ENERGY AND DATA COOPERATION IN ENERGY HARVESTING MULTIPLE ACCESS CHANNELS

BERRAK SISMAN
B.S., Electronics Engineering, Computer Engineering, Işık University, 2015

Submitted to the Graduate School of Science and Engineering
in partial fulfillment of the requirements for the degree of
Master of Science
in
Electronics Engineering

IŞIK UNIVERSITY
2016

IŞIK UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

ENERGY AND DATA COOPERATION IN ENERGY HARVESTING MULTIPLE ACCESS CHANNELS

BERRAK SISMAN

APPROVED BY:

Assoc. Prof. Mengüç Öner	Işık University	____________________
Assist. Prof. Ayşegül Tüysüz ERMAN	Işık University	____________________
Assoc. Prof. Onur Kaya (Thesis Supervisor)	Işık University	____________________

APPROVAL DATE: ..../..../....

ENERGY AND DATA COOPERATION IN ENERGY HARVESTING MULTIPLE ACCESS CHANNELS

Abstract

A typical wireless device is limited by its finite battery, and energy limitation is as a critical bottleneck on wireless network performance. In addition to the EM radiation caused by high power wireless devices, the batteries used in those devices need to be recharged frequently, causing fast depletion of earth's resources; and are discarded after a while, causing environmental pollution. Moreover, in some scenarios, such as sensor networks deployed in rural areas, it is simply not feasible to replace the batteries of the wireless nodes, hence using nodes which can replenish their energy is of paramount importance in prolonging the network lifetime. As a result, the concept of green communication and the idea of designing communication protocols based on energy harvesting constraints of individual nodes have recently received tremendous attention. With this motivation in mind, this thesis is devoted to designing cooperation and transmit scheduling techniques for networks powered soleley by harvested energy.

We study energy cooperation in a two user multiple access channel and a two user cooperative multiple access channel with and without battery limitations. We characterize, and optimize the departure region for a two user multiple access channel, under six different models, with varying levels of cooperation and energy storage capabilities. We aim to find the optimum energy management policies of the transmitters to maximize the achievable departure region over a finite transmission duration.

ENERJİ HASADI YAPAN ÇOKLU ERİŞİM KANALINDA VERİ VE ENERJİ PAYLAŞIMI

Özet

Tipik bir kablosuz cihaz halen pilinin kapasitesi ile limitlidir, ve enerji kısıtlılığı kablosuz ağ performansı üzerinde kritik bir dar boğaz teşkil eder. Yüksek güç kullanan kablosuz cihazların sebep olduğu elektromanyetik radyasyonun yanında, bu cihazların sıklıkla şarj edilmesi ya da değişmesi gereken bataryaları, hem yeryüzü kaynaklarının hızla tükenmesine, hem de atıldıklarında çevrenin kirlenmesine sebep olmaktadır. Dahası, kırsal alanlarda faaliyet gösteren duyarga ağları gibi senaryolarda, duyarga düğümlerinin pillerinin değişmesi makul değildir, bu nedenle kendi enerjilerini doğadan temin edebilen düğümlerin kullanılması, ağ ömrünün uzaması için kilit rol oynamaktadır. Bunların sonucunda, yeşil haberleşme kavramı, takiben de haberleşme protokollerinin düğümlerin enerji hasadı kısıtlarını gözetecek şekilde yeniden tasarlanması fikri ortaya çıkmış, ve hızla ilgi görmüştür. Son yıllarda, noktadan noktaya, tümegönderim, çoklu erişim, aktarım, karışım kanal modelleri enerji hasadı çerçevesinde baştan ele alınmıştır.

Bu projede enerji hasat eden bir çoklu erişim kanalı (genellenmiş geribeslemeli çoklu erişim kanalı) modeli ele alınmıştır. Çoklu erişim kanalını altı farklı model altında inceledik. Her bir sistem modeli için gönderim alanını optimize eden güç dağılımlarını bulduk.

Acknowledgements

Foremost, I would like to express my sincere gratitude to my advisor Dr. Onur Kaya for his patience, motivation, enthusiasm, and immense knowledge. I am also thankful to him for reading my reports, commenting on my views and helping me understand and enrich my ideas. His guidance helped me in all the time of research and writing of this thesis.

Most importantly, this thesis would not have been possible without the love and patience of my family and Emir. Their support and care helped me overcome setbacks and stay focused.

At last, I am grateful to TÜBİTAK for supporting me through grant 113E556 during my graduate education.

To my family...

Table of Contents

List of Tables

List of Figures

List of Abbreviations

MAC	**M**ultiple **A**ccess **C**hannel
SNR	**S**ignal to **N**oise **R**atio
I.I.D.	**I**ndependent **I**dentically **D**istributed
KKT	**K**arush-**K**uhn-**T**ucker
AWGN	**A**dditive **W**hite **G**aussian **N**oise

Chapter 1

Introduction

The batteries used in wireless devices need to be recharged frequently, causing fast depletion of Earth's resources and environmental pollution. Also in some rural areas, it is simply not feasible to replace the batteries of the wireless nodes. As a result, concept of green communication and the idea of designing communication protocols based on energy harvesting constraints of inividual nodes have received tramendous attention. This thesis is devoted to designing cooperation and transmit scheduling techniques for mutiple access channel (MAC) powered solely by harvested energy.

In an energy harvesting point to point Gaussian channel it was found that the capacity of the AWGN channel with such stochastic energy arrivals is equal to the capacity with an average power constraint equal to the average recharge rate [7]. Triggered by this, many classical information theoretic models were revisited, to optimize transmission strategies under energy harvesting constraints. In [8], transmission completion time minimization is solved for an infinite battery in energy harvesting network. Transmission with energy harvesting nodes in fading wireless channels is considered in [14]. In [15] optimization of energy harvesting communication system with battery imperfections is considered. Communication over a broadband fading channel powered by an energy harvesting transmitter is studied in [16]. In [13], the problem of two-hop relaying in the presence of energy harvesting nodes is considered.

There has also been some recent work about cooperation in wireless channels. In [23], the authors show that, even though the interuser channel is noisy, cooperation leads not only to an increase in capacity for both users but also to a more robust system, where users achievable rates are less susceptible to channel variations. In [5], a cooperative MAC model with energy harvesting transmitters is considered and indicated significant gains over no cooperation and one-sided cooperation.

As far as cooperation in energy harvesting is concerned, energy cooperation is a more recent topic which involves wireless transfer of energy. In [25], wireless power transfer via strongly coupled magnetic resonances was studied. Using self-resonant coils in a strongly coupled regime, efficient non radiative power transfer over distances up to 8 times the radius of the coils was demostrated experimentally . Energy transfer among energy harvesting wireless nodes was first studied in [21] for a two-hop network with a full duplex infinite-buffer relay capable of uni-directional energy transfer from the source node to the relay node. Transferring energy and information jointly has also been studied in [24] for an inductively coupled model and in [22] for a binary energy exchange model. Communication sytems with energy exchange are investigated in [29] and [34]. The optimal transmit power and bi-directional energy transfer allocations that achieve the sum-capacity of the system in the multiple access channel (MAC) and the two-way channel (TWC) were found in [10]. It is observed that in the multiple access channel, a node either transfers no energy, or transfers all of its energy to a single user to achieve sum-capacity. For the two-way channel, the optimal policy is found to have a directional water-filling interpretation with two non-mixing fluids whenever optimal energy transfer is non-zero [10]. Gaussian two-way and two-user multiple access channels with uni-directional energy cooperation was studied in [19] proposing a two dimensional directional water-filling algorithm with meters to obtain the weighted sum-rate maximizing policy. Reference [10] proved that to obtain the jointly optimal transmission and energy transfer policy that maximizes the sum-rate, it is sufficient to find the energy transfer policy for each time slot and the consumed power allocation policy across the time slots. This is established by restricting the feasible policy set to procrastinating power policies, which are shown to include at least one optimal power policy. Several basic multi-user network structures such as relay channel, two way channel and multiple access channel with energy harvesting and uni directional wireless energy transfer capabilities are further considered in [10]. In [20], a two-way communication channel is investigated where users can harvest energy from nature and energy can be transferred in one-way from one of the users to the other. It is found that the optimal solution equalizes the energy levels as much as possible both among users and among slots, permitted by causality constraints of the energy arrivals and one-way energy transfer. In [11], an energy harvesting diamond channel is considered. It is found that if the source sends more energy to relay, then it sends less data, showing how data and energy should flow together optimally.

In the energy harvesting framework, there is also a line of work which considers more practical constraints such as finite battery capacity at the transmitting nodes. In [26], the problem of determining the capacity of an energy-harvesting transmitter with finite battery communicating over a discrete memoryless channel is considered. The minimization of the transmission completion time with a battery limited energy harvesting transmitter in a two-user AWGN broadcast channel is considered in [28]. In [39], the problem of maximizing the transferred data in an energy harvesting node under a deadline constraint, i.e. the short-term throughput is considered and it was found that employing optimum power allocation is beneficial for transmitters with limited battery capacity.

Due to the major need for efficient use of energy resources, our aim is to combine energy and data cooperation in energy harvesting wireless networks. In this thesis, we characterize and optimize the departure region of MAC model with energy harvesting tranmitters for six different models; MAC with battery limited transmitters, energy cooperation in MAC with battery limited transmitters, energy cooperation in MAC without battery constraints, data cooperation in MAC with battery limited transmitters, data and energy cooperation in MAC, data and energy cooperation in MAC with battery limited transmitters.

We develop optimal transmit scheduling, data and energy cooperation policies that maximize the departed number of bits by the users, by a deadline. We demonstrate that the joint usage of data and energy cooperation leads to significant rate gains for the multiple access channel.

Chapter 2

Background Theory

2.1 Gaussian Channel Capacity

Gaussian channel is the basis of modern communication and information theory introduced by Shannon. Gaussian channel can be modelled as a discrete time, continuous alphabet channel with independent identically distributed (i.i.d.) additive white noise at output where X_i and Y_i are the input and output signals, respectively and Z_i is the additive noise, [9], Chapter 5:

$$Y_i = X_i + Z_i \quad \text{where} \quad Z \sim \mathcal{N}(0, N). \tag{2.1}$$

The limit on mutual information between input and output is the information capacity of the Gaussian channel. The information capacity for a Gaussian channel with power constraint is defined as

$$C \triangleq \max_{E[X^2] \leq P} I(X;Y) \tag{2.2}$$

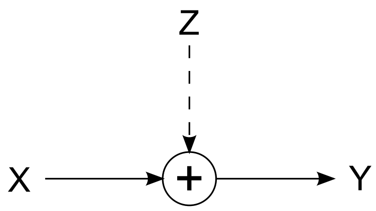

Figure 2.1: Gaussian channel model

where P is the power constraint and and $E[X^2]$ is average energy of input signal X. We can calculate the information capacity by expanding mutual information between X and Y,

$$I(X;Y) = h(Y) - h(Y|X) \tag{2.3}$$
$$= h(Y) - h(X+Z|X) \tag{2.4}$$
$$= h(Y) - h(Z|X) \tag{2.5}$$
$$= h(Y) - h(Z) \tag{2.6}$$

since Z is independent of X. Since $h(Z) = \frac{1}{2}\log 2\pi e N$ is known, we can calculate

$$E[Y^2] = E[(X+Z)^2] = E[X^2] + 2E[X]E[Z] + E[Z^2] = P + N. \tag{2.7}$$

By using this equality in equation (2.6), we get

$$I(X;Y) = h(Y) - h(Z) \tag{2.8}$$
$$\leq \frac{1}{2}\log\Big(2\pi e(P+N)\Big) - \frac{1}{2}\log(2\pi e N) \tag{2.9}$$
$$= \frac{1}{2}\log\Big(1+\frac{P}{N}\Big) \tag{2.10}$$

Therefore, the capacity is found as

$$C \triangleq \max_{E[X^2]\leq P} I(X;Y) = \frac{1}{2}\log\Big(1+\frac{P}{N}\Big) \tag{2.11}$$

since the maximum is achieved when $X \sim \mathcal{N}(0,P)$. It was shown by Shannon, by an elegant achievability result and a converse, that this information capacity is in fact the maximum rate at which reliable communication can be carried out, namely, it is also the channel capacity.

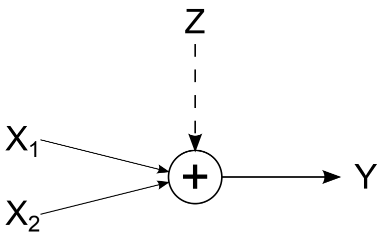

Figure 2.2: A simple two-user multiple access channel model.

2.2 Gaussian Multiple Access Channels

Multiple access channels (MAC) can be defined as channels, where more than one users transmit their own signals to be decoded by one receiver [1], [2]. In the Gaussian version of MAC, the signals are superposed at the receiver, in the presense of Gaussian noise. The receiver can decode the signals jointly, or sequentially, depending on the decoding technique being used. For a multiple access channel with two users transmitting to a common receiver, the received signal at time instant i is

$$Y_i = X_{1i} + X_{2i} + Z_i \tag{2.12}$$

where Z_i is defined as:

$$Z \sim \mathcal{N}(0, N). \tag{2.13}$$

All the users in the channel have power constraints,

$$E[X_1^2] \leq P_1 \tag{2.14}$$

$$E[X_2^2] \leq P_2. \tag{2.15}$$

The capacity regions of users in a MAC is the convex hull of rates satisfying the constraints,

$$R_1 \leq I(X_1; Y|X_2) \tag{2.16}$$

$$R_2 \leq I(X_2; Y|X_1) \tag{2.17}$$

$$R_1 + R_2 \leq I(X_1, X_2; Y) \tag{2.18}$$

In the Gaussian case, selecting the inputs from Gaussian distributions, i.e., $X_i \sim \mathcal{N}(0, P_i),\ i \in \{1, 2\}$ is optimal.

The derivation of the capacity region is a straightforward extension to equations (2.8)-(2.10), see [9]:

$$I(X_1; Y|X_2) = h(Y) - h(Y|X_1, X_2) \tag{2.19}$$
$$= h(X_1 + X_2 + Z|X_2) - h(X_1 + X_2 + Z|X_1, X_2) \tag{2.20}$$
$$= h(X_1 + Z|X_2) - h(Z|X_1, X_2) \tag{2.21}$$
$$= h(X_1 + Z|X_2) - h(Z) \tag{2.22}$$
$$= h(X_1 + Z) - h(Z) \tag{2.23}$$
$$= h(X_1 + Z) - \frac{1}{2}\log(2\pi e N) \tag{2.24}$$
$$= \frac{1}{2}\log\Big(2\pi e(P_1 + N)\Big) - \frac{1}{2}\log(2\pi e N) \tag{2.25}$$
$$\leq \frac{1}{2}\log(1 + \frac{P_1}{N}) \tag{2.26}$$

similarly;

$$R_2 = \frac{1}{2}\log(1 + \frac{P_2}{N}). \tag{2.27}$$

For sum rate constraint,

$$R_1 + R_2 \leq I(X_1, X_2; Y) \tag{2.28}$$
$$= h(Y) - h(Y|X_1, X_2) \tag{2.29}$$
$$= h(X_1 + X_2 + Z) - h(X_1 + X_2 + Z|X_1, X_2) \tag{2.30}$$
$$= h(X_1 + X_2 + Z) - h(Z|X_1, X_2) \tag{2.31}$$
$$= h(X_1 + X_2 + Z) - h(Z) \tag{2.32}$$
$$= \frac{1}{2}\log\Big(2\pi e(P_1 + P_2 + N)\Big) - \frac{1}{2}\log(2\pi e N) \tag{2.33}$$

$$\leq \frac{1}{2}\log(1+\frac{P_1+P_2}{N}) \tag{2.34}$$

can be found.

The encoding and decoding in the two user Gaussian MAC can be summarized as follows. User one and two generate codebooks of Gaussian random codewords and send transmit them in the channel simultaneously. Since the transmitters send codewords from their private codebook arbitrarily, the receiver starts to decode one user's signal treating other user's signal as noise.

$$R_1 \leq \frac{1}{2}\log(1+\frac{P_1}{P_2+N}) \tag{2.35}$$

After decoding the signal of user 1, the receiver subtracts first user's signal and decodes second users signal at the rate

$$R_2 \leq \frac{1}{2}\log(1+\frac{P_2}{N}) \tag{2.36}$$

If we generalize this channel to m users, the total rate will be

$$R_1 + R_2 + \ldots + R_m \leq \frac{1}{2}\log(1+\frac{mP}{N}), \tag{2.37}$$

therefore, as $m \to \infty$, the sum rate also goes infinity, yet individual rates on the average will be

$$R_i \leq \frac{1}{2m}\log(1+\frac{mP}{N}), \quad i \in \{1, 2, \ldots, m\}. \tag{2.38}$$

2.3 Data Cooperation in Multiple Access Channel

This thesis is based on the MAC model given in section 2.2 and cooperative MAC model given in this section. We extend these models to an energy harvesting framework. In reference [23], a method of transmit diversity for mobile users, user cooperation is presented. The results indicate that user cooperation is beneficial and can result in substantial gains over a noncooperative strategy. In a cooperative MAC, users over-hear each other's transmission, form common messages out of these over-heard signals by decoding, and beamform data to the receiver, achieving higher throughput for the system. The signals observed at the receiver (denoted as node 0), user 1 and user 2, respectively, are given by

$$Y_0 = X_1 + X_2 + N_0 \tag{2.39}$$

$$Y_1 = X_2 + N_1 \tag{2.40}$$

$$Y_2 = X_1 + N_2 \tag{2.41}$$

where X_{ki} is the transmitted codeword of user k and N_0, N_1,N_2 are the AWGN at the nodes. Let p_{kj} and p_{Uk} denote the powers associated with each codeword in slot i. For the multiple access channel with cooperating users, the achievable rate pair (R_1, R_2) can be written as follows:

$$R_1 < \frac{1}{2}\log(1 + p_{12}) \tag{2.42}$$

$$R_2 < \frac{1}{2}\log(1 + p_{21}) \tag{2.43}$$

$$R_1 + R_2 < \frac{1}{2}\log(\frac{\sigma_0^2 + p_1 + p_2 + 2\sqrt{p_{U1}p_{U2}}}{\sigma_0^2}) \tag{2.44}$$

All users in the channel have power constraints,

$$E[X_1^2] \leq P_1 \tag{2.45}$$

$$E[X_2^2] \leq P_2. \tag{2.46}$$

Using Lagrangian optimization method and KKT conditions, optimum power values can be easily solved.

2.4 Energy Harvesting AWGN Channel

In wireless networking applications nodes (e.g., sensors nodes) can harvest energy from nature through various different sources, such as solar cells, vibration absorption devices, water mills, thermoelectric generators, microbial fuel cells, etc. In such systems, energy that becomes available for data transmission can be modeled as an exogenous recharge process. Therefore, unlike traditional battery-powered systems, energy is not a deterministic quantity in these systems, but is a random process which varies stochastically in time.

Reference [7] considers a scalar AWGN channel characterized by the input X, output Y, additive nose N with unit normal distribution $\mathcal{N}(0,1)$). E_1,...E_n is the time sequence of supplied energy in n channel uses. E_i is an i.i.d sequence with average value P. The battery is initially empty and energy needed for communication of a message is obtained from the arriving energy prior to the transmission of the corresponding codeword, subject to causality. The cumulative power constraints on the channel inputs are given by,

$$\sum_{i=1}^{k} X_i^2 \leq \sum_{i=1}^{k} E_i \tag{2.47}$$

for k=1,2,....,n.

Let $\sum_{i=1}^{n} E_i = nP$. Then, the the channel capacity under the energy constraint (2.47) is bounded by the following equation given below.

$$C \leq \frac{1}{2}\log(1+P) \tag{2.48}$$

It was shown in [7] that the upper bound in (2.48) can be achieved even if the channel inputs are constrained by the random i.i.d energy arrival sequence, and the capacity of a point to point energy harvesting Gaussian channel with an infinite size battery is equal to the classical AWGN capacity with average power constraint P

$$C = \frac{1}{2} \log(1 + P) \tag{2.49}$$

Reference [7] established the capacity of the AWGN channel under stochastic energy harvesting where an unlimited sized battery buffers communication energy between an uncontrolled recharge process and the transmitter. Two different achievability schemes that achieve the capacity given (2.49) are proposed namely, save-and-transmit and best effort transmit.

In reference [5], after using the causality constraints and rate expressions, the departure region maximization problem is written and the optimum transmit and cooperation scheduling problem for an energy harvesting cooperative MAC is solved. It is found that the diversity created by different energy arrivals at the users can be taken advantage of using cooperation, and may translate to significant rate gains, in both mutual cooperation and relaying.

In this thesis, we extend this energy harvesting data cooperative multiple access channel model to an energy coperation framework.

2.5 Lagrange multipliers and Karush-Kuhn-Tucker conditions

In this thesis, we use Lagrange multipliers and Karush-Kuhn-Tucker (KKT) conditions while finding the optimum power management policies. The method of Lagrange multipliers (named after Joseph Louis Lagrange) is a strategy for finding the local maxima and minima of a function subject to equality constraints. KKT conditions are used in convex optimization with mixed constraints. They ensure optimality provided that some regularity conditions are satisfied.

The standart form of a convex optimization problem is given by [32], in Chapter 5.

$$\min f_0(x) \tag{2.50}$$

$$\text{s.t.} \quad f_i(x) \leq 0 \tag{2.51}$$

$$i = 1, ..., m \tag{2.52}$$

$$Ax = b \tag{2.53}$$

f_0, f_1, f_2,..., f_m, are convex; equality constraints are affine. Problem is quasiconvex if f_0 is quasiconvex. It is important to know that feasible set of a convex optimization problem is convex.

Lagrange Theorem can also be generalized to deal with problems having both equality and inequality constraints. The standart form is given below.

$$\min L(x) \tag{2.54}$$

$$\text{s.t.} \quad f(x) \leq 0 \tag{2.55}$$

$$g(x) = 0 \tag{2.56}$$

and x_0 is the optimal value to be found. In that case, the constraint is active if

$$\left.\frac{\partial L}{\partial x}\right|_{x_0} = 0, \tag{2.57}$$

or the constraint is inactive for all admissible values of x when

$$\left.\frac{\partial L}{\partial x}\right|_{x \in S} = 0 \tag{2.58}$$

where S is the set of all admissible values of x. Firstly, we can write the Lagrangian as

$$\mathcal{L}(x, \lambda, \gamma) = L(x) + \lambda f(x) + \gamma g(x) \tag{2.59}$$

where λ and γ are the Lagrange multipliers. Solution characterized by Karush-Kuhn-tucker conditions. The sufficient and necessary condition for a point x_0 to be an optimal solution is the existence of λ and γ such that

$$\frac{\mathcal{L}(x,\lambda,\gamma)}{\partial x} = 0, \text{ for } \lambda \geq 0 \text{ and } \gamma \geq 0 \tag{2.60}$$

which is equivalent to

$$\frac{\partial L}{\partial x} + \lambda \frac{\partial f}{\partial x} + \gamma \frac{\partial g}{\partial x} = 0 \tag{2.61}$$

$$\lambda f(x_0) = 0 \tag{2.62}$$

$$f(x_0) \leq 0 \tag{2.63}$$

$$\lambda \geq 0 \tag{2.64}$$

$$\gamma \geq 0 \tag{2.65}$$

These conditions are called the KKT conditions for optimality.

2.6 Wireless Energy Transfer

In the early 20th century, before the electrical wire grid, Nikola Tesla devoted much effort toward schemes to transport power wirelessly. However, typical embodiments (e.g., Tesla coils) involved undesirably large electric fields. A recent paper, reference [29] presented a detailed analysis of the feasibility of using resonant objects coupled through the tails of their nonradiative fields for midrange energy transfer. Intuitively, two resonant objects of the same resonant frequency tend to exchange energy efficiently, while dissipating relatively little energy in extraneous offresonant objects.

According to reference [25], in systems of coupled resonances (e.g., acoustic, electromagnetic, magnetic, nuclear), there is often a general strongly coupled regime of operation. If one can operate in that regime in a given system, the energy transfer is expected to be very efficient. Midrange power transfer implemented in this way can be nearly omnidirectional and efficient, irrespective of the geometry of the surrounding space, with low interference and losses into environmental objects . The above considerations apply irrespective of the physical nature of the resonances. Magnetic resonances are particularly suitable for everyday applications because most of the common materials do not interact with magnetic fields, so interactions with environmental objects are suppressed even further.

In references [29] and [25], wireless energy transfer is considered and using self-resonant coils in a strongly coupled regime, it is experimentally demonstrated efficient nonradiative power transfer over distances up to 8 times the radius of the coils. 60 watts is transferred with $\frac{4}{10}$ efficiency over distances in excess of 2 meters. Motivated by these results, there have been several recent efforts to incorporate the possibility of wireless energy transfer into the energy harvesting setup for many channel models. In this thesis, we extend this line of work to multiple access channels.

Chapter 3

Multiple Access Channel with Energy Cooperation

In this chapter, we aim to find the optimum power management and energy transfer policies for the two user multiple access channel. We consider three scenarios: battery limited MAC with no energy cooperation, battery limited MAC with energy cooperation and MAC with energy cooperation as the battery capacity tends to infinity. We start with the battery limited MAC withn no energy cooperation, as even in this case the departure region is not known. Then we factor in the energy transfer, and develop an algorithm which results in the jointly optimum energy and power allocation policy.

3.1 Battery Limited MAC

3.1.1 System Model

We consider a MAC model with energy harvesting transmitters, the transmission model of which is given by (2.12). In this model, transmitters have limited battery. Each user has a data queue and an energy queue. We assume that the energy harvesting times and harvested energy amounts are known before transmission starts. Time slots assumed to be fixed length 1. We aim to find the optimum power management policy such that energy level in the battery never exceeds the battery capacity E_{max}. Let us denote the transmit power for the first and second user as p_{1i} and p_{2i}, respectively. Then, the transmission rate pair R_{1i}, R_{2i} must be within the capacity region defined by p_{1i} and p_{2i}. The capacity region for this two-user multiple access channel is

$$R_1 \leq f(p_{1i}) \tag{3.1}$$

$$R_2 \leq f(p_{1i}) \tag{3.2}$$

$$R_1 + R_2 \leq f(p_{1i}) \tag{3.3}$$

where $f(p) = \frac{1}{2}\log(1+p)$. The achievable set of total number of bits departed from both of the users, denoted as B_1 and B_2, is a pentagon defined as

$$B_1 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i})}{2} \tag{3.4}$$

$$B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{2i})}{2} \tag{3.5}$$

$$B_1 + B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i}+p_{2i})}{2} \tag{3.6}$$

There are two constraints on power management policy, due to energy arrivals during transmission and also due to finite battery storage capacity. Since energy that has not arrived yet cannot be used for data transmission, there is a causality constraint on the power management policy which can be stated as:

$$\sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell} p_{1i} \geq 0 \tag{3.7}$$

$$\sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell} p_{2i} \geq 0 \tag{3.8}$$

Also, due to the finite battery storage capacity, we need to make sure that energy level in the battery never exceeds E_{max}.

$$\left(\sum_{i=1}^{\ell-1} p_{1i} - \sum_{i=1}^{\ell} E_{1i} + E_{max}\right) \geq 0 \tag{3.9}$$

$$\left(\sum_{i=1}^{\ell-1} p_{2i} - \sum_{i=1}^{\ell} E_{2i} + E_{max}\right) \geq 0 \tag{3.10}$$

3.1.2 Departure Region Maximization

The optimization is subject to the causality constraints on the harvested energy, and the finite storage constraint on the battery. The energy causality constraints force the energy consumption to slow down not to exceed the harvested amount, while the no energy overflow constraints force energy consumption to speed up to open space in the battery for new energy arrivals. In problem formulation part, we will find the lower bound values of the powers that transmitter 1 and transmitter 2 should use in each epoch for protecting the system from energy overflow. Also, we will use Lagrangian optimization method, which results in a waterfilling algorithm and combine these techniques with the lower bound values of powers that are found from constraints (3.9) and (3.10) for finding the optimum power management policy of MAC. The departure region maximization problem can be formulated as:

$$\mathbf{P1} : \max \ \mu_1 B_1 + \mu_2 B_2$$

$$\text{s.t.} \ B_1 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i})}{2}, \tag{3.11}$$

$$B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{2i})}{2}, \tag{3.12}$$

$$B_1 + B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i}+p_{2i})}{2}, \tag{3.13}$$

$$\sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell} p_{1i} \geq 0, \tag{3.14}$$

$$\sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell} p_{2i} \geq 0, \tag{3.15}$$

$$\left(\sum_{i=1}^{\ell-1} p_{1i} - \sum_{i=1}^{\ell} E_{1i} + E_{max} \right) \geq 0, \tag{3.16}$$

$$\left(\sum_{i=1}^{\ell-1} p_{2i} - \sum_{i=1}^{\ell} E_{2i} + E_{max} \right) \geq 0 \tag{3.17}$$

The problem is a concave maximization problem with convex constraints. Substituting (3.11), (3.12) and (3.13) in the objective function, and assigning Lagrange multipliers λ_1, λ_2, λ_3 and λ_4 to the inequality constraints (3.14), (3.15), (3.16) and (3.17), it can be shown that the solution should satisfy the KKT conditions given below.

$$\sum_{\ell=i}^{N}(\lambda_{1\ell}-\lambda_{3\ell}) = \frac{\mu_1-\mu_2}{1+p_{1i}} + \frac{\mu_2}{2(1+p_{1i}+p_{2i})} \tag{3.18}$$

$$\sum_{\ell=i}^{N}(\lambda_{2\ell}-\lambda_{4\ell}) = \frac{\mu_{2i}}{2\,(1+p_{1i}+p_{2i})} \tag{3.19}$$

For each time slot, the lower bounds for p_1 and p_2 can be found by using no energy overflow constraints (3.9) and (3.10).

$$p_{1(\ell-1)} \geq \sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell-2} p_{1i} - E_{max} \tag{3.20}$$

$$p_{2(\ell-1)} \geq \sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell-2} p_{2i} - E_{max} \tag{3.21}$$

We now propose algorithm, to find the optimum powers of transmitter 1 and transmitter 2 for a battery limited MAC. This algorithm, which we call Algorithm 1, uses generalized iterative waterfilling where the water levels are given by the left hand sides of (3.18) and (3.18) respectively, in conjunction with (3.20) and (3.21) creates a restriction in the flow of energy from one time slot to another. This means that in every epoch powers of transmitter 1 and transmitter 2 can not be smaller than $p_{1\ell-1}$ and $p_{2\ell-1}$ respectively. A water equalization method which never falls below these limits and satisfies the KKT conditions given in (3.18) and (3.19), gives us the optimum power management policy of the battery limited multiple access channel. To demonstrate the effect of battery limitation and its importance in energy cooperation scenerio, we present our simulations in section 3.2.

Algorithm 1
Get $\mathbf{E_1}$, $\mathbf{E_2}$, σ_0
Initialization:
for $\ell = 1 : N$ **do**
  Set $E_{1\ell} = E_{max}$ if $E_{1\ell} > E_{max}$.
  Set $E_{2\ell} = E_{max}$ if $E_{2\ell} > E_{max}$
  Determine water levels $v_{1\ell}$ and $v_{2\ell}$ using KKT conditions (3.18) and (3.19).
end for
Body:
repeat
  By using constraint (3.16), find p_{1lower} for each time slot.
  By using constraint (3.17), find p_{2lower} for each time slot.
  for $\ell = 1 : N$ **do**
    Check power restrictions and equalize waterlevel values of transmitter 1 $v_{1\ell}$
  end for
  for $\ell = 1 : N$ **do**
    Check power restrictions and equalize waterlevel values of transmitter 2 $v_{2\ell}$
  end for
until no energy flow is necessary between time slots

3.2 MAC with Energy Cooperation, Limited Battery

3.2.1 System Model

In this section, we investigate the effect of possible energy cooperaton on the MAC departure region. The system model is identical to that of section 3.1, and the formulation of the departure region is identical to (3.4) - (3.6), once the transmit powers are fixed. However now the users are given a chance to share their energy queues, over a lossy energy transfer link. Therefore, the energy constraints will now be different, as the energy cooperation provides an additional degree of freedom. The system model is depicted in Figure (4.1). There is a separate unit that enables energy transfer from the first user to the second user and from second user to first user with an efficiency $0 < \alpha_{12}$,$\alpha_{21} < 1$. When the first transmitter transfers δ_{12} amount of energy to the second transmitter, δ_{12} amount of energy exits the first transmitter's energy queue and $\alpha_{12}\delta_{12}$ amount of energy enters the second transmitters energy queue in the same slot. Wireless energy transfer from

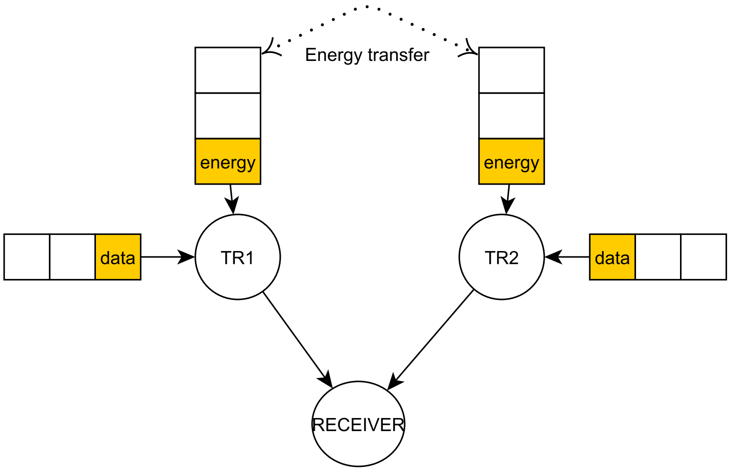

Figure 3.1: Battery limited MAC with energy and data cooperation

one user to other occurs right before the beginning of each time slot. There are two constraints on power management policy, due to energy arrivals at random times and also due to finite battery storage capacity. Since energy that has not arrived yet cannot be used for data transmission, there is a causality on the power management policy as:

$$\sum_{i=1}^{\ell} E_{1i} - p_{1i} - \delta_{12i} + \alpha_{21}\delta_{21i} \geq 0 \tag{3.22}$$

$$\sum_{i=1}^{\ell} E_{2i} - p_{2i} - \delta_{21i} + \alpha_{12}\delta_{12i} \geq 0 \tag{3.23}$$

Also, due to the finite battery storage capacity, we need to make sure that energy level in the battery never exceeds E_{max}.

$$\left(\sum_{i=1}^{\ell-1} p_{1i} - \sum_{i=1}^{\ell} E_{1i} - \delta_{12i} + \alpha_{21}\delta_{21i} + E_{max}\right) \geq 0 \tag{3.24}$$

$$\left(\sum_{i=1}^{\ell-1} p_{2i} - \sum_{i=1}^{\ell} E_{2i} - \delta_{21i} + \alpha_{12}\delta_{12i} + E_{max}\right) \geq 0 \tag{3.25}$$

3.2.2 Departure Region Maximization

For battery limited MAC with energy cooperation, the departure region maximization problem can be stated as

$$
\begin{aligned}
\mathbf{P1}: \max \ & \mu_1 B_1 + \mu_2 B_2 \\
\text{s.t. } & B_1 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i})}{2}, && (3.26)\\
& B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{2i})}{2}, && (3.27)\\
& B_1 + B_2 \leq \sum_{i=1}^{N} \frac{\log(1+p_{1i}+p_{2i})}{2}, && (3.28)\\
& \sum_{i=1}^{\ell} E_{1i} - \delta_{12i} + \alpha_{21}\delta_{21i} - \sum_{i=1}^{\ell} p_{1i} \geq 0, && (3.29)\\
& \sum_{i=1}^{\ell} E_{2i} - \delta_{21i} + \alpha_{12}\delta_{12i} - \sum_{i=1}^{\ell} p_{2i} \geq 0, && (3.30)\\
& \left(\sum_{i=1}^{\ell-1} p_{1i} - \sum_{i=1}^{\ell} E_{1i} - \delta_{12i} + \alpha_{21}\delta_{21i} + E_{max} \right) \geq 0, && (3.31)\\
& \left(\sum_{i=1}^{\ell-1} p_{2i} - \sum_{i=1}^{\ell} E_{2i} - \delta_{21i} + \alpha_{12}\delta_{12i} + E_{max} \right) \geq 0 && (3.32)
\end{aligned}
$$

KKT conditions are given below.

$$
\sum_{\ell=i}^{N} (\lambda_{1\ell} - \lambda_{3\ell}) = \frac{\mu_1 - \mu_2}{1+p_{1i}} + \frac{\mu_2}{2(1+p_{1i}+p_{2i})} \quad (3.33)
$$

$$
\sum_{\ell=i}^{N} (\lambda_{2\ell} - \lambda_{4\ell}) = \frac{\mu_{2i}}{2\,(1+p_{1i}+p_{2i})} \quad (3.34)
$$

$$
\sum_{\ell=i}^{N} (\lambda_{1\ell} - \lambda_{3\ell}) = \alpha_{12} \sum_{\ell=i}^{N} (\lambda_{2\ell} - \lambda_{4\ell}) + \xi_{5i} \quad (3.35)
$$

$$
\sum_{\ell=i}^{N} (\lambda_{2\ell} - \lambda_{4\ell}) = \alpha_{21} \sum_{\ell=i}^{N} (\lambda_{1\ell} - \lambda_{3\ell}) + \xi_{6i} \quad (3.36)
$$

The optimization is subject to the causality constraints on the harvested energy, and the finite storage constraint on the battery. Optimum power management algorithm for energy cooperation in battery limited MAC is given in Algorithm 2.

Algorithm 2
Get $\mathbf{E_1}$, $\mathbf{E_2}$, σ_0
Initialization:
for $\ell = 1 : N$ **do**
  Set $E_{1\ell} = E_{max}$ if $E_{1\ell} > E_{max}$.
  Set $E_{2\ell} = E_{max}$ if $E_{2\ell} > E_{max}$
  Determine water levels $v_{1\ell}$ and $v_{2\ell}$ using KKT conditions (3.18) and (3.19).
end for
Body:
if $\sum_{\ell=i}^{N} \lambda_{1\ell} > \sum_{\ell=i}^{N} \lambda_{2\ell}\alpha_{12}$ **then**
  if $\sum_{\ell=i}^{N} \lambda_{1\ell}\alpha_{21} > \sum_{\ell=i}^{N} \lambda_{2\ell}$ **then**
    repeat
      1. Find p_{1lower} and p_{2lower}.
      2. Increase $E_{1\ell}$ and decrease $E_{2\ell}$.
      3. Determine new non-decreasing vectors v_1 and v_2 by changing p_1 and p_2 for each time slot.
      4. Determine new $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
    until $\sum_{\ell=i}^{N} \lambda_{1\ell}\alpha_{21} = \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
else if $\sum_{\ell=i}^{N} \lambda_{1\ell} < \sum_{\ell=i}^{N} \lambda_{2\ell} * \alpha_{12}$ **then**
  if $\sum_{\ell=i}^{N} \lambda_{2\ell} > \sum_{\ell=i}^{N} \lambda_{1\ell} * \alpha_{21}$ **then**
    repeat
      1. Find p_{1lower} and p_{2lower}.
      2. Increase $E_{1\ell}$ and decrease $E_{2\ell}$.
      3. Determine new non-decreasing vectors v_1 and v_2 by changing p_1 and p_2 for each time slot.
      4. Determine new $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
    until $\sum_{\ell=i}^{N} \lambda_{1\ell} = \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
end if

3.2.3 Simulations for Battery Limited MAC and Energy Cooperation in Battery Limited MAC

In this section, we present some simulation results for battery limited MAC and for battery limited MAC with energy coperation by using Algorithm 1 and 2. In

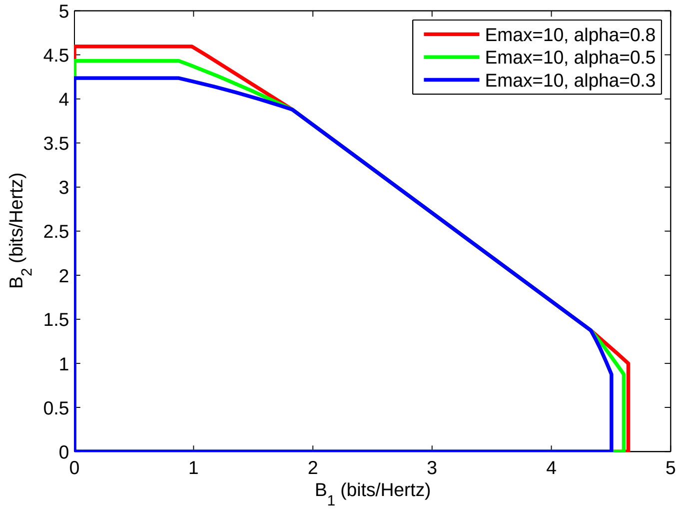

Figure 3.2: Departure region of battery limited MAC with energy cooperation E1=[3 7 12 13] and E2=[1 6 11 14], Emax=10

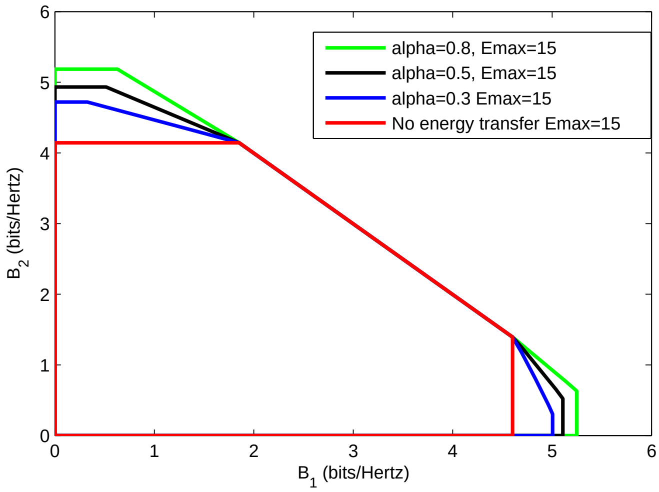

Figure 3.3: Departure region of battery limited MAC with energy cooperation E1=[3 7 12 13] and E2=[1 6 11 14], Emax=15

Algorithm 1, inputs are harvested energy values of transmitter 1 and transmitter 2, μ_1, μ_2 and σ_0. This algorithm outputs the optimal rate, power and transferred energy vectors. While calculating these, we used an iterative approach. As can be seen in Algorithm 1 and 2, we create some power restrictions to provide no energy overflow situation. These restrictions directly effects the energy overflow between epochs in battery limited MAC scenerio.

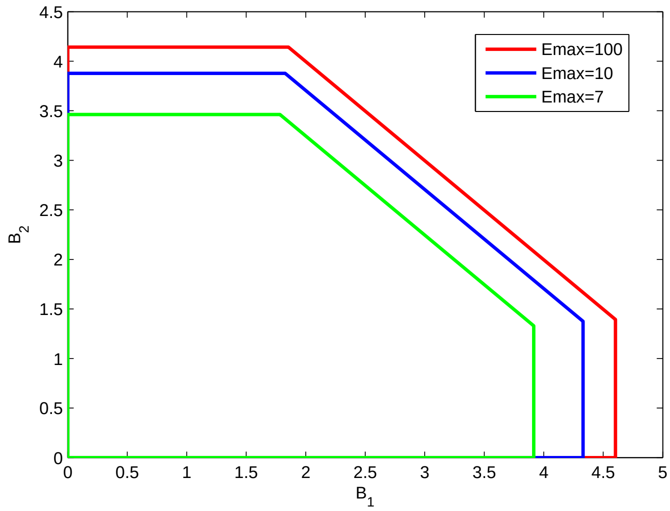

Figure 3.4: Departure region of battery limited MAC E1=[3 7 12 13] and E2=[1 6 11 14], Emax=100,10,7

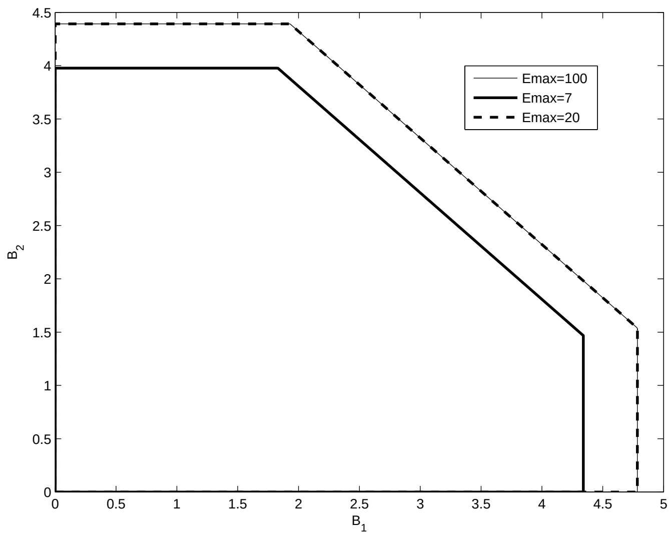

Figure 3.5: Departure region of MAC with limited battery and unlimited battery, E1=[9 9 9 8] and E2=[5 5 10 10], Emax=7, 20, 100

In algorithm 2, we combine our battery limited MAC algorithm with energy cooperation idea. The power restriction that we get from battery limitation sometimes directly effects the amunt and direction of the energyflow between users. To demonstrate the effect of battery limitation and the improvement we get with energy cooperation, we present some simulation results.

