Non Linear and Efficient RF Energy Harvesting for Backscatter Sensor Network with Extended Communication Range

A DISSERTATION

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By

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CANDIDATE'S DECLARATION

I declare that the work presented in this dissertation with title " **Non Linear and Efficient RF Energy Harvesting for Backscatter Sensor Network with Extended Communication Range**" towards the fulfillment of the requirement for the award of the degree of **Master of Technology** submitted in the **Department of Electronics and Communication Engineering**, **Indian Institute of Technology Roorkee**, India. It is an authentic record of my own work carried out under the supervision of **Dr. D. Ghosh**, Professor, Department of Electronics and Communication Engineering, IIT Roorkee.
The content of this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

DATE : .... SIGNATURE:

PLACE: Roorkee (Mandeep Malik)

CERTIFICATE

This is to certify that the statement made by the candidate is correct to the best of my knowledge and belief.

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Date : ....

Place : Roorkee (Mandeep Malik)

Abbreviations

WSN	Wireless Sensor Network
SWIPT	Simultaneous Wireless Information and Power Transfer
RF	Radio Frequency
RFID	Radio Frequency Identification
IoT	Internet-of-Things
MIMO	Multiple Input Multiple Output
SNR	Signal-to-Noise Ratio
PAPR	Peak-to-Average Power Ratio
OFDM	Orthogonal Frequency Division Multiple
PDF	Probability Density Function
CDF	Cumulative Distribution Function
MPPT	Maximum Power Point Tracking
AWGN	Additive White Gaussian Noise
LoS	Line of Sight
NLoS	Non Line of Sight
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CE	Carrier Emitter
SDR	Software Defined Radio
MSK	Minimum Shift Keying
FSK	Frequency Shift Keying
ML	Maximum-likelihood
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access

Symbols and Notations

d	Distance
λ	Wavelength
d_0	Reference distance
v	Path loss exponent
d	Distance
M	Nakagami Fading parameter
P_R	Transmit Power
F_c	Carrier Frequency
P_{sen}	Harvester Sensitivity
Z_0	Antenna Connected to Input Load (Absorbing)
Z_1	Antenna Connected to Output Load (Scattering)
P_{in}	Input Power Interval
T_C	Single Coherence Block
T_P	Packet Duration
T_S	Symbol Duration
$L(d)$	Path-Gain Coefficient
$p(.)$	Harvester Efficiency Function
τ_d	Fraction of Time Antenna is in Absorbing State
P_c	Power Used for Communication purpose
β	BER Threshold
σ_u	Scalled Value of AWGN at Interogator
X	Input Power Dedicated for RF Energy Harvesting
h	Complex Baseband Channel Response
w	Additive White Complex Gaussian Noise
s	Transmitted Symbol
W	Degree of Polynomial
N	Set of Tags
L	Set of CEs
d_k	Distance between reader and n^{th} tag
ΔF_l	Carrier frequency offset
$\Delta \phi_l$	Phase offset

Abstract

This work provides an insight into all Non linear energy harvesting models and there comparison under different fading environments to substantiate the work carried out in previous semester where non linear energy harvesting was proposed along with sensitivity and saturation effects. It is the building block for IoT which works on a giant network of sensors and devices, all these billions of ultra low power devices can be powered by means of energy harvesting and also give boost to green communication. Different rectenna configurations are also compared to find a suitable one which gives high conversion efficiency for a below zero dBm input power also. study is carried out on Passive RFID with non linear energy harvesting for a plethora of IoT applications. In addition to the work carried out in last semester on aa single passive RFID, here comparison and analysis of a number of RFID topologies have been carried out. Multi-static and Mono-static RFID architecture is studied and there placement schemes are verified for successful reception and minimum information outage. Passive RFID also called back-scatter radio or communication by means of scattering is a building technology which works on energy harvesting and can be used in a number of application, like tracking, logistics management and precision agriculture where a network of tags are placed in a geographical area and the data is shared by means of reflection with a software defined radio called a reader.

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Chapter 1

Introduction

1.1 Overview

Big Data and Internet of Things (IoT) is the latest innovation that is driving a plethora of electronic devices to a combined network for latest update and data analytics. IoT is nothing but interconnection of all devices to a global giant network for better assimilation of data, however rapid growth of IoT dramatically increases power consumption of associated wireless devices which can be subdued by use of RF energy harvesting to tap ambient electromagnetic energy in environment[1]. Simultaneous wireless information and power transfer (SWIPT) is a promising solution for operation of IoT devices and facilitates use of sensors and low power devices by means of radio frequency identification (RFID). IoT devices are ultra low powered devices working on a few $mWatt$ while the power for these devices is generally harvested from the incident waves which are strong enough to power a low power device. Energy harvesting is a process by which electromagnetic waves meant for cellphones, TV transmission and radio communication, present in the environment are captured and converted into electrical energy. RF Energy harvesting is carried out for ultra low power devices operating in milli-watt or even micro-watt power level.

Energy-harvesting schemes require stages of Antenna, Rectifier, signal conditioning and storage which can be anything like batteries or capacitors that store harvested energy. wireless network sensors (WSN) have the capability to scavenge energy, either from remote ambient or dedicated RF sources. Energy harvesting conventionally has been done from motion, sun or heat. A typical RFID along with a Software Defined Radio (SDR) as reader and an Carrier Emitter (CE) is shown in Fig 1.1. It can be seen that the RFID does not have any radio parts like mixers or amplifiers while it does communication by means of reflection i.e. using the incident illumination waves. The Reader however is a normal radio and its task is to read the reflections of RFID. Reader can also act like a emitter in case separate CEs are not used in the topology[2].

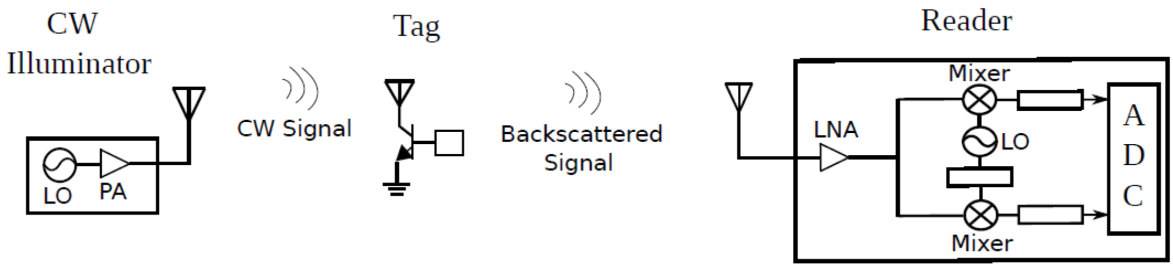

Figure 1.1: Block Diagram of a Passive RFID with SDR based Reader and Carrier Emitter for Illumination

Demand for wireless sensor networks (WSNs) has been increasing, which also drives the need for external power supply other than the problems of recharging and replacement of external/ internal batteries there are also issues linked to size and weight of batteries and there adverse environmental effect[3]. In order to resolve the above mentioned issues, innovation is required in communication for providing effecteve power for these ultra low power devices. Scavenging of energy from omnipresent ambient electromagnetic sources is a novel idea which also minimizes maintenance and cost operation, also the use of batteries[4]. The main building block of a energy harvester comprises of a harvesting antenna, an impedance matching circuit and a device for voltage regulation, harvester antenna captures electromagnetic waves, amplify the same using matching circuit and then convert to a voltage value. The combination of harvesting antena, impedence matching network, and rectifier is usually called a rectenna, which has the task to convert RF to direct current. to power the ever expanding WSNs energy harvesting is a prominent solution which decentralizes a WSN and impedes the use of centralized power supply. The DC voltage generated by the energy harvester is temporarily stored in a capacitor for further supplying power to the communication circuit. Antenna is an energy harvester is different from a communication receiver as its sensitivity is lesser by a few dBm than the communication receiver and also it is itself a combination of diodes and impedance matching network. Radio frequency identification (RFID) is an important ingredient of WSNs and is expected to drive research and innovation for IoT scenarios and Simultaneous Information and Power Transfer (SWIPT). There is also need to quantify the amount of energy that can be recovered/ generated from the electromagnetic waves to fulfill the energy requirement of a particular sensor node. RF energy harvesting requires, RF antenna that can harvest energy from a variety of sources, that includes TV signals (ultrahigh frequency (UHF)), mobile cellular phones (900–950 MHz) or towers ,WiFi hot-spots (2.45 GHz/ 5.8 GHz)[5]. RF signal captured by the antenna is actually an alternating current (AC) signal and to convert the same to a DC signal, the efficiency of the RF–DC power conversion system should be high[6]. Rectification subsystem consists only of diodes (for rectification) and capacitors(for storage). Use of rectification circuits depends on the RF signal, its source and the distance of the source from harvester[7].

It is also highlighted that the power consumption for these devices is very low and thus a single CE will be able to illuminate large number of RFIDs in a Line of sight (LoS) and non Line of sight (NLoS) scenario. RFIDS are used in logistic management, product tracking, toll tax collection and data collection, however with the advent of IoT it can be further used in smart agriculture schemes like precision agriculture where RFIDs are placed along with a soil moisture sensor near to plants and will provide information regarding the level of moisture in soil for precision agriculture. It finds application in those countries which have limited water resources and use organic farming[8].

1.2 Literature Review of IoT

IoT is the latest innovative technology that is a game changer as it tries to make a giant global network of all devices which have any kind of electronic parts[9]. Main purpose of IoT is to connect every device other than the conventional ones like Laptops , PCs, Tablets and Mobiles. In past few years RFID technology has evolved and is being used for sharing of data related to smart sensors and WSNs. The data is further analysed with help of Big-data and other Internet protocols to evaluate and gather requirement of a particular system. IoT with advant of time can convert all electronic devices to speak to each other in order to promote sharing and develop a huge internet network for controlling and administering almost all connected devices. This requires a huge global infrastructure of networking equipment and high data speeds and also power for billions of devices [10]. The upcoming IoT technology will have large opportunities and will find application for high quality of life and work as catalyst to :

- Grow the world economy by automation.
- Sense environmental statistics.
- Improve the general awareness of people.

Big Data also uses IoT for gathering data and its analysis, it also can help in making sensors more accurate and reduce malfunctions. IoT is being used and also has future prospects in large industrial application and service industry. Some of the application of IoT are as follows :

- In Hospitals and patient management which includes identification, patient tracking, and vital statics collection.
- Precision agriculture, soil moisture data collection, environmental monitoring,
- Tracking of valuables, inform thefts.
- Supply chain management, tracking and identification.
- Inventory management and production administration.

1.3 Thesis Objectives

Contribution of this thesis to overall IoT and to energy harvesting in RFID based application is as enumerated :

- This work compares different Linear and Nonlinear energy harvesting models for use in passive RFIDs.
- Harvested power modeled as an arbitrary nonlinear, continuous function of input RF power with sensitivity and saturation accounted for.
- Signal model with TDMA, FDMA incorporated for mono-static and multi-static systems with path loss and fading effects.
- BER performance and Information outage analysis for different topology models and grid configuration.

1.4 Organization of Thesis

This thesis is the next step for enabling IoT and powering ultra low power devices. In the previous semester study was carried out Linear and Non linear energy harvesting and adding sensitivity, saturation effects to the same. A realistic study of Non linear harvesting using approximations and monte carlo experiments was done to analyze behavior of harvester in different fading environment. A case study on Passive RFIDs was also carried out to find the energy and information outage events.

Chapter 2 of this thesis gives an insight into the models of Nonlinear far field RF energy harvesting and compares a number of models which show strong non linearity and also the erstwhile linear models. It also discusses the communication of a single RFID, its BER outage and information outage events and scenarios.

Chapter 3 discusses a network architecture for RFIDs and provide details of Mono-static and Multi-static architecture, Detection schemes at reader and effects of fading in LoS and NLoS. Communication by means of reflection is proposed and its mathematical model.

Chapter 4 and 5 provides numerical and simulation results for outage analysis in Mono-static and Multi-static topologies. It also discusses scatter network and diversity reception.

Chapter 2

Sensitive and Nonlinear Energy Harvesting for Backscatter Radio

There is a ocean of electromagnetic waves surrounding us but remains largely unused, though the number of electromagnetic transmitters are increasing exponentially in form of cellular towers, FM stations and Wifi Hotspots the ambient energy available across the frequency spectrum remains untapped and is available for harvesting. The engineering challenge is to collect all these unused electromagnetic waves and make them power backscatter radio sensor network for vast IoT applications.

2.1 Literature Survey

IoT and SWIPT are the current scenarios and a lot of research papers related to these field have been published in last few years. Study has been carried out to understand the importance of IoT which is a driving force for all the work being carried out in fields of energy harvesting and SWIPT. Work in [1] provided details on enabling technologies for IoT, its application and the general protocol architecture to include its frequency management and security issues. Transporting Information and Energy Simultaneously [5] was the very first paper to describe SWIPT and deals with fundamental tradeoff between transmitting energy and transmitting information over a single noisy line. It provided a coding theorem and also gave a proposition to the problems related to powerline communication and RFID systems.

Shannon meets Tesla (wireless information and power transfer)[6] uses magnetic resonance coupling for energy harvesting to bring a tradeoff between Claude Shanon for information transfer and Nikola Tesla for energy transfer. It tries to bring a compromise between power efficiency which can be attained with maximization of narrow-band links that perforce have to operate at low frequencies while if using data signals they will require larger bandwidths a communication of data is in kilobytes, for which we will be requiring higher operating frequencies so that the bandwidth is increased. Work in [11] proposes a nonlinear energy harvesting model and compares the same with a linear energy harvesting model, it also proposes a iterative algorithm for optimizing resource allocation in SWIPT and then carries out a comparison with the current linear energy harvesting model with non convex optimization.[11] Also carries out a study based on simulation to increase the number of energy harvesting receivers to facilitate resource allocation mismatch for the baseline scheme and leading to an increase in average harvested energy.

Work in[12] is a realistic model on energy harvesting and the ultra sensitive Rectenna described in [12] is used in all studies and simulations carried out in this paper and forms the basis for this paper along with the commercially available powerCast module. In our study of SWIPT and energy harvesting we have in the last semester compared the non linear and linear models based on the powercast and the ultrasensitive rectenna model prescribed in this paper while for comparison of non linear models only the ultra sensitive rectenna model is used as its RF conversion efficiency is very high and also it is sensitive. The simulated and measured rectenna efficiency was 28.4 percent for 20dBm power input. In order to increase sensitivity and to increase the amount of energy harvested even at low operating incident RF energy, rectennas were connected in series configuration (voltage summing), forming rectenna arrays to cater for the large power requirement for communication purpose.

Work in [13] gives an insight into the network architecture and topology of RFIDs for large scale implementation of the same. It also compares three technologies i.e. Monostatic, