OPTIMAL TRANSMISSION SCHEDULING FOR ENERGY HARVESTING SYSTEMS AND IMPLEMENTATION OF ENERGY EFFICIENT SCHEDULING ALGORITHMS ON SOFTWARE DEFINED RADIO

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ABSTRACT

OPTIMAL TRANSMISSION SCHEDULING FOR ENERGY HARVESTING SYSTEMS AND IMPLEMENTATION OF ENERGY EFFICIENT SCHEDULING ALGORITHMS ON SOFTWARE DEFINED RADIO

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Recently, improving energy efficiency in the rapidly evolving technology field of wireless communications has become an important need. To improve the ease of use, extend the field of application of wireless communications, and sustain the applications that use the technology for longer durations with less energy expenditure, study of energy harvesting systems has gained momentum. In this thesis, an offline scheduling problem in an energy harvesting system has been solved and three scheduling alorithms have been implemented in hardware. Optimal power and rate allocation for data packets arriving at arbitrary but known instances is studied by taking the channel state, the state of energy and data buffers into account over an energy harvesting fading channel. In addition, a near-optimal transmission scheduling policy, Expected Threshold Lazy Scheduling Policy (ETLS) from recent literature, is implemented and compared with Hasty and Constant Policies which are also implemented in the scope of this thesis. A point-to-point communication prototype employing

802.11g transmission schemes is set up on software defined radio.

Keywords: Energy Harvesting, Energy Efficiency, Optimization, Software Defined Radio, Implementation, Offline Solution, Lazy Scheduling

ÖZ

ENERJİ HARMANLAYAN SİSTEMLERDE OPTİMAL İLETİM ÇİZELGELEMESİ VE ENERJİ VERİMLİ ÇİZELGELEME ALGORİTMALARININ YAZILIM TANIMLI RADYO ÜZERİNDE UYGULANMASI

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Son dönemlerde, hızla gelişen teknoloji alanlarından olan kablosuz haberleşme teknolojisinde enerji verimliliğini artırmak önemli bir ihtiyaç haline gelmiştir. Kablosuz haberleşme teknolojisinin kullanım kolaylığını artırmak, uygulama alanlarını genişletmek ve bu uygulamaların daha az enerji tüketerek çok daha uzun süre idame ettirilmesini sağlamak amacıyla yapılan çalışmalar ivme kazanmıştır. Bu çalışmada enerji harmanlayan bir sistem için çevrimdışı çizelgeleme problemi çözülmüş ve üç adet çizelgeleme algoritması donanım üzerinde uygulanmıştır. Keyfî, ancak bilinen anlarda gelen veri paketleri için en uygun güç ve veri hızı dağılımı; kanal kazancı, enerji durumu ve veri ara belleği göz önünde bulundurularak sönümlü kanalda enerji harmanlayan bir sistem üzerinde çalışma yapılmıştır. Buna ek olarak, optimuma yakın bir çizelgeleme politikası, güncel literatürde de bulunan Beklenen Eşikdeğer Tembel Çizelgeleme Politikası (ETLS), uygulanmış ve yine bu tez kapsamında uygulanmış olan Aceleci ve Sabit politikalar ile karşılaştırılmıştır. 802.11g iletim şemasını kullanan iki nokta arası haberleşme prototipi, yazılım tanımlı radyo üzerinde kurulmuştur.

Anahtar Kelimeler: Enerji Harmanlama, Enerji Verimliliği, Optimizasyon, Yazılım Tanımlı Radyo, Uygulama, Çevrimdışı Çözüm, Tembel Çizelgeleme

To my family and friends

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
M2M	Machine to Machine
EWMA	Exponentially Weighted Moving Average
WCMA	Weather-Conditioned Moving Average
KSEP	Kalman based Solar Energy prediction
SSEP	Simple Solar Energy prediction
CSI	Channel State Information
SUMT	Sequential Unconstrained Minimization Technique
SNR	Signal to Noise Ratio
SDR	Software Defined Radio
USRP	Universal Software Radio Peripheral
UHD	USRP Hardware Driver
ETLS	Expected Threshold Lazy Scheduling
NTP	Number of Transmitted Packets
NRP	Number of Received Packets
PSR	Packet Success Rate
NPR 80	Number of Packets Retransmitted for %80 Packet Success Rate
FTW	Forschungszentrum Telekommunikation Wien

CHAPTER 1

INTRODUCTION

Indiscriminate usage of resources up to now caused a major damage in the world. For instance, oil and gas reserves are estimated to be exhausted in about 100 years. This worried people about how the future of the world will be and triggered us to focus on researches on different energy sources and efficiency in any research area.

Efficiency and renewable sources gained importance on communication systems. Communication devices independent of cable that brings mobility and ease of operation in terms of energy to the applications having been frequently used. All these devices such as mobile phones, tablets, sensors can operate longer with ambient energy usage. Especially for Wireless Sensor Networks, usage of harvested ambient energy will be more efficient due to the predictable energy usage schedule. Providing energy from renewable sources makes energy efficiency more important in these types of applications.

Energy can be gathered by environment friendly sources such as solar power, thermal energy, wind energy, salinity gradients, and kinetic energy. With the use of environmental energy applications needs to work in conditions that is very difficult to change batteries have been implemented. Usage of harvested energy should be controlled accurately to use it more efficient in all these wireless sensor network applications. Controlling the limited energy depending on variable sources comes with various problems. Resources such as buffer, energy and time should be scheduled such that energy consumption would be minimized.

In the next chapter, energy harvesting systems are reviewed with types, usage areas and related researches. In the third chapter of the thesis, transmission completion time minimization problem is set up and solved developing a method for computing an optimal power and rate allocation. An offline solution that needs to adjust its transmission power and rate over the course of transmission with respect to channel state, packet arrivals and energy harvests for the problem with a rechargeable transmitter is proposed under fading conditions.

Paralleling the growing need for a sustainable ICT infrastructure, there is growing interest on energy efficiency in the design of communication systems. A strong and consistent thread in the related literature has been the theoretical work on energy efficient data transmission scheduling on point-to-point communication links.

Minimizing energy consumption on point-to-point channels relies on the basic relation of transmission rate and required power for a fixed bit error rate which suggests transmission of data packets over longer periods in order to exploit high bit/energy ratios at low transmission rates. In Chapters 4 & 5, the main criticism often received about the basic assumption of a convex relationship between energy consumption & communication rate is practically justified on an experimental testbed, software defined radio. On the other hand, delay requirements restrict unlimited extension of data packets and this makes packet delivery at lowest possible rates impractical. Accordingly, energy minimization objective and delay constraints apply opposing tensions on the transmission time of individual packets.

Theoretically energy reduction by *lazy schedules* [1] based on this assumption have been shown to be possible. However, transmission schedules have not been evaluated on an actual communication systems, particularly due to hardware constraints of commercial transceiver architectures, and partly because of the difficulty of adapting transmission rate or power in response to higher layer state information (such as the state of packet buffers). In the second main part of the thesis, starting from chapter 4, theoretical works based on this observation are investigated in practical dimension. Implementation of three transmission policy is realized on an actual transmission media using software defined radio.

The thesis is composed of two main parts. The first part including Chapter 2 and Chapter 3 is directly related to the theoretical work on packet scheduling on energy harvesting sensor networks. The second main part, composed of Chapters 4, 5, is concerned with implementation of energy efficient scheduling algorithms. Implementation of energy efficient algorithms is perfomed on software defined radio. Experimental work and obtained results are stated with figures in Chapter 4. Software defined radio, related hardware and software requirements to set up experimental environment are reviewed in Chapter 5.

CHAPTER 2

ENERGY HARVESTING SYSTEMS AND RELATED WORKS

Energy harvesting is the use of ambient energy captured from sources such as solar irradiation, the temperature difference, wind power, salinity gradients, and motion and vibrations to provide electrical power for small electronic and electrical devices.

Advanced technical developments have increased the efficiency of devices in capturing trace amounts of energy from the environment and transforming them into electrical energy. Wireless communication technology allows electronics and sensors to transmit data from remote locations. Through the wireless technology, researches and applications that contain sensor technology become feasible and useful in most scenarios that can not be implemented by sensors or communication devices with cable. However, for some applications such as habitat monitoring [2], volcano monitoring [3], structural monitoring [4], [5] and vehicle tracking [6], it is a hassle to ensure the continuity of applications due to the shortage of power supply. When a wireless node is deployed at a remote site where a wall plug or a battery is either unreliable or unavailable, energy harvesting can augment or supply power.

2.1 Energy Sources and Characteristics

Solar Energy is captured from sunlight or artificial lighting via photo sensors, photo diodes, or solar panels. Solar outdoor irradiation can be characterized as uncontrollable and predictable. Amount of available energy per cm^2 is 100mW and 15mW/cm^2 can be harvested due to 15% conversion efficiency characteristic with solar cell technology [7]. A solar panel can be considered as a current source and the current obtained is directly related to the size of the panel. In addition, intensity of the light becomes an important factor of deriving more current. Solar Energy harvesting can be used in a system that intelligently manages energy transfer for perpetual operation without human intervention or servicing [8], building micro-solar power subsystems for wireless sensor network nodes [9]. Some implementations of solar energy harvesting wireless sensor nodes are illustrated in Fig. 2.1(a) and Fig. 2.1(b). Key issues and tradeoffs which arise in the design of solar energy harvesting must be considered to maximize the efficiency of harvesting procedure[10],[11].

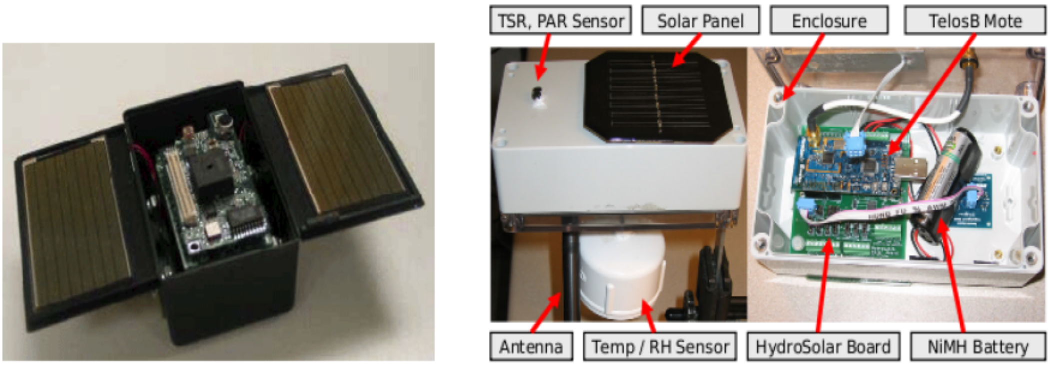

Figure 2.1: (a) HydroWatch weather node [9].(b) The Heliomote prototype node[10].

Wind is an alternative ambient resource which is *also* predictable and uncontrollable. Anemometers are used to harvest energy which can reach up to 1200mWh/day from wind power.

Finger Motion and footfalls are kinetic energy sources that can be obtained user's everyday actions to generate power through electromagnetic or piezoelectric [12], [13]. This type is fully controllable and has 19mW and 67mW available energy under piezoelectric technology. This technology uses piezo-electric elements. Electric energy is generated via applying force upon piezo-electric films and ceramics and deform. With 11% and 7.5% conversion efficiency, 2.1mW and 5mW energy can be harvested from these type of active human power.

Exhalation, Breathing and Blood Pressure can also be used as energy resources [13]. They are characterized as uncontrollable and predictable passive human power. Efficiencies of these type are relatively high that is about 40-50% and on average 0.4mW can be harvested.

2.2 Using Harvested Energy

Overall, harvested energy usage can be divided into two architectures. 1)Harvest-Use, 2)Harvest-Store-Use.

2.2.1 Harvest-Use

Harvested energy directly supplies the node and is used instantly in harvest-use method. In this case, energy must be much more than the energy that operation needs. This causes the node to be ON or OFF. If harvested energy is less than required, the node will be disabled. This architecture can be built on active or passive user activities such as walking, pedaling, pushing a key so that energy can be provided to send short wireless messages [14]. Likewise, a piezoelectric material placed inside a shoe can be deformed when walking and running and can be used to monitor the energy collected and track the user by sending RFID signals [12], [13], [15].

2.2.2 Harvest-Store-Use

In this architecture, harvested energy is used for transmission and stored at the same time. When harvested energy available is more than current usage, storing is useful. Energy can be used when uncontinuous harvesting profile occurs or the system requires more energy such as in heavy data traffic. The mode that using the harvested energy at an appropriate rate such that the system continues to operate over a prolonged period is defined as energy-neutral operation. A harvesting node is said to achieve energy neutral operation if a desired performance level can be supported forever [16]. Energy-neutral operation of a wireless sensor network of MicaZ motes is demonstrated through electromagnetic vibration energy harvesting in [17].

As an example, a Harvest-Store-Use system can use solar energy characterized as uncontrolled but predictable [8]-[11]. When the resource is available, daytime, energy is used for work and also stored for later use. When the resource is unavailable, the stored energy is conservatively used to power the sensor node. Another advantage of this system is providing an optimization chance to use stored energy efficiently.

2.3 Energy Efficiency

Harvesting energy from environmental sources is an important facility for a wireless sensor and M2M networks [18] to sustain itself. Different technologies to harvest energy and constraints mainly based on storage capacity, delay, communication rate and quality leads to different problems. Recently, maximizing the lifetime of such systems become an important research area [19]. Optimal packet scheduling problem that mainly focuses on minimizing transmission duration of all data packets by adaptively change the transmission rate according to traffic and available energy in a single-user energy harvesting wireless communication system is considered in [20]. The minimization of transmission completion time problem is solved for 2-user AWGN Broadcast Channel with a static data pool using an iterative offline algorithm, Flowright, in [21]. This problem is extended to the scenario which lets data arrivals to occur during transmission in [22], [23]. In [24] and [25] capacity bounds of an AWGN channel are studied. Shannon Capacity of a sensor node with energy harvesting source is found when it is transmiting over a fading AWGN channel [26]. Transmission completion time minimization problem on a fading channel with static data pool is solved in an offline manner so that energy arrivals and channel states are known [27]. In [28], a finite-horizon online throughput-maximizing scheduling problem formulation is formed and the optimal solution structure of the problem within a dynamic programming formulation and a low complexity online scheduling policy are proposed. A solution to a scheduling problem under two scheduling scenarios is provided in [29]. A common decision theory problem, Restless Multi Armed Bandit, is applied to a single hop network that is composed of m energy harvesting nodes and a fusion center collecting data from these nodes. An online heuristic that does not need prior knowledge of data and energy arrival is shown to achive closely to optimal in [30]. A low complexity online algorithm obtaining near-optimal performance both in asymptotically and short-term is derived in [31]. In [32], a common multiple-antenna access point that receives feedback from energy harvesting users is considered. Optimization of the number of feedback bits allocated by the users is studied. Another feedback optimization problem is studied for miso downlink multiuser system with energy harvesting users in [33]. Optimization in the duty cycle is a way to provide energy efficiency and increasing the lifetime of a wireless sensor network. An algorithm that changes the duty cycle of the sensor node is proposed and the implementation of a new communication technology, Bluetooth Low Energy (BLE), in a way to ensure energy neutral operation is realized in [34]. The allocation problem of renewable energy is considered and represented as stochastic knapsack problem formulation for an energy harvestin acces point on the move in [35].

2.4 Prediction of Energy Harvesting

In section 2.0.1, some energy resources are classified as predictable and unpredictable. Prediction of an energy source such as sun will not be exactly accurate due to sun's cycle and weather conditions. However, smart algorithms can estimate energy that can be gathered from the source sufficiently. Predictable resources can be traced for a time period and future arrivals from the source can be estimated. Exponentially weighted moving average (EWMA) algorithm is a way to predict a source. This algorithm is a type of infinite impulse response filter that applies exponentially decreasing weighting factors. An efficient and reliable solar prediction algorithm, Weather-Conditioned Moving Average (WCMA) that is shown to achive gains of more than 90% in energy utilization with respect to EWMA on a node is proposed in [36]. An online resource allocation algorithm called PTF-on that can estimate energy arriving to a base station is proposed in [37], [38]. The prediction algorithm, Kalman Based Solar Energy Predictor (K-SEP), uses Kalman filter for solar energy prediction. S-SEP, simple solar energy prediction algorithm is also proposed in [37], [38] to deal with simpler computations. Performance comparison of S-SEP and K-SEP for sunny and cloudy conditions is illustrated in Fig.2.2.

Prediction algorithms can help in going from offline solutions that generally assumes energy and data arrivals are known to online solutions. Next, we will study some offline optimization approaches.

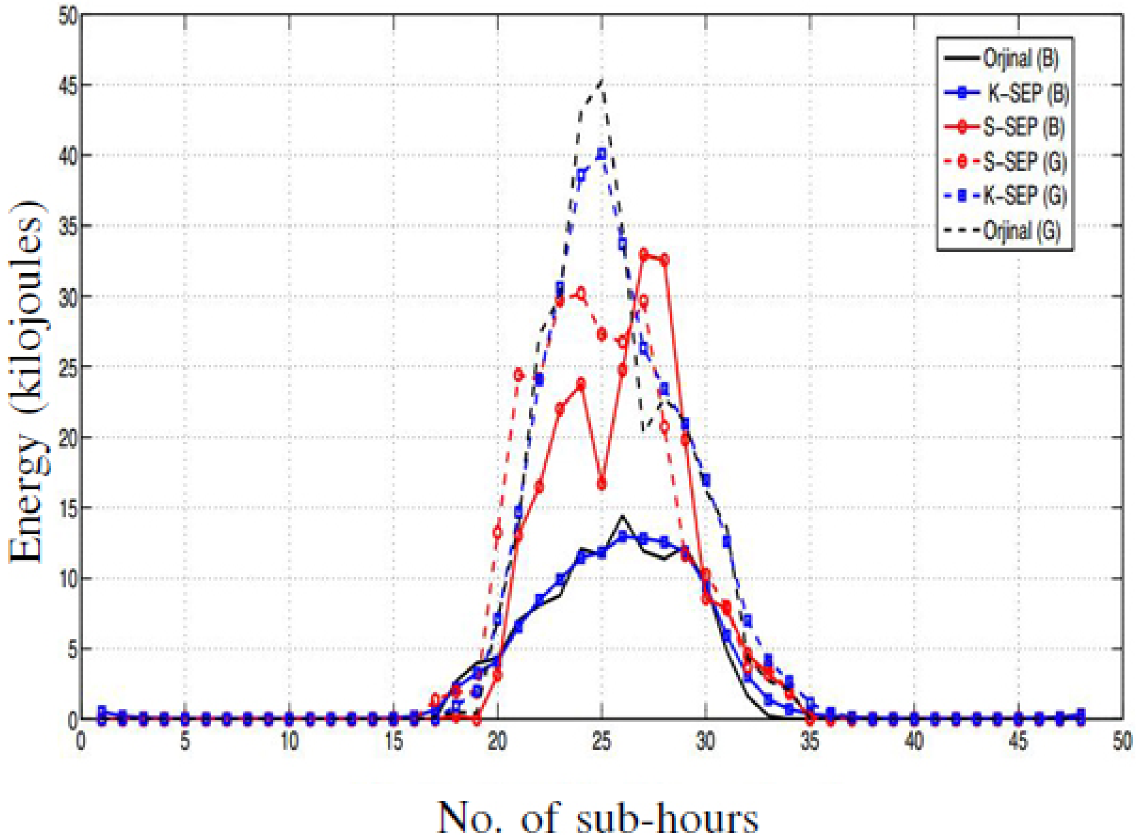

Figure 2.2: Performances of K-SEP and S-SEP compared for both sunny and cloudy conditions [37]

CHAPTER 3

THE OFFLINE PROBLEM OF TRANSMISSION COMPLETION TIME MINIMIZATION FOR AN ENERGY HARVESTING TRANSMITTER UNDER FADING CHANNEL

In the previous chapter, energy harvesting systems, types of harvesting resources and problems on the area are considered. It is shown that offline solutions allow us to see the limits of the system and they mostly appear in the literature as the starting point of the online solutions. In this chapter, the offline problem, minimization of transmission duration of data packets over an energy harvesting fading channel is studied.

Energy harvesting communication systems use environmental resources that produce energy in an arbitrary manner. The uncertainty in obtaining energy requires us to use our resources such as battery, buffer, channel carefully. Smart transmission policies are of critical importance to use energy as efficient as possible. Forming the optimal schedule for a transmission period, requires having exact information about the future of channel, data ready to be transmitted, available energy in the battery, channel state etc. However, in practice, data in the buffer or energy arrivals are not known exactly in general.

Offline scheduling policies assume that no randomness in the system such as data, energy arrivals or channel state is known for any slot. This approach may not be practically justifiable. Although in practice it is not possible to know all uncertainties exactly in the system model, offline solutions are crucial to see the boundries of the system. Knowledge about the best solution of the problem is beneficial in terms of developing the performance and discussing adequacy of our solutions.

In this part of the thesis, the problem formulation in [27] that considers optimization of point-to-point data transmission with an energy harvesting transmitter in a fading channel is extended by changing static data pool assumption. Specifically, optimal power and rate allocation for data packets arriving at arbitrary but known instances is studied. Communication takes place under a fading channel and transmitter is restricted with a limited energy storage capability. An optimal policy takes into account the channel state as well as the state of energy and data buffers. Moreover, a solution needs to strike a trade off between energy efficiency and delay. By exhibiting an equivalent convex problem, the unique optimal scheduling solution is obtained through an iterative convex optimization technique, *sequential unconstrained minimization*. The optimal solution under finite and infinite energy storage is examined on problem instances. [39] is a compressed version of the study presented in this chapter of the thesis.

3.1 System Model

Consider a point-to-point communication system under fading channel with additive Gaussian noise. In this offline formulation, we shall assume channel side information (CSI) is available at transmitter through a non-causal perfect feedback channel so that transmitter has knowledge of future channel states before transmission starts. Transmission is supplied by the harvested energy, arriving at arbitrary instances, which are also known at t = 0. We also let data packets to arrive at arbitrary known times during the course of transmission as illustrated in Figure 3.1.

