A GAME THEORETICAL APPROACH TO GREEN COMMUNICATIONS IN SEAMLESS INTERNET OF THINGS

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ABSTRACT

A GAME THEORETICAL APPROACH TO GREEN COMMUNICATIONS IN SEAMLESS INTERNET OF THINGS

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Internet of Things is one of the rapidly developing technologies pervading all walks of life. Most IoT devices are wirelessly connected using different wireless technologies such as Wi-Fi, Bluetooth and Zigbee. As each of these wireless technologies has varied transmit power and supports different data rates, IoT devices with different in-built technologies must be optimized to energy efficient communication. In this work we propose Seamless a IoT platform that promotes periodic switching between two different technologies such as Wi-Fi, Zigbee based on the current data rate requirements and transmit power. A network model with heterogeneous IoT devices is formulated after taking into consideration of interference, received power, arbitrary locations and distance between the devices. Adapting the concept of the Game Scheme the optimal transmit power which ensures energy efficiency was calculated using MATLAB followed by simulations of convergence of Nash Equilibrium, Utility and transmit power, sum data rate.

I dedicate this work of mine to:

Dr. Feng Ye

Research Team colleagues

My parents

Grandparents

ACKNOWLEDGMENTS

My thesis work is a result of conglomerative efforts of various professionals to whom I submit and dedicate this work of mine. I take this opportunity to thank them all, first my thesis advisor Dr. Feng Ye, Assistant Professor, Department of Electrical and Computer Engineering for his extending his unconditional support to me at every instant of time. I always regard him to be my “God’s gift”. If it were not for him, this work wouldn’t have progressed. He has been very approachable and quick to respond to all my questions whenever I ran into troubles.

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I would also like to acknowledge my entire family - my parents, my grandparents for their consistent support. They had been a ray of hope since my childhood. I’m here due to their encouragement and realize their vision for me. They made me feel very special and pertinent during my low moments. I cannot envision a moment without them.

Last but not the least I would to express my gratitude to God for have given me this opportunity, a gift I never asked for. He is my impetus and without his blessings I’m nihilistic.

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CHAPTER I

INTRODUCTION

Internet-of-Things (IoT) is a rapidly growing technology that connects different objects in the world through Internet [1]. It paves way for the next step in the evolution of Internet by bringing new possibilities for collecting, analyzing and distribution of data .It is such an all pervasive technology that its growth rate is projected to be about 64 billions by 2025 [1],[2]. Wireless technologies such as Wi-Fi, Bluetooth, Zigbee can be used to entrench data transfer between IoT devices [3]. This plethora of wireless technologies poses constraints on power to be used, range and the maximum possible throughput from these devices [4].

Although IoT has become all pervasive in different spheres of life such as health care [5], industries [6], smart home [7] and several other applications [8]. it is pertinent to ponder about establishing communication or data transfer between heterogeneous IoT devices working on different wireless technologies. For instance, consider a smart home with IoT devices operating on different wireless technologies, these devices would fail to communicate with each other due to their operation on different wireless technologies. To tackle this issue, we propose a Seamless IoT platform that promotes communication and data transfer between heterogeneous ioT devices. The salient feature of this platform will be to ensure a Seamless Connectivity between these devices in an energy efficient manner.

Fig. 1.1 shows the overview of our proposed scheme. It can be inferred that there are two sections in this figure: first section is the Seamless IoT section that comprises of switches that switch between the two wireless technologies taken into consideration (Zigbee and Wi-Fi), based on the transmitted technology. Corresponding energy efficiency is known as “Optimized Energy”. The second part of this figure comprises of heterogeneous IoT devices operating on different wireless technologies such as Wi-Fi, Zigbee. Through this

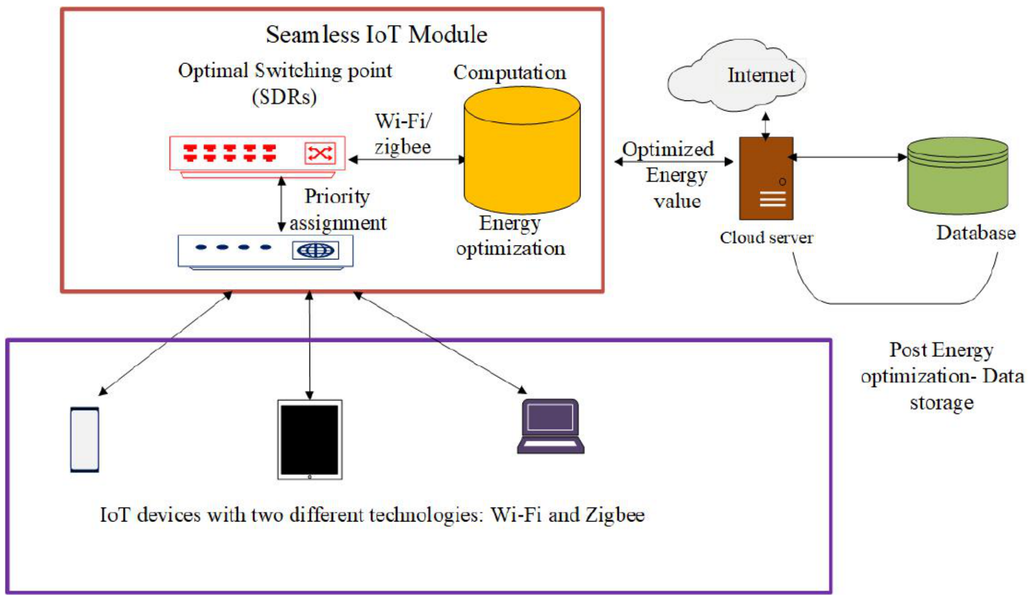

Figure 1.1: Overview of our Proposed Scheme

work we intend to facilitate data transfer between such heterogeneous IoT devices in an energy efficient manner. The most important aspect of this figure is the first part that involves Seamless IoT module. This entire thesis work revolves around developing Seamless IoT platform that promotes switching between any two wireless technologies alternatively and accurately based on the optimal settings of transmit power and data rate.

There are three main steps involved in developing this Seamless IoT platform: (a) Implementation of Wi-Fi and ZigBee using Software-Defined Radio (SDR), (b) optimal power control through game theoretical approach, (c) computer based simulation for validation and evaluation of the proposed power control scheme. The objective of the first step was to ensure that the considered wireless technologies transmit and receive data correctly. To do so we entrenched Zigbee and Wi-Fi based communication using SDR B200 as a test bed and GNU Radio Companion for developing these associated blocks. Initially Wi-Fi communication was established, we transmitted a series of data at a frequency of about 2.4GHz from transmitter and received the same at the receiver vindicating the proper Wi-Fi communication. In this way, tuning the frequencies, transmitter gain and modulation scheme different data were transmitted and received. In the similar fashion Zigbee based communication was also established. In the second step we developed an optimal power control through game theoretical approach, to ensure that in a network with 'N' devices each of them transmit at maximum possible data rate and achieve maximum energy efficiency. This step is pertinent because, the objective of every pair of device is achieve energy efficiency to achieve this they tend to change their transmit power levels. If each of them tunes their transmit power to higher levels it leads to increased interference and loss of data packets which in turn reduces the energy efficiency. Therefore, with the help of Game theoretical approach we tend to model the transmit power of all the devices in the network to ensure that this transmit power provides maximum possible data rate and energy efficiency.The third step in our approach was the Computer based Simulation for our proposed control scheme. With the help of Game scheme a theoretical model created needs to be validated. This model was developed in MATLAB along with modelling of various parameters such as interference, data rate and path loss. A stopping distance or convergence threshold was setup to ensure that the iterative process of calculating an optimal power concludes.

In this work, efforts has been taken to demonstrate the effect of Seamless IoT platform using SDR B200. Software Defined Radios (SDR) B200 [9] has been developed for wireless communication community, more details of the same are shared in the Chapter IV. With the help of SDR first Wi-Fi, followed by Zigbee transceivers were developed. Then these two blocks were combined to form Seamless IoT module that tends to emulate Zigbee and Wi-Fi signals based on the directions from the user.

The entire thesis work presented endeavors to explain these aforementioned process in detail along with associated simulations and mathematical equations. The remainder of this work is as follows: Chapter - II provides insight to the associated works on energy efficiency the approaches utilized or formulated by various authors, Chapter - III presents the technical contribution made to this work, Chapter - IV presents Evaluation Results that comprises of software simulations and Hardware Implementations, Chapter - V concludes this thesis along with the future works that would be built upon this.

CHAPTER II

RELATED WORKS

Seamless IoT platform, our proposed work, aims to ensure seamless connectivity as well as energy efficiency in a network of heterogeneous IoT devices. There has been quite a number of research works published by various authors targetting energy efficiency in IoT devices although not much work has been found in promoting Seamless Connectivity between these IoT devices [10],[11],[12],[13],[14] operating on different wireless technologies. This section endeavors to provide insights about few of such pertinent works as a part of this thesis.

Before dwelling into the works published by different authors, it is necessary to construe the significance of Energy Efficiency in IoT devices. These reasons can be classified into three different categories : (a) Battery life (b) Network Life time (c) Data rates (d) Resources [15] [16]. In today's world these IoT devices are utilized for various operations and based on the location and nature of operations these devices are either battery operated such as temperature sensor or operated from main supply in case of parking camera [10] or hosptial equipment [11] as it needs incessant supply of power for it to be functional. In the case of former, i.e., battery operated devices, it is necessary to prolong the life time of the battery as frequent replacement of these batteries will be expensive and not practical in some cases. Also unlike in other networks it would be fatal to replace exhausted battery due to the hostile nature of the environment [14]. Therefore, by achieving energy efficiency, battery life can be prolonged [12]. In addition to this, the cost associated with the replacement of these batteries and that of these IoT devices is high [13] therefore by modelling energy efficiency, besides improving the life time of the network we can make these devices cost-efficient.

Similarly, the network life time which is defined as, the time until the fraction of alive nodes falls below a pre-defined threshold β, needs to be increased [14]. The utlimate goal of every network is to ensure Seamless Connectivity and higher transfer of data rate. But this goal will be tangible if and only if, the network life time is maintained, which in turn depends on energy consumption. Through energy efficient communication and data transfer, the life time of the network can be improved. Thirdly, the data transfer rate depends on the energy efficiency. A simple and obvious measure to improve energy efficiency will be to use low power wireless technologies such as Zigbee and Bluetooth Low Energy (BLE) [17] for communication, but due to its low-power requirements, the data transferred will also be lesser leading to higher loss of data packets thereby diluting the objective of energy efficiency. Fourthly, since most of the IoT devices are deployed in resource constrained environment it is important to improve the capability and the life expectancy of these devices by optimizing the energy consumption [18]. Finally, since IoT is going to be a pervasive technology its sustainability and environmental effects too are important. Energy efficiency and overall resource optimization would make it the long term technology of the future [19]. Therefore, due to all these reasons energy efficiency is important.

Authors in [20] have suggested the usage of optimized interfaces and optimized communication protocols to combat energy consumption that happens to be one of the key aspects of Internet Applications [21]. By doing so, the need for frequent replacement of batteries when two or more interconnected device communicate will be resolved. Due to high power consumption in active state and low power consumption in the sleep state, it has been suggested in [14] to increase the period of sleep state of these devices as a scheme to prolong or extend the battery life while such periodic switching between these two modes will result in unnecessary activation of the devices that could decrease its energy efficiency [20]. Authors in [22] have proposed Deep Scheme, a scheme that alleviates the channel congestion by deferring the wake up time of these devices thereby saving alteast 75% of the energy per delivered packet and they proved that this scheme of theirs improves the overall performance of the system too. These authors have suggested that by granting higher channel access priority for low energy devices dynamically, energy effiiency can be improved. Authors in [23] have cited several media access protocols such as B-MAC, STEM, WiseMAC, S-MAC or UBMAC to achieve energy efficiency, but these protocols target ultra-low power operation that cannot be made use of this work that deals with the transfer of higher rate of data bits (in Mbps). The authors of [24] compared multiple energy efficient WSN protocols such as LEACH, HEED but these protocols had a limitation of being applicable to static and stationary nodes.

Authors in [18] presented different approaches for energy efficiency such as power-down mechanism, defining systems with two or multiple states, scheduling with minimizing response time, complementing hardware, different system-based approaches etc. While in [25] the author has detailed literature survey of the various challenges present in each layer of IoT by segregating them as power-hungry and power non-hungry. Based on this, the energy efficiency at each layers has been discussed, in effect proposing a new layered architecture. The authors in [13] has provided a detailed review about the major challenges thwarting the energy efficiency besides proposing solutions such as energy harvesters that converts power from ambient sources, including an additional energy storage units besides the energy harvesters to maximize the energy efficiency. Due to its inability to ensure continious power supply this cannot be adapted, so by utilizing shallow sleep and deep sleep methods in microcontrollers, not only the energy efficiency but the operational life time of the battery will also be extended to years. The authors in [18] have proposed energy efficiency protocols such as Pruned Adaptive IoT Routing (PAIR) for heterogeneous IoT that establishes the routing path based on the energy reservoir of the nodes in the system. But although many such energy efficiency techniques were proposed in papers, the cost will be the major impediment. Development of new architecture or installation of energy harvesting devices adds on to the cost and increases the size of the system. In addition to these, there has not been any explicit mention of the technologies or the number of technologies that could be supported by their schemes. Keeping in view of these concerns, this work of ours proposes a network model that not only adddresses the above mentioned concerns but also ensures the entire work is cost-efficient as the existing network is used with certain modifications to achieve the energy efficiency which in turn extends the network life time.

Authors in [26] have provided several energy efficiency schemes such as radio optimization, data reductions, sleep/wake up cycles. While authors in [27] have identified routing mechanism as an approach to energy efficiency. They have discussed and categorized different routing mechanisms such as clustering architectures where in the cluster head takes the responsbility of coordinating with other members in the cluster; using energy as a routing metric, since in many situations the distance is considered to be the deciding factor for the next hop while using energy too as a metric besides focusing on the shortest path, lowest energy path too can be considered as a factor for the next hop. Authors in [15],[28] have listed techniques and protocols that makes uses of WSNs to reduce overall energy. One such technique is proactive planning in connection among multiple IoT devices. Such a planning will lead to both energy efficiency and seamless sharing of informations. In fact, the utilization of Zigbee [29], a low power wireless technology could produce energy efficiency but this can be adapted for lower rate of data transfer and might lead to loss of data packets when transmitting large data bits.

In [30], reducing the number of bits has been projected as one of the approaches towards attaining energy efficiency, but this compressing of bits will consume power that balances the power needed to transmit such many number of bits. Another possible approach mentioned is to reduce the distance of separation of nodes, as this will be significant in cases of long distance communication. In [31],[32] the authors have suggested the collision arising due to the data transmission from multiple IoT devices as one main source of energy consumption. The sources of these collisions depends on a variety of factors such as transmission speed, size of data, number of bits connected [33] so on and so forth. This paper dwells on promoting collision-resolution techniques that reduces these collisions which in turn reduces energy efficiency.

These are few related works pertaining to energy efficiency produced by various authors and research publications. The approach shown in this work is based on Cross Technology Communication [34]. By periodic switching between two different wireless technologies, better energy efficiency can be attained because for lower data rate and sensing purposes it is more efficient to utilize low power technologies such Zigbee due to its low energy requirements while for higher data rate transmission it is better to use Wi-Fi due to its larger bandwidth. In this way better energy efficiency as well as data rate could be attained.

Keeping these related works as reference, we focused on developing Seamless IoT platform with the help of the steps outlined in Chapter I. We first developed Seamless IoT platform with single technology, this same concept can be extended to the second technology and with this knowledge switching point that provides energy efficiency can be attained. As shown in Fig. 2.1, we can see this Seamless IoT platform comprises of two IoT devices operating on different wireless technologies, Wi-Fi and Zigbee transceivers, and an end device. This work focuses on developing Sensing and Switching platform whose main function

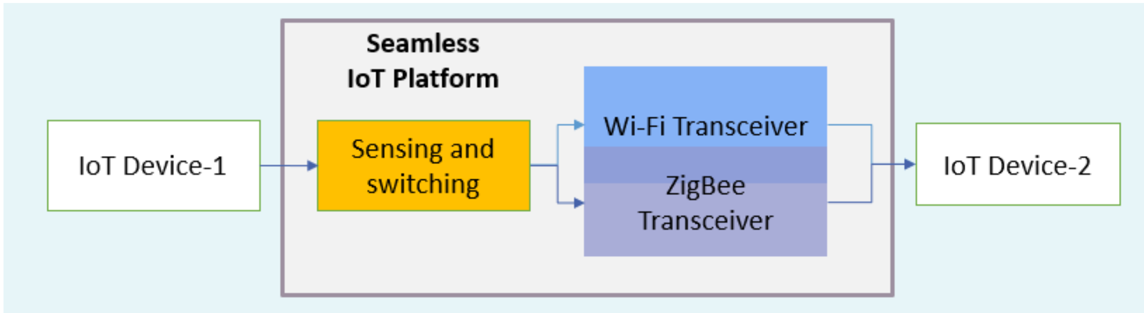

Figure 2.1: Seamless IoT Platform

is to sense the incoming signal, switch to different technology based on optimal switching point ensuring energy efficiency. In our considered we have 'N' devices although only two devices are shown as an example in Seamless IoT platform.

Also, in this work, we have modelled a network taking into consideration different parameters that affects the energy efficiency which in latter stages with the help of Game Scheme the transmit power of every transmitter for a single technology is calculated, and by applying the same concept to the second technology the transmit power that provides energy efficiency can be deduced. A simple ratio between the transmit powers of both these technology that provides energy efficiency can be calculated and this point serves as an optimal switching point. Any transmit power when exceeds this switching point will switched to different technology thereby achieving energy efficiency.

CHAPTER III

A GAME THEORETICAL APPROACH TO GREEN COMMUNICATIONS IN SEAMLESS INTERNET OF THINGS

In Chapter I, our proposed scheme of Seamless IoT platform was elicited. While in this chapter a broader picture of our proposed scheme of game theoretical approach to green communications in Seamless Internet of Things will be shown.

3.1 Network Model

In the Chapters I and II, the overview as well as the Seamless IoT platform was shown. While in this section, mathematical description of our proposed scheme will be shown. In this section, a network model will be created with 'N' devices incorporated with dual technologies- Wi-Fi and Zigbee. A salient feature of this approach is that it promotes mathematical representation of SINR, interference, noise besides utilizing the convex optimization technique to maximize the energy efficiency for a given data rate and sutiable communication technology. In the next chapter, the simulations obtained after the theoritical implementation of this approach is included to draw suitable inferences.

From the Fig. 3.1 it can be observed that the transmitter n_i located at a point (x_i, y_i) receiver n_j stationed at (x_i, y_j) are separated by a distance of $d_{(i,j)}$.

$$d_{(i,j)} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3.1}$$

In this way, all the devices in the network are arbitrarily located with associated distance of separations. It may be noted here that n_i and n_j are grouped to form a transmitter-receiver pair respectively with n_i transmitting at a power of p_i and n_j receiving a power

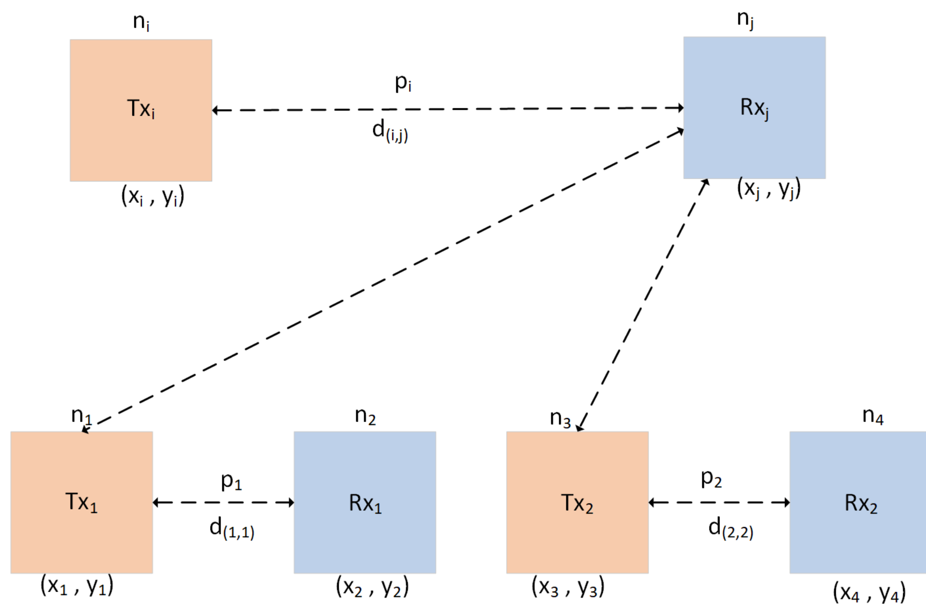

Figure 3.1: Network Model Of Our Proposed Scheme

of r_j. Since these two devices are separated by a distance, the power received at n_j will be path loss times the transmitting power. Here free space path loss model is considered due to which the path loss is inversely proportional to the square of separation distance. Another important parameter that needs to be discussed is the interference, which arises during the transmission between n_i and n_j. During the data transmission between these two devices, the other transmitters in the model n_{-i} will impede in the communication process by transmitting interference signal. The total interference will be the sum of the individual interferences, denoted by $\sum I_{(-i,j)}$, results in the loss of packets ultimately reducing the energy efficiency and the data rate of the pair under consideration.

Considering the network model shown in Fig. 3.1. The node Tx_i is transmitting with a transmit power of p_i to receiver Rx_j. This receiver receives interferences from other devices in the network $I_{(2,j)}$ is the interference power from the second transmitter, while $I_{(3,j)}$ is

Table 3.1: Mathematical notations used

p_i	Transmitting power
r_i	Receiving power at device n_i
$d_{(i,j)}$	Euclidean distance between n_i and n_j
$I_{(-i,j)}$	Interference from n_{-i} to n_j
(x_i, y_i)	Arbitrary location of the device n_i
$\mathcal{S}_i$	Strategy set of the i^{th} player
$\mathcal{S}$	Strategy set of all the players
$\mathcal{S}_{-i}$	Strategy set of all the players other than the i^{th} player
$D_{(i,j)}$	Achievable Data rate between n_i and n_j
SINR	Signal to Noise plus Interference Ratio
B	Bandwidth of the technology used
σ	Additive White Gaussian Noise

the interference from the third transmitter, therefore the total interference power to the receiver Rx_j can be expressed in general as:

$$I_{(-i,j)} = I_{(2,j)} + I_{(3,,j)} + \ldots + I_{(n,j)} \tag{3.2}$$

Besides interference, the presence of additive white Gaussian Noise denoted by σ should not be ignored, therefore the data rate of a pair calculated at the receiver end depends on the received power r_j, the cumulative interference $\sum I_{(-i,j)}$ and the noise σ. Table 3.1 shows the description of the mathematical notations used in this work.

In the next few sub-sections, the mathematical equations for free space path loss, Noise, Interferences, data rate will be shown and discussed for better understanding.

3.2 Preliminaries

3.2.1 Free Space Path Loss

There are different types of path loss models that can be chosen based on the applications in [35]. Out of all we have chosen a basic free space path loss model as it suits appropriately to this IoT application of ours. This is because, while developing this network model, it was mentioned that these devices are separated by a distance 'd'. When any two devices are separated by a distance, there will be losses in the transmitted power by a path loss factor when it reaches the receiver. There will be an increase in attenuation of the signal with the increase in the distance, this plays a key role in determining the data rate received at the receiver section. This sub section deals with modelling that path loss factor. Let r_j be the power received at the receiver n_j, p_i be the transmitted power transmitted by the transmitter n_i, λ be the wavelength in meters. Mathematically,

$$r_j = \frac{G_t G_r p_i}{4 * \pi * d^2} \tag{3.3}$$

where, G_t is the Gain of the transmit antenna, G_r is the Gain of the receiver antenna.

3.2.2 Additive White Gaussian Noise

For this work, Additive White Gaussian Noise has been considered because of the following features [36]:

(i) It is additive in nature as it get accrued to any inherent noise present in the information system.

(ii) It has uniform power accross the frequency band

(iii) It has a normal distribution.

3.2.3 Signal to Interference Plus Noise Ratio (SINR)

For our network, we have considered SINR which is the Signal to Noise Plus Interference Ratio, which gives the theoritical upper bounds on channel capacity. It is defined as the ratio between received power and the sum of Noise and Interference. Here Noise is the Additive White Gaussian Noise and the interference is the transmitted powers from all the other transmitters in the network. When a pair of devices are transferring data, the

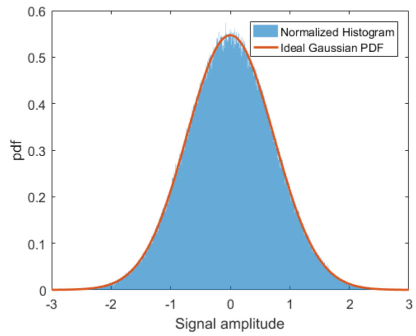

Figure 3.2: Representation Of Ideal Gaussian PDF
(Source: Wikipedia)

transmitted power from the other transmitters impede the transmission process of this pair causing reduction in their data rate and energy efficiency. Therefore care must be taken while modelling the transmitting power as increase in transmitting power causes increase in interference thereby reducing overall energy efficiency.

$$SINR = \frac{r_j}{\sum I_{(i,j)} + \sigma^2} \tag{3.4}$$

3.2.4 Data Rate

The objective of every pair of devices is to increase their energy efficiency by increasing their rate of data transmission. But the amount of data produced at the receiver depends on a number of factors such as path loss, interference, the transmit power, gain, distance of separation. In other words, it depends on the SINR. Mathematically, it can be computed as,

$$D_{(i,j)} = 2B \log_2(1 + SINR) \tag{3.5}$$

3.3 Problem Statement

In the network, it can been seen that there are $\frac{N}{2}$ pairs of devices with each pair comprising of a transmitter and receiver. Each of these pairs wishes to maximize their Energy Efficiency which is defined as the is defined as the number of bits sent per unit power consumption [37]. Mathematically, it can be represented as:

$$\text{Energy Efficiency [bits/Joule]} = \frac{\text{Data rate [bits/s]}}{\text{Energy [Joules/s]}} \tag{3.6}$$

$$\text{We know that, Energy} = \text{p} \times \text{t} \tag{3.7}$$

$$t = \frac{1}{D} \tag{3.8}$$

$$\text{Substituting (3.8) in (3.6) we get,}$$

$$\text{utility } u_i = \frac{D^2_{(i,j)}}{p_i} \tag{3.9}$$

To maximize their utility, each of these pairs transmit at a maximum power which causes an equivalent increase in the interference and reduction in data rate resulting in reduced utility. Therefore a mechanism must be developed so as to ensure maximum utility at the given data rate for all the players. This problem can be represented mathematically as,

$$\max u_i \ \forall i \tag{3.10}$$

subject to constraint: $0 < p_i \leq p_i^{max}$

In the previous sections, an emphasis on utility has been laid. Every pair of device in the network aspires to maximize their utility function for which they transmit at maximum power level causing increased intereference. In such situations where a strategy of a player depends on the strategies of other players, it will be feasible and succinct if the entire problem is modelled using Game theory. Game Scheme is a mathematical tool that is used to provide models of conflicts, negotiations and helps us to understand why a particular person makes a particular move. With the help of this powerful tool, we have formulated a Game Scheme of the proposed problem and derived solution from it.

3.3.1 Applications of Game Theory

It was mentioned about developing a Game Scheme of the problem statement to take in account the strategies of all the players and ensure maximum possible utility function to every player in the game. These are the possible applications of the Game theory: [38]

(i) It provides a systematic quantitative approach for deciding the best strategy in competitive situations.

(ii) It allows the players to change their strategies in response to that of the other players in the game.

(iii) Nodes in the network are independant and they can take their own decisions for their own interests.

(iv) Game theory provides sufficient tools to analyze every players' actions and behaviors.

(v) It ensures that every player in the game has the maximum possible utility function at that given instant.

3.3.2 Limitations of Game theory

Although the Game theory is very useful in competitive situations and ensures maximum utility to all the players in the game, it has it's own limitations that are outlined below: [38]

(i) Game theory focuses on solving the Nash Equilibrium but does not take into account the interaction of the players in the Game to achieve NE.

3.3.3 Game Scheme Formulation of Problem Statement

There are three important or keys terms related to Game theory: Players, Strategies and Utility functions. These terms may be different representations at different levels, but in this work we have clearly explained terms after formulating a non-cooperative dynamic Game theory wherein the strategy of a player depends on the strategies of other players in the game.

Mathematically this Game can be represented as, $\mathcal{G}$=$(N, \mathcal{S}_i, u_i)$.

1. *Players:* Let (n_i,n_j) be a pair of transmitter-receiver.
2. *Strategies:* $\mathcal{S}_i$ represents the actions that a player n_i may take at any stage in this game. Each player may transmit with a minimum transmit power greater than 0 and a maximum transmit power of p^{max}. Therefore, $\mathcal{S}_i$ = [0 p_i^{max}] and the strategy profile

for all the players is $\mathcal{S} = \prod_{i=1}^{n} \mathcal{S}_i = [0\ p_1^{max}] \times [0\ p_2^{max}] \times \ldots \times [0\ p_i^{max}] \times \ldots \times [0\ p_n^{max}]$

3. *Utility function:* Each player in the network has an objective to maximize its utility function (u_i) over the range $[0\ p^{max}]$. Out of the various possible utility functions such as logarithmic, square root, linear, exponential and sigmoidal [39], we chose this quasi-concave utility function designed specifically to IoT devices alone ensures that every player in the game has a maximum possible data rate and utitity. The utility increases increases initially with the increase in the transmit power reaches a maximum point and then decreases with the increase in the transmit power.

$$u_i = \frac{D_{(i,j)}^2}{p_i} \tag{3.11}$$

$$p_i = \arg \max_{0 < p_i < p_i^{max}} u_i(N, \mathcal{S}_i, \mathcal{S}_{-i}) \tag{3.12}$$

where, $\mathcal{S}_i$ is a set of strategies of the i^{th} player, $\mathcal{S}_{-i}$ is a set of strategies of all the players other than the i^{th} player.

The Game Scheme of the problem has been formulated. The objective of this Game Scheme is to calculated an optimal transmit power p_i^* for all the transmitters in the game that could provide energy efficiency. This entire Game scheme has been developed to deduce p_i^* for a single technology only but the same thing can be extended to another technology and optimal power corresponding to that technology can be obtained. This ratio of optimal powers of two different technologies will provide optimal switching point say, p_s. If any transmit power greater than p_s arrives, it is switched to technology 1 else to technology 2, thereby providing maximum possible energy efficiency at that data rate.

3.4 Solution to the Problem

In the previous section, a Game Scheme of the problem was modelled to explain the problem faced by the IoT devices in the network. In this section, we endeaavor to provide a mathematical solution to this problem which will be simulated and corresponding results are displayed and dicussed in detail in the next chapter. The objective of every device in the network is to maximize their utility. The Game Scheme provides a mechanism to ensure that every device transmit at an optimal transmit power (p^*) that ensure maximum possible utility and data rate at that given instant. This point is known as a stable point. At this point any change in strategy of any player will not bring out any change in its outcome, and at this junction Game is said to have achieved Nash Equilibrium.

But before dwelling into the solution for this problem, it is imperative to ensure if this Game has a unique Nash Equilibrium. The unique Nash Equilibrium will ensure that the device has reached its maximum possible potential. This unique NE is based on the Best Response Function of every player. The Best Reponse Function is the point that provides maximum utility at a particular transmit power p_i.

Therefore at the outset we need to prove that this Game $\mathcal{G}$ has a NE which is unique, followed by the calculation of Best Response Function (BRF) and algorithm to provide solution to this problem.

3.4.1 Existence of Nash Equilibrium

In the Game Scheme, the process of negotiations continues until Nash Equilibrium is obtained. It is defined as a stable point or an equilibrium point where change in strategy of one player does not provoke change in strategies of other players. In others irrespective of the number of iterations post NE, the strategies of all the players will continue to remain the same [40],[41],[42]. In the same way, in this case too the NE is attained when all the players achieve their respective optimal transmit power p_i^*. Mathematically it can be denoted as: Mathematically, it can denoted as:

$$u_i(p_i^*, p_{-i}^*) \geq u_i(p_i, p_{-i}^*) \tag{3.13}$$

But before that, it is pertinent to prove the existence and the uniqueness of the NE. The rest of this sub-section deals with proving them mathematically.

1. Existence of Nash Equilibrium: To prove the existence of Nash Equilibrium, the Nikaido-Isodra theorem can be made use of [16, 43]: The Game $\mathcal{G}$ has atleast one NE if and only if $\forall$ $(n_i, n_j) \in$ N, the strategy set $\mathcal{S}_i$ is compact and convex, $u(p_i, p_{-i})$ is a continious function in the profile strategies s $\in \mathcal{S}$, and concave in $\mathcal{S}_i$.

   Proof:

   (a) The strategy set of all the players are denoted by $\mathcal{S}=\prod_{i=1}^{n} p_i$, $\forall$ i$\in$ N. Mathematically, $\mathcal{S}_i$ = [0,p_i^{max}] which proves that the strategy set of each player is closed and bounded. Hence the set $\mathcal{S}_i$ is compact.

   (b) Consider x_1, x_2 be two points from the set and λ = [0 , 1]. Thus, 0$\leq$ λx_1 + (1-λ)$x_2 \leq p_i^{max}$. This proves that $\mathcal{S}_i$ is convex $\forall$ $i \in$ N.

   (c) To prove the concave nature of the strategy set $\mathcal{S}_i$, we need to compute the Hessian matrix of $u(s)$ with s=$\{p_i\}$ as shown in the following matrix:

$$H(s) = \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ D_{n1} & D_{n2} & \dots & D_{nn} \end{bmatrix} \tag{3.14}$$

where, $D_{ij} = \left(\frac{\partial^2 u_j}{\partial pt_i \partial pt_j} \right)$,$\forall$ (i,j) $\in$ N.

$$D_{ij} = -\Big\{1 - \log(\frac{I_{(-i,j)} + p_i}{I_{(-i,j)}})\Big\}\forall(i,j) \in N \tag{3.15}$$

From (3.15) it can be observed that, the leading principal minor of H(s), we can see that H(s) is a negative definite for all the strategies s $\in$ S, therefore, $u_i(p_i, p_{-i})$ is strictly concave in S_i $\forall$ $i \in$ N. Since the conditions laid by Nikaido-Isodra theorem has been satisfied, the developed Game has at least one NE.

2. Uniqueness of the Nash Equilibrium can be proved by using the Rosen theorem [43, 44]. Let υ=$\{\upsilon_1, \upsilon_2, ..., \upsilon_n\}$ be a random set of positive parameters. Using the Rosen's theorem, the weighed positive sum of the utility function $u_j(p_i, p_{-i})$, $\forall$ $(i,\ j) \in$ N, which is mathematically defined as:

$$\gamma(p_i, p_{-i}) = \sum_{j=1}^{n-1} \sum_{i=2}^{n} \upsilon_j u_i(p_i, p_{-i}), \upsilon_j > 0 \tag{3.16}$$

where, the pseudo-gradient of $\gamma(\sigma_i, \sigma_{\text{-}i}; \upsilon)$ is given by:

$$g(p_i, p_{-i}; \upsilon) = \begin{bmatrix} \upsilon_1 \nabla u_1(p_2, p_{-2}) \\ \upsilon_1 \nabla u_2(p_3, p_{-3}) \\ \vdots \\ \upsilon_{n-1} \nabla u_{n-1}(p_n, p_{-n}) \end{bmatrix} \tag{3.17}$$

With $\nabla u_i(p_i, p_{-i})$ =$I_{(-i,j)}\{e^{W(\frac{-2}{e^2})+2} - 1\}$

$$J(p_i, p_{-i}; \upsilon) = \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1n} \\ B_{21} & B_{22} & \dots & B_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \dots & B_{nn} \end{bmatrix} \tag{3.18}$$

where $B_{i,j}$ =$\upsilon_j D_{(i,j)}, \forall(i,j) \in$ N. By substituting the values of $D_{(i,j)}$ from (3.10) in (3.15) we can clearly see that the symmetric matrix [J+J^T] is negative definite for all (p_i, p_{-i}), $\in \mathcal{S}$. Consequently, the function $\gamma(p_i, p_{-i}; \upsilon)$ is diagonally strictly concave in $\mathcal{S}_i$ according to Rosen's theorem. Therefore, the game $\mathcal{G}$ has unique NE in its pure strategy space, according also to Rosen's theorem. ■

3.4.2 Calculation of Best Response Function

In the previous sub-section, the existence and uniqueness of the NE was proved, with this idea we calculate the best response function which is defined as function that results in a stable point among all the players in the game. In other words, this point is defined as the optimal point that results in maximum possible data rate at that instant and the maximum energy efficiency. The optimization of the system performance is achieved by maximizing the overall energy efficiency and achievable data rate with minimum required transmission power set [45],[46]. This can be achieved by differentiating the utility function with respect to p_i and equating it to zero.Mathematically it can be represented as:

$$\frac{\partial u_i}{\partial p_i} = 0 \tag{3.19}$$

From equation 3.19,

$$p^* = I_{(-i,j)}\{e^{W(\frac{-2}{e^2})+2} - 1\} \tag{3.20}$$

where W represents Lambert function

3.4.3 Algorithm to Solve the Problem

In this subsection, the algorithm to solve the problem has been dicsussed to provide greater understanding. The process first begins with determining the players in the game which are the devices (n_i, n_j), the strategies of these players which is changing their transmit power (p_i) over a given range and utility. The objective of this process is to achieve NE therefore a stopping distance or convergence threshold must be defined to stop this iterative process. A convergence threshold ϵ is a difference in the transmit power values of the last and the penultimate iterations. If their difference reaches this value it can be concluded that every device is transmitting at their optimal power p^*. In the first iteration every device will determine their transmit power. For an instance, player n_i will determine its transmit power to be say p_i, and other devices n_i will produce their own strategies (transmit powers) p_{-i} in response to the one proposed by the n_i. Based on the transmit powers of n_{-i} the n_i will change its transmit power once again. This process continues until there reaches a stage in which for a change in the transmit power of n_i the n_{-i} will not change their transmit powers. This means the difference in the transmit power values of the final and the penultimate has reached the convergence threshold and NE is said to have been achieved. This NE is based on the BRF of all the players in the game. It can be observed that at this point of convergence every device in the game would have obtained the maximum utility and the transmit power will be the same even if this iteration proceeds for several times.

Algorithm 1 Compute Nash Equilibrium

Require: S= $\{p_1, p_2, \ldots, p_n\}$
Ensure: S^*
  Convergence threshold = ϵ
  a =1
  while $|p_i^{(a)} - p_i^{(a-1)}| > \epsilon$ **do**
    a = a + 1
    for $i = 1 : n$ **do**
      $p_{-i}^{new} = \sum_{i \neq k} p_k^{new}$
      $p_i^* = I_{(-i,j)}\{e^{W(\frac{-2}{e^2})+2} - 1\}$
      $p_i^{new} = p_i^*$
      $p_i^{(a)} = p_i^{new}$
    end for
  end while

CHAPTER IV

EVALUATION RESULTS

In Chapter III, the problem statement was stated which was formulated into a Game Scheme with players, strategies, utility functions of all the players stated very clearly. The uniqueness and existence of NE for this Game gave us a confidence to compute Best Response Function which explains the how the strategies of a player depends on the strategies of other players in the game. With theoritical formulation, we will not be able to derive any proper conclusion, therefore this model was simulated in MATLAB. Three different types of simulations are shown here: (a) Convergence of p_i, (b) Simulation of pt vs Utility, (c) Convergence of Sum data rate. These three simulations will aid us in proper understanding of our game scheme. The second section of this Chapter comprises of Hardware Implementation of Seamless IoT. It has been emphasized in several Chapters of this thesis about development of Seamless IoT platform. Here we have shown the setting up of Wi-Fi and Zigbee transceivers, which was combined into a single module at latter stages to emulate Zigbee and Wi-Fi based on the user's input. In fact this implemenation was the cardinal step in our work that gave us an impetus to move forward towards adapting Game Scheme. The main idea behind this implementation was to ensure that, this switching between two different wireless technologies is pragmatic and not theortical. More details about this will be provided in those respective sections.

4.1 MATLAB Simulation

The theoritical model of our approach was simulated using MATLAB R2019a. While developing the code care was taken to ensure that all the parameters mentioned such as interference, received power, data rate, distance and path loss were automatically calculated as soon as the number of pairs of devices needed was mentioned. While developing MATLAB code care was taken to mention stopping distance or stopping point, technically a point at which NE is achieved and further iterations will not bring any change. Here, ϵ, the stopping point was considered to be around 0.001. The algorithm that was adapted to code is shown in Algorithm 1. Based on this Algorithm the MATLAB code was drafted, the associated simulations are shown and analyzed. The obtained simulations are discussed here: In

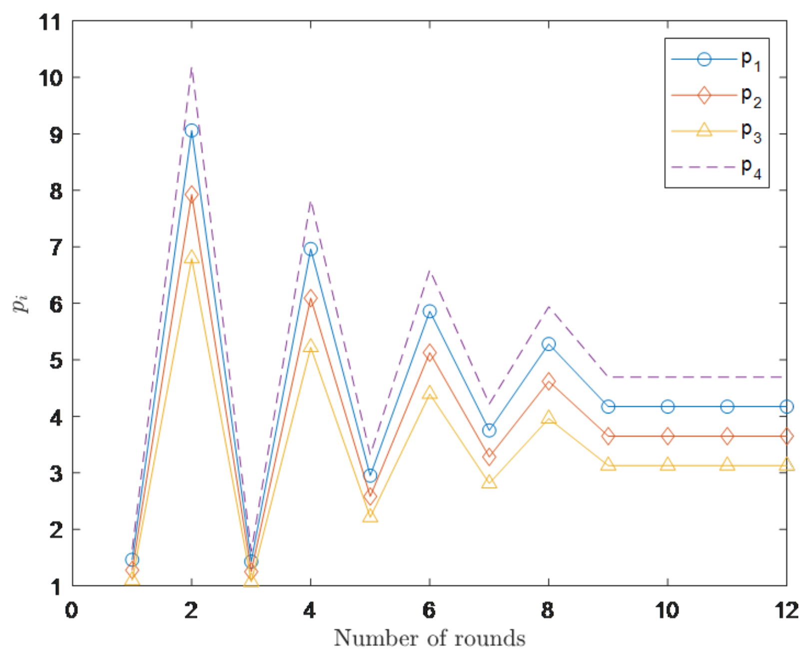

Figure 4.1: Convergence of Transmit Power p_i (mW)

Fig. 4.1, we can see the convergence of p_i for all the players. Initially each player had varying transmit powers, but as the iterations continued this p_i started to decrease and increase based on the strategies of the other players in the game as the objective of every player is to achieve maximum efficiency at a given data rate and transmit power. After the 8^{th} round, we can see that this power seem to remain the same despite the increase in iterations. When the stopping distance is reached, all the players have constant p_i with no changes. This stage is known as stable point or equilibrium point or it can be said that the Nash Equilibrium is attained. Beyond this point, despite the increase in iterations there will not be any change. Hence we can conclude that every player has attained its own optimal transmit power that could fetch energy efficiency for them. In Fig. 4.2, we can see

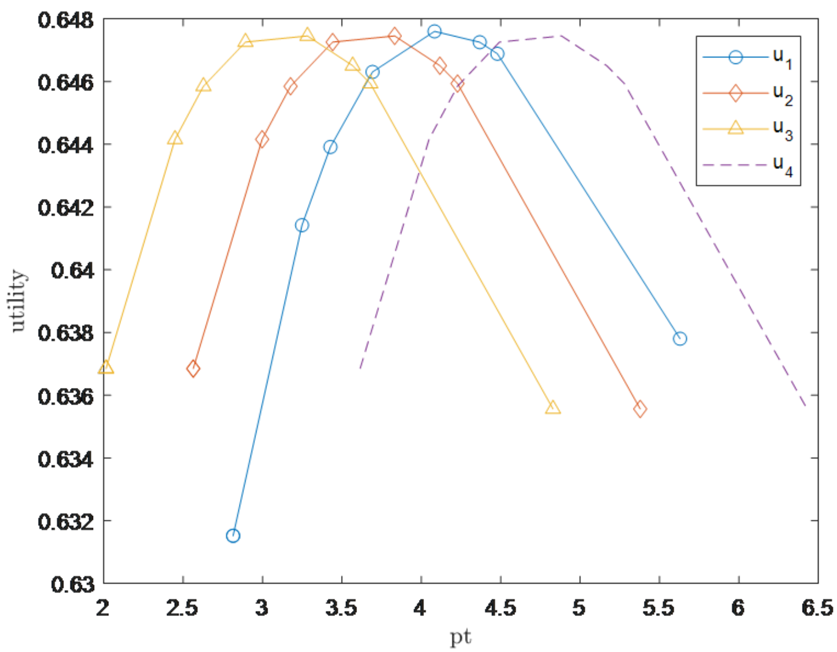

Figure 4.2: Effect of Transmit Power On Utility

the effect of transmission power on the utility function of all the players in the game. As mentioned the objective is to maximize the energy efficiency, for which the transmit power is increased, the utility too increases as seen in the figure. But after a certain point increase in pt results in decrease of utility function. This means pt has no effect on the utility post optimal transmit power. For instance, player 1 has an optimal power at about 3.028 but after this level the utility decreases with the increase in the utility. This happens because the maximum energy efficiency happens at this point beyond which energy efficiency will be reduced. The Fig. 4.3 represents the sum data rate of the overall network model. Here

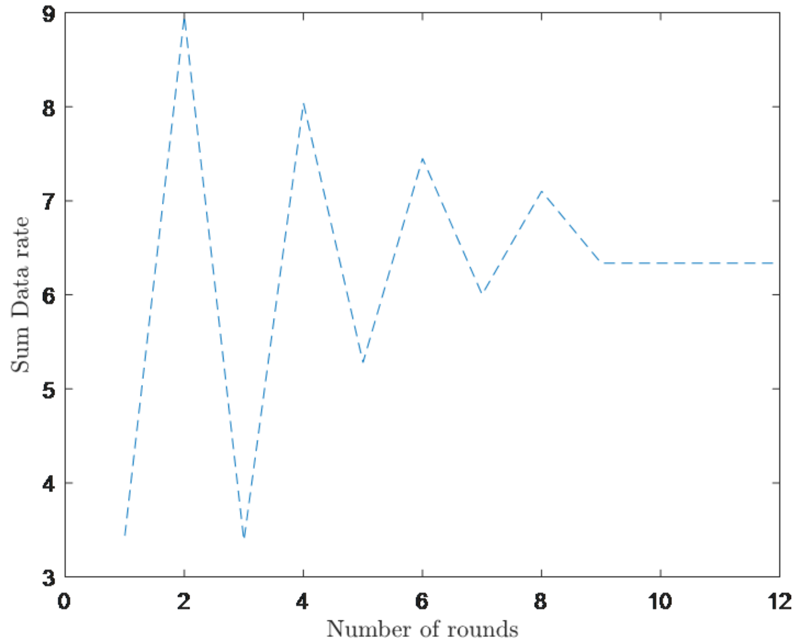

Figure 4.3: Sum Data Rate (Mbps)

we are computing the overall sum data rate instead of individual data rate because the received power at the receivers will be the same for all the receivers. Therefore the data rate obtained will also be almost the same. Another way of looking at this is, the throughput of any system is the total data rate (or Sum Data rate) obtained from the network. We can observe from this plot that the sum data rate too fluctuates in accordance to the transmit power and finally after the 8^{th} round, the sum data rate too becomes constant and does not change. At this point equilibrium point is said to be achieved.

4.2 Hardware Implementation

The pertinence of Hardware Implementation in this work is to validate the existence of Seamless IoT platform using SDR. SDR happens to be an affordable and capable radio used in both teaching and researching [47],[48],[49], [50]. There are several series of SDR such as N series, B series that can be made use of based on our requirements. In this work with the help of SDR B200 we had first established Wi-Fi communication followed by the Zigbee transceiver followed by combining these two transceivers into a single module that emulates Zigbee or Wi-Fi signals based on the directions from the user. Before dwelling into its implementation, it is necessary to include and discuss the Hardware and Software requirements and reasons for selecting them for this implementation in detail. There are two sub sections in this section Hardware and Software Requirements that speaks about the ingredients needed for implementation; Steps involved in realization of this implementation in detail.

4.2.1 Hardware Requirements

The Fig. 4.4 shows the Hardware Implementation set-up used in this work. As can be seen it comprises of two laptops, two testbeds and GNU radio Companion software operating on Linux Ubuntu operating system [51]. The detailed specifications are given below:

(i) Two Thinkpads T430 that serves as transmitter and receiver.

(ii) USRP SDR B200 - a product of Ettus Research.

There are different versions of USRP SDR's released by the Ettus Research of which we choose SDR B200 and this device has the following features: [52]

(i) Product of Ettus Research

(ii) 1 TX & 1 RX, Half or Full Duplex

(iii) Xilinx Spartan 6 XC6SLX75 FPGA

(iv) Up to 56 MHz of instantaneous bandwidth

(v) USB Bus powered.

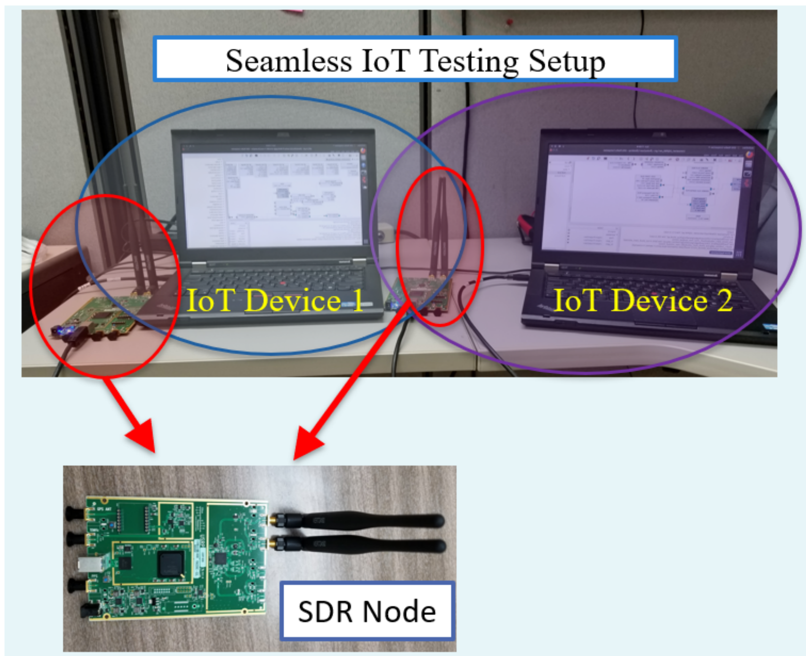

Figure 4.4: Hardware Implementation Set-up

4.2.2 Software Configurations

The following are the Software Configuations required:

(i) Operating system- Linux Ubuntu 10.16 [53]

(ii) GNU radio companion (GRC) [54],[55]

(iii) Python 2.5 (or above)

(iv) Python-LXML 2.0 (or above) [Cheetah Template Engine 2.0 (or above)]

(v) Python-GTK 2.10 (or above)

4.2.3 Steps Involved in Implementation

There are about 6 steps towards realizing this goal of ours as elicited below:

Step:1 Setting up of Ubuntu Linux Operating System

Step:2 Installing the GNU Radio Companion (GRC) along with its associated drivers.

Step:3 Testing of the GRC using an arbitrary FM radio receiver

Step:4 Setting up of the Wi-Fi-receiver& transmitter

Step:5 Setting up of the Zigbee receiver & transmitter

Step:6 Setting up of the cross communication between the Zigbee and Wi-Fi

The Figures 4.5 and 4.6 represents the software installation. These are the steps involved in installation the operating system, GNU Radio Companion and the SDR B200. With these figures we can arrive at a conclusion about the compability of the device with the system, the system configurations including antenna, the maximum Gain at Tx frontend and the Rx frontend.

4.2.4 Wi-Fi Transceiver

In the previous subsections, the installation of the software and hardware environment for Hardware Implementation was seen while in this subsection, the establishment of Wi-Fi transceiver will be discussed. From Fig. 4.7 we can see that the GNU blocks on the left correponds to the Wi-Fi transmitter while the one on the right corresponds to receiver. The transmitter blocks comprises of Message Strobe which is used to transmit the required data be it series of ‘x’ or ‘1’, Wi-Fi MAC that provides the source and destination address, Wi-Fi

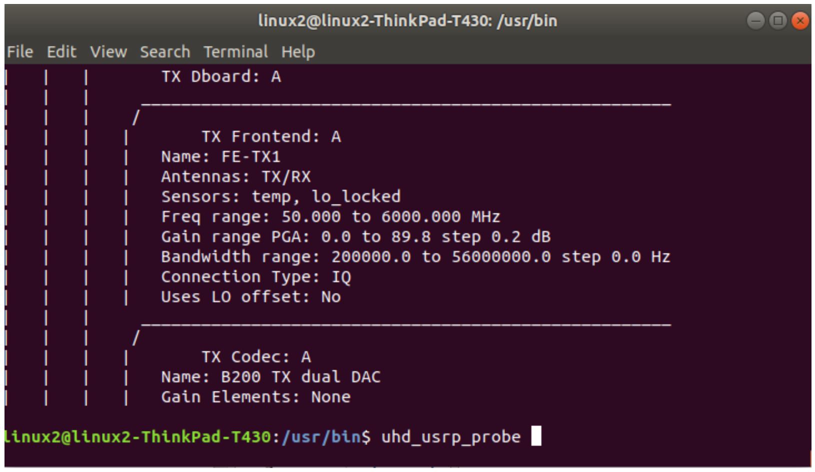

Figure 4.5: Software Installation

PHY Hier that allows tuning of center frequency and UHD USRP Sink that comprises of Center frequency, Gain value and Gain type.

At the receiver side, the excat opposite process happens, modulation at the transmitter becomes demoodulation at the receiver. The data bits from the transmitter are grouped into a packet with a header that contains information about the protocols used, is sent to the receiver which then breaks the packets to bits and retrieves the transmitted data. In the Fig. 4.8, the Wi-Fi receiver console is shown. Here at the transmitter side when a series of 'x' was sent the same was received by the receiver and appears in the console. This shows that Wi-Fi transceiver is working properly and Wi-Fi communication is established. In fact with the help of Wireshark these data packets can be captured and analyzed. The Fig.4.9 shows the data packets collected by Wire shark.

