibrium
NICs	Network Interface Cards

PD	Prisoner′s Dilemma
RTS	Request-to-Send
SIFS	Short Inter-Frame Spacings
TDMA	Time Division Multiple Access
WLAN	Wireless Local Area Network

Preface

This report is a result of master thesis work carried out between 1st February 2007 and 14th June 2007 by group 07gr1116 as a part of master program in Mobile Communication at Aalborg University, Denmark.

This thesis documents the study and investigation on medium access control layer design for cooperative network with game theory modeling. It includes the understanding of basic concepts, a medium access control design, and performance evaluation of existing system as well as proposed one. Later on with software simulation using NetLogo, proposed system behavior is further investigated.

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Chapter 1

Introduction

Battery lifetime is a crucial factor of a wireless devices to support its mobility and quality. Higher battery lifetime can support higher mobility and higher data rate in a long term. The development of wireless link has accomplished a high data rate in a high mobility environment, making the wireless devices spend more and more power. Unfortunately, this development does not coped with the development of battery lifetime. The system can answer to this issue by implementing protocols that attempt to reduce energy consumption. The report discusses cooperation technique as one of energy saving technologies which is a critical factor in the wireless devices.

1.1 Motivation

Cooperation is one of the concepts for energy saving technologies that recently has been discussed in many research topics. The main idea of cooperation is to gain mutual benefit for all parties. This benefit can be in terms of throughput, utility, or power. Using cooperation as a mean to reduce energy consumption has been discussed in several works namely in [2–4]. However, previous works have not yet discussed user's decision to cooperate and the effect of each user decision on system performance. Users have to cooperate whether the cooperation lead to their benefit or not. This may not happen in the real system.

The environment where users can choose to cooperate is best illustrated by the game theory, a mathematical model for a situation where the decision of each player influences other players, thus making it a suitable model for the scenario of cooperation. Furthermore, it also models the players as rational players which is very close to machine behavior.

By modeling the cooperation using the game theory, it is predicted to show closer approach to real system and to investigate further on how the cooperation can help in reducing the energy consumption.

1.2 Problem Definition

The previous work by [5] has investigated that cooperation with the game theory model results in a promising power performance. However, it gives very little detail on what happen in MAC layer where the energy saving technology mostly takes part. The existence of MAC layer in the system is predicted to reduce the energy saving performance.

The goal of this thesis is to investigate the potential of cooperative technologies in wireless networks, focusing on the energy efficient MAC layer protocol. The system will be modeled with game theory approach. The thesis will discuss several possible solutions for energy saving technology and investigate their performance through simulations.

1.3 Assumptions

The section provides overview on assumptions that are used in the simulation test bed and scenario of investigation in this thesis. The scenario of interest is depicted in Figure 2.2 and its corresponding assumptions are listed as follows.

- All mobile devices have two Network Interface Cards (NICs), one is

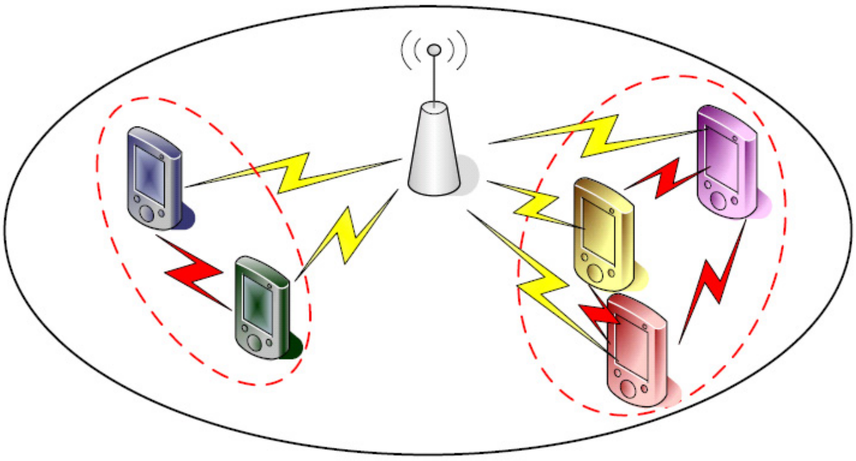

Figure 1.1: A scenario of investigation

connected to the Access Point (AP), serves as cellular link to receive data from AP, and the other one is connected to other mobile devices, serves as a short range link for the cooperation. In the case of not used, these NICs are switched to its minimum energy consumption.

- IEEE 802.11 or Wireless Local Area Network (WLAN) is used for both communication to the AP and communication among mobile devices in the cluster, consequently Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) protocol is used as the MAC layer protocol according to IEEE 802.11 specification.
- The area of investigation is a single cell with one AP and several mobile devices having the same data stream from the AP in a broadcast / multicast service.
- A rate adaptive protocol-based mechanism is available in the system as suggested in IEEE 802.11a/g. The rate for the link from the AP to all mobile devices is set to be the lowest rate (6 MBits/s) as the AP provides broadcast /multicast service to all the mobile devices, regardless of their position and channel condition.

- Each mobile device can sense the signal from all other mobile devices in the cooperative cluster, thus it is assumed that no hidden / exposed devices problem occurred in it.
- It is assumed that each cluster is assigned to different channel in a cell, or to a different channel to its neighbors, thus no significant interference is experienced by other clusters.
- It is assumed that power components in the mobile devices are ideal, i.e. no overhead in power and time to change between power states (e.g. to change from transmit to receive, or from idle to receive).

The parameter of interest in this thesis is average normalized energy consumption in the system. It is defined as the total energy consumed by all NICs of every mobile device in the system in the whole simulation time averaged by number of mobile devices and simulation time, and normalized it with non-cooperation energy consumption. The system performance is then evaluated in different environments and compared to the performance of non-cooperative system.

1.4 Report Outline

The report begins with the theoretical review in Chapter 2 where the cooperation concept, the game theory overview, and IEEE 802.11 standard are being elaborated. Having laid back the theoretical review, the report continues with the problem definition, comparing the ideal system and the existing system and trying to assess the problem within the existing system in Chapter 3. Solution and proposed algorithm are discussed in Chapter 4 while their performance under different environments, and their respective analysis are presented in Chapter 5. In the end, conclusions and some possible future developments are given in Chapter 6.

Chapter 2

Theoretical Review

This chapter begins with the discussion on the concept of cooperation and benefits behind it, continues with the concept of game theory and some examples. In the end, an overview of MAC layer of IEEE 802.11 as the scenario of interest in this thesis is also being elaborated.

2.1 Cooperation in Wireless Grids

Before continuing with the thesis, it is necessary to understand the concept of cooperation and motivation of or benefits gained from the cooperation, and also an introduction to wireless grids as the network of interest. This section provides an overview of wireless grids and the motivation to cooperate.

2.1.1 Introduction to Wireless Grids

Wireless grids are wireless computer networks, consisting of different types of electronic devices with the ability of sharing their resources with any other devices in the network in an ad-hoc manner. In other words, a definition of wireless grids can be given as: ad-hoc, distributed resource-sharing networks between heterogeneous wireless devices. Ad hoc means that the network is characterized by distributed, dynamic, and self-organizing architecture.

Wireless grids can be divided into two types [6]. The first type is fixed wireless grids that consists of fixed location wireless devices. This type of wireless grids usually consists of fixed wireless servers and terminals such as personal computers with wireless connection capability, or wireless links that connect several buildings. The second type is mobile wireless grids that consists of several mobile wireless devices. Some key characteristics to illustrate mobile wireless grids are : small and low powered devices, dynamic and unstable resources [6].

2.1.2 Motivation to Cooperate

In general, cooperation is a strategy of a group of entities that work together to achieve a common or individual goal. Every entity gains advantage by giving or sharing its resources [2].

In the upcoming wireless communication systems, e.g. 4G, it is expected that mobile devices need to support large variety of rich content services that require complex hardware with increasing power consumption. The state of the art of wireless networks architecture is based on a cellular architecture, as illustrated in Figure 2.1. The cell consists of a central controller and several mobile devices within an area of coverage. The mobile devices need to have the capabilities to support various services. Both hardware complexity and large energy consumption can be a big challenge to the market potential.

Therefore, one of the solutions to overcome the energy consumption problem is by doing cooperation among mobile devices. Cooperation in this case means that several mobile devices create a cluster in an ad hoc manner to share their resources to achieve common or individual goals. Here, it is assumed that each mobile device has capability to communicate both with AP and other mobile devices simultaneously, as illustrated

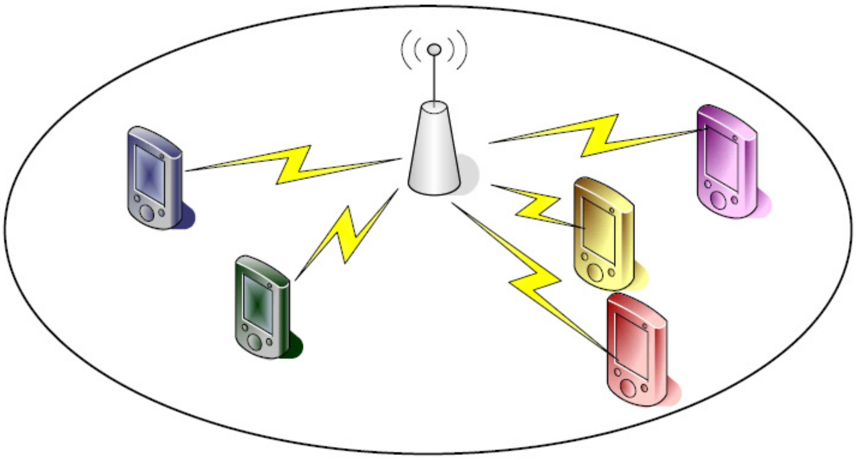

Figure 2.1: An illustration of cellular architecture in wireless network

in Figure 2.2. The short range communications among mobile devices require less energy consumption and provide higher data rate than the cellular communication.

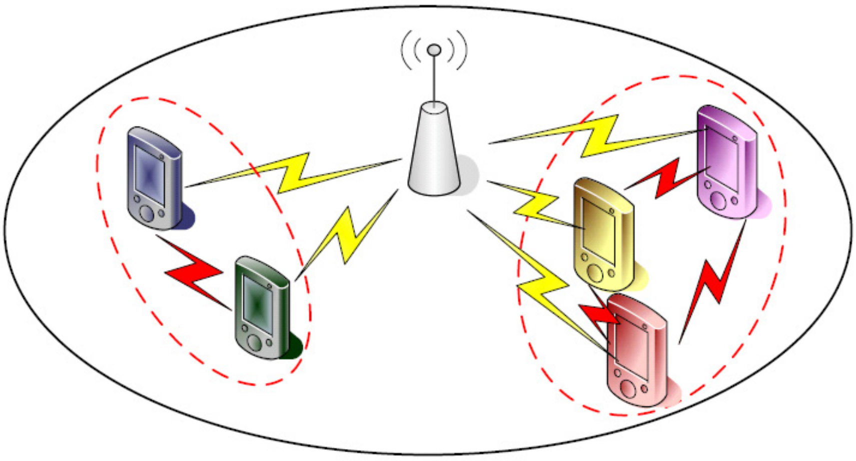

Figure 2.2: An illustration of cluster in wireless network

In this thesis, IEEE 802.11 is used for the cellular network, as well as for the communication within the cluster among mobile devices. All mobile devices request the same information in broadcast / multicast link. The information is sent by the AP in n-substream with n is the number of mobile devices in a cluster. Each mobile device in the cluster only receives one distinct substream and forwards it to other mobile devices.

The motivation behind this is that the total energy consumption by doing cooperation must be less than without doing cooperation. Let $P_{c,rx}$ be the power that is used to received information from the AP, $P_{s,rx}$ be the power that is used to received information from the short range using ad hoc link, and $P_{s,tx}$ be the power that is used to transmit information from short range using ad hoc link. If there are n mobile devices, it is shown in Equation (2.1) that in certain conditions, doing cooperation results in better performance in term of energy consumption.

$$P_{c,rx} + n \cdot P_{s,tx} + n \cdot P_{s,rx} < n \cdot P_{c,rx} \tag{2.1}$$

2.2 Game Theory for Cooperation in Wireless Grids

2.2.1 An Introduction to the Game Theory in Wireless Grids

Game theory is a mathematical model for the analysis of interactive decision-making processes where the decision of a player influences others and overall system. It provides model for predicting what might happen when players with conflicting interests interact.

Examples of this games in the real world ranging from card games like poker, negotiation of purchasing items, predicting politic (election result), or economic behavior in a region. However, clear distinction should be made to distinguish games with the optimization problem. The later involves only one decision maker or player. Games have many independent players.

A game consists of three basic components: a set of players, a set of actions, and a set of preferences [7]. The players are the decision makers in the modeled scenario. In a wireless system, the scenario can be a throughput, power, or link allocation with wireless nodes as its players. The actions are the alternatives available to each player and may change over time. The action in wireless networks can be the choice of links, coding rate, protocol, cooperation, modulation scheme, flow control parameter, transmit power level, or other parameters. When each player chooses an action, the results can influence other players and the system. The goal of the game is to maximize each player's certain parameter. In a wireless scenario, the optimized outcome parameter might be a high signal to noise ratio, a low interference, a more robust connection, a low bit error rate, or in this thesis is a low energy consumption.

An example of a payoff table in a game of two players is presented in Table 2.1. Player 1 is the row while player 2 is the column. The values in each cell represents the payoff each player obtains if certain strategies are selected. Take one example that player 1 chooses action **T** and player 2 chooses action **W** then player 1 receives $1 - c$ and player 2 receives 0. The decision of player 1 alone does not provide the result of player 1 without the decision of player 2. The parameter c ranging from 0 to 1.

Table 2.1: Game Theory payoffs

Player 1 \ Player 2	**T**	**W**
T	(-c ,-c)	(1 - c ,0)
W	(1 - c ,0)	(0,0)

One of the goals of the game theory is to predict what will happen when a game is played. The most common prediction of what will happen is called the "Nash Equilibrium (NE)". An NE is an action profile at which no players have any incentive for unilateral deviation.

The game shown above has two NE. The NE are the action profiles (T,W) and (W,T). Consider the action profile (T,W). In this case, player 1 plays the action T and receives a payoff of $1 - c$ while player 2 plays the action W and receives a payoff of 0. Player 1 has no incentive to deviate, because changing her action to W would decrease her payoff from $1 - c$ (a positive number) to 0. Player 2 has no incentive to deviate, because changing her action to T would decrease her payoff from 0 to $-c$.

On the other hand, consider a non-NE action profile, (T,T). From this action profile, player 1 could increase her payoff by unilaterally changing her action. Such a unilateral deviation would change the action profile to (W,T), thereby increasing player 1's payoff from $-c$ to $1-c$.

In a wireless grids, energy consumption can be reduced with cooperation [2]. However, in making the decision to cooperate, the mobile devices may seek their own good selfishly, or worse, behave maliciously, seeking to ruin network performance for other mobile devices. One can see the application of game theory straightforwardly in those cases.

Game theory has been widely used for solving communication problems such as routing, flow control, Code Division Multiple Access (CDMA) power control, and trust management. Now it is also used for modeling agents in cooperative networks.

2.2.2 Introduction to Prisoner's Dilemma

One of the most classic problem in game theory is the Prisoner's Dilemma (PD) which its payoff table is shown in Table 2.2. From the table, it can be shown that PD is a game that does not have a single equilibrium or a single solution. From the system point of view, it is better if both players cooperate, but if a player decide to cooperate and the other decides to defect, the cooperate player receives less benefit. This makes the players tend to choose to defect, but in fact they will receive more benefit if they both cooperate. A player's decision to cooperate or not in a cooperative networks is one examples of PD problem.

Iterative Prisoner's Dilemma (IPD) is the common method used for solving or modeling PD [8]. This method throws a set of players and makes them interact in a number of games (sufficiently large enough) and calculates the total gain. Strategies used for IPD range from simple tit for tat, tit

Table 2.2: Prisoner’s Dilemma payoffs

Player 1 \ Player 2	**Cooperate**	**Defect**
Cooperate	(2, 2)	(0 ,3)
Defect	(3,0)	(1,1)

for tat with memory, to combination of strategies. Here is the description of several of these strategies.

Tit for tat is a simple strategy, where a player starts with cooperate then choose whatever strategy its previous opponent chooses.

Tit for tat With Memory is similar to tit for that but it can memories several steps before.

Defect is a strategy where all players choose to defect.

Cooperate is a strategy where all players choose to cooperate.

Wise is a strategy where players can choose to cooperate or defect depends on some criteria.

Combination is a strategy where there is more than one strategies in the area of investigation.

The concept of IPD can also be implemented for the cooperation in wireless grids. The idea is to set a number of mobile devices in an area, and makes them interact many times (sufficiently large enough). As the main goal of this thesis is to investigate the impact of cooperation among mobile devices to their energy consumptions, the average values can be achieved by making them interact many times.

Another important factor about the energy consumptions is that how the mobile devices share the wireless medium as they are using the same frequency bandwidth. In order to optimize the energy saving achieved by cooperation, a study of MAC technology is a must. In the next section, the state of the art of MAC layer for IEEE 802.11 Technology will be presented.

2.3 State of the Art of MAC Layer for IEEE 802.11

This section provides an overview of MAC layer technology and the power management in IEEE 802.11.

MAC in IEEE 802.11 is used to manage the entities in its network to access the shared medium in order to get a collision free transmission. The IEEE 802.11 support two kinds of links, which are unicast link and broadcast link. For unicast link, CSMA/CA and Acknowledgment (ACK) are used, but for broadcast link, only CSMA/CA is used. Request-to-Send (RTS) / Clear-to-Send (CTS) is used to provide a virtual carrier sense function to protect against hidden entities.

2.3.1 CSMA/CA

CSMA/CA is the MAC method employed in IEEE 802.11 or WLAN. A WLAN node cannot detect a collision while transmitting as it operates in half duplex. The basic principles of CSMA/CA are listen before talk and contention. If a collision occurs, the transmitting node will not receive an ACK from the intended receiving node. For this reason, ACK packets have a higher priority than all other network traffic. Once all data transmission has been completed, the receiving node will transmit an ACK before any other node can begin transmitting a new data packet. All other nodes must then wait for a longer period of time before they begin transmission.

The protocol starts by listening the channel, and if the channel is found to be idle, it sends the first packet in its transmit queue. If the channel is busy or interference occurs, the node waits until the end of the current transmission and then starts the contention or wait a random amount of time. When its contention timer expires, if the channel is still idle, the node sends the packet. Because the contention is a random number and is done for every packet, each node is given an equal chance to access the channel.

This contention is usually slotted, it means that a transmission may start only at the beginning of a slot. For IEEE 802.11 with Frequency Hopping, the slot period is $50\ \mu$s, and $20\ \mu$s for IEEE 802.11 with Direct Sequence. This makes the average contention delay larger, but reduces significantly the collisions.

Contention in the communication medium can be further reduced using RTS and CTS messages between sender-receiver pairs. Communication in this mode consists of the transmission of a RTS by the node. If this is received intact by the AP, it replies with CTS. This is the signal for the node to send a packet. The communication is terminated by the ACK from the AP.

The delays that precede and follow the transmission of control frames (RTS, CTS or ACK) or data frames are called Inter-Frame Spacings (IFS). Before the transmission of an RTS, nodes are required to wait for a time equal to the Distributed Inter-Frame Spacings (DIFS). On the other hand, a destination node is required to send a CTS or an ACK frame within a Short Inter-Frame Spacings (SIFS) amount of time after the reception of RTS and DATA frames from the source, respectively. If the sending node senses the medium is idle after the DIFS interval and its Back-off (BO) is zero, it chooses a BO from a range of contention window and then an associated timer starts counting down to zero. It senses the channel for slot period, and if the channel is idle until the end of slot period, BO counter is decremented. If the channel is busy during the slot time, the sending node stops the BO countdown and resumes the BO countdown when the channel is idle again. When the timer counts down to zero, the sending node attempts to transmit the frame and waits for ACK. If the transmission is success (i.e. ACK is received), then it senses the channel for another DIFS time. If the transmission fails and collision occurs (i.e. no ACK is received) then it doubles its contention window and senses the channel for another DIFS period and the process repeats, as illustrated in Figure 2.3. The BO counter is doubled if collision is detected, reset after a successful transmission, and frozen while other node is transmitting or during the sensing period.

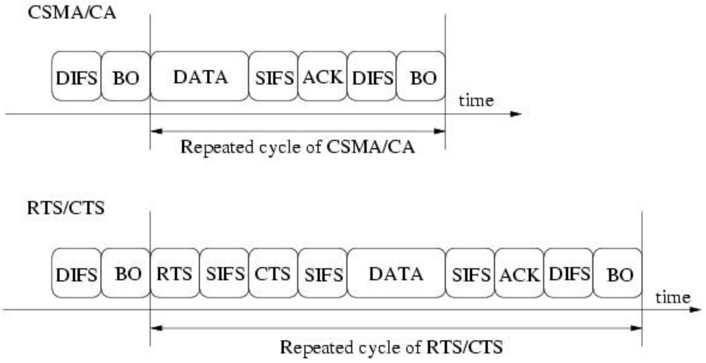

Figure 2.3: An illustration of CSMA/CA without and with RTS/CTS

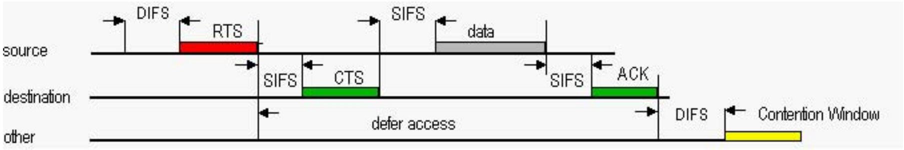

Figure 2.4: An illustration of CSMA/CA with RTS/CTS

2.3.2 Power Management and Specification

Power Mode in a IEEE 802.11 devices is consisted of *Awake* and *Doze* states [9]. The awake state comprises state of which the device transmits, receives, or is connected actively. The doze state is the state which the device can not either transmit or receive thus main parts of transmitter and receiver can be turned off to reduce power consumption. The way IEEE 802.11 technology handles its power states differs in infra-structured and ad-hoc manner as depicted in Table 2.3 [9].

- Infra-structured Network

The device turns to doze state and informs AP by using power management bit in the header of its packets. Upon receiving this, the AP stores packets destined to the corresponding device in its buffer. The packets will be transmitted later after the device wakes up. The doze device periodically wakes up to receive beacon from the AP which informs the existence of packets in the buffer. In the case where there is a packet or more in the buffer, the doze device may switch itself awake to receive the packet and switch back to doze state again.

- Ad-hoc Network

  The task to save packets / traffic to the device during the time it is in doze state is distributed among other devices, since no AP exists. The device switches back to awake state periodically in a Announcement Traffic Indication Message (ATIM) window time to receive the information about its traffic in ATIM frame. The problem in this scenario is that due to the non existence of the AP, there is no or weak synchronization in the system, resulting to asynchronized ATIM window. This situation may lead to the device not receiving any ATIM frame while it is supposed to be.

Device's power consumption differs in the awake state and doze state. In the awake state, it has different power consumption for its transmit, receive and idle state. Table 2.4 summarizes WLAN power consumption of terminals as specified by several manufacturers. Sense is the state where the terminal senses the channel without actively receiving (i.e. sensing in CSMA/CA) while Idle is the state where the terminal in power saving mode and most of the RF circuitry is turned off [10]. The report uses power specified by Atheros [11] as it is used in [5].

Table 2.3: WLAN power parameter

Parameter	**Values**
Typical output power	30 - 100 mW (15 - 20 dBm)
Procedures used for the network setup	For ad hoc networks: scan, authentication, while for infra-structured: scan, authentication, association.
Average time in the network setup without external interferences	$n \cdot c \cdot 1.35$ ms for an unsaturated network with c is the probed channels ($1 \leq c \leq 13$) and n is the number of devices, excluding the AP (active scan time for infra-structured topology)
Typical absorbed current	100 - 350 mA
Power save modes	Awake and Doze

Table 2.4: Power consumption for several IEEE 802.11 device

Device's Mode	**Consumed Power in Atheros [11]**	**Consumed Power in Lucent WaveLan [12]**
Transmit	2 W	1.65 W
Receive	0.9 W	1.4 W
Sense	-	1.15 W
Idle	0.04 W	0.045 W

2.4 Introduction to Netlogo

This section will explain about NetLogo as the simulator that is used in this thesis as well as the motivation to use it, and the model in NetLogo for cooperation in wireless Networks.

NetLogo is a programmable modeling environment for modeling complex systems which are developing over time. It is well suited for simulating natural and social phenomena. Modelers can give instructions to hundreds or thousands of independent *agents* concurrently. This makes it possible to explore the connection between the micro-level behavior of each agent and the macro-level patterns that emerge from the interaction of many agents.

NetLogo is written in Java so it can run on all major platforms (Mac, Windows, Linux, et al). It is run as a standalone application. Individual models can be run as Java applets inside a web browser. It is developed at the Center for Connected Learning (CCL) and Computer-Based Modeling of the Northwestern University of Evanston, United States of America, and it is freely available in their website [13,14].

Although NetLogo was not developed specifically for telecommunication, in principle this tool can be used for modeling and analyzing a dynamic interactions among entities in the wireless network. Moreover, this tool can be well suited for the distributed (e.g ad hoc) and centralized (e.g cellular) network which behavior can be modeled as every entity in the network interacts with other entities which can give impact to some particular parameters of interest of the overall system, such as throughput, power consumption, delay, etc). Furthermore, it also can be used to study the wireless networks behavior using a game theory.

The screenshot of simulation model for this work is depicted in Figure 2.5. It can be seen that the model consists of one AP, modeled as grey square in the middle of cell, and mobile devices scattered around it. Green mobile devices indicate selfish mobile devices and blue mobile devices indicate wise mobile devices while yellow mobile devices indicates selfish cluster heads and purple mobile devices indicate wise cluster heads. Selfish and Wise are strategy names for the model and will be described in section 3.1.2. Yellow links that connect them are the communication links inside cluster. The yellow circles also indicate cluster range with cluster head as its center. The figure shows several mobile devices cooperate in small to medium clusters while others remain alone. The decision of cooperation is independently decided by each terminal.

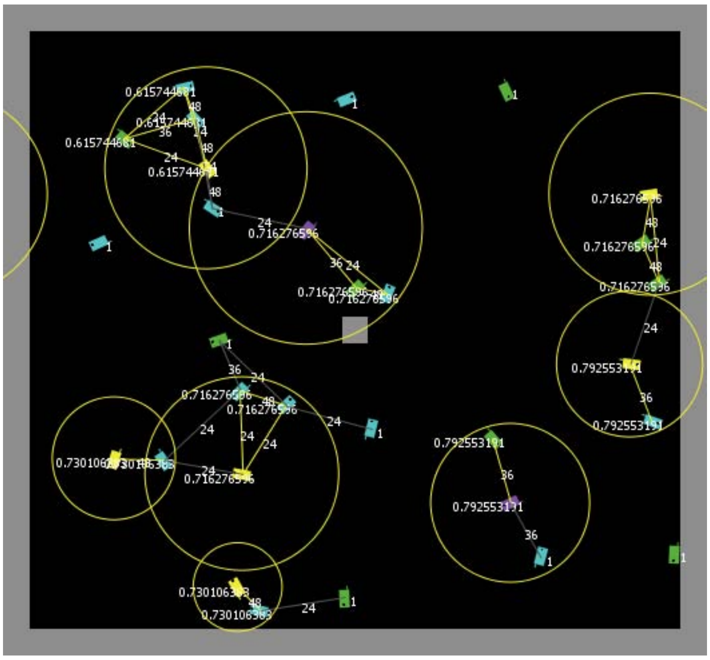

Figure 2.5: Netlogo Screenshot of Simulated Model

Chapter 3

Problem Definition

The current state of the art in wireless communication comes from many new services supporting various and rich data contents which may result in a constraint of energy capacity for mobile devices. Energy consumption of mobile communication devices is a major subject of concern. This thesis investigates energy consumption of cooperative mobile communication devices. One of the existing work regarding this issue by [5] has proven that in ideal scenario, cooperative network among mobile devices can reduce the energy consumption in term of system level by exploiting the combined data transmission rate between AP and mobile devices (cellular network), and a short range link between mobile devices in cooperative network for a specific fundamental network application.

In this chapter, a detail description about the system model and the scenario of investigation of [5], the existing system and its behavior in cooperative system, and the implementation of MAC Layer in Cooperative WLAN and its performance evaluation will be presented.

3.1 Ideal System

The focus of [5] is to analyze the cooperative energy saving strategies in mobile wireless networks, which is illustrated in Figure 3.1, with the following assumptions :

- The scenario is a Time Division Multiple Access (TDMA) multicast transmission, where a number of mobile devices are distributed under the coverage of a AP which is located in the center of the cell.
- Multicast means that all mobile devices are interested in receiving the same data stream (e.g a video broadcast signal)
- Every wireless mobile device has two independent wireless network interfaces so that it can communicate over cellular network with AP and short range link with other mobile devices simultaneously (parallel cooperation scenario).
- A rate adaptive protocol-based mechanism is available as suggested by standard IEEE 802.11a/g for WLAN technology.
- It is assumed that all mobile devices are distributed randomly in the cell, and to accommodate all mobile devices, the cellular data rate, R_c, is R_c, is set to 6 Mbits/s. On the other hand, the short range R_{SR}, is dynamically change, depending on the distance among the mobile devices.
- It is also assumed that a number of mobile devices are located in a close proximity one to each other, exchanging the data from AP with higher data rate than the cellular one (R_{SR} > R_c). This motivates the implicit assumption for the success of cooperative technique.
- The power levels are chosen according to the typical present-day WLAN devices as mentioned in Table 2.4.

It is underlined that the efficiency of energy saving by cooperation mainly depends on the ratio between the cellular and the short range data rates which is assumed to be bigger than 1 ($\frac{R_{SR}}{R_c} \geq 1$), and the capability to exploit the low-power mode of the mobile devices during idle periods. Thus,

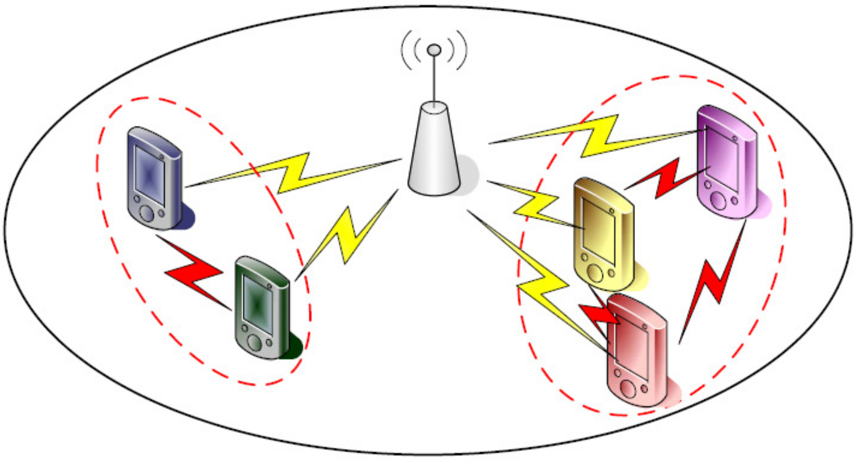

Figure 3.1: Illustration of the scenario for cooperative network

the objective is to find the best cooperative clusters in term of energy saving gain.

3.1.1 Theoretic Analysis

A mathematical model for the scenario is required for the analysis of energy saving in cooperative scenario. The potential *payoffs* of the cooperation are described as follows. It is assumed that a multicast services is provided, and the service can be splitted into n substreams, with n is the number of mobile devices in a close proximity, which forms a cooperative cluster. With a specific cooperative strategy, which will be described in the next section, a group of mobile devices which are close to each other, agree to cooperate in order to exploit the more efficient communication, in term of higher data rate than cellular one, using short range link.

In this manner, the energy consumption can be reduced by switching off the mobile devices during idle periods. The energy consumption for this scenario is given by Equation 3.1, where Z is the ratio between the cellular and short range data rate, thus $Z = \frac{R_{SR}}{R_c}$. n is the number of mobile devices in the cooperative cluster, P_{Tx},P_{Rx}, and P_{Id} are the power levels for transmitting, receiving, and idle periods, which are defined in Table 2.4, with the subscript of C and SR means the cellular link and the short range link.

$$\begin{aligned} P_{coop}(Z,n) &= \tfrac{1}{n}P_{Rx,C} + (1-\tfrac{1}{n})P_{Id,C} + \tfrac{1}{n\cdot Z}P_{Tx,SR} + \dots \\ &\quad \tfrac{n-1}{n\cdot Z}P_{Rx,SR} + (1-\tfrac{1}{Z})P_{Id,SR} \end{aligned} \tag{3.1}$$

Table 2.4 shows that the mobile device requires low power to be in idle state compares to being in the transmitting and receiving state, provide the possibility to save power.