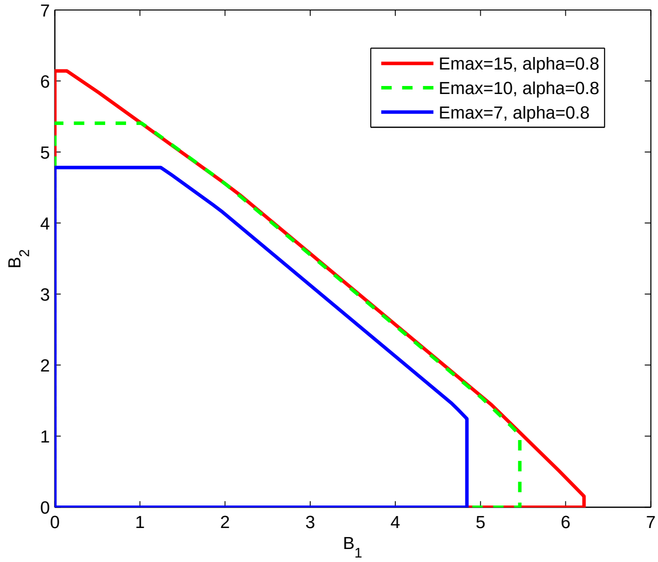

Figure 3.6: Departure region of MAC with different battery limitations E1=[12 12 8 8] and E2=[5 5 10 10], Emax=15, 10, 7, energy transfer efficiency=0.8

In Figures 3.2, 3.3 and 3.4, the harvested energy amounts for transmitter 1 and transmitter 2 are E1=[3 7 12 13] and E2=[1 6 11 14]. In figure 3.3, battery is limited to 10 and in Figure 3.4 it is limited to 15. In these figures, effect of energy transfer efficiency for transmitters with different battery limitations can be seen. It is also shown that energy cooperation increases departure region of two user multiple access channel. As shown in Figures 3.4, 3.5 and 3.6, departure region graphs are directly related with E_{max} because E_{max} restricts the energy flow from one epoch to another which creates a smaller departure region. In Figures 3.2, 3.3 and 3.6, it is seen that E_{max} also restricts the energy cooperation between users as we represent in theory and in our algorithms. Also it seen that, there is no gain from energy cooperation in sumrate points, μ_1=1 and μ_2=1. The reason is energy cooperation is a lossy event and while calculating capacity region in sumrate points, we are just adding the powers that transmitter 1 and transmitter 2 used. Energy cooperation decreases the sum power. In Figures 3.8 and 3.9, it can be seen that the energy values of transmitter 1 and transmitter 2 for Emax=10 and 15 in point A and point B. Energy transfer efficiency is given as 0.8. In consistent with priorities, in Point A, transmitter 2 sends a huge amount

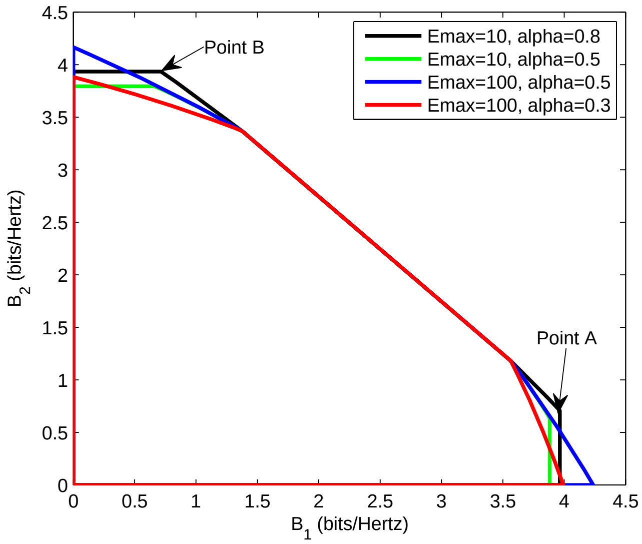

Figure 3.7: Departure region of battery limited MAC with energy cooperation E1=[7.63 8.13 9.47], E2=[4.87 8.45 9.87]

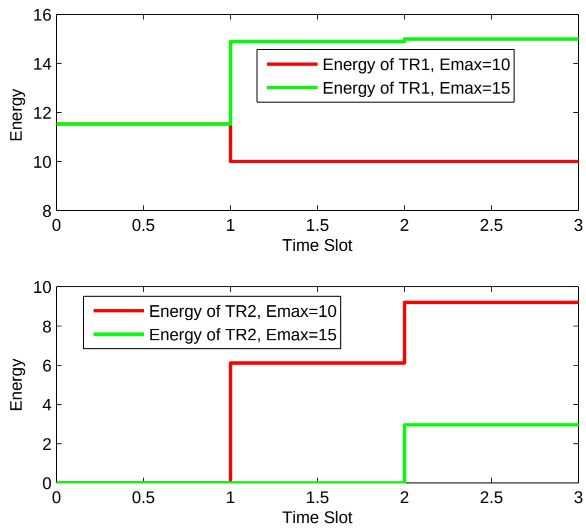

Figure 3.8: Energy values of transmitters in a battery limited MAC with energy cooperation scenerio, Emax=15, 10, point A, alpha=0.8

of energy to transmitter 1 and for point 2, transmitter 1 sends higher amount of energy to transmitter 1 to increase the total gain from energy cooperation.

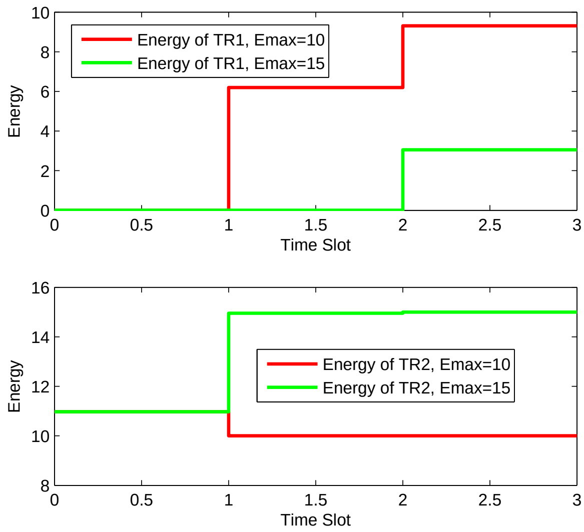

Figure 3.9: Energy values of transmitters in a battery limited MAC with energy cooperation scenerio, Emax=15, 10, point B, alpha=0.8

3.3 MAC with Energy Cooperation, Unlimited Battery

3.3.1 System Model

In this part, we consider bi-directional energy cooperation in a multiple access channel and aim to find the optimum energy management policies of the transmitters to maximize the achievable departure region over an finite transmission duration. Let us denote the transmit power for the first and second user as p_{1i} and p_{2i}, respectively. Then, the transmission rate pair R_{1i}, R_{2i} must be within the capacity region defined by p_{1i} and p_{2i}. The capacity region for this two-user multiple access channel is defined as (3.3).

As the energy that has not arrived can not be used for data transmission or energy transfer, the power policies of the transmitters are constrained by the causality of energy in time. For $\ell = 1, .., N$. There is a separate unit that enables energy transfer from the first user to the second user and from second user to first user with an efficiency $0 < \alpha_{12}$,$\alpha_{21} < 1$. When the first transmitter transfers δ_{12} amount of energy to the second transmitter, δ_{12} amount of energy exits the

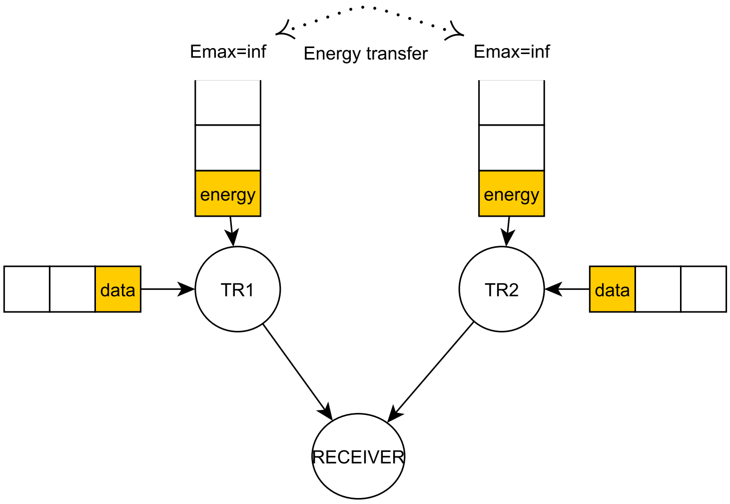

Figure 3.10: Battery unlimited MAC with energy cooperation

first transmitter's energy queue and $\alpha_{12}\delta_{12}$ amount of energy enters the second transmitters energy queue in the same slot.

$$\sum_{i=1}^{\ell} E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - p_{1i} > 0 \tag{3.37}$$

$$\sum_{i=1}^{\ell} E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - p_{2i} > 0 \tag{3.38}$$

3.3.2 Departure Region Maximization

For given priorities $0 \leq \mu_1 \leq 1$ and $0 \leq \mu_2 \leq 1$, our maximization problem is defined as

$$\mathbf{P1} : \max \ \mu_1 B_1 + \mu_2 B_2$$

$$\text{s.t. } B_1 \leq \sum_{i=1}^{N} \frac{1}{2}\log(1 + p_{1i}), \tag{3.39}$$

$$B_2 \leq \sum_{i=1}^{N} \frac{1}{2}\log(1 + p_{2i}), \tag{3.40}$$

$$B_1 + B_2 \leq \sum_{i=1}^{N} \frac{1}{2} \log(1 + p_{1i} + p_{2i}), \tag{3.41}$$

$$\sum_{i=1}^{\ell} E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - p_{1i} \geq 0, \tag{3.42}$$

$$\sum_{i=1}^{\ell} E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - p_{2i} \geq 0, \tag{3.43}$$

$$\sum_{i=1}^{\ell} p_{1i} \geq 0, \ \sum_{i=1}^{\ell} p_{2i} \geq 0 \tag{3.44}$$

KKT conditions which are used in energy transfer algorithm is given below.

$$\sum_{\ell=i}^{N} \lambda_{1\ell} = \frac{\mu_1 - \mu_2}{1 + p_{1i}} + \frac{\mu_2}{2(1 + p_{1i} + p_{2i})} \tag{3.45}$$

$$\sum_{\ell=i}^{N} \lambda_{2\ell} = \frac{\mu_{2i}}{2\,(1 + p_{1i} + p_{2i})} \tag{3.46}$$

$$\sum_{\ell=i}^{N} \lambda_{1\ell} = \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell} + \xi_{5i} \tag{3.47}$$

$$\sum_{\ell=i}^{N} \lambda_{2\ell} = \alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} + \xi_{6i} \tag{3.48}$$

Firstly, we prove that both transmitters can not transfer energy to each other at the same slot. Then, we determine the conditions which other cases will occur and develop a recursive algorithm to show the departure regions and power values of transmitter 1 and transmitter 2 after energy cooperation.

Lemma 3.1. *In a given epoch, both transmitters can not transfer energy to each other.*

Proof. Firstly, we should write (3.47) and (3.48) for the last epoch, $i = N$:

$$\lambda_{1N} = \lambda_{2N}\alpha_{12} + \xi_{5N} \tag{3.49}$$

$$\lambda_{2N} = \lambda_{1N}\alpha_{21} + \xi_{6N} \tag{3.50}$$

Assume that, ξ_{5N} =0 and ξ_{6N} =0. This assumption has the same meaning with $\delta_{21N} > 0, \delta_{12N} > 0$. In this case, $\lambda_{1N} = \lambda_{2N}\alpha_{12}$ must be satisfied. For $i = N$:

$$\lambda_{1N} = \lambda_{1N}\alpha_{12}\alpha_{21} \tag{3.51}$$

As we know, energy cooperation can not be done without energy loss, $\alpha_{12}\alpha_{21}$ should always be less then 1. The only way for satisfying condition is $\lambda_{1N} = 0$ and $\lambda_{2N} = 0$. But this is not possible, in last epoch all energy should be depleted. Same argument holds for every time slot. To sum up, we can say that, in a given epoch i, at least one of the Lagrange multipliers ξ_{5i} or ξ_{6i} should be greater than zero. This also means that at least one transmitter can not transfer energy to the other. □

Lemma 3.2. *In time slot i, if conditions* $\sum_{\ell=i}^{N} \lambda_{1\ell} > \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ *and* $\sum_{\ell=i}^{N} \lambda_{2\ell} > \alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell}$ *are satisfied at the same time, there will be no energy cooperation between transmitter 1 and transmitter 2.*

Proof. Assume that $\sum_{\ell=i}^{N} \lambda_{1\ell} > \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ and $\sum_{\ell=i}^{N} \lambda_{2\ell} > \alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell}$ are satisfied. By using (3.47) and (3.48), the lagrange multipliers corresponds to δ_{12i} ve δ_{21i} should be greater than zero. Conditions $\delta_{12i}\xi_{5i} >= 0$ and $\delta_{21i}\xi_{6i} >= 0$ must be satisfied. For that reason δ_{12i} and $\delta_{21i} = 0$ must be equal to zero. □

Lemma 3.3. *In time slot i, if conditions* $\sum_{\ell=i}^{N} \lambda_{1\ell} \leq \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ *and* $\sum_{\ell=i}^{N} \lambda_{2\ell} > \alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell}$ *are satisfied at the same time, transmitter 1 transfers* δ_{12i} *amount of energy to transmitter 2.*

Proof. For satisfying (3.47) and (3.48), ξ_{5i} should be equal to zero and ξ_{6i} should be greater than zero. Conditions $\delta_{12i}\xi_{5i} >= 0$ and $\delta_{21i}\xi_{6i} >= 0$ must be satisfied. For that reason, δ_{12i} >0 and $\delta_{21i} = 0$ should be satisfied. □

Lemma 3.4. *If conditions* $\sum_{\ell=i}^{N} \lambda_{1\ell} > \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ *and* $\alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} \geq \sum_{\ell=i}^{N} \lambda_{2\ell}$ *are satisfied, then there will be* δ_{21i} *amount of energy transfer from transmitter 2 to transmitter 1.*

Proof. KKT conditions (3.47) and (3.48) should always be satisfied. For that reason ξ_{5i} should greater than zero and ξ_{6i} is equal to zero. This yields that δ_{12i} =0 and $\delta_{21i} > 0$. □

Algorithm 3
Take $\mathbf{E_1}$, $\mathbf{E_2}$, α_{12}, α_{21}, μ_1, μ_2 and σ_0
for $\ell = 1 : N$ **do**
  EnergyTransfer(ℓ)
  repeat
    for $k = 1 : \ell$ **do**
      EnergyTransfer(k)
    end for
  until no change in E1 and E2
end for

Algorithm 3- Energy coperation in MAC
Start:
for $\ell = 1 : N$ **do**
  $p_{1\ell} = E_{1\ell}$ and $p_{2\ell} = E_{2\ell}$.
  find $p_{1\ell}$,$p_{2\ell}$ and waterlevels $v_{1\ell}$ and $v_{2\ell}$
  Calculate $\lambda_{1\ell}$ and $\lambda_{2\ell}$
end for
Body:
if $\sum_{\ell=i}^{N} \lambda_{1\ell} > \sum_{\ell=i}^{N} \lambda_{2\ell}\alpha_{12}$ **then**
  if $\sum_{\ell=i}^{N} \lambda_{1\ell}\alpha_{21} > \sum_{\ell=i}^{N} \lambda_{2\ell}$ **then**
    repeat
      1. increase $E_{1\ell}$ and decrease $E_{2\ell}$.
      2. For every slot, change p_1 ve p_2 and calculate new water levels $v_{1\ell}$ and $v_{2\ell}$
      3.Find new $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
    until $\sum_{\ell=i}^{N} \lambda_{1\ell}\alpha_{21} = \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
else if $\sum_{\ell=i}^{N} \lambda_{1\ell} < \sum_{\ell=i}^{N} \lambda_{2\ell}\alpha_{12}$ **then**
  if $\sum_{\ell=i}^{N} \lambda_{2\ell} > \sum_{\ell=i}^{N} \lambda_{1\ell}\alpha_{21}$ **then**
    repeat
      1. Increase $E_{2\ell}$ and decrease $E_{1\ell}$
      2. For every slot, change p_1 ve p_2 and calculate new water levels $v_{1\ell}$ and $v_{2\ell}$
      3. Find new $\lambda_{1\ell}$ and $\lambda_{2\ell}$
    until $\sum_{\ell=i}^{N} \lambda_{1\ell} = \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
end if

3.3.3 Simulation Results

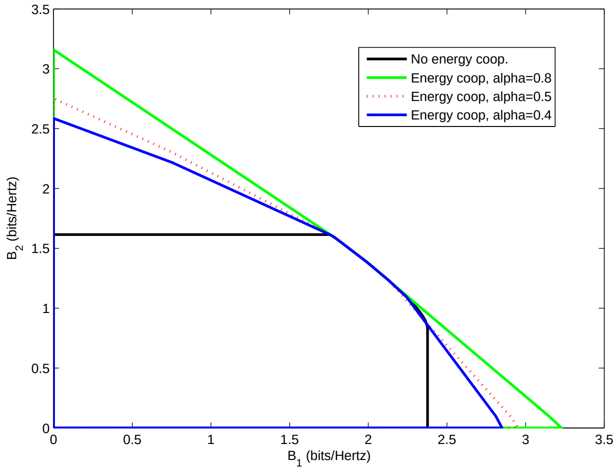

Figure 3.11: MAC with energy cooperation, different energy transfer efficiencies, E1=[5 7 0] and E2=[1 0 10]

In this section, we show that existence of energy cooperation increases the departure region of the two energy harvesting transmitters if we compare the same network without energy cooperation. We explain algorithm 3. The optimum energy cooperation management algorithm takes the channel coefficients α_{12}, α_{21}, harvested energy values of transmitter 1 and transmitter 2, μ_1, μ_2 and σ_0. This algorithm outputs the optimal rate, power and transferred energy vectors. While calculating these, we used a recursive approach. To demonstrate the improvement, we present some simulation results for MAC with bi-directional energy cooperation. It seen that, there is no gain from energy cooperation in sumrate points, μ_1=1 and μ_2=1. In Figure 3.11, the harvested energy amount are [5, 7, 0] for transmitter 1 and [1 0 10] for transmitter 2. As it expected, a larger energy transfer efficiency yields a larger departure region.

3.4 Conclusion

In this part, we investigate battery limited MAC, battery unlimited MAC with energy cooperation and battery limited MAC with energy cooperation. In section 3.1, transmitters have limited battery and we aim to find the optimum power management policy such that energy level in the battery never exceeds the battery capacity. We aim to maximize the departure region using Lagrangian optimization. In our solution, we found the lower bound of powers that transmitter 1 and transmitter 2 should use for protecting the batteries from energy overflow. Then, we combine the lower bound idea with water filling algorithm. The directional water filling algorithm aims to distribute the water equally over time. This algorithm walls at the points of energy arrival and allows water to flow only to the right. This is the implementation of energy causality constraint. Energy can not be used before it has arrived. Lower bound power values of transmitter 1 and transmitter 2 , effects the flow of energy from one time slot to another and creates some restrictions in waterlevel values of transmitter 1 and transmitter 2. These techniques yields us to find the optimum power management policy for MAC with battery limitations.

In section 3.2 and 3.3, MAC with energy cooperation is considered. We used Lagrangian optimization and directional water filling algorithm. The directional water filling algorithm aims to distribute the water equally over time. In our departure region figures, it is shown that energy cooperation in MAC does not increase the departure region while mu_1=mu_2=1. Although energy cooperation in MAC does not effect the systeml gain in sumrate points, in corner points of the departure region we see the enlargement. In battery limited scenerio, we used the same energy coperation algorithm but due to the finite battery storage capacity, we make sure that energy level in the battery never exceeds E_max and no energy overflow constraint forces energy consumption to speed up to open space in the battery.

We showed that in a given epoch, both transmitters can not transfer energy to each other at the same time. Also it is shown that in battery limited MAC, energy cooperation increases the departure region.

Chapter 4

Multiple Access Channel with Data Cooperation

4.1 MAC with Data Cooperation, Limited Battery

4.1.1 System Model

In this part, we consider a cooperative multiple access channel with energy harvesting transmitters. The time slots are assumed to be of fixed length 1. The energy harvesting times and harvested energy amounts are known before transmission starts. We aim to find the optimum energy management policies of the transmitters to maximize the achievable departure region over a finite transmission duration. The received signals are given as below:

$$Y_{0i} = X_{1i} + X_{2i} + N_{0i} \tag{4.1}$$

$$Y_{1i} = X_{2i} + N_{1i} \tag{4.2}$$

$$Y_{2i} = X_{1i} + N_{2i} \tag{4.3}$$

where X_{ki} is the transmitted codeword of user k and N_{0i}, N_{1i},N_{2i} are the AWGN at the nodes. p_{kji} and p_{Uki} denote the powers associated with each codeword in slot i.

$$\sum_{i=1}^{\ell} p_{12i} + p_{U1i} = \sum_{i=1}^{\ell} p_{1i} \tag{4.4}$$

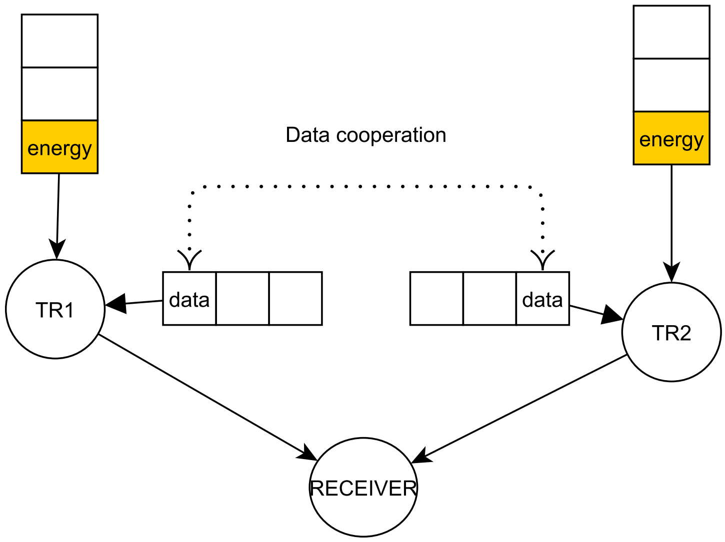

Figure 4.1: System model for battery limited cooperative MAC

$$\sum_{i=1}^{\ell} p_{21i} + p_{U2i} = \sum_{i=1}^{\ell} p_{2i} \tag{4.5}$$

For the multiple access channel with cooperating users, the rate pair (R_{1i}, R_{2i}) can be written as folllows

$$R_{1i} < \frac{1}{2}\log(1 + p_{12i}) \tag{4.6}$$

$$R_{2i} < \frac{1}{2}\log(1 + p_{21i}) \tag{4.7}$$

$$R_{1i} + R_{2i} < \frac{1}{2}log(\frac{\sigma_0^2 + p_{1i} + p_{2i} + 2\sqrt{(}p_{U1i}p_{U2i})}{\sigma_0^2}) \tag{4.8}$$

There are two constraints on power management policy, due to energy arrivals at random times and also due to finite battery storage capacity. Since energy that has not arrived yet cannot be used for data transmission, there is a causality on the power management policy as:

$$\sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell} p_{12i} + p_{U1i} \geq 0 \tag{4.9}$$

$$\sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell} p_{21i} + p_{U2i} \geq 0 \tag{4.10}$$

Also, due to the finite battery storage capacity, we need to make sure that energy level in the battery never exceeds E_{max}.

$$\left(\sum_{i=1}^{\ell-1} p_{12i} + p_{U1i} - \sum_{i=1}^{\ell} E_{1i} + E_{max} \right) \geq 0 \tag{4.11}$$

$$\left(\sum_{i=1}^{\ell-1} p_{21i} + p_{U2i} - \sum_{i=1}^{\ell} E_{2i} + E_{max} \right) \geq 0 \tag{4.12}$$

4.1.2 Departure Region Maximization

In problem formulation part, we use Lagrangian optimization method and water-filling algorithm for finding the optimum power management policy of the data cooperative MAC with limited battery.

For battery limited cooperative MAC, the problem is concave maximization problem with convex constraints. The departure region maximization problem can be stated as:

$$\mathbf{P2} : \max \sum_{i=1}^{N} R_{\mu_i}$$

$$\text{s.t. } R_{\mu_i} \leq \frac{\mu_1}{2} \log(1 + p_{12i}) + \frac{\mu_2}{2} \log(1 + p_{21i}) \tag{4.13}$$

$$R_{\mu_i} \leq \frac{\mu_1 - \mu_2}{2} \log(1 + p_{12i}) + \frac{\mu_2}{2} \log(\frac{\sigma_0^2 + p_{1i} + p_{2i} + 2\sqrt(p_{U1i} p_{U2i})}{\sigma_0^2}) \tag{4.14}$$

$$\sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell} p_{12i} + p_{U1i} \geq 0, \tag{4.15}$$

$$\sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell} p_{21i} + p_{U2i} \geq 0, \tag{4.16}$$

$$\left(\sum_{i=1}^{\ell-1} p_{12i} + p_{U1i} - \sum_{i=1}^{\ell} E_{1i} + E_{max} \right) \geq 0, \tag{4.17}$$

$$\left(\sum_{i=1}^{\ell-1} p_{21i} + p_{U2i} - \sum_{i=1}^{\ell} E_{2i} + E_{max}\right) \geq 0 \tag{4.18}$$

We assigned the non negative Lagrange multipliers λ_{1i}, λ_{2i}, λ_{3i}, λ_{4i}, γ_{1i}, γ_{2i} to the constraints (4.13), (4.14), (4.15), (4.16), (4.17), (4.18). The KKT conditions of our problem are given below.

$$\gamma_{1i} + \gamma_{2i} = 1, \tag{4.19}$$

$$\sum_{\ell=i}^{N} \lambda_{1\ell} - \lambda_{3\ell} \leq \frac{\gamma_{1i}\mu_1}{2(1+p_{12i})} + \frac{\gamma_{2i}(\mu_1-\mu_2)}{2(1+p_{12i})} + \frac{\gamma_{2i}\mu_2}{2S_{P1}}, \tag{4.20}$$

$$\sum_{\ell=i}^{N} \lambda_{1\ell} - \lambda_{3\ell} \leq \frac{\gamma_{2i}\mu_2(\sqrt{p_{U_1i}} + \sqrt{p_{U_2i}})}{2S_{P1}\sqrt{p_{U_1i}}}, \tag{4.21}$$

$$\sum_{\ell=i}^{N} \lambda_{2\ell} - \lambda_{4\ell} \leq \frac{\gamma_{1i}\mu_2}{2(1+p_{21i})} + \frac{\gamma_{2i}\mu_2}{2S_{P1}}, \tag{4.22}$$

$$\sum_{\ell=i}^{N} \lambda_{2\ell} - \lambda_{4\ell} \leq \frac{\gamma_{2i}\mu_2(\sqrt{p_{U_1i}} + \sqrt{p_{U_2i}})}{2S_{P1}\sqrt{p_{U_2i}}}. \tag{4.23}$$

For each time slot, we can find the lower bounds for p_1 and p_2 by using no energy overflow constraints (4.11) and (4.12).

$$p_{1(\ell-1)} \geq \sum_{i=1}^{\ell} E_{1i} - \sum_{i=1}^{\ell-2} p_{1i} - E_{max} \tag{4.24}$$

$$p_{2(\ell-1)} \geq \sum_{i=1}^{\ell} E_{2i} - \sum_{i=1}^{\ell-2} p_{2i} - E_{max} \tag{4.25}$$

In algorithm 4 given below, we found the optimum power management policy which maximizes the departure region of cooperative multiple access channel. The lower bounds for the powers of transmitter 1 and transmitter 2 are used while finding the optimum waterlevel values of transmitter 1 and transmitter 2. The idea is very similar to limited battery MAC. These lower bounds calculated from constraints (4.24) and (4.25), restrict the energy flow between the time slots. A water equalization method which never falls below these power thresholds and satisfies the KKT conditions given in (4.19), (4.20), (4.21), (4.22) and (4.23) gives us the optimum power management policy of the battery limited cooperative multiple access channel.

Algorithm 4
Get $\mathbf{E_1}$, $\mathbf{E_2}$, σ_0
Initialization:
for $\ell = 1 : N$ **do**
  Set $E_{1\ell} = E_{max}$ if $E_{1\ell} > E_{max}$.
  Set $E_{2\ell} = E_{max}$ if $E_{2\ell} > E_{max}$
  Determine water levels $v_{1\ell}$ and $v_{2\ell}$.
end for
Body:
repeat
  By using constraint (4.24), find p_{1lower} for each time slot.
  By using constraint (4.25), find p_{2lower} for each time slot.
  Find the optimum powers of transmitter 1 and transmitter 2 for cooperative MAC while E_{max}=∞
  for $\ell = 1 : N$ **do**
    Check power restrictions and equalize waterlevel values of transmitter 1 $v_{1\ell}$
  end for
  for $\ell = 1 : N$ **do**
    Check power restrictions and equalize waterlevel values of transmitter 2 $v_{2\ell}$
  end for
until no energy flow is necessary between time slots

4.1.3 Simulation Results

In this section, we present our simulations for battery limited MAC with data cooperation. The optimum power management algorithm takes harvested energy values of transmitter 1 and transmitter 2, μ_1, μ_2 and σ_0. This algorithm outputs the optimal rate and power vectors. While calculating these, we used a recursive approach. Harvested energy arrivals are given as E1=[9 9 9 8] and E2=[5 5 10 10], Figure 4.2. As in Chapter 3, it can be seen that battery limitation decreases the departure region of multiple access channel in data cooperative scenerio too. Figures 4.3 and 4.4 show the power values of transmitter 1 and transmitter 2 for the maximum priority points of transmitter 1 and transmitter2. In Figure 4.3,

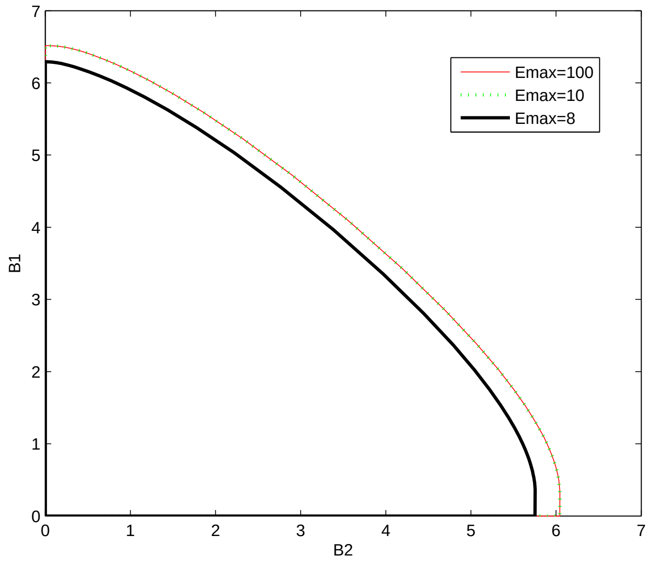

Figure 4.2: Departure regions of MAC with limited and unlimited battery E1=[9 9 9 8] and E2=[5 5 10 10], Emax=100,10,8

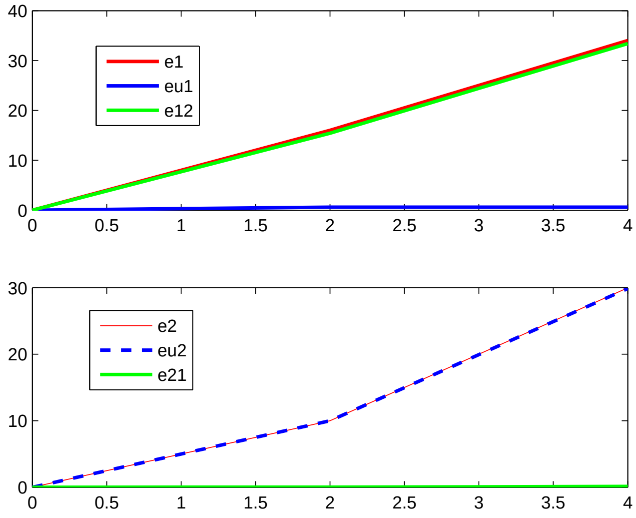

Figure 4.3: Power values of transmitter 1 and transmitter 2, battery limited cooperative MAC E1=[9 9 9 8] and E2=[5 5 10 10], Emax=10, mu1=1, mu2=0.62

it is shown that transmitter 2 uses its all energy to send common information to transmitter 1. It is an expected result because in this simulation, transmitter 1 has highest and transmitter 2 has lowest priority. We can make the opposite

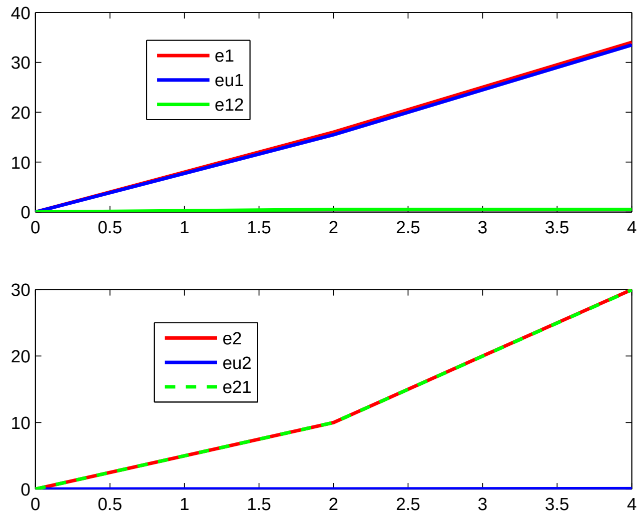

Figure 4.4: Power values of transmitter 1 and transmitter 2, battery limited cooperative MAC E1=[9 9 9 8] and E2=[5 5 10 10], Emax=10, mu1=0.62, mu2=1

argument for Figure 4.4.