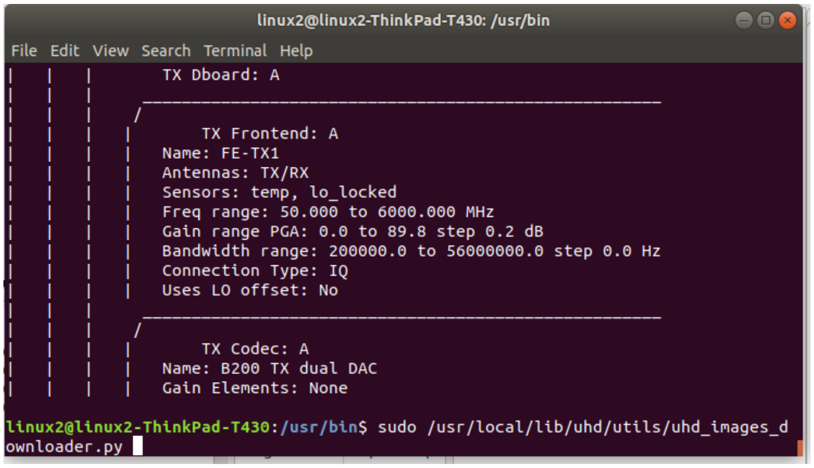

Figure 4.6: Software Installation

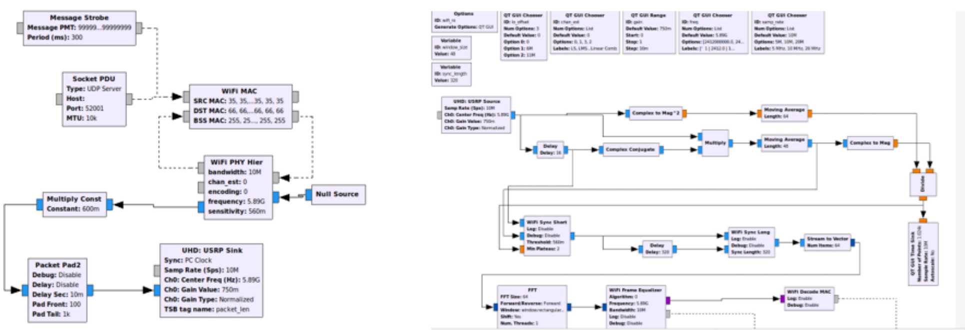

Figure 4.7: GRC Blocks Of Wi-Fi Transceiver
(Source:GitHub)

4.2.5 Zigbee Transceiver

Similar to the Wi-Fi transceiver, Zigbee transceiver too was established using GNU radio companion. The GNU blocks from GitHib was made use of for the construction of Zigbee. It comprises of Message strobe that transmits any message, RIME stack comprises of series of light weight networking protocols that can be made use for wireless networks; UHD USRP Source that helps in fine tuning of the center frequency; IEEE 802.15.4 MAC that comprises of source and destination address and other self-explanatory blocks. Here

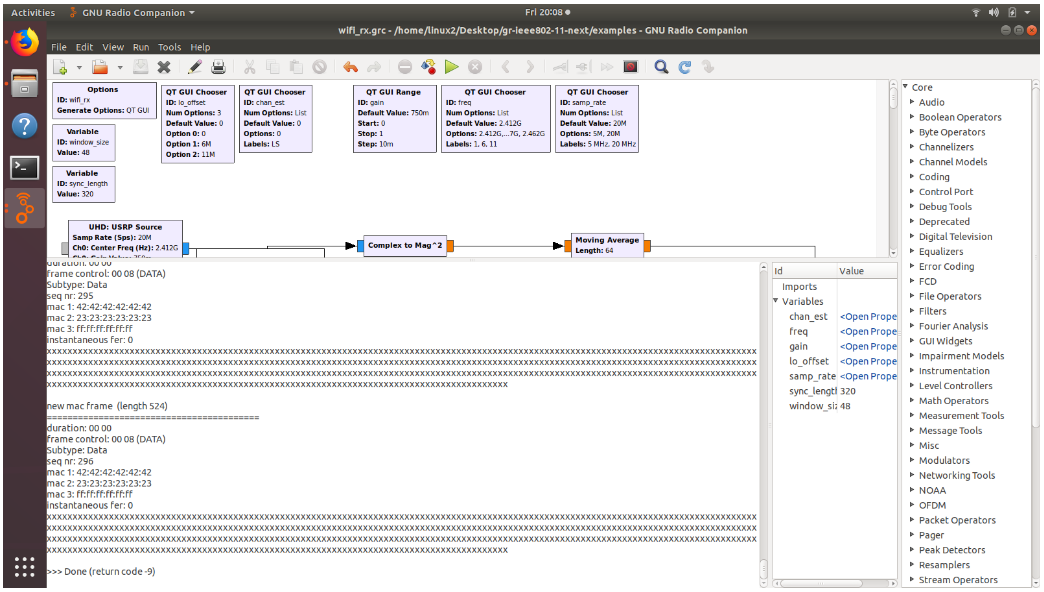

Figure 4.8: Wi-Fi Receiver Console

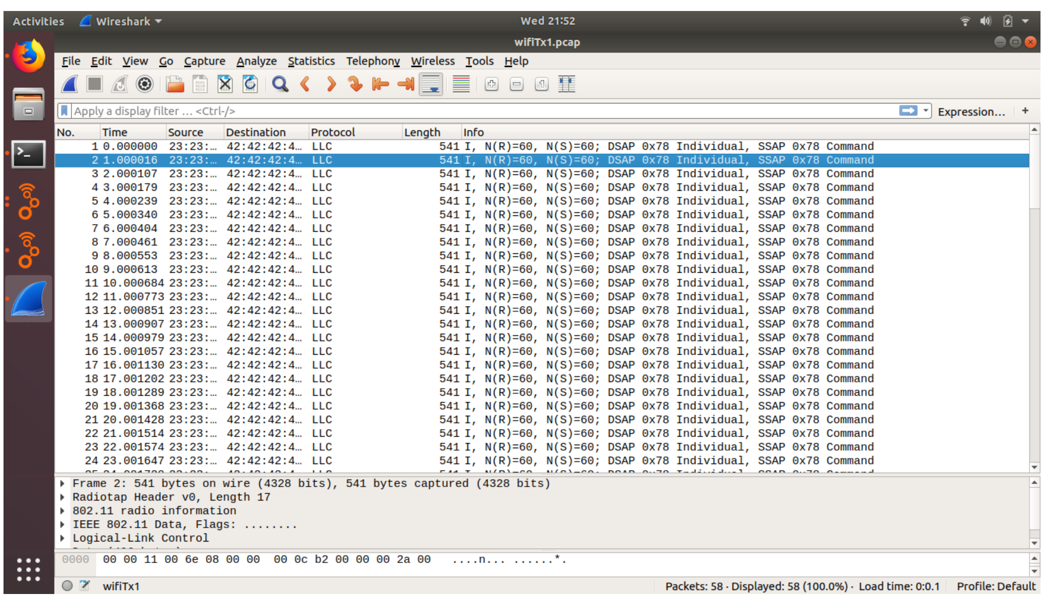

Figure 4.9: Data Packets Captured By Wireshark

the data packets were captured by Wireshark and saved it in a File for analysis. Therefore to check if this Zigbee transceiver is working, we use the waveform that appears when the Zigbee transceiver is turned ON, Fig. 4.11

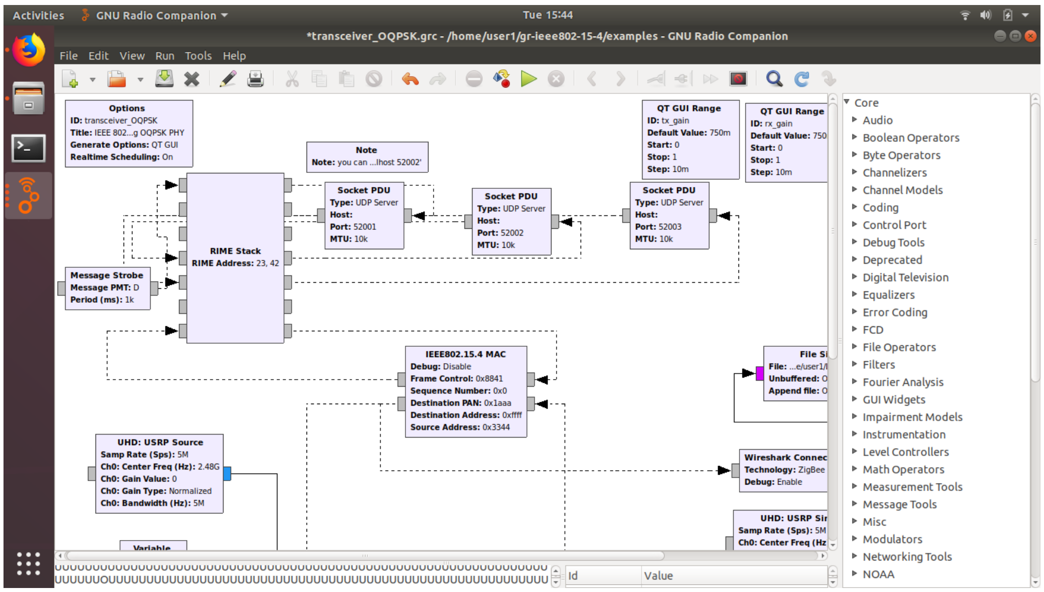

Figure 4.10: GRC Block Of Zigbee Transceiver

4.2.6 Combining Wi-Fi & Zigbee Transceivers

The final step in this Hardware Implementation was combining these two transceivers into a single module that emulates Zigbee or Wi-Fi signals based on the input from the user. The user specifies the type of wireless technology to be used for transfer of data. Since this was at the primitive stage, we seeked the direction from the user but at latter stages as seen in the previous Chapters we developed our own optimal switching point that switches alternatively between the two technologies based on the given data rate and transmit power. The Fig. 4.13 shows the switching point between the two technologies. A