Using the power level defined in Table 2.4 and normalizing it with the energy consumption where the wireless mobile device is not cooperating, which is 0.94 watt (receive and idle power), the value of P_{coop} for one wireless mobile device for different values of Z and n can be obtained which is depicted in the Table 3.1. It is assumed that Table 3.1 is provided in every wireless mobile device. Note that the values in the tables are different from the original one in [5] since it was not normalized with the value 0.94 as explained above.

The calculation of values in Table 3.1 is explained with an example as follows. Take an example of $Z = \frac{R_{SR}}{R_c}$, where R_{SR} is from 54 Mbits/s to 6 MBits/s and R_c is set to be always 6 MBits/s. The normalized energy consumption for a cluster of three mobile devices at 24 MBits/s is 0.716 compare to the power consumed by a mobile device when it is not cooperating, which are set to unit after normalizing, as explained before.

It has to be noted that energy consumption for cooperation is not always better than operating alone. It depends on the data rates ratio between cellular and short range links, and the value of transmitting, receiving, and idle power, as cooperation mainly exploit the idle state.

It also has to be noted that this model does not include some overhead, e.g the overhead in MAC layer for TDMA, as in the beginning of the cluster

Table 3.1: Normalized power consumption table for cooperative energy saving

Z	**Number of mobile devices**								
	2	3	4	5	6	7	8	9	10
9 (54 Mbps)	0.709	0.535	0.448	0.396	0.361	0.336	0.317	0.303	0.291
8 (48 Mbps)	0.730	0.553	0.465	0.412	0.376	0.351	0.332	0.317	0.306
6 (36 Mbps)	0.792	0.608	0.515	0.460	0.422	0.396	0.376	0.361	0.349
4 (24 Mbps)	0.916	0.716	0.616	0.555	0.515	0.486	0.465	0.448	0.434
3 (18 Mbps)	1.042	0.825	0.716	0.651	0.608	0.576	0.553	0.535	0.520
2 (12 Mbps)	1.292	1.042	0.918	0.842	0.792	0.757	0.730	0.709	0.692
1.5 (9 Mbps)	1.542	1.260	1.119	1.034	0.978	0.937	0.907	0.883	0.864
1 (6 Mbps)	2.042	1.695	1.521	1.417	1.348	1.298	1.261	1.232	1.208

formation, there should be a phase how they agree on the medium access to avoid collision in data exchange. Later, a proposed scheme for MAC layer is proposed in order to solved this problem.

3.1.2 Cooperative Strategies : Selfish and Wise Cooperation

Table 3.1 shows that most of the cases, mobile devices will consume less energy if they are cooperating. In these conditions, cooperation in a cluster is preferred rather than operating alone. Note that this is different from the case of cooperation in the concept of relaying (packet forwarding) where it involves a resource draining and the relay nodes might be tempted to cheat (e.g drop the packet). In this concept, there is no intention for the mobile devices to cheat as they can instantaneously save the energy if they cooperate.

However, a cooperative strategy is required as the fundamental for modeling the network, since there are a few cases that cooperation will not give benefit (e.g in the situation of two mobile devices devices are cooperating with 9 Mbits/s data rate). In those cases, devices should choose to operate alone.

There are two kinds of strategies that are implemented in this scenario. The first strategy is *Selfish Cooperation*. This strategy represents the basic attitude of rational and self-regarding individuals, which is trying to minimize their energy consumption, as well as to prevent from loosing energy whenever profitless condition is happening. This strategy is not always be the best in term of saving the energy if it is used in a *heterogeneous network* where different short range data rates are used, depending on the distance between mobile devices. For example, three mobile devices (P_1, P_2, and P_3) are connected with different data rates as illustrated in the Figure 3.2.

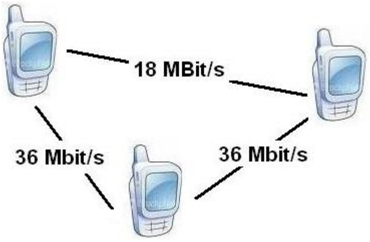

Figure 3.2: An example scenario

Assuming that T_1 searches for cooperative cluster, there are two choices. The first one is scenario A, the case where T_1 implements selfish strategy, thus cooperating with T_2 (with the energy consumption of 0.792) because it has better data rate compare to the data rate T_3 (with the energy consumption of 0.825). The second scenario, or scenario B, is to cooperate with both T_2 and T_3 (with the energy consumption of 0.825).

On one side, the scenario A gives better energy saving to T_1 and T_2, but not for T_3 who has to spend unit power. For the scenario B, T_1 and T_2 get less advantage, but more profitable for T_3.

From this point, there is question about which is the better. From the individual point of view, scenario A will be chosen by T_1 and T_2. However, from the system point of view, it is better to choose scenario B because every mobile devices gets the benefit of the cooperation. Moreover, the total consumed energy for scenario A is higher than scenario B, as can be seen in Equation (3.2).

$$\begin{aligned} P_{total}^{scenarioA} \quad &is \quad 0.792 + 0.792 + 1 = 2.584 \\ P_{total}^{scenarioB} \quad &is \quad 0.825 + 0.825 + 0.825 = 2.475 \end{aligned} \tag{3.2}$$

Therefore, another strategy is implemented, which is *Wise Cooperation*. In this strategy, it is assumed that each mobile device knows about the actual energy consumption of every other mobile devices in the current range (e.g the mobile device gets this information when looking for reachable mobile devices as a feedback to its searching request). With this assumption, a wise mobile device can calculate the power consumption of the cluster and use it as a consideration in its decision to cooperate. Note that based on the example, it might happen that T_1 is wise mobile device, but T_2 and T_3 are not, thus the scenario B might not happen.

It should be noted that a wise mobile device will not choose to cooperate if the total energy consumption in its cluster is higher than if all the mobile devices in the cluster is operating alone, which is in the same manner as selfish strategy.

One may wonder why should use wise strategy, giving up the best condition, while there is a better choice to save the energy by implementing selfish strategy. There should be a kind of incentive to encourage the mobile mobile devices to choose wise strategy.

The incentive is based on IPD where the cooperative games are repeated multiple times and the mobile mobile devices are having the same situations in the future, thus they may use a strategy to get better average energy saving in the long run.

In the following section, some result regarding the two strategies will be presented.

3.1.3 Performance Evaluation

Before presenting the performance evaluation, it is important to explain about the parameters that appear in the graph. The average normalized system power consumption per mobile device (which is later also refers as the average normalized system *energy* consumption per mobile device), $\bar{P}$), is calculated using Equation 3.3 where P_i is the total normalized power consumed by mobile devices at iteration *i*, and N_T is the number of mobile devices. The iteration is set to be *100.000* to make sure that the graph is smooth and the values are similar for each iteration, indicating that the result has already stable.

$$\bar{P} = \frac{\sum_{i=1}^{I} P_i}{I \cdot N_T} \tag{3.3}$$

The normalized power saving gain (which is later also refers as the normalized *energy* saving gain), $\bar{G}$, is obtained by subtracting unit with $\bar{P}$ as expressed in Equation 3.4.

$$\bar{G} = 1 - \bar{P} \tag{3.4}$$

The average number of cluster versus number of mobile devices or data rate, $\bar{N_{Cl}}(N_{mobile\,devices})$ *and* $\bar{N_{Cl}}(N_R)$, are calculated by Equation 3.5 and Equation 3.6 where $N_{Cl}(N_{\text{mobile devices}})$ is the number of cluster which contains $N_{mobile\,devices,i}$ number of mobile devices at iteration *i*, $N_{Cl}(N_R)$ is the number of cluster which is using *R* Mbits/s data rate at iteration *i*, and *I* is the number of iterations.

$$\bar{N_{Cl}}(N_{\text{mobile devices}}) = \frac{\sum_{i=1}^{I} N_{Cl}(N_{\text{mobile devices},i})}{I} \tag{3.5}$$

$$\bar{N_{Cl}}(N_R) = \frac{\sum_{i=1}^{I} N_{Cl}(N_{R,i})}{I} \tag{3.6}$$

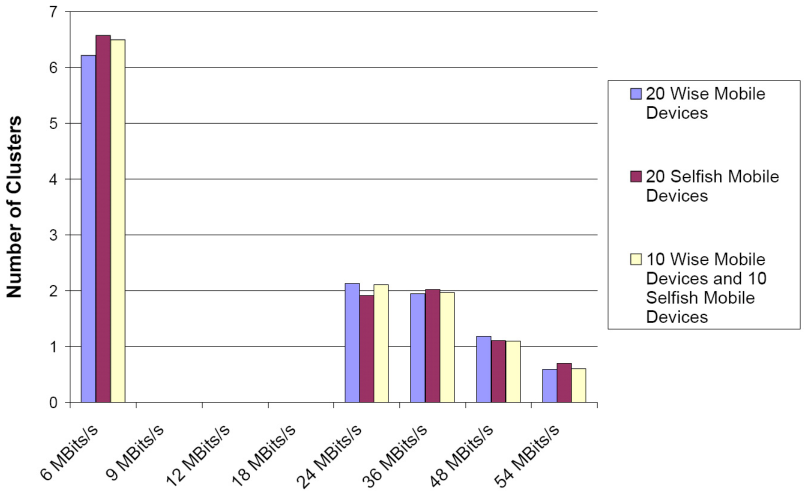

Figure 3.3: Data Rate Histogram for 20 Mobile Devices

Performance Evaluation for Wise and Selfish Strategies in Pure Environment

In these simulations, the wise strategy and selfish strategy are implemented purely. It means that in one simulation, all mobile devices are set to have wise strategy only, and so on.

Table 3.2: Average normalized power consumption per mobile device

Strategy	**Ideal System**
Pure selfish (20 mobile devices)	0.8234
Pure wise (20 mobile devices)	0.8200
Mixed (10 wise mobile devices and 10 selfish mobile devices)	0.8633 (for wise mobile devices) and 0.8543 (for selfish mobile devices)

It can be seen from Table 3.2 that the average normalized energy consumption per mobile device for wise strategy is better than selfish strategy.

The average number of cluster versus number of mobile devices or data rate can be seen in Figure 3.4. The selfish mobile devices tend to form a

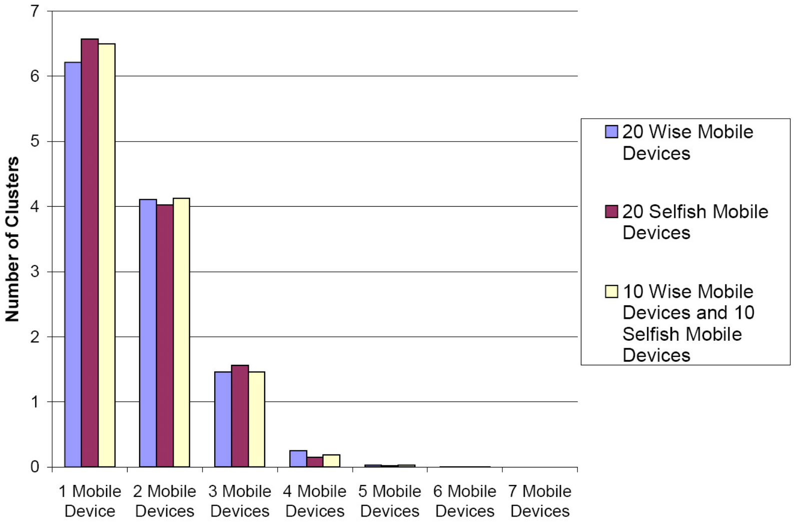

Figure 3.4: Cluster Size Histogram for 20 Mobile Devices

cluster with small number of members, while the wise mobile devices are more likely to form a cluster with larger number of members, giving more opportunities to the mobile devices to achieve more energy saving.