4.2 Conclusion

We find the departure regions and power management policies of battery limited energy harvesting transmitters over a multiple access channel. We aim to maximize the departure region of battery limited cooperative MAC. We used Lagrangian optimization technique and water filling algorithm. Battery limitation constraint effects the optimum power values. We always need to make sure that energy level in the battery never exceeds E_{max}. In our solution, we found the lower bound of powers that transmitter 1 and transmitter 2 should use for protecting the batteries from energy overflow. Then, we combine the lower bound idea with water filling algorithm. Lower bound values of the powers that transmitter 1 and transmitter 2 should use, effects the flow of energy from one time slot to another and creates some restrictions in waterlevel values of transmitter 1 and transmitter 2. These techniques yields us to find the optimum power management policy for cooperative MAC.

Chapter 5

Multiple Access Channel with Joint Energy and Data Cooperation

5.1 MAC with Joint Energy and Data Cooperation, Unlimited Battery

5.1.1 Introduction

In this part, we aim to find the optimum energy transfer and power policies of the transmitters to maximize the achievable departure region of cooperative MACover a finite transmission duration. In our system models, users have unlimited batteries to store energy for future use. Energy harvests are known by the transmitters a priori. In particular, transmitters maintain the energy required for data transmission from the harvested energy after it is buffered in a battery. We used techniques such as Lagrangian optimization, generalized iterative water filling and directional water filling. The departure region obtained with our bi-directional energy cooperation policy is shown to be significantly larger than the same network without energy cooperation.

5.1.2 System Model

In this part, we consider an energy harvesting network where transmitters are powered solely by harvested energy and can share their energy as well as their information. There is a separate unit that enables energy transfer from the first user to the second user and from second user to first user with an efficiency $0 < \alpha_{12},\alpha_{21} < 1$. When the first transmitter transfers δ_{12} amount of energy to the second transmitter, δ_{12} amount of energy exits the first transmitter's energy queue and $\alpha_{12}\delta_{12}$ amount of energy enters the second transmitters energy queue in the same slot. For both transmitters, the energy that has not arrived yet cannot be used for data transmission or energy transfer. The incoming energy packets are used for only transmission purposes and can be stored at the energy storage of that user for later use. We aim to find the optimum energy management policies of the transmitters.

The receiver and each user decodes the following streams at the epoch i where N_i is the noise that corrupts the message at user k for the epoch i.

$$Y_0 = \sqrt{s_{10}}X_1 + \sqrt{s_{20}}X_2 + N_0 \quad (5.1)$$

$$Y_1 = \sqrt{s_{21}}X_2 + N_1 \quad (5.2)$$

$$Y_2 = \sqrt{s_{12}}X_2 + N_2 \quad (5.3)$$

p_{kji}, p_{Uki} denote the powers associated with codewords used for establishing common information and sending common information respectively, and the total power used in slot h p_{ki} is defined as;

$$p_{ki} = p_{kji} + p_{Uki} \quad (5.4)$$

$$k = 1, 2 \quad (5.5)$$

As the energy that has not arrived can not be used for data transmission or energy transfer, the power policies of the transmitters are constrained by the causality of energy in time.

$$\sum_{i=1}^{\ell} E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - (p_{12i} + p_{U1i}) > 0 \quad (5.6)$$

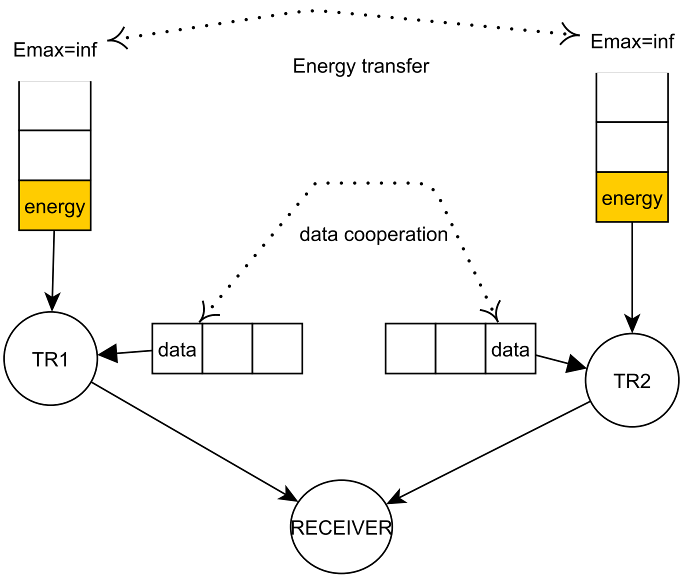

Figure 5.1: System Model of MAC with joint data and energy cooperation, unlimited battery

$$\sum_{i=1}^{\ell} E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - (p_{21i} + p_{U2i}) > 0 \tag{5.7}$$

The transmission rate pair R_{1i} ,R_{2i} must be within the capacity region defined by p_{1i} and p_{2i}. The capacity region for this two-user cooperative multiple access channel is

$$R_{1i} < \frac{1}{2}\log(1 + h_{12}p_{12i}) \tag{5.8}$$

$$R_{2i} < \frac{1}{2}\log(1 + h_{21}p_{21i}) \tag{5.9}$$

$$R_{1i} + R_{2i} <$$
$$\frac{1}{2}\min\left[\log\left(1 + h_{10}p_{1i} + h_{20}p_{2i} + 2\sqrt{h_{10}h_{20}p_{U1i}p_{U2i}}\right),\right.$$
$$\left.\log\left(1 + h_{12}p_{12i}\right) + \log\left(1 + h_{21}p_{21i}\right)\right] \tag{5.10}$$

5.1.3 Departure Region Maximization

The total number of bits departed from both of the users denoted as B_1 and B_2. The achievable departure region is then defined as the set of B_1, B_2 pairs that can simultaneously be supported under the rate constraints (5.8), (5.9) and (5.10). For any given energy pattern, points on the departure region can be obtained by maximizing a weighted sum

$$B_\mu \triangleq (\mu_1 B_1 + \mu_2 B_2) = \sum_h (\mu_1 R_{1i} + \mu_2 R_{2i}) \triangleq \sum_h R_{\mu i} \tag{5.11}$$

for given priorities $0 \leq \mu_1 \leq 1$ and $0 \leq \mu_2 \leq 1$. We write the Lagrangian function for our problem as

$$\begin{aligned} L = & \sum_{i=1}^{N} R_{\mu i} + \sum_{i=1}^{N} \gamma_{1i} \Big[\frac{\mu_1}{2} \log(1 + h_{12} p_{12i}) \\ & + \frac{\mu_2}{2} \log(1 + h_{21} p_{21i}) - R_{\mu i}\Big] \\ & + \sum_{i=1}^{N} \gamma_{2i} \left[\frac{\mu_2}{2} \log(S_i) + \frac{\mu_1 - \mu_2}{2} \log(1 + h_{12} p_{12i}) - R_{\mu i}\right] \\ & + \sum_{\ell=1}^{N} \lambda_{1\ell} \sum_{i=1}^{\ell} [E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - (p_{12i} + p_{U1i})] \\ & + \sum_{\ell=1}^{N} \lambda_{2\ell} \sum_{i=1}^{\ell} [E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - (p_{21i} + p_{U2i}))] \\ & + \sum_{i=1}^{N} [\xi_{1i} p_{12i} + \xi_{2i} p_{U1i} + \xi_{3i} p_{21i} + \xi_{4i} p_{U2i} + \xi_{5i}\delta_{12i} \\ & + \xi_{6i}\delta_{21i}] \end{aligned} \tag{5.12}$$

The corresponding KKT conditions are:

$$\gamma_{1i} + \gamma_{2i} = 1 \tag{5.13}$$

$$\sum_{\ell=i}^{N} \lambda_{1\ell} T - \xi_{1i} = \Big(\frac{\gamma_{2i} h_{12}(\mu_1 - \mu_2)}{2(1 + h_{12} p_{12i})} + \frac{\gamma_{2i}\mu_2 h_{10}}{2S_i}\Big)$$

$$+\frac{\gamma_{1i}\mu_1 h_{12}}{2(1+h_{12}p_{12i})} \tag{5.14}$$

$$\sum_{\ell=i}^{N}\lambda_{2\ell}T-\xi_{3i}=\frac{\gamma_{1i}\mu_2 h_{21}}{2(1+h_{21}p_{21i})}+\frac{\gamma_{2i}\mu_2 h_{20}}{2S_i} \tag{5.15}$$

$$\sum_{\ell=i}^{N}\lambda_{1\ell}T-\xi_{2i}=\frac{\gamma_{2i}\mu_2\left(\sqrt{\frac{h_{10}h_{20}p_{U_2 i}}{p_{U_1 i}}}+h_{10}\right)}{2S_i} \tag{5.16}$$

$$\sum_{\ell=i}^{N}\lambda_{2\ell}T-\xi_{4i}=\frac{\gamma_{2i}\mu_2\left(\sqrt{\frac{h_{10}h_{20}p_{U_1 i}}{p_{U_2 i}}}+h_{20}\right)}{2S_i} \tag{5.17}$$

$$\sum_{\ell=i}^{N}\lambda_{1\ell}-\xi_{5i}=\sum_{\ell=i}^{N}\lambda_{2\ell}\alpha_{12} \tag{5.18}$$

$$\sum_{\ell=i}^{N}\lambda_{2\ell}-\xi_{6i}=\sum_{\ell=i}^{N}\lambda_{1\ell}\alpha_{21} \tag{5.19}$$

5.1.4 Optimal Energy Cooperation Policy

There can be 3 different scenarios in time slot i for i=$1, 2..., N$.

1. $\delta_{12}=0, \delta_{21}=0$,
2. $\delta_{12}>0, \delta_{21}=0$,
3. $\delta_{21}>0, \delta_{12}=0$.

Firstly, we prove that both transmitters can not transfer energy to each other at the same slot. Then, we determine the conditions which other cases will occur and develop a recursive algorithm to show the departure regions and power values of transmitter 1 and transmitter 2 after energy cooperation.

Lemma 5.1. *In a given epoch, both transmitters can not transfer energy to each other.*

Proof. Firstly, we should write (5.18) and (5.19) for the last epoch, $i=N$:

$$\lambda_{1N}=\lambda_{2N}\alpha_{12}+\xi_{5N} \tag{5.20}$$

$$\lambda_{2N} = \lambda_{1N}\alpha_{21} + \xi_{6N} \tag{5.21}$$

Assume that, ξ_{5N} =0 and ξ_{6N} =0. This assumption has the same meaning with $\delta_{21N} > 0, \delta_{12N} > 0$. In this case, $\lambda_{1N} = \lambda_{2N}\alpha_{12}$ must be satisfied. For $i = N$:

$$\lambda_{1N} = \lambda_{1N}\alpha_{12}\alpha_{21} \tag{5.22}$$

As we know, energy cooperation can not be done without energy loss, $\alpha_{12}\alpha_{21}$ should always be less then 1. The only way for satisfying condition (5.22) is $\lambda_{1N} = 0$ and $\lambda_{2N} = 0$. But this is not possible, in last epoch all energy should be depleted. Same argument holds for every time slot. To sum up, we can say that, in a given epoch i, at least one of the Lagrange multipliers ξ_{5i} or ξ_{6i} should be greater than zero. This also means that at least one transmitter can not transfer energy to the other. □

Lemma 5.2. *In time slot i, if conditions* $\sum_{\ell=i}^{N}\lambda_{1\ell} > \alpha_{12}\sum_{\ell=i}^{N}\lambda_{2\ell}$ *and* $\sum_{\ell=i}^{N}\lambda_{2\ell} > \alpha_{21}\sum_{\ell=i}^{N}\lambda_{1\ell}$ *are satisfied at the same time, there will be no energy cooperation between transmitter 1 and transmitter 2.*

Proof. Assume that $\sum_{\ell=i}^{N}\lambda_{1\ell} > \alpha_{12}\sum_{\ell=i}^{N}\lambda_{2\ell}$ and $\sum_{\ell=i}^{N}\lambda_{2\ell} > \alpha_{21}\sum_{\ell=i}^{N}\lambda_{1\ell}$ are satisfied. By using (5.18) and (5.19), the lagrange multipliers corresponds to δ_{12i} ve δ_{21i} should be greater than zero. Conditions $\delta_{12i}\xi_{5i} >= 0$ and $\delta_{21i}\xi_{6i} >= 0$ must be satisfied. For that reason δ_{12i} and $\delta_{21i} = 0$ must be equal to zero. □

Lemma 5.3. *In time slot i, if conditions* $\sum_{\ell=i}^{N}\lambda_{1\ell} \leq \alpha_{12}\sum_{\ell=i}^{N}\lambda_{2\ell}$ *and* $\sum_{\ell=i}^{N}\lambda_{2\ell} > \alpha_{21}\sum_{\ell=i}^{N}\lambda_{1\ell}$ *are satisfied at the same time, transmitter 1 transfers* δ_{12i} *amount of energy to transmitter 2.*

Proof. For satisfying (5.18) and (5.19), ξ_{5i} should be equal to zero and ξ_{6i} should be greater than zero. Conditions $\delta_{12i}\xi_{5i} >= 0$ and $\delta_{21i}\xi_{6i} >= 0$ must be satisfied. For that reason, δ_{12i} >0 and $\delta_{21i} = 0$ should be satisfied. □

Lemma 5.4. *If conditions* $\sum_{\ell=i}^{N} \lambda_{1\ell} > \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ *and* $\alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} \geq \sum_{\ell=i}^{N} \lambda_{2\ell}$ *are satisfied, then there will be* δ_{21i} *amount of energy transfer from transmitter 2 to transmitter 1.*

Proof. KKT conditions (5.18) and (5.19) should always be satisfied. For that reason ξ_{5i} should greater than zero and ξ_{6i} is equal to zero. This yields that δ_{12i} =0 and $\delta_{21i} > 0$. □

Algorithm 5
Get $\mathbf{E_1}$, $\mathbf{E_2}$, α_{12}, α_{21}, μ_1, μ_2, σ_0 and i.
Initialization:
for $\ell = 1 : N$ **do**
  Set $p_{1\ell} = E_{1\ell}$ and $p_{2\ell} = E_{2\ell}$.
  Determine subpowers $p_{12\ell}$, $p_{21\ell}$, $p_{U_1\ell}$, $p_{U_2\ell}$, water levels $v_{1\ell}$ and $v_{2\ell}$ using KKT conditions (5.14), (5.15), (5.16) and (5.17).
  Inverse of water levels $v_{1\ell}$ and $v_{2\ell}$ are $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
end for
Body:
if $\sum_{\ell=i}^{N} \lambda_{1\ell} > \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$ **then**
  if $\alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} > \sum_{\ell=i}^{N} \lambda_{2\ell}$ **then**
    repeat
      1. Increase $E_{1\ell}$ and decrease $E_{2\ell}$.
      2. Determine new non-decreasing vectors v_1 and v_2 by changing p_1 and p_2 for each time slot.
      3. Determine new $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
    until $\alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} = \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
else if $\sum_{\ell=i}^{N} \lambda_{1\ell} < \sum_{\ell=i}^{N} \lambda_{2\ell}\alpha_{12}$ **then**
  if $\sum_{\ell=i}^{N} \lambda_{2\ell} > \alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell}$ **then**
    repeat
      1. Increase $E_{2\ell}$ and decrease $E_{1\ell}$.
      2. Determine new non-decreasing vectors v_1 and v_2 by changing p_1 and p_2 for each time slot.
      3. Determine new $\lambda_{1\ell}$ and $\lambda_{2\ell}$.
    until $\sum_{\ell=i}^{N} \lambda_{1\ell} = \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$
  end if
end if

The direction of energy cooperation is directly related with $\sum_{\ell=i}^{N} \lambda_{1\ell}$ and $\sum_{\ell=i}^{N} \lambda_{2\ell}$ as seen in Lemma 3.1, 3.2, 3.3, 3.4. We create some set of conditions which manage the optimal energy cooperation policy and make a decision for existence

Algorithm 5-Main

Get $\mathbf{E_1}$, $\mathbf{E_2}$, α_{12}, α_{21}, μ_1, μ_2 and σ_0
Initialization:
for $\ell = 1 : N$ **do**
  EnergyTransfer(ℓ)
  repeat
    for $k = 1 : \ell$ **do**
      EnergyTransfer(k)
    end for
  until No change in E1 and E2.
end for

and also direction of energy cooperation in each time slot. The algorithm that was written for energy cooperation, aims to find the exact amount of energies that should be transferred from transmitter 1 to transmitter 2 and from transmitter 2 to transmitter 1, δ_{12i} and δ_{21i} in epoch i to increase the departure region of the two energy harvesting transmitters over a cooperative multiple access channel. In our system model, if transmitter 1 or transmitter 2 should cooperate energy, they should decide the amount of energy that will be transfer and send it in one move. But in our algorithm, we are trying to converge the exact amount of energy that should be send by sending smaller amounts of pieces and control the values of $\sum_{\ell=i}^{N} \lambda_{1\ell}$ and $\sum_{\ell=i}^{N} \lambda_{2\ell}$. For the case where transmitter 1 transfers δ_{12i} amount of energy to transmitter 2 in epoch i, the energy cooperation should continue until $\sum_{\ell=i}^{N} \lambda_{1\ell} = \alpha_{12} \sum_{\ell=i}^{N} \lambda_{2\ell}$. This boundary gives us the exact amount of δ_{12i}. Similar arguments will be done if transmitter 2 transfers δ_{21i} amount of energy to transmitter 1. By using a recursive approach, we can find the exact amount of δ_{21i}. In this case the energy cooperation should continue until $\alpha_{21} \sum_{\ell=i}^{N} \lambda_{1\ell} = \sum_{\ell=i}^{N} \lambda_{2\ell}$. In this way, we have to repeat all these steps after each time slot. By doing this we aim to find the optimum energy management policies of the transmitters to maximize the achievable departure region over a finite transmission duration.

5.1.5 Simulation Results

In this section, we present our simulations for MAC with jointly data and energy cooperation. We show that existence of joint data and energy cooperation increases the departure region of the two energy harvesting transmitters if we compare the same network without energy cooperation. We explain our optimum energy cooperation management algorithm. In Figure 5.2, energy transfer

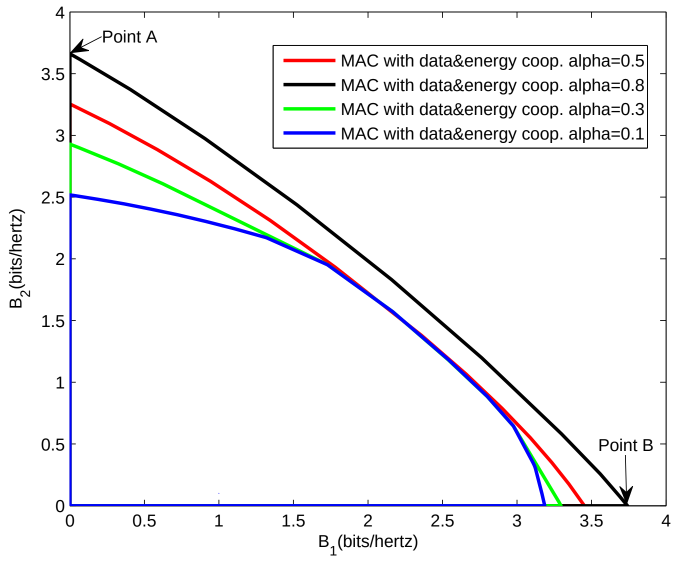

Figure 5.2: Given E1=[5 7 0] and E2=[1 0 10] with different energy transfer efficiencies, departure regions of cooperative MAC

efficiencies α_{12} and α_{21} are assumed to be 0.5, 0.8, 0.3, 0.1 respectively. The Gaussian noise variance on the direct link is 2 for given priorities $0 \leq \mu_1 \leq 1$ and $0 \leq \mu_2 \leq 1$ for a 3 s transmission. It is shown that the achievable departure region depends on directly the channel coefficients α_{12} and α_{21}. The optimum energy cooperation management algorithm takes the channel coefficients α_{12}, α_{21}, harvested energy values of transmitter 1 and transmitter 2, μ_1, μ_2 and σ_0. This algorithm outputs the optimal rate, power and transferred energy vectors.

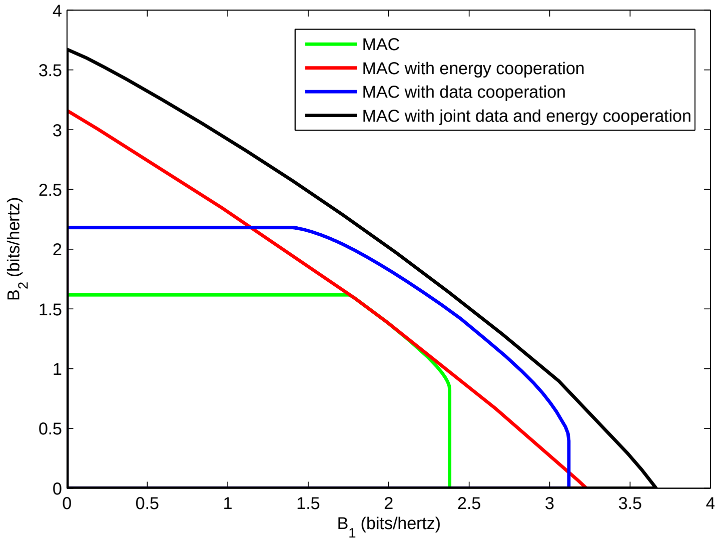

Figure 5.3: Energy transfer efficiencies are α_{12}=α_{21}=0.8, E1=[5 7 0] and E2=[1 0 10]

As shown in Figure 5.3, our optimum energy cooperation policy achieve higher rates over the multiple access channel, data cooperative multiple access channel and energy cooperative multiple access channel.

5.2 MAC with Joint Energy and Data Cooperation, Limited Battery

5.2.1 Introduction

In this work, we consider an energy harvesting network over a multiple access channel where nodes can share their energy, their data or both. Transmitters maintain the energy required for data transmission from the harvested energy after it is buffered in a battery. In our system model, energy harvests are known by the transmitters a priori. We aim to find the optimum energy transfer and power policies of the transmitters to maximize the achievable departure region for battery limited cooperative MAC.

5.2.2 System Model

In this part, energy harvesting transmitters with batteries of finite energy capacity are considered. The incoming energy first buffered in the battery before it is used in data transmission, and the transmitter is allowed to use the battery energy only. We assume that $E_{ki} \leq E_{max}$ for i=1,2 and i=1,..,N where N is number of time slots. Otherwise excess energy can not be accommodated in the battery anyway.

There are two constraints on power management policy, due to energy arrivals at random times and also due to finite battery storage capacity. Since energy that has not arrived yet cannot be used for data transmission, there is a causality on the power management policy as:

$$\sum_{i=1}^{\ell} E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} \geq \sum_{i=1}^{\ell} (p_{12i} + p_{u1i}) \tag{5.23}$$

$$\sum_{i=1}^{\ell} E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} \geq \sum_{i=1}^{\ell} (p_{21i} + p_{u2i}) \tag{5.24}$$

Also, due to the finite battery storage capacity, we need to make sure that energy level in the battery never exceeds E_{max}.

$$\sum_{i=1}^{\ell} (E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - E_{max}) \leq \sum_{i=0}^{\ell-1} (p_{12i} + p_{u1i}) \tag{5.25}$$

$$\sum_{i=1}^{\ell} (E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - E_{max}) \leq \sum_{i=0}^{\ell-1} (p_{21i} + p_{u2i}) \tag{5.26}$$

5.2.3 Departure Region Maximization

The optimization is subject to the causality constraints on the harvested energy, and the finite storage constraint on the battery. The energy causality constraints forced the energy consumption to slow down not to exceed the harvested amount,

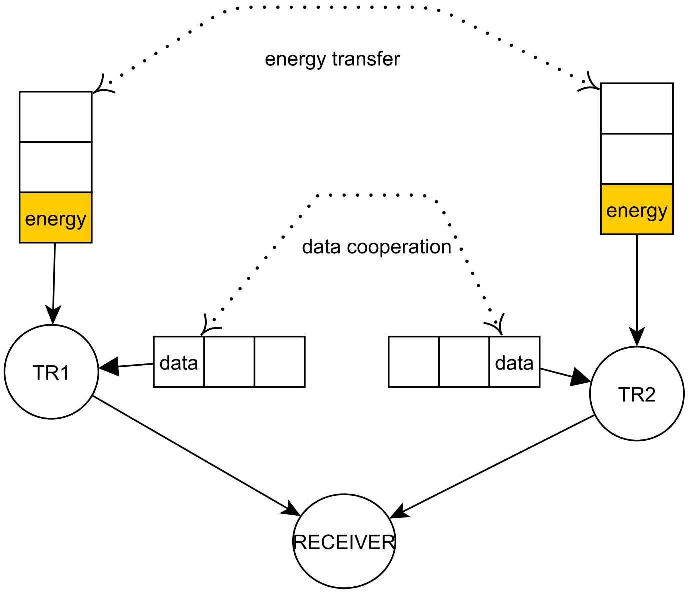

Figure 5.4: System Model of MAC with joint data and energy cooperation, limited battery

while the no energy overflow constraint forces energy consumption to speed up to open space in the battery for new energy arrivals. Our optimization problem is a convex optimization problem. We define the Lagrangian function as follows: L=

$$
\begin{aligned}
&\sum_{i=1}^{N} R_{\mu i} + \sum_{i=1}^{N} \gamma_{1i} \left(\frac{\mu_1}{2} \log(1 + h_{12} p_{12i}) + \frac{\mu_2}{2} \log(1 + h_{21} p_{21i}) - R_{\mu i} \right) \\
&+ \sum_{i=1}^{N} \gamma_{2i} \left(\frac{\mu_2}{2} \log(S_i) + \frac{\mu_1 - \mu_2}{2} \log(1 + h_{12} p_{12i}) - R_{\mu i} \right) \\
&+ \sum_{\ell=1}^{N} \lambda_{1\ell} \left(\sum_{i=1}^{\ell} [E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - (p_{12i} + p_{U1i})] \right) \\
&+ \sum_{\ell=1}^{N} \lambda_{2\ell} \left(\sum_{i=1}^{\ell} [E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - (p_{21i} + p_{U2i}))] \right) \\
&+ \sum_{\ell=1}^{N} \lambda_{3\ell} \left(\sum_{i=0}^{\ell-1} (p_{12i} + p_{U1i})\, T - \sum_{i=1}^{\ell} (E_{1i} + \alpha_{21}\delta_{21i} - \delta_{12i} - E_{max}) \right) \\
&+ \sum_{\ell=1}^{N} \lambda_{4\ell} \left(\sum_{i=0}^{\ell-1} (p_{21i} + p_{U2i})\, T - \sum_{i=1}^{\ell} (E_{2i} + \alpha_{12}\delta_{12i} - \delta_{21i} - E_{max}) \right) \\
&+ \sum_{i=1}^{N} (\xi_{1i} p_{12i} + \xi_{2i} p_{U1i} + \xi_{3i} p_{21i} + \xi_{4i} p_{U2i} + \xi_{5i}\delta_{12i} + \xi_{6i}\delta_{21i})
\end{aligned}
\tag{5.27}
$$

KKT conditions are given below.

$$\gamma_{1i} + \gamma_{2i} = 1 \tag{5.28}$$

$$\sum_{\ell=i}^{N}(\lambda_{1\ell} - \lambda_{3\ell}) - \xi_{1i} = \frac{\gamma_{1i}\mu_1 h_{12}}{2(1+h_{12}p_{12i})} + \Big(\frac{\gamma_{2i}h_{12}(\mu_1-\mu_2)}{2(1+h_{12}p_{12i})} + \frac{\gamma_{2i}\mu_2 h_{10}}{2S_i}\Big), \tag{5.29}$$

$$\sum_{\ell=i}^{N}(\lambda_{2\ell} - \lambda_{4\ell}) - \xi_{3i} = \frac{\gamma_{1i}\mu_2 h_{21}}{2(1+h_{21}p_{21i})} + \frac{\gamma_{2i}\mu_2 h_{20}}{2S_i}, \tag{5.30}$$

$$\sum_{\ell=i}^{N}(\lambda_{1\ell} - \lambda_{3\ell}) - \xi_{2i} = \frac{\gamma_{2i}\mu_2\left(\sqrt{\frac{h_{10}h_{20}p_{U_2 i}}{p_{U_1 i}}} + h_{10}\right)}{2S_i} \tag{5.31}$$

$$\sum_{\ell=i}^{N}(\lambda_{2\ell} - \lambda_{4\ell}) - \xi_{4i} = \frac{\gamma_{2i}\mu_2\left(\sqrt{\frac{h_{10}h_{20}p_{U_1 i}}{p_{U_2 i}}} + h_{20}\right)}{2S_i} \tag{5.32}$$

$$\sum_{\ell=i}^{N}(\lambda_{1\ell} - \lambda_{3\ell}) = \alpha_{12}\sum_{\ell=i}^{N}(\lambda_{2\ell} - \lambda_{4\ell}) + \xi_{5i} \tag{5.33}$$

$$\sum_{\ell=i}^{N}(\lambda_{2\ell} - \lambda_{4\ell}) = \alpha_{21}\sum_{\ell=i}^{N}(\lambda_{1\ell} - \lambda_{3\ell}) + \xi_{6i} \tag{5.34}$$

We apply the KKT optimality conditions to this Lagrangian. Similar to the scenario $E_{max} = \infty$, ξ_5, ξ_6 are the Lagrange multipliers which have direct relationship between δ_{12} and δ_{21}. δ_{12} is the amount of energy that transmitter 1 transfers to transmitter 2 and δ_{21} is the amount of energy that transmitter 2 transfers to transmitter 1. The KKT conditions given below shows us the relation of the Lagrange multipliers ξ_5, ξ_6 with $\lambda_1, \lambda_2, \lambda_3$ and λ_4.

The directional water-filling algorithm aims to distribute the water equally over time. This algorithm requires walls at the points of energy arrival and allows water to flow only to the right. This is the implementation of energy causality constraint, i.e., energy can be saved and used in the future but the energy that will arive in the future can not be used before it has arrived. Also, this algorithm allows at most E_{max} amount of water to flow to the right. λ_1, λ_2 are the Lagrange multipliers that enforce energy causality and λ_3, λ_4 are the Lagrange multipliers that enforce no energy overflow conditions.

If $E_{max} = \infty$, then constraints in (5.25) and (5.26) are satisfied without equality and λ_3, λ_4 are equal to zero. Whenever constraints in (5.23) and (5.24) are not satisfied with equality, it means that some energy is available for use. This energy can be used for energy cooperation or is transferred to future epochs. If E_{max} is finite, its effect on the optimal power allocation is observed through λ_3 and λ_4. If the constraints in (5.25) and (5.26) are satisfied without equality, then λ_3 and λ_4 should be 0. However, whenever constraints in (5.25) and (5.26) are satisfied with equality, constraints with the same index in(5.23) and (5.24) should be satisfied without equality. Therefore, non zero λ_3, λ_4 and zero λ_1, λ_2 will appear.

We restrict our optimal energy cooperation policy where there is no energy flow in the batteries of transmitter 1 and transmitter 2 because of energy cooperation. The proposed energy cooperation strategy should achieve higher rates over the multiple access channel. If we have overflowing energy because of energy cooperation, we cannot achieve higher rates. In a given epoch, if the battery of transmitter 2 is full, we would prefer not to transfer any amount of energy to that transmitter. In our optimal energy cooperation solution, λ_3 and λ_4 should be 0. In energy cooperation, batteries should not overflow. To sum up, we restrict our optimal energy cooperation policy where there is no energy flow in the batteries of transmitter 1 and transmitter 2 because of energy cooperation. In a given epoch, if the battery of transmitter 2 is full, we would prefer not to transfer any amount of energy to that transmitter. E_{max} does not change the direction of the energy cooperation but constraint restricts power levels, the energy that can be transferred to the future epochs and energy cooperation between two transmitters. It is observed that in each epoch, the value of the transferred energy δ_{12} or δ_{21} will be limited by E_{max}.

5.2.4 Simulation Results

Even though energy arrivals are smaller than Emax value, limitation in the battery changes the power and energy management policy. The result of this change can be seen by looking the departure region, Figure 5.5. In Figure 5.5 harvested energy arrivals are E1= [7.63 8.13 9.47], E2=[4.87 8.45 9.87], Emax=10.

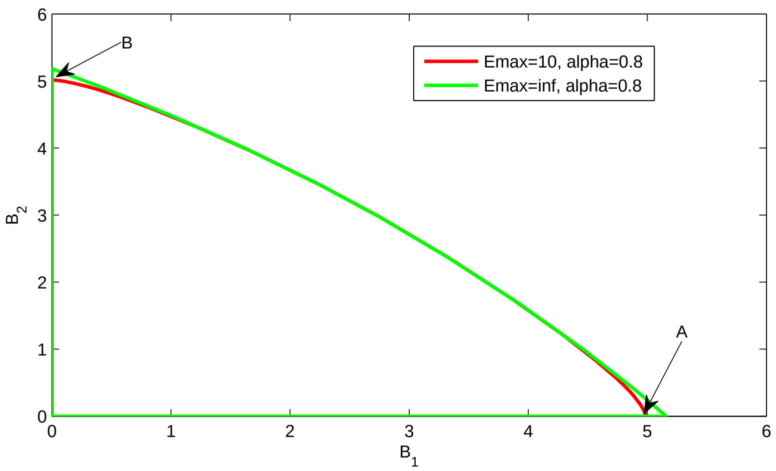

Figure 5.5: Departure regions of E1= [7.63 8.13 9.47], E2=[4.87 8.45 9.87], Emax=10, inf. alpha=0.8

In this section, we simulate battery limited MAC with joint data and energy co-operation. We explain our optimum energy cooperation management algorithm. The optimum energy cooperation management algorithm takes the channel coefficients α_{12}, α_{21}, harvested energy values of transmitter 1 and transmitter 2, μ_1, μ_2 and σ_0. Our algorithm creates some lower bound values for p_1 and p_2. These restrictions prevent our batteries from energy overflow.This algorithm outputs the optimal rate, power and transferred energy vectors. While calculating these, we used an iterative approach.

In Figures 5.6 and 5.7 power and energy values of transmitter 1 and transmitter 2 is shown. In this simulations, harvested energy arrivals are E1= [5 7 0] and E2=[1 0 10], battery limitation E_{max} is 10. Energy transfer efficiency between users is 0.8.

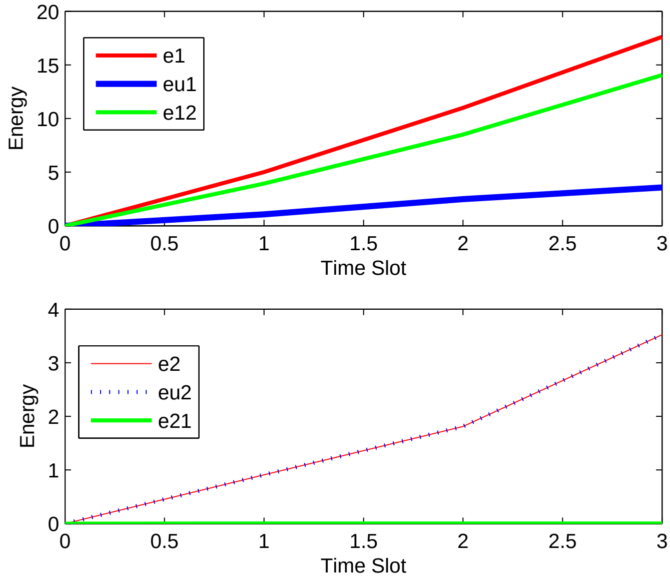

Figure 5.6: Given E1= [5 7 0], E2=[1 0 10], power values of transmitter 1 and transmitter 2 with Emax=10, mu1=1, alpha=0.8

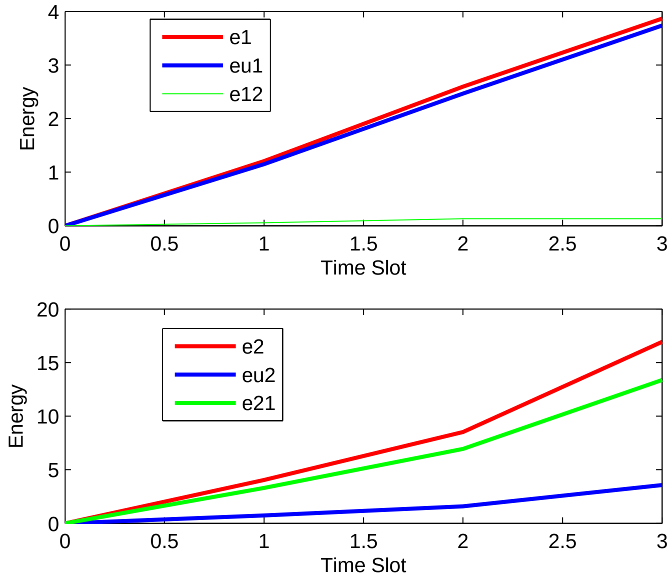

Figure 5.7: Given E1= [5 7 0], E2=[1 0 10], power values of transmitter 1 and transmitter 2 with Emax=10, mu2=1, alpha=0.8

5.3 Conclusion

In this chapter, we aim to maximize the departure regions of two energy harvesting transmitters over a cooperative multiple access channel with and without battery limitations. In cooperative MAC, the goal of energy cooperation is to provide energy to the users in such a way that it optimizes the gain from user cooperation. In section 5.1, the batteries of the transmitters have infinite storage capacity. For that reason, there is a sufficient battery space for each energy arrival and no energy will be wasted. In section 5.2 energy harvesting transmitters with batteries of finite energy capacity are considered. In both chapters, we did Lagrangian optimization and create a water filling algorithm. The directional water-filling algorithm aims to distribute the water equally over time. This algorithm requires walls at the points of energy arrival and allows water to flow only to the right. This is the implementation of energy causality constraint, i.e., energy can be saved and used in the future but the energy that will arive in the future can not be used before it has arrived. In both chapters, the energy causality constraints forced the energy consumption to slow down not to exceed the harvested amount. In section 5.2, due to the finite battery storage capacity, we make sure that energy level in the battery never exceeds E_{max} and no energy overflow constraint forces energy consumption to speed up to open space in the battery for new energy arrivals. Our aim is to maximize the gain in multiple access channel from data and energy cooperation. In section 5.2, we create a new algorithm for battery limited case. In both chapters, we showed that the departure region obtained with our bi-directional energy cooperation policy is shown to be significantly larger than the same network without energy cooperation.

Conclusion

This thesis considers two energy harvesting transmitters over a multiple access channel and a cooperative multiple access channel. For six different scenerios, we find the optimum energy management policies of the transmitters to maximize the achievable departure region over a finite transmission duration.

In section 3.2 and 3.3, energy cooperation in MAC with/without battery limitation is considered. Although energy cooperation in MAC does not effect the system gain in sumrate points, at corner points of the departure region, enlargement occurs. We derive some proofs for energy cooperation policy; such as the direction of energy transfer for each epoch, the amount that should be sent for getting the optimum power management policy. We showed that in a given epoch, both transmitters can not transfer energy to each other at the same time. In battery limited MAC, battery limitation directly restricts the gain that the system gets from energy cooperation. This relation between energy cooperation and battery limitation can be seen in our simulation results.

In chapters 4 and 5, we aim to maximize the departure regions of two energy harvesting transmitters over a cooperative multiple access channel with and without battery limitations. We showed that the departure region obtained with our bi-directional energy cooperation policy is shown to be significantly larger than the same network without energy cooperation. Also, energy cooperation helps us to get more gain from user cooperation in both battery limited and unlimited scenerios. In some cases for battery limited cooperative MAC, the limitation in battery capacity directly effects the energy transfer amount and the direction.

Curriculum Vitae

Berrak Şişman was born on 3 February 1993, in Istanbul. She received her B.S. degree in Electronics Engineering and in Computer Engineering as a double major from Işık University in January 2015 and June 2015 respectively. She worked as an undergraduate and graduate research assistant in a TUBITAK project titled 'User cooperation and resource allocation in energy harvesting wireless networks'. This is a joint project with University of Maryland. She assisted a course called Introduction to Communication System for 2 semesters in Isik University. Her research interests are Wireless Communications, Wireless Energy Transfer and Energy Harvesting Communications.

Publications

[1]B. Gurakan, B. Sisman, O. Kaya, and S. Ulukus, "Energy and Data Cooperation in Energy Harvesting Multiple Access Channel", *2016 IEEE Wireless Communications and Networking Conference Workshops.*

References

[1] R. Ahlswede, Multi-way communication channels, *Proc. 2nd Iit. Symp. Inform. Theory,* Tsahkadsor, Armenian S.S.R., 1971, pp. 23–52.

[2] H. Liao, A coding theorem for multiple access communications, *Int. Symp. Inform. Theory, Asilomar,* 1973.

[3] M. Bierbaum and H. Wallmeier, A note on the capacity region of the multiple-access channel, *IEEE Trans. Inform. Theory*, 1979, vol. IT-25, no. 4, pp. 484–488.

[4] N. T. Gaarder and J. K. Wolf, The capacity region of a multiple access discrete memoryless channel can increase with feedback, *IEEE Trans. Inform. Theory*, 1975, vol. IT-21, pp. 100–102.

[5] N. Su, O. Kaya, S. Ulukus and M. Koca, Cooperative multiple access channel under energy harvesting constraints, *IEEE Global Communications Conference (Globecom)*, San Diego, CA, USA, 2015, pp. 1–6.

[6] Z. Wang, V. Aggarwal and X. Wang, Iterative dynamic water-filling for fading multiple-access channels with energy harvesting, *IEEE J. Sel. Areas Commun.*, 2015, vol. 33, no. 3, pp. 382-395.

[7] O. Ozel, S. Ulukus, Achieving AWGN capacity under stochastic energy harvesting, *IEEE Transactions n Information Theory*, 2012, vol. 58, no. 10, pp. 6471–6483.

[8] J. Yang and S. Ulukus, Optimal packet scheduling in an energy harvesting communication system, *IEEE Trans. Comm.*, 2012, vol. 60, pp. 220-230.

[9] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press, 2005.

[10] K. Tutuncuoglu and A. Yener, Multiple access and two-way channels with energy harvesting and bi-directional energy cooperation, *Information Theory and Applications Workshop,* 2013, pp. 1–8.

[11] B. Gurakan and S. Ulukus, Energy harvesting diamond channel with energy cooperation, *IEEE International Symposium on Information Theory*, 2014, pp. 986–990.

[12] G. Zheng, J. L. Teng, and M. Motani, Base station energy cooperation in green cellular networks, *Global Conference on Signal and Information Processing (GlobalSIP), IEEE,* 2013, pp. 349-352.

[13] D. Gunduz and B. Devillers, Two-hop communication with energy harvesting, *4th IEEE CAMSAP,* 2011, pp. 201-209.

[14] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, Transmission with energy harvesting nodes in fading wireless channels: Optimal policies, *IEEE JSAC,* 2011, vol. 29, pp. 1732-1743.

[15] B. Devillers and D. Gunduz, A general framework for the optimization of energy harvesting communication systems with battery imperfections, *Journal of Comm. and Netw.*, 2012, vol. 14, pp. 130-139.

[16] O. Orhan, D. Gunduz, and E. Erkip, Energy harvesting broadband communication systems with processing energy cost, *IEEE Trans. Wireless Comm.*, 2014, vol. 13, pp. 6095-6107.

[17] J. Xu and R. Zhang, Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power, *IEEE JSAC*, 2014, vol. 32, pp. 322-332.

[18] Y. Luo, J. Zhang, and K. B. Letaief, Optimal scheduling and power allocation for two-hop energy harvesting communication systems, *IEEE Trans. Wireless Comm.*, 2013, vol. 12, pp. 4729-4741.

[19] B. Gurakan, O.Ozel, Jing Y., and S. Ulukus, Two-Way and multiple-access energy harvesting systems with energy cooperation, *IEEE Transactions on Communications*, 2013, vol. 61, no. 12, pp. 58-62.

[20] B. Gurakan, O. Ozel, J. Yang ve S. Ulukus, Energy cooperation in energy harvesting two-way communications, *In Proc. IEEE ICC,* 2013, pp. 3126–3130.

[21] B. Gurakan, O. Ozel, Jing Y., and S. Ulukus, Energy Cooperation in energy harvesting wireless communications, *in Proceedings of IEEE International Symposium on Information Theory (ISIT), IEEE*, 2012, pp. 965–969.

[22] P. Popovski, A. Fouladgar, and O. Simeone, Interactive joint transfer of energy and information, *IEEE Transactions on Communications,* 2012, vol. 61, no. 5, pp. 2086–2097.

[23] A. Sendonaris, E. Erkip, and B. Aazhang, User cooperation diversity. part I. System description, *IEEE Trans. Commun.*, 2003, vol. 51, no. 11, pp. 1927–1938.

[24] P. Grover and A. Sahai, Shannon meets tesla: wireless information and power transfer, *Information Theory Proceedings (ISIT), IEEE International Symposium on. IEEE*, 2010, pp. 2363–2367.

[25] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher ve M. Solja, Wireless power transfer via strongly coupled magnetic resonances, *Science*, 2007, no. 5834, pp. 83–86.

[26] W. Mao and B. Hassibi, On the capacity of a communication system with energy harvesting and a limited battery, *IEEE International Symposium on Information Theory*, 2013, pp. 1789–1793.

[27] K. Tutuncuoglu, O. Ozel, A. Yener, and S. Ulukus, Binary energy harvesting channel with finite energy storage, *Information Theory (ISIT), IEEE International Symposium,* 2013, pp. 1591–1595.

[28] O. Ozel, Jing Y., and S. Ulukus, Broadcasting with a battery limited energy harvesting rechargeable transmitter, *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), International Symposium,* 2011, pp. 205–212.

[29] P. Grover and A. Sahai, Shannon meets Tesla: Wireless information and power transfer, *IEEE ICC proceedings,* 2011, pp. 2363–2367.

[30] C. K. Ho and R. Zhang, Optimal energy allocation for wireless communications with energy harvesting constraints, *IEEE Trans. Signal Proc.*, 2012, vol. 60, pp. 4808–4818.

[31] M. A. Antepli, E. Uysal-Biyikoglu, and H. Erkal, Optimal packet scheduling on an energy harvesting broadcast link, *IEEE JSAC*, 2011, vol. 29, no. 8, pp. 1721-1731.

[32] S. P. Boyd and Lieven Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004.

[33] R. S. Cheng, S. Verdu, Gaussian multiaccess channels with ISI: capacity region and multiuser water-filling, *IEEE Transactions on Information Theory,* 1993, vol. 39, pp. 773–785.

[34] P. Popovski, A. Fouladgar, and O. Simeone, Interactive joint transfer of energy and information, *IEEE Trans. Comm.*, 2013, vol. 61, pp. 2086–2097.

[35] C. Huang, R. Zhang, and S. Cui, Throughput maximization for the Gaussian relay channel with energy harvesting constraints, *IEEE JSAC*, 2013, vol. 31, pp. 1469–1479.

[36] B. Varan and A. Yener, Energy harvesting two-way communications with limited energy and data storage, *Asilomar Conf.,* 2014, pp. 1671–1675.

[37] J. Yang and S. Ulukus, Optimal packet scheduling in a multiple access channel with energy harvesting transmitters, *Journal of Communications and Networks*, 2012, vol. 14, no. 2, pp. 140-150.

[38] O. Ozel, J. Yang, and S. Ulukus, Optimal broadcast scheduling for an energy harvesting rechargeable transmitter with a finite capacity battery, *IEEE Trans. Wireless Commun.*, 2012, vol. 11, no. 6, pp. 2193-2203.

[39] K. Tutuncuoglu and A. Yener, Short-term throughput maximization for battery limited energy harvesting nodes, *IEEE ICC Proceedings,* 2011, pp. 1–5.