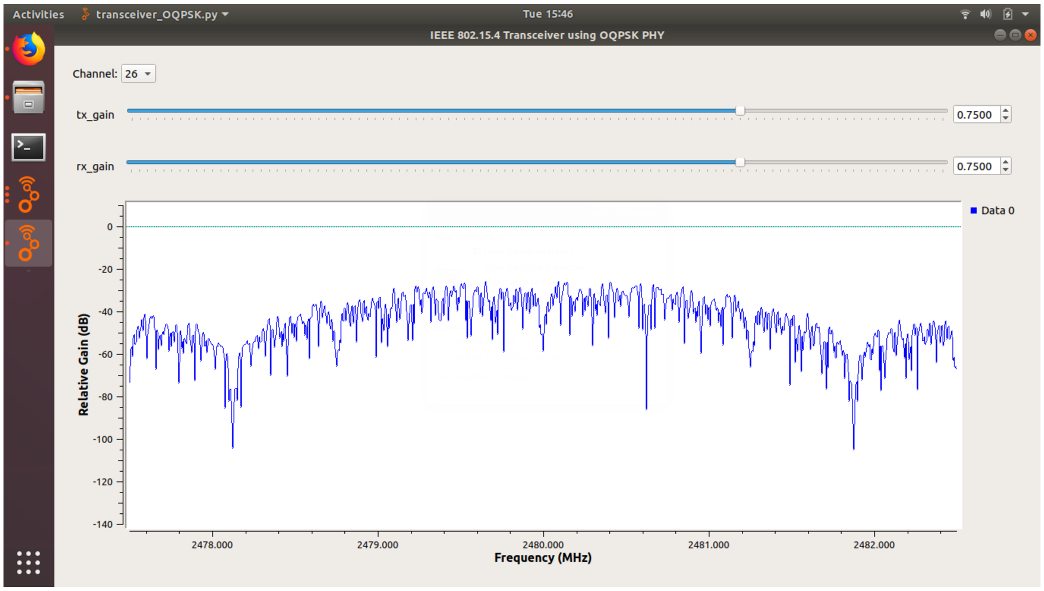

Figure 4.11: Zigbee Transceiver Waveform

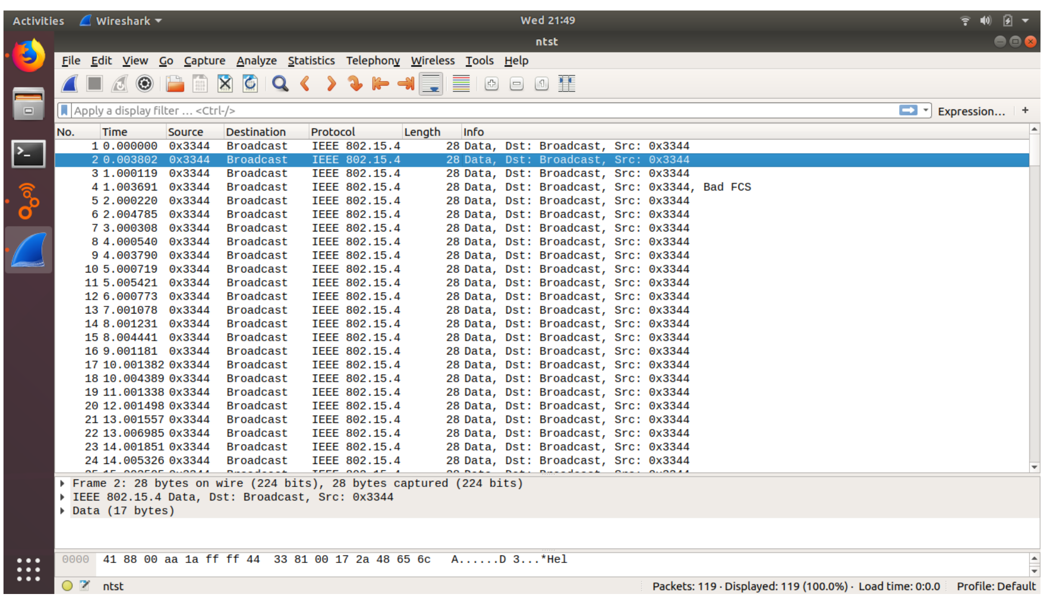

Figure 4.12: Zigbee Wireshark Packets

dot in this simulation represents switching from Zigbee to Wi-Fi as the data rate increases. This is a simple simulation to illustrate the switching between these two technologies. Since Zigbee operates on low power, the data rate will be lower while Wi-Fi operates on higher power therefore the data rate will be higher. Applying the same logic yeilds this simulation.

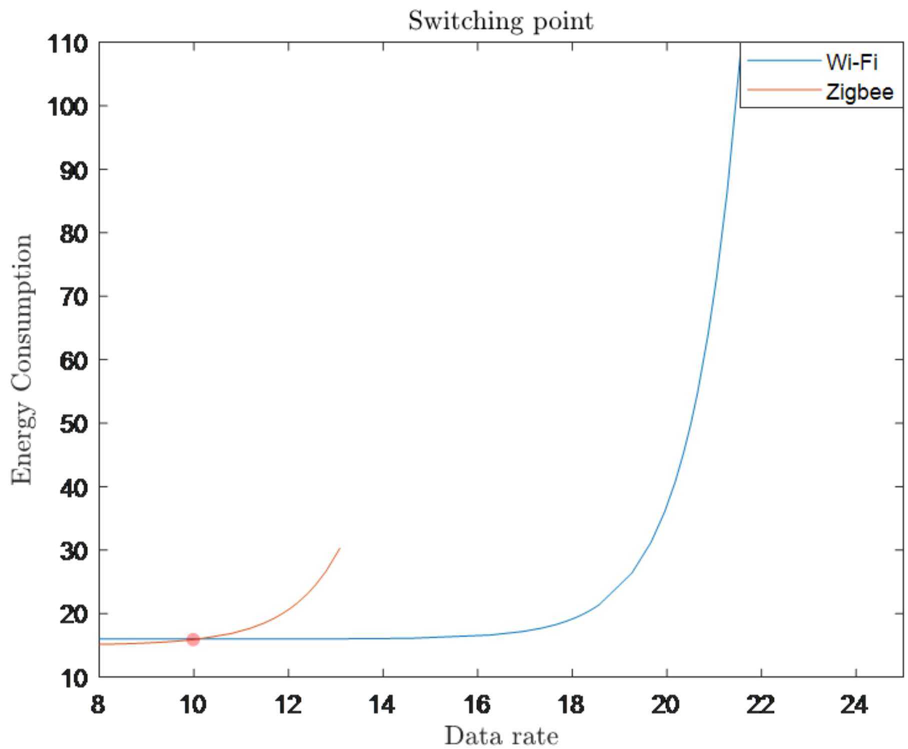

Figure 4.13: Switching Point Between Wi-Fi and Zigbee

CHAPTER V

CONCLUSION AND FUTURE WORKS

IoT devices are rampantly spreading in every sphere of life inluding but not limited to health care, industry, wireless communications. With this increase in these devices, there is increase in the challenges confronted by them too such as Energy Efficiency and Security. This work of ours addressed the Energy Efficiency concern by first understanding the concept of IoT, the works and approaches provided by various authors as discussed in Chapters I and II. Based on our understanding we arrived at a conclusion of utilizing dual technologies to achieve energy efficiency by periodically switching between low power and high power wireless technologies. Understanding the problem of increased interference due to the increased transmit power transmission, we formulated a Game Scheme of the problem. We solved the Game problem after discussing the NE, Best Response Function and associated mathematical equations. This theoretical model was simulated using MATLAB to obtained transmit power of all the devices in the network, followed by the effect of transmit power on utility and sum data rate. In this work we have achieved the optimal transmit power using a single technology, but with the same scheme the optimal transmit power using the second technology too can be determined and switching point will be a ratio between the optimal transmit powers of two different technologies. This will define the wireless technology with which the transmission must proceed.In the hardware section we implemented the Wi-Fi and Zigbee transceivers using USRP B200 and tried to transmit streams of data bits under different frequencies and modulations.

In the future as continuation of this step, we will develop an optimal power control that determines that paves a way by providing the first step in the development of Seamless IoT Central Coordinator. This central coordinator will determine the transmit power, the point of switching and energy efficiency. Another salient feature of this Central Coordinator will be providing flexibility in the network model, in this present network model we considered nodes to be fixed and they cannot leave the network. While in future we will work on providing this above mentioned flexibility.

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