Another interesting result is that the number of cluster which has one member (i.e non-cooperating mobile devices which data rate is 6 MBits/s) for the selfish mobile devices are higher than the wise mobile devices. This shows that the wise mobile devices are more likely to form a cluster rather than isolated.

However, for both strategies, the mobile devices are unlikely form a cluster with large number of member (e.g five mobile devices, or more) because there is small probability that a larger number of mobile devices are close to each other.

Figure 3.3 shows the number of cluster versus data rate. The wise mobile devices tend to form a cluster with slower data rate compare to the selfish mobile devices. This is because of the behavior of the wise mobile devices to sacrifice their best solution to achieve a better group energy saving gain, as explained in the Section 3.1.2.

Based on the two histograms (number of cluster versus number of mobile devices and data rate), it is likely that a cluster with large number of members tend to have lower data rate. However, this kind of cluster is unlikely to happen for the selfish mobile devices, since they prefer more to form a cluster with small number of members which is likely to have a higher data rate.

Performance Evaluation for Wise and Selfish Strategies in a Mixed Simulation

Table 3.2 shows that if wise mobile devices and selfish mobile devices are placed in the same simulation, the average system energy saving, that is calculated for selfish mobile devices only, is better than wise mobile devices only.

The reason comes from the fact that there are two different strategies that are exist in the simulation. For example, a wise mobile device offers to cooperate with one or some possible neighbor mobile devices. Each neighbor mobile device could possibly get better energy saving in another group (selfish) or find a better optimizing solution from their specific knowledge on the current network state (wise). On the other words, every neighbor mobile device can evaluate its best potential solution according to its strategy and offers to its possible neighbor mobile devices to cooperate.

In average, the selfish mobile devices achieve better energy saving because they "exploit" the wise mobile devices by cooperating with them if the energy saving is better for them, and refuse to cooperate if it is worsen, while the wise mobile devices are willing to sacrifice their best solution to get better energy saving in term of cluster or group energy saving.

The work of [5] also try to solve this problem by implementing *safe-wise cooperation*. The basic idea is to play wise with wise mobile devices and play selfish with selfish mobile devices. The result shows that this strategy is capable of preserving the optimal energy saving of wise mobile devices in the presence of selfish mobile devices. A more detail about this strategy can be found in [5] since this thesis does not concern with this issue.

However, as in [5], this thesis does not consider the non-cooperating mobile devices (e.g mobile devices that are not aware of energy saving potentials or mobile devices that can not perform cooperation with other mobile devices), or mobile devices that might harm the networks by doing defection to worsen the energy savings gain.

3.2 Existing System and Its Behavior in a Cooperative System

Section 3.1 has shown that cooperation can result in a reduce of energy consumption. But to implement the cooperation in the real system, a study of its performance in existing system should be performed. The imperfection occurred in the system may reduce the performance of cooperation, reducing gain achieved by cooperation shown in Section 3.1.3.

As has been previously stated in chapter 1, the system of interest is IEEE 802.11 thus we derive all the protocol in this scenario to be within IEEE 802.11 legacy system. The mobile devices update their cooperative clusters after every period of time, called T_{cluster}.

Broadcast or multicast streaming service is provided by the AP to all mobile devices. In this case, the link from the AP is synchronized to all mobile devices. The streaming service starts as soon as the simulation starts. In the case of cooperation, mobile devices keep streaming packets until the next T_{cluster} before start sending to other mobile devices in corresponding cluster links. This to avoid the delay caused of data rate difference between AP link and cluster link. The link between mobile devices in a cluster is unsynchronized thus medium access protocol that does not require synchronization is needed here.

Links between AP and mobile devices are allocated to one channel, and

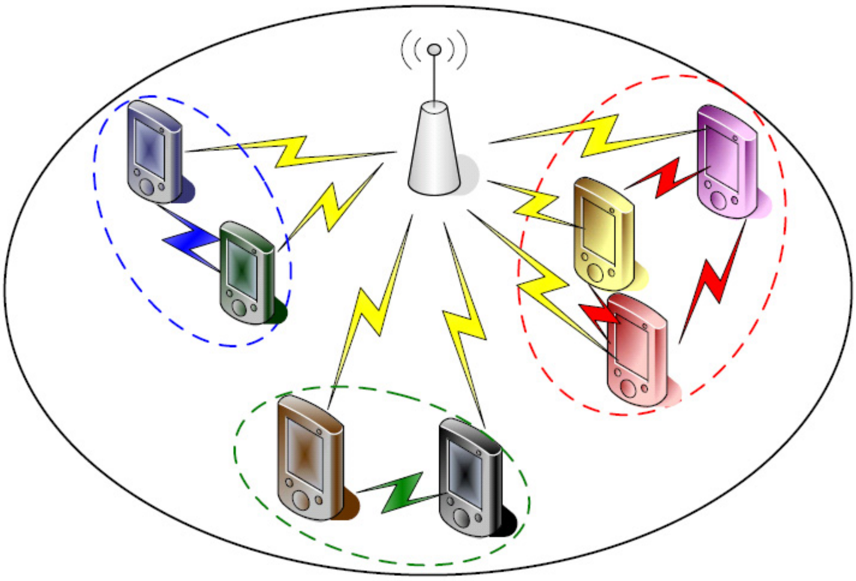

Figure 3.5: An illustration of channel allocation in a cell

each cluster is allocated to its own channel. As depicted in Figure 3.5 each cluster is assigned with different channel which is represented by different color for each cluster. Notice that the communication link to AP is the same for all mobile devices, i.e same color for link to AP. In the case that number of cluster is more that number of channel, a channel is assigned so that each cluster has different channel with its neighbor. Channel allocation is assigned by AP, thus a cluster does not experience significant interference from other clusters.

3.2.1 MAC Layer in Cooperative WLAN

CSMA/CA is the medium access technology used in IEEE 802.11 standard. In this scenario, CSMA/CA is used as medium access technology for mobile devices in the same cluster given that each cluster employs one channel. This protocol also suitable for cooperation, since no synchronization is needed. Mobile devices can also synchronize themselves after the first successful packet.

The system employs TDMA for the downlink from AP to all mobile devices, and CSMA/CA for the link within the cluster. CSMA/CA flowchart is depicted in Figure 3.6. The parameters that are used in this scenario are listed in Table 3.3 which are taken from [15] with a slight adjustment to the scenario. The minimum and the maximum contention window are reduced to be 16 and 128, considering the low number of mobile devices in the cluster, i.e. not more that 10.

Table 3.3: Parameter for CSMA/CA protocol

Parameter Name	**Value**
Slot time	$50\ \mu$s
DIFS	$128\ \mu$s
SIFS	$28\ \mu$s
Minimum contention window ($\mathrm{CW_{min}}$)	16
Maximum contention window ($\mathrm{CW_{max}}$)	128
Packet payload	8184 bits
Physical header	128 bits
MAC header	272 bits
ACK	Physical header + 112 bits
ACK time out	$300\ \mu$s

3.2.2 Performance Evaluation and Comparison of Ideal and Existing System in a Cooperative Manner

The performance of the system is being evaluated with 100000 iteration to make a good average over space and players. The result is depicted in Table 3.4 along with system performance under ideal system as mentioned in section 3.1.3.

It can be seen that for pure wise strategy, the cooperation only gives insignificant improvement of around 2 % or worsen the cooperative system

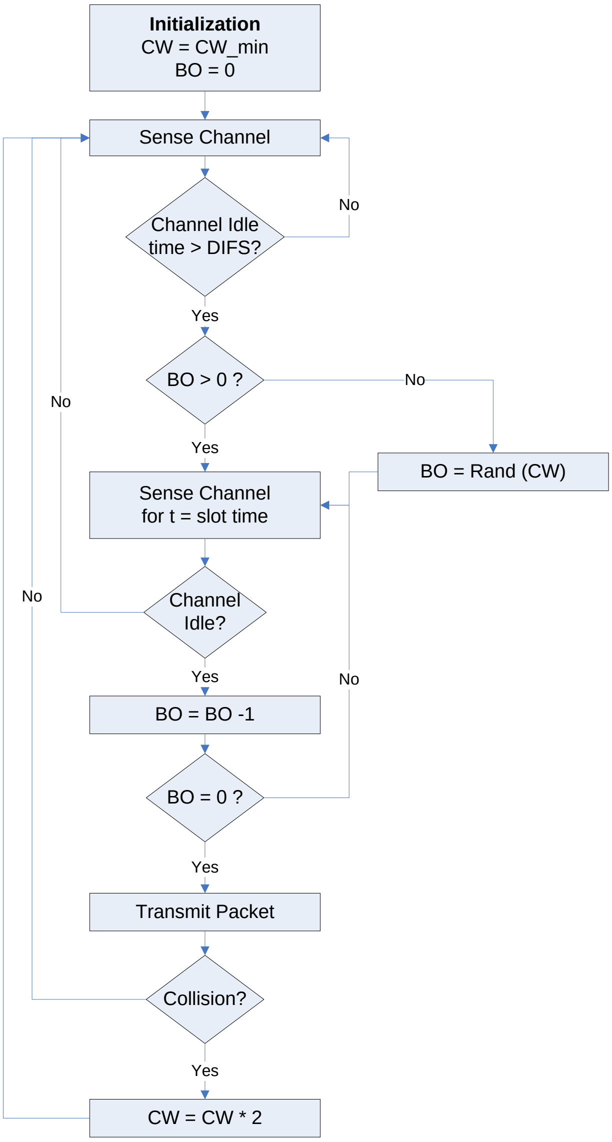

Figure 3.6: CSMA/CA flowchart

performance by 16 % which is due to the overhead from CSMA/CA protocol. In this case, the number of mobile devices in a cell is 20 mobile devices, which gives the average number of mobile devices in a cluster to be 3 or 4. This value gives a very high CSMA/CA overhead. As the number of mobile devices increases, the system performance also increases, but the overhead from CSMA/CA protocol remains the same.

It can be seen that for pure selfish strategy, the cooperation only gives insignificant improvement of around 1% or worsen the system performance by 16% which is also due to the overhead from CSMA/CA protocol. Notice that the CSMA/CA overhead results in the same degradation in the system performance. However, as the number of mobile device increases, the system performance also increases.

Table 3.4: Average normalized power consumption per mobile device

Strategy	**Ideal System**	**CSMA/CA System**
Pure Selfish	0.8234	0.9878
Pure Wise	0.8200	0.9872

3.3 Conclusion

The comparison between system performance in the ideal condition and system performance in the existing system is depicted in Table 3.4. The result shows that cooperation runs on top of existing system does not perform as good as it is expected. The existing MAC layer protocol worsen the performance because it is not designed for this scenario. A new and improved MAC layer protocol is needed for this scenario, yet the protocol should also be easy to develop on top of the existing system. This issue will be addressed in the next chapter.

Chapter 4

Proposed Scheme for an Energy Efficient MAC Layer in Cooperation

In this chapter, a proposed scheme for MAC layer protocol in cooperation will be explained, together with the performance evaluation and comparison with the previous work by [5].

4.1 Proposed Protocol

In general, the previous work does not include some overhead, e.g the TDMA assignment overhead in MAC layer, as in the beginning of the cluster formation, there should be a phase how they agree on access to the shared medium to avoid data collision. Later in this section, a proposed scheme for MAC layer is proposed in order to solved this problem.

As can bee seen in the Section 3.2.2 about the overhead caused in the system that implements CSMA/CA in the cooperation, the consumed energy raises, and in some cases, energy consumption exceeds the energy consumption of mobile devices which are operating alone (i.e. no cooperation is implemented). Therefore, an energy efficient MAC protocol should be designed such a way so that the benefit of cooperation in terms of energy consumption is optimized.

In this thesis, a novel scheme for MAC layer protocol is proposed to address the energy consumption shortcoming of CSMA/CA implementation in cooperation. Basically, the proposed scheme consists of three phases namely :

- Setup phase
- Pilot tone
- Steady state phase

The flowchart describing the proposed scheme is depicted in Figure 4.1. At the beginning of cluster formation, before the proposed scheme takes part, every mobile device creates a link to its surrounding mobile devices within certain coverage area and calculates the links between. Mobile device then decides with whom it cooperates (i.e. creates cluster). After this step, every mobile device tries to select the cluster head by sending an Identity (ID) packet, and the first mobile device which gets the channel is selected as the cluster head. The remaining mobile devices then content the channel to send their ID packet to the cluster head as a sequence for their time slot and member registration. Cluster head sends the sequence of ID to all members and marks the beginning of data exchange phase.

Contention method used in selecting cluster head and sequence is based on CSMA/CA to reuse existing protocol within IEEE 802.11 legacy. In this way, protocol adoption to existing system is easier and simpler. The scheme also employs distributed approach by giving the sequence assignment task to the cluster head, thus reducing dependency to AP.

In the following section, a more detail description on each phase is explained.

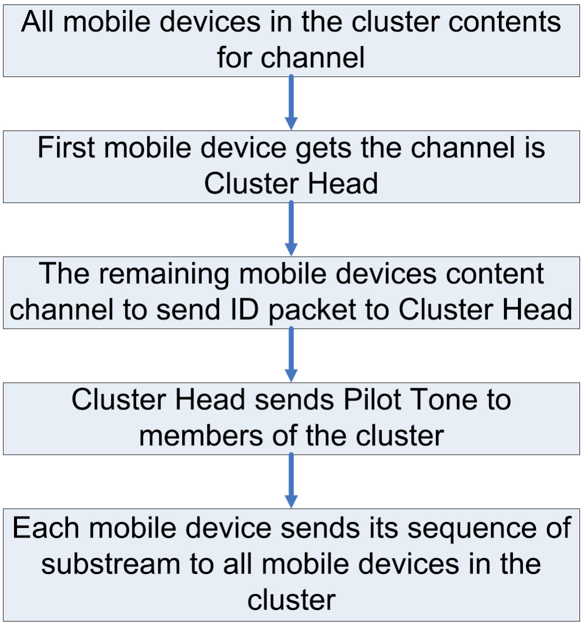

Figure 4.1: Proposed scheme flowchart

4.1.1 Contention Period : Selecting Head of Cluster

Assuming that a group of mobile devices have agreed on performing cluster by establishing a link to all mobile devices in its surrounding within certain coverage area, the first step to be done is to select the cluster head. The main responsibility for the cluster head is to give every mobile device the time slot assignment to access medium or channel to send data stream to other mobile devices in order to avoid collision. Cluster head does the task by assigning a time slot occupation sequence for all mobile devices.

The selection of the cluster head is done as follows. Every mobile device tries to access the medium by sending small identity packet to other mobile devices with broadcast method. The MAC layer protocol used in this phase is based on CSMA/CA to make the most of existing protocol built in IEEE 802.11. The first mobile device that accesses the medium will be the cluster head. The others know who the cluster head by receiving the identity packet from the mobile device that successfully accesses the medium, since one of the mechanism in CSMA/CA is sensing the channel before sending. While sensing the channel, if the mobile device senses the incoming packet, then it will not send its identity packet and recognize the incoming packet as a packet from the cluster head.

After selecting the cluster head, the remaining mobile devices send small identity packet to cluster head. Cluster head creates time slot assignment sequence based on the sequence of incoming identity packet.

4.1.2 Pilot Tone

The next step is to assign the access to the medium to every mobile device in the cluster. Basically it is an assignment of sequence for mobile devices when to send the packet. The cluster head sends a multicast packet to all of its members in the cluster. The packet contains the time slot assignment for every mobile device in cluster. It is assumed that every mobile device in the cluster is loosely synchronized after this phase since every mobile device listens to cluster head transmission, and can start the timer/transmission right after the end of cluster head transmission.

4.1.3 Data Exchange Period : Steady State Phase

As soon as every mobile device gets the information on transmit sequence, the data exchange is started. In this situation, it is assumed that there will be no further collision. A mobile device starts its corresponding transmission as soon as the end of transmission of the previous sequence mobile device. And since the data rate of short range link is higher than the cellular one, there is a possibility of an idle period in the end of the period T_{cluster}.

4.1.4 Cluster Period (T_{cluster})

The sequence of setup phase, pilot tone, and data exchange phase is repeated every T_{cluster} period.

The duration of T_{cluster} is based on the data rate for the cellular link. It is calculated as in Equation 4.1, where N_{packet} is number of packets, 8584 is the size of one CSMA/CA packet in $bits$, and R_c is the data rate for the cellular link.

$$T_{\text{cluster}} = 8584\text{bits} \cdot \frac{N_{packet}}{R_c} \tag{4.1}$$

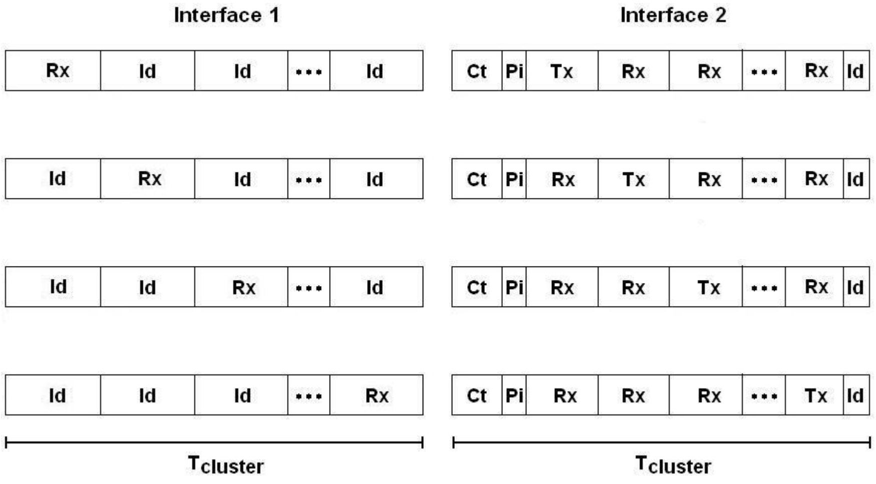

Figure 4.2: An Illustration of T_{cluster}

Note that in this thesis, a phase where mobile devices are looking for possible cluster to be form are not considered in this proposed scheme since it has been discussed in [5]. The proposed scheme begins when a group of mobile devices have already agreed that they are in one cluster, performing cooperation to exchange data stream coming from AP.

4.1.5 Identity Packet Dataframe

Small identity packet sent by mobile devices is basically a packet containing receiver ID and sender ID. This can be obtained by using CSMA/CA

MAC header without payload. The header has four ID fields, thus using the general CSMA/CA format but delimiting the data payload, it is ready to be used as ID packet dataframe. The ID packet dataframe is depicted in Figure 4.3.

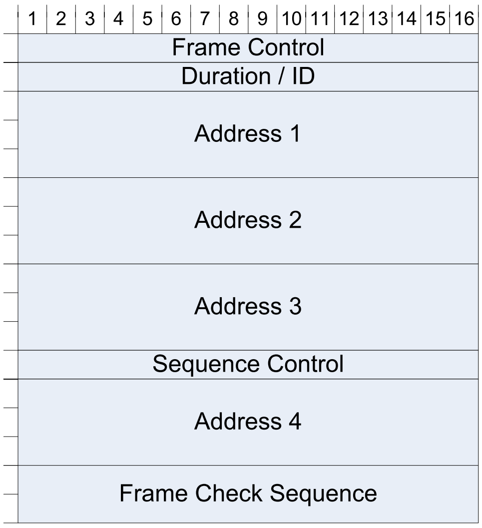

Figure 4.3: Dataframe of identity packet

4.1.6 Performance Evaluation

The proposed solution is then simulated and compared with results obtained in chapter 3 which are depicted in Table 4.1. The results show that the cooperative system performance is worsen by 16.72 % for pure wise strategy and 16.44 % for pure selfish strategy which is due to the overhead from CSMA/CA protocol. In this cases, the number of mobile devices in a cell is set to be 20 mobile devices, which gives the average number of mobile device in a cluster to be 3 or 4. This value gives a very high CSMA/CA overhead. Notice that the CSMA/CA overhead results in the same degradation in system performance. As the number of mobile devices increases, the system performance also increases, but the overhead from CSMA/CA protocol remains the same. This indicates that the state of the art MAC employed in cooperating system nearly destroys the cooperative gain. This is because the MAC is not design for this particular scenario. A new and improved MAC design is needed to solve this problem.

The proposed scheme is then simulated and compared with results obtained previously. The result shows that the proposed scheme improves system performance so that it approaches the ideal system performance by 3.33 % for pure wise strategy and 3.16 % for pure selfish strategy. This gives an improvement of around 13.39 % from the existing system performance for pure wise strategy and around 13.28 % from the existing system performance for pure selfish strategy. The improvement gained from CSMA/CA system is because the proposed scheme uses TDMA for data exchange, minimizing CSMA/CA overhead. It performs slightly worse than ideal system due to the contention and pilot tone phase.

Table 4.1: Performance evaluation of cooperation model with 20 mobile devices

Strategy	**Ideal System**	**CSMA/CA System**	**Proposed Scheme**
Pure Selfish	0.8234	0.9878	0.8550
Pure Wise	0.8200	0.9872	0.8533

4.2 Mobility Model

The model discussed so far has applied mobility in its mobile device, however the model only applies a uniform mobility for every mobile device. This section describes the further development of the mobility model by implementing three types of mobility in the system.