The transmitter is capable of storing harvested energy and data in the battery and a data buffer, respectively. An example arrival and fade level sequence is shown in Figure 3.1. In this model, we assume energy and data to become available instantly and until a given time instance t, total amount of harvested energy and arrived data are denoted by E(t) and B(t), respectively. In addition, fade level of the channel at time t is given by h(t). Any arrival of energy or data or a change in fade level is called an event and an epoch is defined as the inter-arrival times between any two pipelined events. The length of the i^{th} epoch is ξ_i = t_{i+1} - t_i. The received signal is $y = \sqrt{h}x + n$, where x and $\sqrt{h}$ are the discrete time channel input symbol and channel

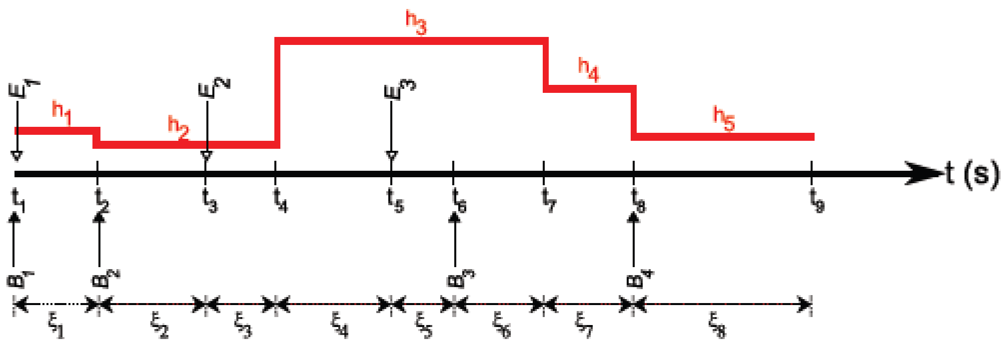

Figure 3.1: An example sequence of events: t_i, $i \geq 1$ are event times (energy harvests marked as E_i, channel state changes, h_i, or data arrivals B_i). The ξ_i denote inter-event epoch durations.

gain, and n is zero-mean unit variance Gaussian noise. Assuming the channel state h lasts sufficiently long for an average power constraint P, capacity of the discrete-time real AWGN channel is given by,

$$C = \frac{1}{2}log_2(1 + hP)$$

The achievable rate in i^{th} epoch is given by: $r_i = \frac{1}{2}log_2(1 + h_i p_i)$. The transmitter is assumed to achieve this rate with a certain tolerable error probability so that it is possible to transmit a finite number of bits with a finite amount of energy. The power level used to transmit a codeword at the achievable rate r_i on a channel with $\sqrt{h_i}$ channel gain level in the i^{th} epoch is given by: $g(r_i) = \frac{2^{2r_i}-1}{h_i}$.

3.2 Transmission Time Minimization Problem

We are interested in finding the schedule, that is, sequence of rate and power allocation, in order to minimize the overall transmission completion time for packets arriving by a certain time window W < ∞.

Only resources available up to that point can be used in an optimal policy (causality constraint). Due to the concavity of rate as a function of power, one can further narrow down the possible set of allocations by considering schedules that do not change power levels within epochs. With this statement, we are now ready to state the problem in terms of power allocation to each epoch. A final technical assumption, which is that there is at least a feasible schedule completing transmission within the first k^{up}, is required to guarantee the existence of the solution.

Problem 1: **Transmission Time Minimization of Packets on an Energy Harvesting Fading Channel:**

Minimize $T = T(\{r_i\} 1 \leq i \leq k^{up})$

subject to: $r_i \geq 0$

$$\sum_{i=1}^{k} g(r_i)\xi_i \leq E(t_k), \sum_{i=1}^{k} r_i\xi_i \leq B(t_k) \tag{3.1}$$

$$\sum_{i=1}^{k^*} r_i\xi_i + r_{k^*+1}(T - \sum_{i=1}^{k^*} \xi_i) = B(T) \tag{3.2}$$

for $k = 1, 2, ..., k^* = max\{i : \sum_{j=1}^{i} \xi_j \leq T\}$

In Problem 1, last epoch used in the schedule is denoted by k^*. First part of (3.1) is energy causality constraint while the second part is data causality constraint. (3.1) prevents the use of energy and data more than available. Equation (3.2) ensures that all data in the buffer are transmitted at the end of the transmission period.

3.2.1 An Equivalent Problem & Solution

In the previous section we have defined the problem in terms of a non-convex optimization problem. For the solution of the Problem 1, we follow a similar approach as in [40]. Specifically, we define another optimization problem which is convex and equivalent to the Problem 1. Given a deadline constraint T, Problem 2 aims to find an optimal scheme which maximizes the number of transmitted bits. The problem is again built on the causality and data completion constraints. However, this time we do not restrict the number of available data bits in the last epoch so that there will always be a solution to the problem. Note that, the reason for formulating Problem 2 is to find a solution to the Problem 1. In the following lemma we state the equivalence of these two problems.

Problem 2: **Energy Consumption Minimization of Packets on an Energy Harvesting Fading Channel:**

$$\text{Minimize } E(T) = \sum_{i=1}^{k^*} g(r_i)\xi_i + g(r_{k^*+1})(T - \sum_{i=1}^{k^*} \xi_i)$$

subject to: $r_i \geq 0$

$$\sum_{i=1}^{k} g(r_i)\xi_i \leq E(t_k), \sum_{i=1}^{k} r_i\xi_i \leq B(t_k) \quad (3.3)$$

$$\sum_{i=1}^{k^*} r_i\xi_i + r_{k^*+1}(T - \sum_{i=1}^{k^*} \xi_i) = B(T) \quad (3.4)$$

for $k = 1, 2, ..., k^* = max\{i : \sum_{j=1}^{i} \xi_j \leq T\}$

Lemma 1: When problems 1 and 2 are defined over the same event sequence, any solution of Problem 2 with the deadline constraint *T* is also a solution to Problem 1 with the minimum transmission completion time specified as *T*.

Proof. Consider two different allocations (schedules) S^1 and S^2 as an optimal solution to the problems 1 and 2, respectively. Let T_1 be the completion time of S^1, and the deadline constraint of S^2. By T_1 the corresponding number of transmitted data of both schedules must be the same since the opposite claim will contradict the optimality of the allocation resulting in a smaller number of transmitted bits. Now we have 2 different schedules completing the transmission of same number data at the same time. Thus, both allocations S^1 and S^2 are possible solutions to problems 1 and 2. Convexity of Problem 2 is shown next.

Lemma 2: Problem 2 is a convex optimization problem.

Proof. Since the feasible set of allocations forms a convex region and objective function of the problem is a non-negative weighted sum of increasing concave functions, problem 2 is convex [41].

Corollary 1: Solution of Problem 1 is unique.

Proof. Uniqueness of Problem 2 follows from the convexity of the problem. Since any solution of Problem 1 is $also$ a solution to Problem 2, Problem 1 must $also$ have a unique solution. In the next, we will loosely refer to Problem 1 as the "primal problem", without establishing a Lagrangian duality between the two problems.

3.2.1.1 Solution of the Equivalent Problem

As shown in Lemma 2, Problem 2 is a convex optimization problem. To solve this problem, we use the same optimization technique as in [40]. Specifically, sequential unconstrained minimization technique (SUMT) is applied for the setting of Problem 2. This technique is based on formulating a constrained convex problem as an unconstrained optimization problem with additional penalty terms. For our case, Problem 2 can be redefined as an unconstrained minimization problem as follows:

Problem 3: **Unconstrained Minimization Problem:**

Minimize: $F(r) = \left(\sum_{i=1}^{k^*} g(r_i)\xi_i + g(r_{k^*+1})(T - \sum_{i=1}^{k^*}\xi_i)\right) + \mu P(r),$

where,

$$P(r) = \sum_{i=1}^{k^*+1} (\max(0, -r_i))^2 \tag{3.5}$$

$$+ \sum_{i=1}^{k^*+1} \left(\max(0, \sum_{i=1}^{k} g(r_i)\xi_i - E(t_k))\right)^2 \tag{3.6}$$

$$+ \sum_{i=1}^{k^*+1} \left(\max(0, \sum_{i=1}^{k} r_i B(t_k))\right)^2 \tag{3.7}$$

$$+ \left(\sum_{i=1}^{k^*} r_i\xi_i + r_{k^*+1}(T - \sum_{i=1}^{k^*}\xi_i) - B(T)\right)^2 \tag{3.8}$$

Problem 3 is obtained from Problem 2 by adding penalty terms (3.5, 3.6, 3.7, 3.8) to the objective function. Note that, if an allocation is feasible, corresponding additional penalty becomes zero. The algorithm begins with an initial constant power allocation, consuming all the harvested energy without considering causality or battery size constraints, and an initial penalty parameter μ. After each iteration parameter μ, which determines the effect of penalty terms, is doubled and power allocation vector is updated by Newton's method. Newton's method is a powerful optimization technique for unconstrained minimization problems. This method iteratively approaches the global minimum working over first and second order partial derivatives. We have a modified rate allocation vector after the n^{th} iteration as follows:

$$r^{n+1} = r^n - [[\nabla^2 F(r^n)]^{-1} \nabla F(r^n)]$$

In this method, Newton decrement is an important quantity and defined as: $\lambda(r^n) = (\nabla F(r^n)^T [HF(r^n)]^{-1} \nabla F(r^n))^{1/2}$. The algorithm terminates if either reaches a predefined value or the Newton decrement becomes smaller than a predefined threshold. This algorithm is the basis of the solution of Problem 1, which we detail in the next subsection.

3.2.2 Solution of Problem 1

So far we have shown a way to solve Problem 2. To the solution of primal problem, our approach is to utilize the equivalence of these two problems. First we note that, it is possible to find upper and lower bounds on the transmission completion time of Problem 1. Since the total number of transmitted data D(T) is a monotonically increasing and continuous function of T [27], one can obtain upper and lower bounds on the solution by running SUMT for different deadline values. We first select the deadline as the end of last data arrival epoch and check the number of transmitted data. If it is not possible to complete transmission within this deadline, we increase it by the next epoch length. This procedure is repeated until the resulting number of transmitted data is more than total number of available bits so that upper and lower bounds are obtained. Next, we keep running SUMT iteratively regarding bisection method. After each iteration upper and lower bounds are updated and a new deadline is chosen as the average of these bounds. The difference between upper and lower bounds is strictly decreasing and procedure is stopped when this difference goes below a predefined threshold.

1: $r_i \leftarrow \frac{B(T)}{T}, \mu \leftarrow initialvalue$

2: **repeat**

3: **r** $\leftarrow InnerMethod(r)$

4: $\mu \leftarrow \eta\mu$

5: **until** $\mu \geq \mu_{max}$

Algorithm 1: SUMT Algorithm

1: **repeat**

2: $F_{previous} \leftarrow F(r)$

3: $\nabla r =$ - [HF(r^n)]$^{-1}$ $\nabla F(r)$

4: $\lambda(r)$ =($\nabla F(r)^T [HF(r)]^{-1} \nabla F(r))^{1/2}$

5: r $\leftarrow r + \nabla r$

6: **until** $\lambda(r) \leq \epsilon_N$

Algorithm 2: Newton's Method

N $\leftarrow \underset{k \in [1,2,\ldots,k^{up}]}{\text{argmin}} (B(t_{k^{up}}) = B_{t_k})$
repeat
N $\leftarrow N + 1$
$E_{min} \leftarrow SUMT\_Algorithm(t_N)$
until $E_{min} \leq Et_N$
$T^{min} \leftarrow t_{N-1}, T^{max} \leftarrow t_N$
repeat
T $\leftarrow (T^{min} + T^{max})/2$
$E_{min} \leftarrow SUMT\_Algorithm(T)$

$T^{min} \leftarrow T$
endif
until $T^{max} - T^{min} \leq \epsilon_b$
$T^{min} \leftarrow T$

Algorithm 3: Time Minimization with SUMT Algorithm

3.3 Numerical Results

In this section we will examine an example run of the completion time minimization algorithm. Event sequence illustrated in Figure 3.1 is considered in the problem.We consider an AWGN fading channel with bandwidth of W = 1 kHz. The penalty parameter μ used in unconstraint minimization problem and growth parameter η is initialized as 1 and 2 respectively. The threshold values for Newton's method, SUMT (Sequential unconstrained minimization technique) and bisection are 10^{-8}, 10^{-10} and 10^{-3}, respectively. Under these circumstances, final schedules obtained from time minimization algorithm shown in Figure 3.2.

An example event sequence is given in Figure 3.2.b. The time interval from the initial time to the first change in channel state, $t = 2s$, is the first epoch of the scenario. It can be understood from Figure 3.2.b that there are 5 epochs in this event sequence. In Figure 3.2.a, the power used in each epoch is stated according to the final schedule returned by completion time minimization algorithm. It can be said that the algorithm

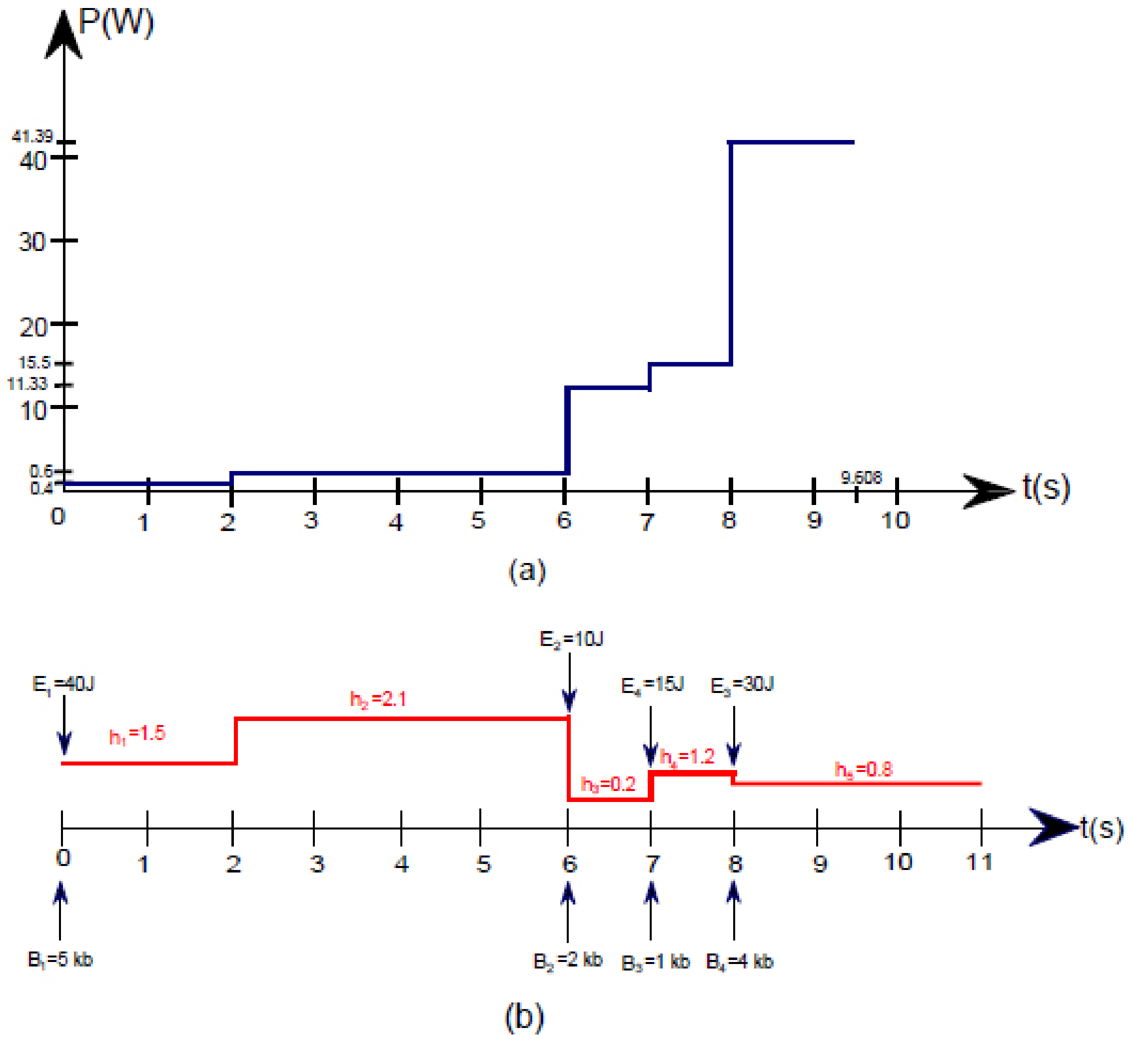

Figure 3.2: (a) Final schedule returned by completion time minimization algorithm. (b)An example event sequence. The SNR in the i^{th} epoch is h_i, the bandwidth is W = 1 KHz, energy harvest amounts and arriving data are marked as E_i and B_i, respectively.

uses the chance to transmit data using low power levels due to the sparse data arrivals and relatively good channel states. We can see that the algorithm tries to profit by good channel states and sparse data arrivals to use the energy in worse conditions.

CHAPTER 4

IMPLEMENTATION OF ENERGY EFFICIENT TRANSMISSION SCHEDULING POLICIES ON SOFTWARE DEFINED RADIO

Theoretical work on energy efficient transmission occasionally received criticism on the premise of the assumption about the convex and monotonic relation between energy and rate being simplistic. One of the reasons for the criticism is the fact that in many architectures, the RF energy consumption does not dominate the overall system energy consumption. This is true for many low power systems, such as wireless sensor nodes. Another criticism is that the effect of link layer mechanisms, such as packet headers, CRC checks, ARQ, etc, which, especially for the transmission of small packets, may destroy the idealized convex and monotone relationship between transmission rate and power.

Providing flexible control over physical layer parameters, software defined radio (SDR) platforms [42]-[45] facilitated the implementation and experimental validation of new wireless communication methods [46]-[49]. Besides, SDR implementations, which are compliant with popular and well studied specifications [50], are rather open to rapid prototyping and standardization.

This work set out to implement and test an analytically proposed energy efficient transmission scheme on hardware, to understand the degree to which the latter criticism is valid. To the best of our knowledge, this is the first implementation of energy efficient transmission scheduling policies based on power-rate adaptation in response to data traffic. Another contribution is measurements relating transmission power levels and 802.11g standard transmission regimes. The perfomance of transmission schedules are compared in terms of total energy consumption as well as backlogged data and packet success ratio. A compressed form of this study is given in [51].

This chapter of this thesis is organized as follows. A basic online lazy scheduling framework is described. Next, Expected Threshold Lazy Scheduling Policy (ETLS Policy) proposed in previous literature, and two benchmark policies, Hasty and Constant Policies, are introduced. Then the experimental setup and its specifications are described. Lastly, ETLS and two other predefined policies are compared , Hasty and Constant policy, in terms of consumed energy for transmission through implementation experiment.

4.1 ONLINE LAZY SCHEDULING

Consider a device receiving arbitrary amounts of data that need to be transmitted to a further destination within a finite time interval. Define a slot duration as the smallest interval of time in between two adjustments of rate/power. We will focus on the energy-efficiency of the transmission over a finite period of N slots. As a measure of energy effiency, we will use the sum of the total energy consumption within N slots and a nondecreasing cost function $C(b)$ which is assigned to penalize backlogging b bits at the end of the time horizon.

Let the data arrival process $\{B_n\}$, $n \geq 1$ be a discrete time process, such that $B_n \geq 0$ is the size of the data (in bits) received at the beginning of slot n. The energy used during one slot for transmitting at rate r (bits/slot) given by the following:

$$e(b, r) = p(r)min(\frac{b}{r}, 1)$$

The power function, $p(r)$, will be assumed to be convex and increasing in r. The minimum function takes care of the case when b, the number of bits stored in the buffer at the beginning of the slot, is less than r, in which case the transmission will cover only part of the slot. In particular, the cost $C(b)$ will be defined as:

$$C(b) = \alpha p(\frac{b}{\alpha})$$

where α is a custom parameter which determines the strictness of the deadline penalty. To model the natural restriction in practical systems where the choice of transmission rates are limited, the rate r will be assumed to belong to a discrete set V.

4.2 EXPECTED THRESHOLD LAZY SCHEDULING POLICY

The previous work shows existence of threshold based optimal policies for discrete power/rate sets [28]. This is not surprizing, as such threshold results often follow from dynamic programming formulations. The significance of the threshold based schedule in [28], however, is its low computational complexity.

We set out to implement the near-optimal heuristic, namely the Expected Threshold Lazy Scheduling (ETLS) policy, introduced in [28]. The ETLS policy will be turned into a low complexity online algorithm to be implemented on a practical system. At each slot, the ETLS policy selects one of the accesible transmission rates in the set V depending on the present data buffer state and the past data arrivals. For example, at slot n, the ETLS policy decides on a transmission rate r_n according to the following:

$$\begin{aligned} r_n &= \min\left\{r \in \mathbf{V} | L_n(B_1^n, r) \geq b_n\right\} \\ L_n(B_1^n, r) &= \max\left(r, r(N - n + \alpha) - \sum_{l=1}^{N-n} E\left[B_l | B_1^n\right]\right) \\ \text{for } r \neq r_{max} \quad &; \quad L_n(B_n^N, r_{max}) = \infty \end{aligned}$$

where b_n is the data buffer state at the slot *n*, B_1^n is the vector of past data arrivals $[B_1 ... B_n]$, r_{max} is the maximum rate in V and $L_n(B_1^n, r)$ is the data buffer threshold for selecting transmission rate *r*. The computation of the threshold value $L_n(B_1^n, r)$ relies on the optimal offline solution provided in [28]. Basically, the threshold $L_n(B_1^n, r)$ is set to a data buffer level at which selecting the transmission rate *r* until the end of time window is just sufficient to deliver the average number of bits that will be received in the remaining time or that are in the data buffer. In a practical scenario where the statistics of the data arrival process are unknown, the sum of data arrivals in the remaining can be estimated by moving average values. In the below,the pseudocode for a practical implementation of the ETLS algorithm is shown in Algorithm 1. In the following, we include several simple and basic suboptimal solutions for comparison purposes.

Hasty Policy: This is essentially a greedy policy. Contrary to the conservative policy above, it always selects the lowest possible transmission rate r_{max} in the set $\mathbf{V}$ that will not cause idleness in the next slot. The rate allocation is $r_{hasty}(b) = \max\{r \in \mathbf{V} | r \leq b\}$.

Constant Rate Policy: This policy uses a single transmission rate that keeps the data buffer stable. In particular, it selects the lowest transmission rate in the set $\mathbf{V}$ which is above the average data arrival rate. In the case where the arrival rate approaches the chosen constant rate (from below), the policy is asymptotically optimal, i.e. throughput maximizing. Such a constant rate policy has been proven to be optimal in the infinite horizon case [52].

```
Data: N, α, r_max
Result: ETLS power-rate decisions (ρ*_n, r*_n)
initalize average data income B̄ ← 0;
initalize r* ← r_max;
forall the n ∈ (1, N) do
    read data buffer b ← b_n;
    update average data income B̄ ← ((n−1)B̄ + B_n)/n;
    foreach r ∈ V do
        if r < r* then
            compute L_n(B_1^n, r) = max(r, r(N − n + α) − (N − n)B̄);
            if L_n(B_1^n, r) ≥ b_n then
                update r* ← r;
            end
        end
    end
    calculate the power level ρ*_n as p(r*);
    apply power-rate decisions (ρ*_n, r*_n);
end
```

Algorithm 4: Practical ETLS

4.3 System Description

In this study, ETLS policy and two alternative policies (Hasty and Constant Policy) are implemented on USRP testbed at the CNRG lab at METU. More information about the USRP hardware can be found in [37, 38].

In theoretical work, ETLS is shown to be near-optimal [30]. However, performance of ETLS and the other policies may change in a practical communication medium with respect to channel conditions and some restrictions on transmission rates. When the number of packets arriving at the receiver side is considered, channel conditions become more important to make a comparison between these policies. Main goal of this study is to investigate the performance of ETLS using 802.11g modulation settings (Regimes 2, 4, 6 and 8).

4.3.1 Hardware Specifications

For the experiments, a practical communication medium is established with a USRP-N200 with SBX daughterboard and 2 PCs. SBX daughterboard is prefered due to its controllable transmitter antenna gain feature and application area that includes 2.4Ghz ISM band. USRP-N200 architecture includes 3A-DSP 1800 FPGA and Gigabit Ethernet connectivity. The device is connected to a PC via its gigabit ethernet interface to stream data to host processors. Another PC is used as receiver side with Wireshark packet capturing application. More information about hardware used in the experiments and set-up instructions can be found in the next chapter.

4.3.2 Software Specifications

In our setup, FTW IEEE802.11a/g/p OFDM Frame Encoder [55, 56] which is able to generate and transmit standard-compliant IEEE802.11a, IEEE802.11g or IEEE802.11p (draft) frames using the GNURadio framework [57] have been employed and organized for compatibility with the new versions of GNURadio (version 3.6.4.1), the operating system (Ubuntu version 12.04) and USRP firmware. In the installation process of the system, UHD (USRP Hardware Driver version $UHD - 003.005.002$) which is the hardware driver for all USRP devices works with Linux, Windows and Mac is used. All tests on channels and the algorithms were implemented with Python Scripting Language (Python 2.7). The Wireshark application is used to detect empty channels and received packets. More information about specifications of software used in the experiments can be found in the next chapter.

4.3.3 Algorithm Implementation Specifications

Experimental section includes implementation of three algorithms which are expected to raise the performance in terms of energy expenditure in an actual communication environment. In a real communication environment, packets success rate (PSR) that means the ratio of transmitted and received packets is important in terms of the quality of the communication. For this reason, theoretical computations on energy computation are expected to change in real environment.

In the experiment IEEE 802.11g Regime-2, Regime-4, Regime-6 and Regime-8 are used for transmission. The main idea in choosing these regimes is to see the effect of just modulation changes on energy efficiency. 802.11g regimes used in the experiments and related modulations are given in Table 4.1.

First, a target PSR (80%) is set. To achieve the desired PSR for all regimes, a number of trials are conducted and RF output power settings for each regime are determined. One of the main reasons to suspect that theoretical transmission powers may not be realizable in practice is the potentially nonideal behaviour of RF output power in each regime. In Figure 4.5, average RF output power for each regime to achieve the target PSR is shown.

Channel 6 (2.437 GHz) is used for the implementation experiments. ETLS Policy is proposed in [30] by assuming that transmission rate is a concave function of transmission power. This implies that packet success ratio decreases as data transmission rate increases (from Regime-2 to Regime-8). To observe this relation in communication medium by using USRP, we investigate how packet success ratio behaves with transmission power. The results of the observation can be seen in Figures 4.1, 4.2, 4.3 and 4.4.

SBX daughterboard has 20dBm of maximum transmission power with 32 dB gain parameter. The real transmission power values may vary a little depending on some parameters such as the calibration of the device and system temperature. With this knowledge, the amount of energy used for each transmission power in each time slot is computed using the following expression and recorded during transmission:

$$E_{mJ} = T_{slot} * 10^{(-12+gain)/10} \tag{4.1}$$

PSR changes with data rate as well as packet size. To send a fixed amount of symbols sent in each regime, data rates in each regime are represented with B/timeslot in the algorithm. 802.11g regimes used and the corresponding Byte/Time Slot values are given in the Table 4.1.

Table 4.1: 802.11g data rates in each regime and corresponding Byte/TimeSlot values in the algorithm

Regime	Modulation	Mbps	Byte/Time Slot
2	BPSK	9	53
4	QPSK	18	106
6	16-QAM	36	212
8	64-QAM	54	318

4.4 Numerical Results

4.4.1 Deriving Antenna Gain vs Packet Success Ratio

Regime-2 uses BPSK modulation. In this case, symbol error rate is lower than that in higher modulation types; therefore, packet success ratio (PSR) with BPSK become higher than that with other modulation types. 80% packet success ratio can be achieved with -2dBm RF output power whereas 92-93% packet success ratio can be achieved with 8dBm (Please see Figure 4.1). The results are derived by repeating the experiment at least ten times for each RF output power and averaging the results, because packet success ratio varies due to changes in the channel. To illustrate, packet success ratio may have a 70% decrease in a test even if RF output power is 8dBm. Although RF output powers are selected from these plots to fulfill 80% PSR goal, this value may not be obtained at the end of the transmission, due to channel variations. To reach 80% PSR, sending packets with regimes showing performance below desired value is considered after transmission. If g=(*Number of transmitted packets-Number of received packets*) and the actual (measured) PSR is p, we transmit an extra g/p packets to reach 80% PSR. The code rate is fixed at $3/4$.

Comparing Regime-2 and Regime-4 results, we observe that 80% PSR is achieved with -2 dbm RF output power for Regime-2 whereas it is achieved with -0.2 - 0 dBm in Regime-4. As the results for Regime-2, the results for Regime-4 are derived by repeating the experiment more than ten times for each RF output power and averaging of results. Due to the channel variations, PSR may rarely become very low (50%) and very high (95%) in some trials. As RF output power increases from -2 dBm to 8 dBm, PSR increases from 75% to 90% (Please see Figure 4.2 .)

In Regime-6, averaging large number of experimental runs, we determine that 80% PSR is achieved on average with 6 dBm RF output power. 76% PSR is achieved with

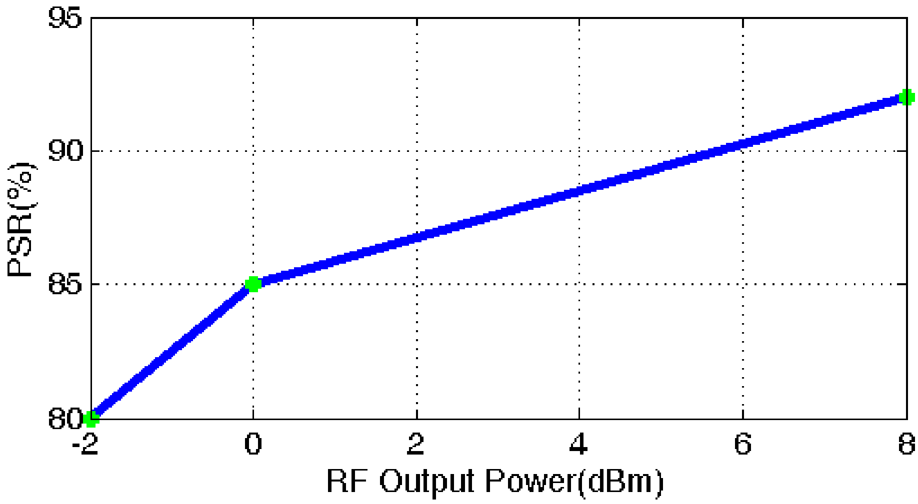

Figure 4.1: PSR vs. RF Output Power for Regime-2 (9 Mb/s data transmission rate) in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

0 dbm whereas 86% PSR is achieved with 20 dBm RF output power. (Please see Figure 4.3.)

In Regime-8, as expected, a much lower PSR than others is observed, and the PSR is much more sensitive to the channel variations, such that even with the highest RF output power (20 dBm), 80% PSR is rare. Regime-8 performs a similar performance for both 18dbm and 20dbm RF output power (Please see Figure 4.4).

Experimental results of PSR-Antenna Gain exhibit a concave relationship, as expected (Please see Figure 4.5). The concave behaviours of each regime can also be seen with RF output power in mW (Please see Figure 4.6).

4.4.2 Comparison of Three Policies

In this experiment, ETLS is compared with Hasty and Contant Policies in terms of packet success ratio and energy consumption. The data arrival process is modeled as a Markovian process with state transition probabilities $p_{00} = 0.75$, $p_{01} = 0.25$, $p_{10} = 0.52$ and $p_{11} = 0.48$. Same data arrival process is used for all experiments.

The *Hasty policy* tries to transmit all data in the data buffer in each time slot. Therefore, the hasty policy sets the transmission rate to the highest possible rate that is not

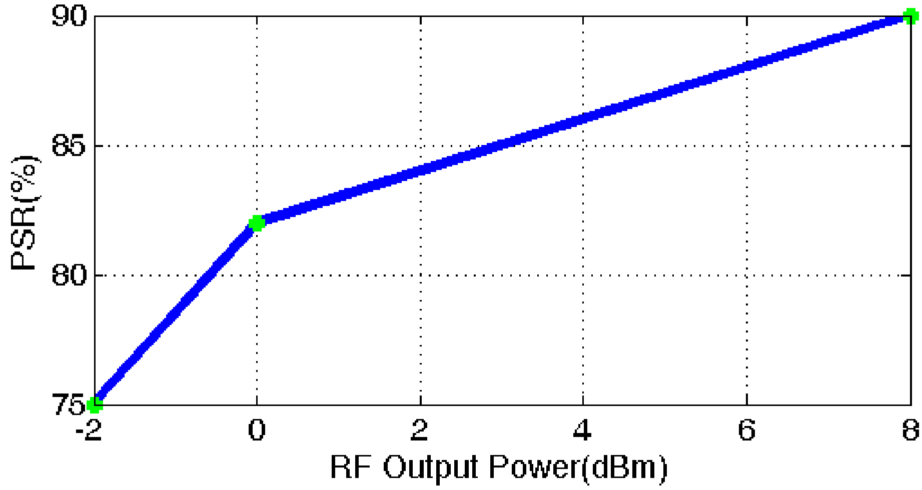

Figure 4.2: PSR vs. RF Output Power for Regime-4 (18 Mb/s data transmission rate) in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

Table 4.2: Packet Success Ratio (PSR) of each regime used in Hasty Policy and the number of packets to be retransmitted for 80% PSR (NPR 80)

	Regime-2	Regime-4	Regime-6	Regime-8	Total
NTP	-	9	34	90	133
NRP	-	7	26	63	96
PSR	-	77.8%	76.5%	70%	76.5%
NPR 80	-	0.25	1.57	12	13.82

too high, considering the amount of data in the buffer (setting rate too high would create idleness within the slot, which is not meaningful.) This policy results in high energy consumption in each slot as illustrated in Figure 4.7.

Hasty policy consumes high energy since the transmission rate is a concave function of data transmission power. In addition, hasty policy consumes more energy to achive desired PSR.

Total PSR, PSR for each regime used during transmission and the number of retransmitted packet to reach 80% PSR are shown in Table 4.2.

Table 4.3 represents total energy consumption in first phase and second phase (after considering packets to be retransmitted for 80% PSR).

ETLS Policy aims to minimize power consumption by spreading the transmission across the transmission window as much as possible. To keep remaining data as low as possible at the end of finite horizon deadline, statistics of the packet arrival

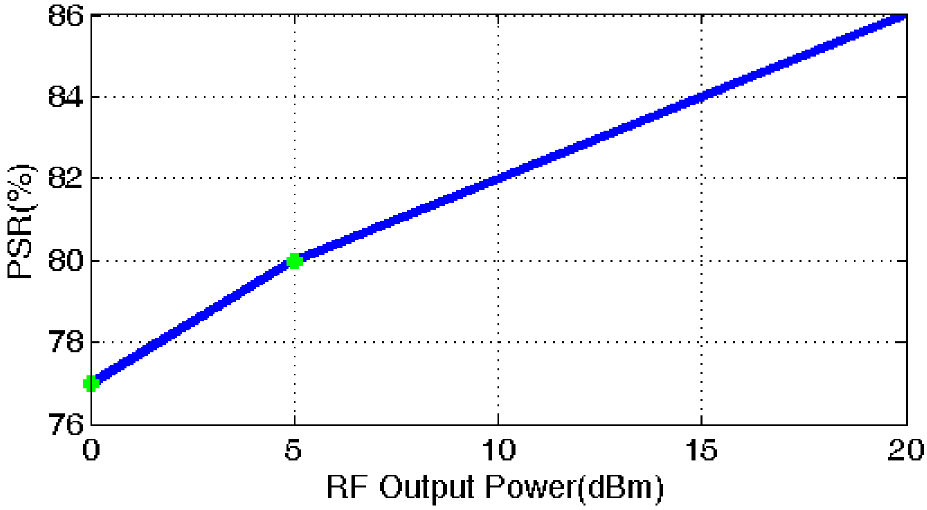

Figure 4.3: PSR vs. RF Output Power for Regime-6 (36 Mb/s data transmission rate) in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

Table 4.3: Total energy consumption of Hasty Policy in first and second phase

Total Energy Consumption in First Phase	261 μJ
Total Energy Consumption after Second Phase	296 μJ

process must be known. In each time slot, packet arrival process is estimated by using statistics of previous data arrival process. Thus, ETLS estimates the statistics of future data arrival process better by time. This results with lower energy consumption than Hasty Policy as illustrated in Figure 4.8.

Total PSR, PSR for each regime used during transmission and the number of retransmitted packet to reach 80% PSR are shown in Table 4.4.

Table 4.5 represents total energy consumption in first phase and second phase (after considering packets to be retransmitted for 80% PSR).

Constant Policy is proposed by assuming that Markov Model data arrival process is known. This knowledge makes Constant Policy more advantageous than other policies. Considering data arrival process, Regime-4 that provides the best result for Constant Policy is chosen.

The consumed energy by Constant Policy in each slot is shown in Figure 4.9. It is expected that consumed energy in each slot be equal. However, in some slots the number of data packets may be lower than the number of packets that can be

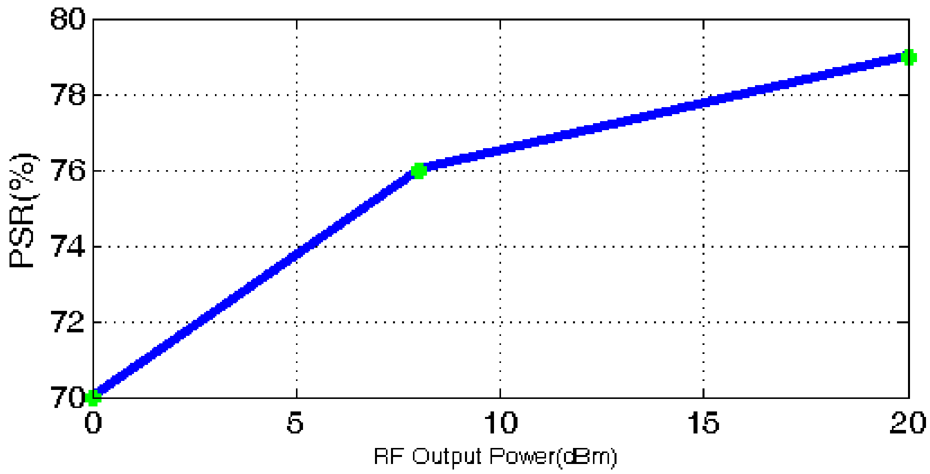

Figure 4.4: PSR vs. RF Output Power for Regime-8 (54 Mb/s data transmission rate) in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

Table 4.4: Packet Success Ratio (PSR) of each regime used in ETLS Policy and the number of packets to be retransmitted to reach an effective 80% PSR (NPR 80)

	Regime-2	Regime-4	Regime-6	Regime-8	Total
NTP	26	106	-	-	132
NRP	20	83	-	-	103
PSR	77%	78.3%	-	-	78.03%
NPR 80	1.04	2.3	-	-	3.34

transmitted with the selected rate in one slot duration. Thus, consumed energy can be less than expected for some slots.

Results in Tables 4.3, 4.5, 4.7 are too small values due to the size of the data packets. At the end of the transmissions, totally, 6.8 kB of data are transmitted. In an operative communication system, transmitted data will be more than this and the energy consumption differences will make more sense. In addition, to operate the communication in a wider area (more than a room), an amplifier will be needed. So, energy consumption differences will be much more important. In this experiment, the main goal is to run these algorithms in a real communication media and see the proportional differences between the policies.

Total PSR, PSR for each regime used during transmission and the number of retransmitted packet to reach 80% PSR are shown in Table 4.6.

Table 4.7 represents total energy consumption in first phase and second phase (after considering packets to be retransmitted for 80% PSR).

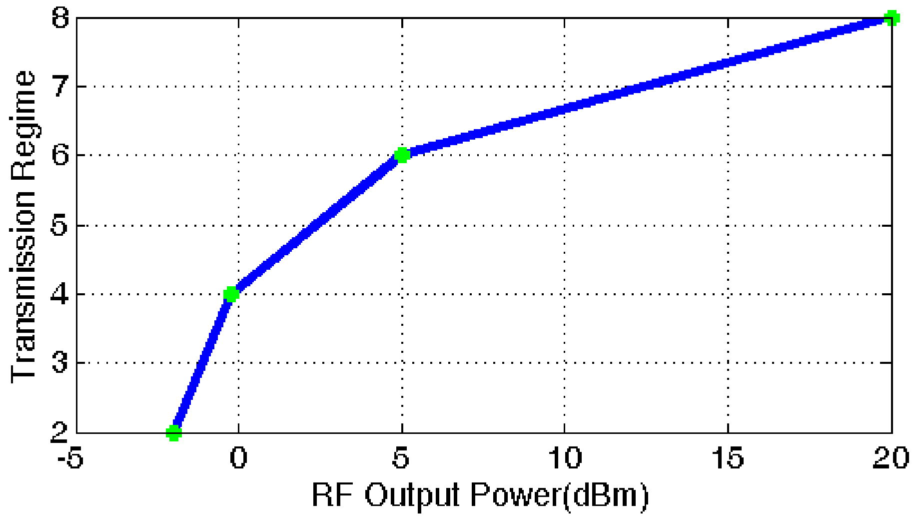

Figure 4.5: RF Output Powers required for 80% Packet Success Ratio vs. Regimes in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

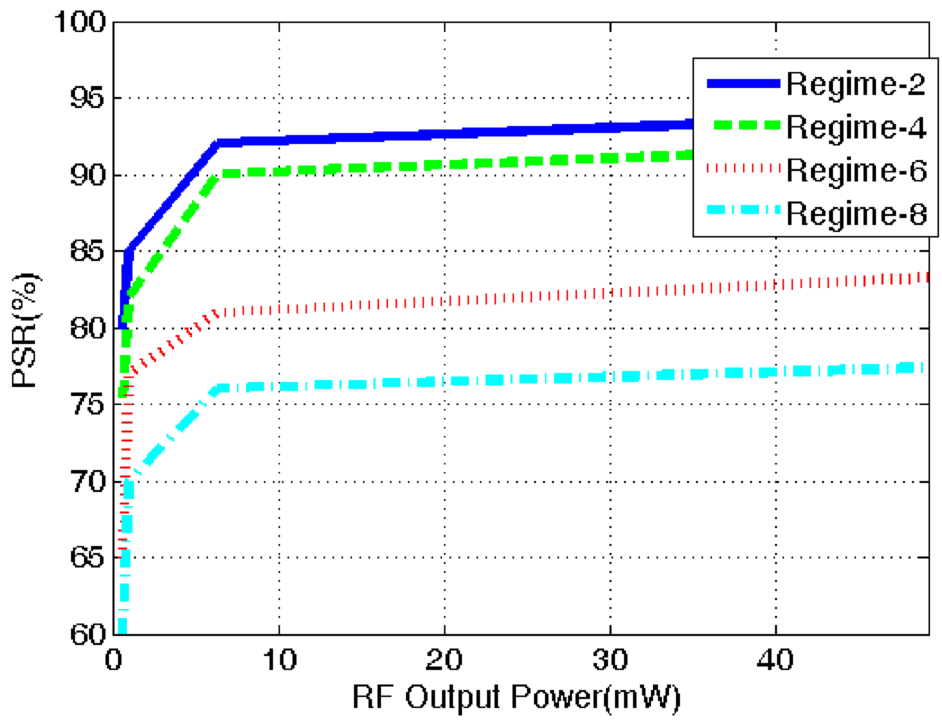

Figure 4.6: RF Output Powers in mW vs Packet Success Rates for each regime in Channel 6 (2.437 GHz). RF output powers are expected values of the output of SBX daughterboard. These values may change depending on calibration and system temperature.

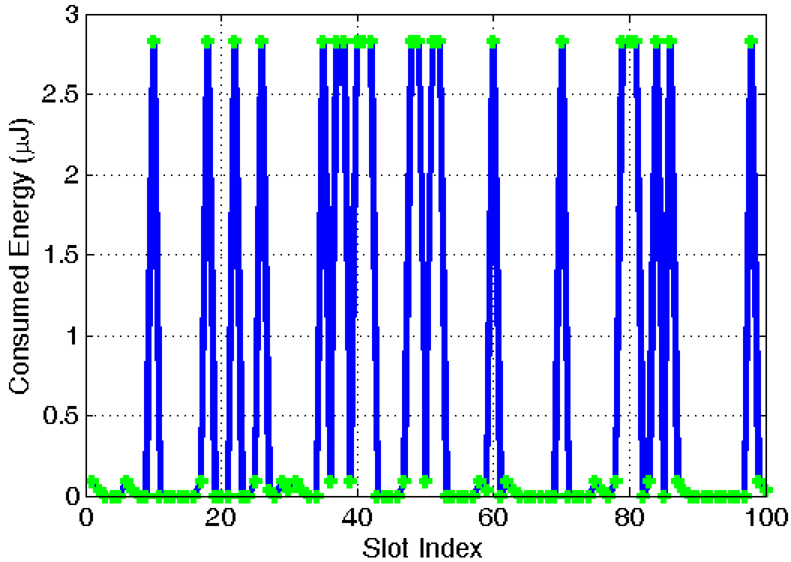

Figure 4.7: The amount of energy consumed by Hasty Policy vs. Time Slot

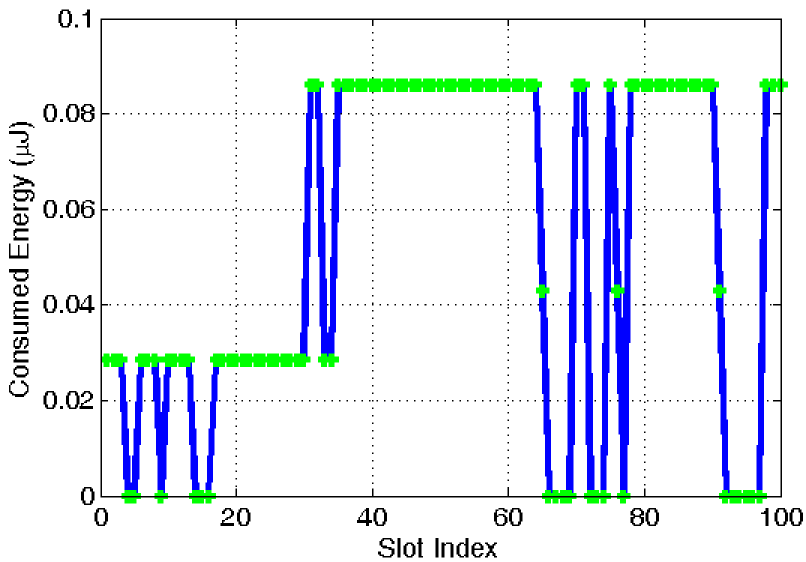

Figure 4.8: The amount of energy consumed by Expected Threshold Lazy Scheduling Policy vs. Time Slot

Table 4.5: Total energy consumption of ETLS Policy in first and second phase

Total Energy Consumption in First Phase	5.290 μJ
Total Energy Consumption after Second Phase	5.419 μJ

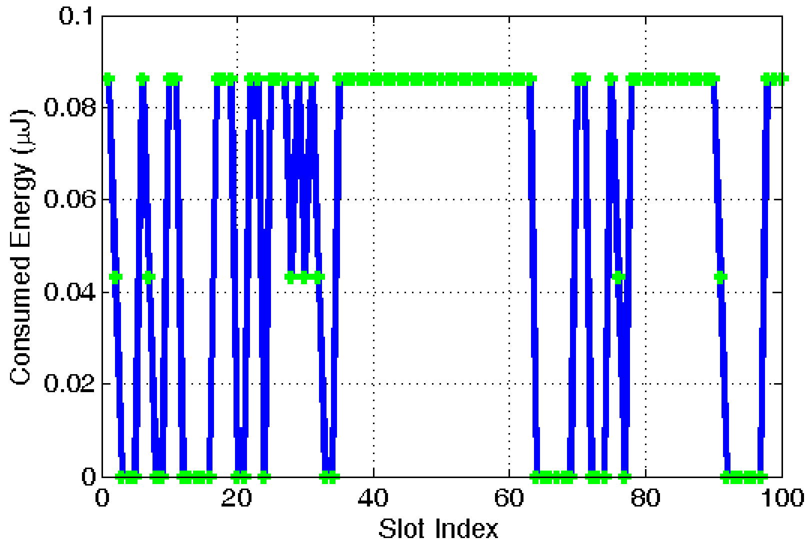

Figure 4.9: The amount of energy consumed by Constant Policy vs. Time Slot

Table 4.6: Packet Success Ratio (PSR) of each regime used in Constant Policy and the number of packets to be retransmitted for 80% PSR (NPR 80).

	Regime-2	Regime-4	Regime-6	Regime-8	Total
NTP	-	132	-	-	132
NRP	-	98	-	-	98
PSR	-	74%	-	-	74%
NPR 80	-	10.27	-	-	10.27

Table 4.7: Total energy consumption of Constant Policy in first and second phase

Total Energy Consumption in First Phase	5.715 μJ
Total Energy Consumption after Second Phase	6.116 μJ

CHAPTER 5

HARDWARE AND SOFTWARE SYSTEM ARCHITECTURE

In Chapter 4, a work on implementing energy efficient algorithms is considered. A real wireless communication media is set up with a software defined radio and two computers. One is a transmitter connected to the software defined radio and the other one is the receiver to trace packet success. In this chapter of the thesis, hardware specifications and information about softwares related with the experiment explained in the previous chapter will be reviewed. This chapter also provides information on the usage of these hardwares and softwares and detailed information on experimental conditions.

5.1 Software Defined Radio

Software Defined Radio (SDR) is a radio communication system whose components (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are implemented on a computer or an embedded system.

With the exponential growth in the ways and means by which people need to communicate, modifying radio devices easily and cost-effectively has become critical. In this context, flexibility and cost efficiency that software defined radio brings us plays an important role to take forward communication science. Traditional hardware based radio devices can support various experiments just by modifying physical components. This work is not efficient, flexible and may be takes long time as expected. Software defined radio technology provides an efficient and comperatively inexpensive solution to this problem, allowing multimode, multi-band and multifunctional

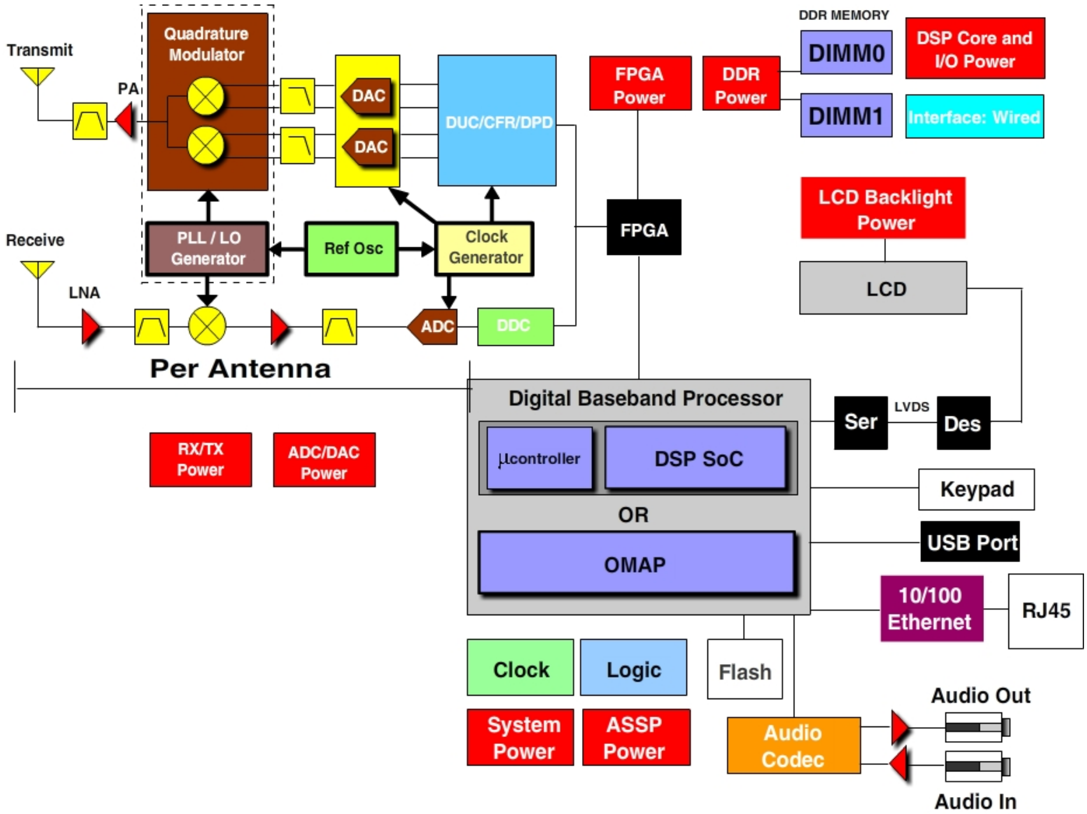

Figure 5.1: Block diagram of a software defined radio [58]

wireless devices that can be enhanced using software upgrades. Block diagram of a software defined radio is provided in Figure 5.1.

5.2 Universal Software Radio Peripheral (USRP)

The Universal Software Radio Peripheral (USRP) products are computer-hosted software radios designed and sold by Ettus Research, LLC and its parent company, National Instruments. USRP SDR offer numerous applications for both educational and scientific purposes. USRP provides chance to work with real-world signals and offers flexibility and functionality for physical layer design.

The N200 and N210 hardware is ideally suited for applications requiring high RF performance and great bandwidth. Such applications include physical layer prototyping, dynamic spectrum access and cognitive radio, spectrum monitoring, record and playback, and even networked sensor deployment [59]. Specifications of this series is illustrated in Figure 5.2.

Specification	Typ.	Unit	Specification	Typ.	Unit
Power			**RF Performance (W/WBX)**		
Dc input	6	V	SSB/LO Subpression	35/50	dBc
Current Consumption	1.3	A	Phase Noise (1.8 Ghz)		
w\ WBX daughterboard	2.3	A	10 kHz	-80	dBc/hz
Conversion Performance and Clocks			100 kHz	-100	dBc/hz
ADC Sample Rate	100	MS/s	1 MHz	-137	dBc/hz
ADC Resolution	14	bits	Power Output	15	dBm
ADC Wideband SFDR	88	dBc	IIP3	0	dBm
DAC Sample Rate	400	MS/s	Receive Noise Figure	5	dB
DAC Resolution	16	bits	**Physical**		
DAC Wideband SFDR	80	dBc	Operating Temperature	0 to 55^0	C
Host Sample Rate (8b/16b)	50/25	MS/s	Dimensions (l x w x h)	22 x 16 x 5	cm
Frequency Accuracy	2.5	ppm	Weight	1.2	kg
w/ GPSDO Reference	0.01	ppm			

Figure 5.2: USRP N200/N210 Networked Series Specifications, [59].

Table 5.1: USRP and Daughterboard Selection for Some Application Areas

Application Area	Common USRP Model	Common Daughterboard
PHY/MAC Research	N200/210	SBX
Radar Research	N200/210	SBX
OpenBTS Deployment	B100	WBX/SBX
Education	N200/210	WBX/SBX
HF Communications	B100	LFRX/LFTX
Signals Intelligence	N200/210	WBX/SBX
Distributed RF Sensors	E100/E110	WBX/SBX
Mobile Radios	E100/E110	WBX/SBX

USRP N200/210 Networked series is used in implementation of the energy efficient algorithms in Chapter 4. In experiment setup, USRP is used as the transmitter side of the system by connecting it to a pc via gigabit ethernet interface. In the experiments, rate-power adaptive algorithms are implemented. Therefore, in the transmission process we need to adjust transmission power for a given packet success rate.

USRP has internal connection with an extansion called daughterboard. Commonly used USRP Models and daughterboards for a few application area is given in Table 5.1. To adjust the transmission power by changing the gain property in the software, SBX daughterboard is choosen with USRP N200/210 series that is a commonly used USRP Model for physical layer applications. SBX daughterboard has 2 quadrature frontends, one is transmit and the other one is receive. The main reasons to choose SBX are its 400MHz-4GHz frequency range that includes our desired band, 2.4 GHz and its adjustable transmit power control with a range of 32dB with 0.5 dB increments [60]. SBX provides maximum 100mW (20dB) of output power and a typical noise figure of 5 dB. SBX output power may vary depending on the calibration of the device and the system temperature. So, the results obtained from the experiments may vary slightly. However, it can be assumed that the proportional relationship will be much the same.

5.2.1 USRP Hardware Driver (UHD)

USRP Hardware Driver is the hardware driver for all USRP devices. It works on all major platforms (Linux, Windows, and Mac) and can be built with GCC, Clang, and MSVC compilers. UHD supplies a host driver and API for Ettus Research products and can be used numerous frameworks such as GNURadio, LabVIEW, Simulink, OpenBTS, Iris, Redhawk, Amarisoft LTE eNodeB. UHD can be installed on Ubuntu 12.04 and upper versions by typing these commands in UBUNTU console:

```
sudo bash -c ’echo "deb http://files.ettus.com/binaries/uhd_stable/repo/uhd/
ubuntu/‘lsb_release -cs‘ ‘lsb_release -cs‘ main" > /etc/apt/sources.list.d/ettus.list’

sudo apt-get update

sudo apt-get install -t ‘lsb_release -cs‘ uhd
```

UHD is used to set up USRP sink in the experiments. Experimental parameters such as sample rate, tx frequency, gain and antenna (tx, rx, tx/rx for some types) are defined by a UHD object. By using an Option Parser object, parameters such as ethernet interface, mac address of the device, USRP carrier frequency, interpolation factor, USRP transmitter gain, regime and payload etc. can be set from console interface in Ubuntu 12.04. In the experiments mac address of the device is set to "a0:36:fa:26:32:e1", interpolation factor is "5" that makes OFDM symbol duration "4us". Regimes of 802.11g that contains transmission rate and modulation type information are changed during transmission by setting regime variable to desired regime from the set of 802.11g regimes.

5.3 GNURadio Framework

In the practical work of the thesis, GNURadio Framework that is most recently used one for this purpose is used with USRP Hardware Driver. GNURadio is a free, open-source software developement toolkit to implement software radios with signal processing blocks. The framework can be used with an external RF hardware to create software defined radios or without hardware in a simulation environment. This software is widely used in hobbyist, academic and commercial environments to support both wireless communications research and real-world radio systems. GNURadio can be used to receive data out of digital streams and push data into digital streams. Then, transmission process can be achieved by using USRP.

A Signal Processing block can be implemented in C++ and a flow graph can be constructed by bringing in GNURadio packages with Python Language. These layers are integrated with a library called SWIG (Simplified Wrapper and Interface Generator).

5.3.1 FTW IEEE802.11a/g/p OFDM Frame Encoder

FTW package generates IEEE802.11g frames in the experiments. This package is also able to generate and transmit IEEE802.11a nad p frames using GNURadio framework. Installation of the package on UBUNTU 12.04 needs some more modifications in make files. After the installation the package is revised for the new version of GNURadio and UHD to be used in the experiments. More information about the content of the package can be obtained from [55], [56].

5.4 Wireshark Software

The experiment is performed in empty channels detected by investigating data traffic with Wireshark. A channel is said to be empty if one or two packets are captured in a

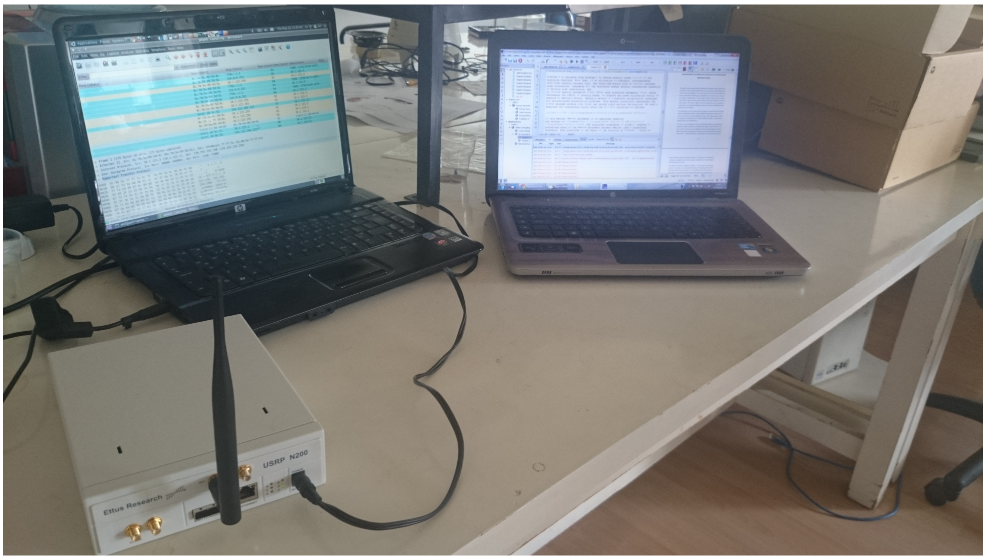

Figure 5.3: USRP test setup with receiver and transmitter in the Communication Laboratory at the METU EE Department.

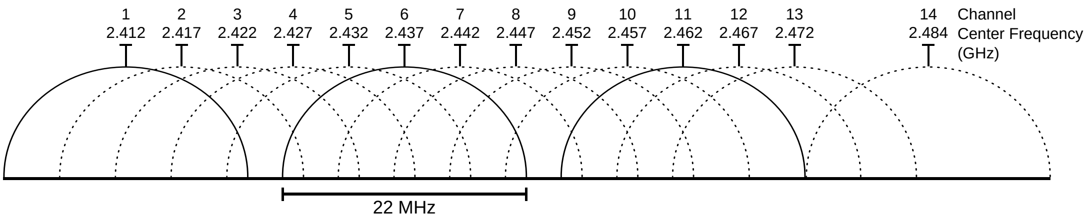

Figure 5.4: Frequency intervals of channels available in 802.11g standard.

few seconds. The empty channel is chosen to prevent much more packet loss arising from packet traffic in a channel. From IEEE 802.11g channels, Channel-6 that has 2.437 GHz center frequency is preferred in the experiments. Frequency intervals of channels available in 802.11g standard are shown in Figure 5.4.

Wireshark, network protocol analyzer software, is also used as receiver side of the system in the experiments. First experiments is carried out to find the required gain parameter for each regime to achieve 80% packet success rate. For each regime, a thousand of data packets (each packet sized are equal and 53 Byte) are broadcasted from USRP. Mac filter of Wireshark is set to the mac address of USRP. Then, packet success rate is said to be equal to $\frac{(The\ number\ of\ received\ packets)}{10}$. A thousand of data packets were used for the test to obtain a more reliable result and all the tests are repeated at least twenty times for each regime. A sample Wireshark screen is given in Figure 5.5. The sender's mac address, destination address, data rates and RSSI value of the captured packet can bee seen in the figure.

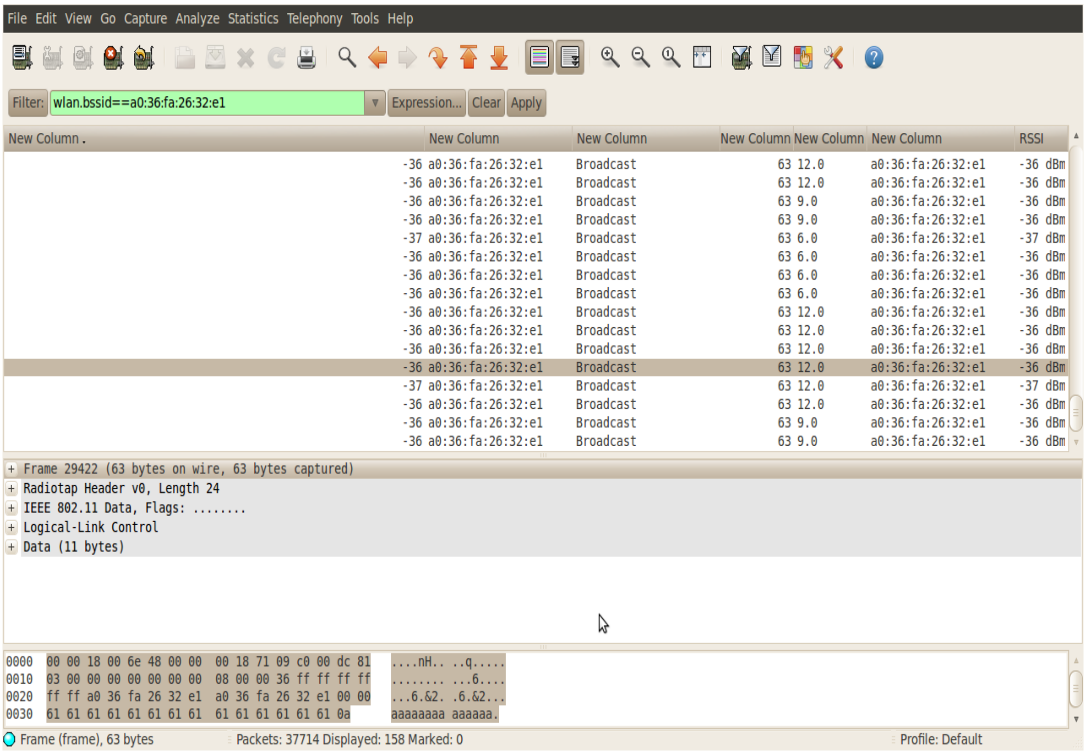

Figure 5.5: Sample Wireshark screen from the tests. MAC address of the USRP (a0:36:fa:26:32:e1) and data rates can be shown in the figure.

To use Wireshark on UBUNTU operating system, wlan interface is changed to monitor mode and channel is set to the desired channel. The commands below are typed in console to make these changes on UBUNTU 12.04:

```
sudo ifconfig wlan0 down
sudo iwconfig wlan0 mode monitor
sudo iwconfig wlan0 channel 6
sudo ifconfig wlan0 up
```

In the second part of the experiment, Expected Threshold Lazy Scheduling Policy, Hasty and Constant Policies are implemented. In the algorithms, transmission power values obtained from the first part of the experiment are used. At the end of the transmission process of a policy, number of transmitted packets with each regime are registered to a txt file on the pc. The received packets are detected by benefiting from the interface of Wireshark that provides the data rate used for each packet.

CHAPTER 6

CONCLUSION

In this thesis, both theoretical and experimental works are considered on energy harvesting and energy efficiency. As a theoretical work, energy harvesting systems are reviewed and the problem of minimization of transmission duration of data packets over an energy harvesting fading channel is solved. It is shown that application of the SUMT algorithm iteratively solves any instance of the problem. This is achieved through exhibiting equivalence to a throughput maximization problem that is shown to be convex. It is shown that due to convexity, the throughput maximization problem has a unique solution which coincides with the solution of the original problem. Examining the properties of this solution (which is left to an extended version of this work) provides insight for simple online heuristics. In some scenarios, the harvest profile may be known in advance or easy to predict, and likewise for data arrivals. In that case, the offline solution would apply for a static channel. This offline solution can be used to see boundries of an online solution and also can be used directly in a system that has known data arrival times with a prediction algorithm for energy.

As for the implementation, a real communication media is set up and some energy efficient policies are implemented. In this part, three energy-efficient transmission scheduling policies, Expected Threshold Lazy Scheduling (ETLS), Hasty and Constant Policies, are implemented on a hardware by using a software defined radio and 802.11g codes. Data arrival process is modeled as a two-state Markov process (arrival or no arrival). ETLS policy, shown to be near optimal in terms of energy consumption in the previous work [30], is compared with other two policies, Hasty and Constant Policies, in terms of consumed energy to transmit data. Numerical results have corroborated the theoretical work of ETLS policy. By this experimental work, we have shown that ETLS consumes much less energy than Hasty and less than Constant policy as it is expected. In this experimental work, not to allow an unfair competition, the rate used in Constant policy is chosen as the most efficient rate to satisfy average data arrival in a time inteval. In line with the results obtained, Hasty Policy's energy expenditure is 261 μJ in the first stage. After considering the energy used for retransmission operation of lost packets to achieve 80% PSR, energy expenditure is evaluated as 296 μJ. In this case, the packet success rate on the receiver has largely come to the fore for this policy. Difference between the first case and the second case, 13.41% of the energy expenditure is very important. The main reason of this situation is using higher regimes and higher cost of lost packets in high regimes. Hasty policy has been the most-energy consuming policy by spending approximately 50 times more energy than Expected Threshold Lazy Scheduling Policy and approximately 45 times more energy than Constant policy. The difference between Hasty Policy and the other is 10 times higher than as it is in the theoretical work [30]. The main reason is high energy consumption of Regime-8 for 80% PSR and the high cost of a lost packet. The difference between the first case and the second case in Constant Policy is 7% while %2.34 in ETLS. Both in the first and the second phase, ETLS Policy has been the least energy consuming policy. Constant Policy spent 8% more energy than ETLS Policy, although Constant Policy seemed to have advantage to know the data arrival process before transmission starts. When 80% of packet success rate in the receiver is considered the difference raises to 12.8%. It is shown that the performance of ETLS policy is better than the others with this study. To the best of our knowledge, this work is the first implementation experiment of power-rate adaptive transmission scheduling policies.

The Offline solution studied in Chapter 3 can be extended by a prediction algorithm and implemented for a real system. In some scenarios, data arrivals can be estimated correctly. An implementation of energy harvesting sensor nodes in such a system that collects the data of the temperature of the environment and transmits the data in every ten minutes can be considered. In this scenario, data arrivals are known and by estimating energy arrivals with a prediction algorithm, the solution can be applied to the system. As a future work, prediction algorithms can be studied.

In implementation of three energy efficient algorithms, USRP is used as transmitter and a pc with wireshark software is used as receiver. As a future work, receiver part can be implemented on another USRP and real-time CSI can be provided by this receiver. Real-time CSI means that antenna gains set before examination can be set while the algorithm is running and a whole system can be set up. In addition, power supply of USRP can be supported with an energy harvesting devices. In this way, a full running system can be implemented and used for an application.

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