The model has already a single mobility employed by [5]. In this mobility model, the mobile device moves forward in a constant speed with a random angle between $-10\,^{\circ}$ to $10\,^{\circ}$. If the mobile device reaches the cell edge and the next move ends outside the cell, it runs the mobility until the next move ends inside the cell. The system employs mobility model in such a way that after one simulation unit distance, the data rate changes to its lower or higher rate. Table 4.2 summarizes the relation between range (in simulation unit distance), data rate (in Mbits/s), and actual range (in meters). With some simplification, it is assumed that one simulation unit distance equals to three meters in actual range which is assumed that the data rate also changes. The mobile devices' moving speed is assumed to be as the average walking speed of a normal person, which is one m/s. With these assumptions and an approach from Table 4.2, the developed model further specifies that the mobile devices have three types of mobility, namely low, medium and high mobility, which are described as :

Low Mobility has around 0.1 m/s speed. It models the speed of a standing person or a person that makes almost no movement.

Medium Mobility has around 1 m/s speed. It models the speed of a walking person.

High Mobility has around 3 m/s speed. It models the speed of a running person, or cycling person.

4.3 Cluster Formation Preservation

The cluster formation remains the same during T_{cluster} period, however one might wonder what the cluster formation for the next T_{cluster} is. It is possible that the next T_{cluster} cluster formation is the same as the current one (in the other words, maintaining the current cluster, or not making new cluster). Considering the common walking speed of one m/s, a link between mobile devices only changes after 1.5 seconds for the worst case

Table 4.2: WLAN range [1]

Range (Simulation Unit Distance)	**Data Rate Mode**	**Range (m)**
8	6 Mbits/s OFDM	> 35
7	9 Mbits/s OFDM	35
6	12 Mbits/s OFDM	28
5	18 Mbits/s OFDM	23
4	24 Mbits/s OFDM	18
3	36 Mbits/s OFDM	15
2	48 Mbits/s OFDM	11
1	54 Mbits/s OFDM	< 10

where both mobile devices walk on the opposite direction. With this in mind, one might be tempted to try to preserve cluster formation for several T_{cluster}, thus reducing overhead from contention phase.

The problems emerged from this scenario is how long should a cluster remains the same. In a homogenous mobility environment, the calculation might be quite straightforward. But in a heterogenous mobility environment, the calculation can be quite tricky. Furthermore, there is a problem on how to inform cluster members if the cluster formation changes (e.g. ones link changes to lower data rate) during T_{cluster}.

In the case of cluster formation is preserved during several T_{cluster} which later called *Cluster Period*, cluster members must send feedbacks containing their link information to cluster head as an update after every T_{cluster}. The feedback can be done in a TDMA fashion with the sequence generated in the contention phase. With this feedback, the cluster head knows if the cluster will remain the same for the next T_{cluster} or a new cluster should be formed.

4.4 Conclusion

This chapter has elaborated the proposed scheme which consists of three phases, namely Setup phase, Pilot tone, and Steady state phase. Setup phase is the phase where cluster members select cluster head and content for steady state TDMA sequence. Pilot tone is the phase where cluster head broadcast sequence information as the result of contention phase to all of its members. This information is used in steady state phase, the phase where mobile devices exchanging data. Further developments on the scheme has also been discussed, covering mobility model and preservation of cluster formation. A heterogenous mobility is introduced to the system to further understand the system performance. Cluster formation preservation is introduced as a way to optimize proposed scheme.

Chapter 5

Result and Analysis

This chapter presents the performance results and the analysis of the proposed scheme in a cooperative WLAN by implementing different simulation parameters.

5.1 Simulation Parameter

In the following sections, the proposed scheme is going to be simulated under different parameters. This section gives basic simulation parameters. Later on, the number of mobile devices, max-range, strategies, and cluster period is going to be varied.

The number of mobile devices is the number of mobile devices in a WLAN cell assigned to a single AP. The max-range is the maximum range at which the mobile devices perform cooperation, as shown in Table 4.2. Pure strategy means that every mobile device in the cell is assigned with the same strategy, be it a wise or selfish strategy. Mixed strategy indicates different strategies are assigned for mobile devices in a cell. It means that several mobile devices are assigned to wise strategy while others are assigned to selfish strategy. The definition of T_{cluster} is already given in section 4.1.4.

The number of mobile devices is chosen to be 20 mobile devices to describe average number of mobile devices in a WLAN cell with mobile devices are assigned pure wise strategy. The max-range is chosen to be 4 unit distance as a medium range. The number of packet (Σ_{packet}) is 25 packets thus gives T_{cluster} to be 35.766ms according to Equation 4.1. These values are summarized in Table 5.1 which are the values of simulation parameters for the entire simulation otherwise if it is stated different.

Table 5.1: Simulation parameters

Simulation Parameter	**Value**
Number of mobile devices	20
Max-range	4
Strategy	Wise
T_{cluster}	35.766ms
Σ_{packet}	25 packets

5.2 Impact of Varying Number of Mobile Devices

The system performance under different number of mobile devices is depicted in Table 5.2. It can be seen that as the number of mobile devices increases, the energy consumption reduces, or energy saving increases. Energy consumption depicted here is the average normalized energy consumption. This is because there are more mobile devices involve in a cluster, thus reducing energy consumption by Equation 3.1.

It also can be seen that the decrease of energy consumption is not linear. The energy consumption decreases 5.75 %, 4.8 %, 3.6 %, and 2.6 % for the increase of mobile devices from 10 to 20, 20 to 30, 30 to 40, and 40 to 50 respectively. The overhead in the proposed scheme increases as the number of mobile devices increases. The contention phase creates larger overhead as the number of mobile devices increases due to the deployed CSMA/CA protocol.

Table 5.2: Average power consumption under varying number of mobile devices

10 Mobile devices	**20 Mobile devices**	**30 Mobile devices**	**40 Mobile devices**	**50 Mobile devices**
0.9108	0.8533	0.8053	0.7686	0.7419

5.3 Impact of Varying Max Range in a Cluster

The system performance under different maximum range in a cluster is depicted in Table 5.3. It can be seen that shortening maximum range reduces energy consumption as it increases data rate difference between cellular and short range (Z) which results in a more portion of idle time in short range link. Another reason is that in high maximum range, more mobile devices involved in a cluster, thus increasing the overhead in contention phase and increasing the energy consumption.

Table 5.3: Average power consumption under varying maximum range in a cluster

Max-Range = 4	**Max-Range = 6**	**Max-Range = 7**
0.8533	0.8588	0.8712

Involving more mobile devices in a cluster increases overall system performance in an ideal system. However, in the proposed scheme, the overhead caused by contention phase also increases. This introduce a trade off, how much a mobile device should cooperate. Another question may also arise whether being a wise mobile device and always cooperate can actually result in higher overall system performance and higher individual performance or being a selfish mobile device is actually more beneficial.

5.4 Impact of Varying Cooperation Strategy

The system performance for varying strategies is depicted in Table 5.4. In this simulation, the number of mobile devices is assigned to be 50 mobile devices to asses the system performance under a high number of mobile devices. The result shows that the average normalized energy consumption per mobile device for wise strategy is better than selfish strategy.

Table 5.4: Average power consumption under varying cooperation strategy

Pure Wise (50 Mobile devices)	**Pure Selfish (50 Mobile devices)**	**Mixed (25 Wise and 25 Selfish Mobile devices**
0.7419	0.7517	0.7654 (wise) 0.7509 (selfish)

To investigate individual benefit of these strategies, information on data rate histogram and cluster size histogram is needed which are depicted in Figure 5.1 and Figure 5.2 respectively.

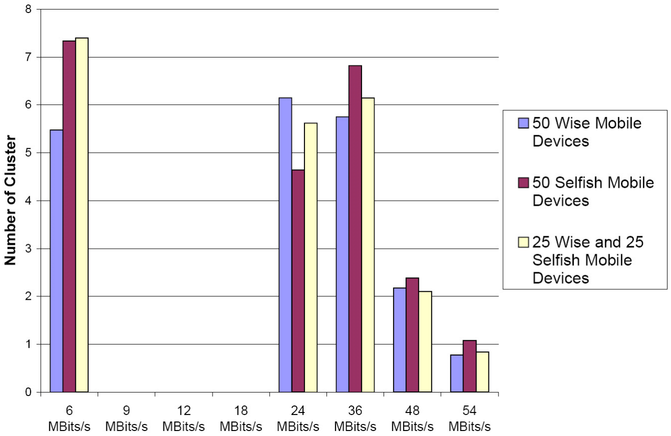

Figure 5.1: Data rate histogram

The selfish mobile devices tend to form a cluster with small number of mobile devices, while the wise mobile devices are more likely to form a

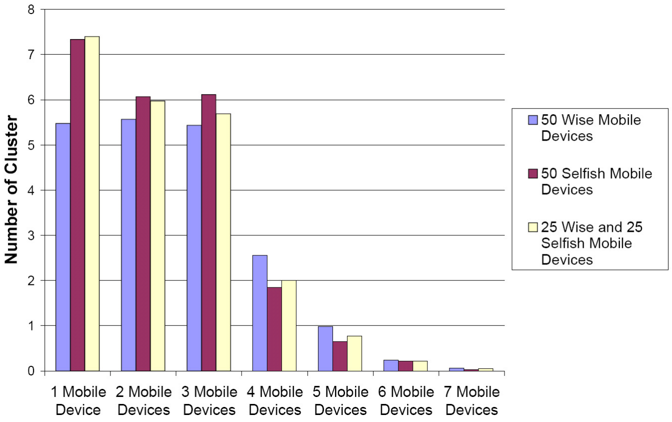

Figure 5.2: Cluster size histogram

cluster with larger number of mobile devices, giving more opportunities to the mobile devices to achieve more energy saving. Another interesting result is that the number of cluster which has one member (i.e non-cooperating mobile devices) for the selfish mobile devices are higher than the wise mobile devices. This shows that the wise mobile devices are more likely to form a cluster rather than isolated.

The histogram also shows the number of cluster versus data rate. The wise mobile devices tend to form a cluster with slower data rate compare to the selfish mobile devices. This is because of the behavior of the wise mobile devices to sacrifice their best solution to achieve a better group energy saving gain.

Based on the two histograms (number of cluster versus number of mobile devices and data rate), it is likely that a cluster with large number of mobile devices tends to have lower data rate. However, this kind of cluster is unlikely to happen for the selfish mobile devices, since they prefer to form a cluster with small number of members which is likely to have a higher data rate.

However, Table 5.4 shows that if wise mobile devices and selfish mobile devices are placed in the same simulation, the average system energy saving, that is calculated for selfish mobile devices only, is better than wise mobile devices. In average, the selfish mobile devices achieve better energy saving because they "exploit" the wise mobile devices by cooperating with wise mobile devices if the energy saving is better for them, and refuse to cooperate if worsen. On the other hand, the wise mobile devices are willing to sacrifice their best solution to get better energy saving in term of cluster or group energy saving.

5.5 Impact of Varying Mobility Distribution

In this section, mobile device's mobility distribution is defined in three cases which are elaborated as :

Case 1 consists of 15 mobile devices with low mobility, 2 mobile devices with medium mobility and 3 mobile devices with high mobility.

Case 2 consists of 3 mobile devices with low mobility, 2 mobile devices with medium mobility and 15 mobile devices with high mobility.

Case 3 consists of 7 mobile devices with low mobility, 6 mobile devices with medium mobility and 7 mobile devices with high mobility.

The system performance is depicted in Figure 5.3 while its power histogram is depicted in Figure 5.4. The system max-range in this case is assigned to be 6. The figures show that different mobility distribution does not effect system performance significantly. The system performs similarly after it reaches its stability. However, it should be noted that the system undergone a high fluctuation in the beginning of simulation. This indicates that in a heterogeneous mobility environment, the system performs differently in a short period of time. The power histogram also shows that each mobile device spends almost similar power regardless its mobility and its mobility case. This is because the simulation is done for a high iteration number, thus a good average over space is achieved.

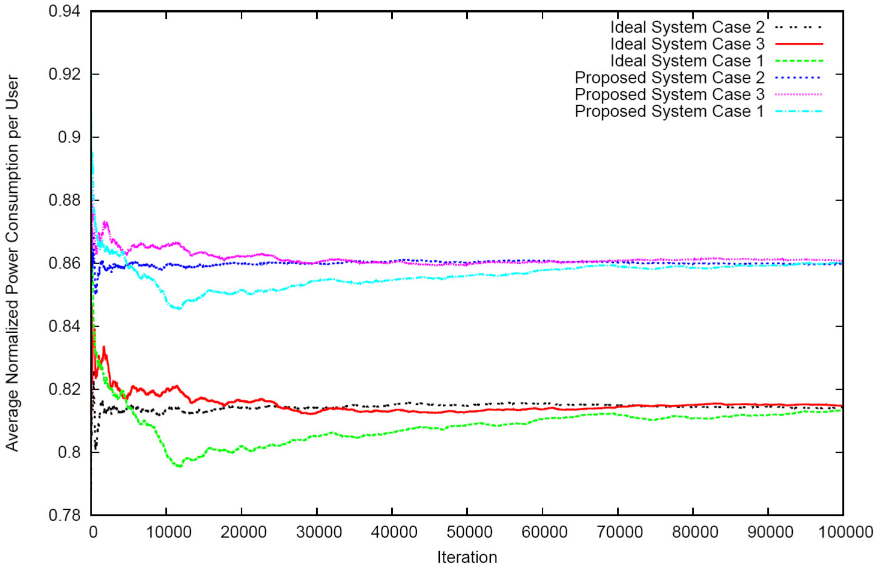

Figure 5.3: Comparison of system performance under different mobility distribution with 20 mobile devices in pure wise strategy

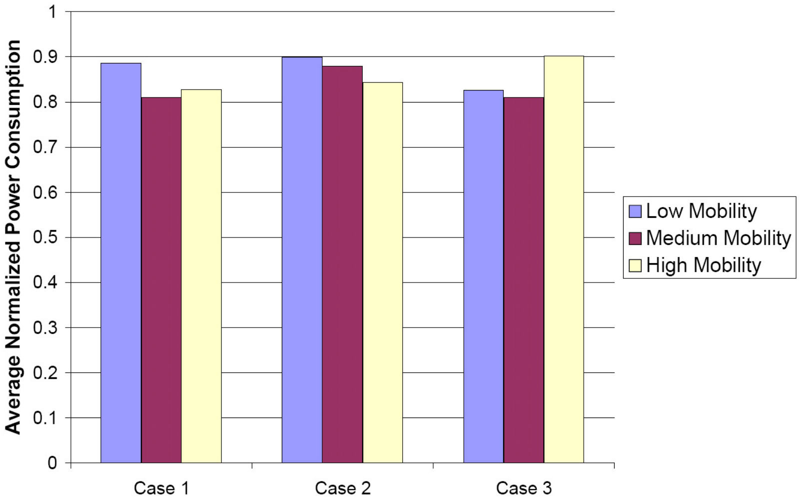

Figure 5.4: Power histogram for 20 mobile devices with different mobility

5.6 Impact of Varying Cluster Period

Table 5.5 shows the normalized energy consumption under different cluster period. The assumption is that all mobile devices are moving with maximum speed of 3 km/h or 1 m/s. From [1] it can be assumed that averagely, the data rate will change if the distance changes around every 2 to 3 meters. The simulation is set to have different T_{cluster} varies from 35.76, 107.3, and 178.83 ms.

Table 5.5: Average power consumption under varying T_{cluster}

$T_{\textbf{cluster}} = 35.76$ **ms**	$T_{\textbf{cluster}} = 107.3$ **ms**	$T_{\textbf{cluster}} = 178.83$ **ms**
0.8533	0.8253	0.8229

However, as the T_{cluster} is set to 107.3 and 178.83 ms, the average normalized energy consumption is similar. This due to the fact that the simulation is run over a long T_{cluster}, thus the overhead energy consumption (i.e overhead from contention period for selecting the cluster head and the pilot tone) are small compare to the data exchange period or steady state phase.

Table 5.5 shows that if T_{cluster} period is longer, than the average normalized energy consumption will decrease. It should be noticed that the T_{cluster} period closely related to the mobility characteristic of the mobile devices. If the mobile devices is most likely to have high mobility (i.e faster speed) then it might happen that during the T_{cluster} period, the data rate is changing and the energy consumption might change. In this case, one should wonder if it is still beneficial to maintain the current cluster or to form a new cluster. Moreover, there should be an extra overhead in the protocol to check periodically the link condition, whether the data rate changes, as it might change the decision to cooperate.

5.7 Cooperation in GPRS/WLAN Environment

General Packet Radio Service (GPRS) is the most common technique for data transfer in cellular network. In the last section of this chapter, the payoff and the benefit of cooperation in GPRS/WLAN environment are also being investigated. This environment employs GPRS as its cellular link instead of WLAN in previous cases. The simulation evaluates the proposed scheme in two different number of GPRS time slots dedicated for broadcast downlink namely 5, and 7 time slots, corresponding to 42.25 Kbits/s, and 63.35 Kbits/s of data rate respectively. The system uses coding scheme one with the consideration that the downlink is broadcast and have to accommodate all mobile devices, i.e. the most robust coding scheme is used.

As explained before, it is assumed that all mobile devices are moving with the velocity of 1 m/s and the data rate will change to the lower or higher rate if the distance increase or decrease around 3 meter. Thus, T_{cluster} is chosen to be around 2.03 seconds which is assumed to be the longest period at which the data rate remains the same. The number of packet depends on the number of GPRS time slots that are allocated as mentioned above. The receiving power is set to be 2.3 watt and idle power is assumed to be 0.04 [5].

With these information, a new power consumption matrix is calculated and shown in Table 5.6. The table is calculated for 7 dedicated time slots in GPRS downlink, which corresponds to 63.35 KBits/s. The values in this table are calculated based on Equation 3.1 and normalized with non-cooperative power consumption (i.e. receiving and idle power in a GPRS/WLAN mobile device equals to 2.34 watt). Some values are shown to be the same because of the rounding made for this table. However values with higher precision are used in the simulation.

The results depicted in Table 5.7 show that GPRS/WLAN cooperation give a very good energy saving gain, which is around 56.31 %, and 55.88 %

Table 5.6: Normalized power consumption table for cooperative energy saving in GPRS/WLAN environment with 7 GPRS time slots

Z	**Number of mobile devices**								
	2	3	4	5	6	7	8	9	10
852 (54 Mbps)	0.517	0.356	0.276	0.227	0.195	0.172	0.155	0.141	0.131
757 (48 Mbps)	0.517	0.356	0.276	0.227	0.195	0.172	0.155	0.142	0.131
568 (36 Mbps)	0.518	0.357	0.276	0.228	0.195	0.172	0.155	0.142	0.131
378 (24 Mbps)	0.518	0.357	0.276	0.228	0.196	0.173	0.156	0.142	0.131
284 (18 Mbps)	0.519	0.357	0.277	0.228	0.196	0.173	0.156	0.142	0.132
189 (12 Mbps)	0.520	0.358	0.278	0.229	0.197	0.174	0.157	0.143	0.132
142 (9 Mbps)	0.521	0.359	0.279	0.230	0.198	0.175	0.157	0.144	0.133
94 (6 Mbps)	0.523	0.361	0.280	0.232	0.199	0.176	0.159	0.145	0.135

Table 5.7: Average power consumption in GPRS/WLAN environment for 50 mobile devices

System	**5 Time slots**	**7 Time slots**
Ideal System	0.4233	0.4285
Proposed Scheme System	0.4369	0.4412

for 5, and 7 time slots respectively in the ideal system. The energy saving gain for the proposed scheme system also give a very similar to the ideal system. The energy saving reduces from 7 to 5 time slots because the system uses the same T_{cluster} that corresponds to more packets in 7 time slots, due to the higher datarate, thus more energy is needed to transfer more data.

It should be noted that the energy saving gains for different GPRS time slots are quite similar. This is due the fact that the difference of the data rate for 5, 7 time slots are not high compare with the difference with the short range data rate.

It also should be noted that the performance of the ideal system and the proposed scheme system also quite similar. This is because that the portion of idle periods is large. For example, if the GPRS time slots is set to be 7, then in around 2.03 seconds the data in the buffer for every mobile device after T_{cluster} is $1.286.005$ bytes. If the short link data rate in the cluster is 24 Mbits/s, then each mobile device needs only 0.054 seconds to send the data to the other members of the cluster. The rest of the time until the next T_{cluster} (which is 2.03 seconds) can be used by every mobile device in its idle state.

The high energy saving gain is achieved because of the great difference of the data rate between GPRS and WLAN, thus the mobile devices can be in idle mode longer while waiting the data stream from the Base Station (BS) to be exchanged among members of their cluster. In this case the energy saving gain of cooperation is more beneficial.

Chapter 6

Conclusion and Future Developments

6.1 Conclusion

In this thesis, the potential of energy saving for a new communication architecture based on cooperation among mobile devices operating within a cellular communication system has been investigated.

This thesis has investigated the performance of cooperative system in ideal case and compare it with the cooperative system performance using IEEE 802.11 or WLAN. The comparison shows that cooperation using omnipresent technology does not perform as well as it is expected. The existing MAC layer protocol worsen the performance because it is not designed for this particular scenario. A new and improved scheme is needed for the scenario, and yet it should also be easy to develop on top of existing system. This issue is addressed by a energy saving scheme that is proposed in this work.

The proposed scheme is then simulated and compared with ideal condition (where no collision occurs) and IEEE 802.11. The result shows that the proposed scheme gives significant improvement from 802.11. In the subsequent investigations, it is also found that the system works better under higher number of users and higher cluster period. The later even approaches proposed scheme's performance closer to ideal case. The simulation also proves that the average system energy saving for a pure environment of wise strategy is better than selfish strategy. However, if wise mobile devices and selfish mobile devices are placed in the same simulation, the average system energy saving for selfish mobile devices is better than wise mobile devices as a result of the selfish mobile devices exploit the wise mobile devices.

Subsequent investigations also show that smaller cluster size, indicates higher short range data rate, also contributes to better system performance. The influence of significant difference between cluster and short range data rate is also illustrated by the last investigation in GPRS/WLAN environment. In this case, proposed system performs closely to ideal system. This case also shows a very high benefit of cooperation.

6.2 Future Developments

The work so far only discussed on cluster members joining and leaving cluster at the beginning and the end of cluster period. The procedure for members joining and leaving a cluster during cluster period which may results in more energy consumption is not yet considered. On the other hand, hardware overhead can also cause higher energy consumption. Changing power state may not be as ideal as it is in this work.

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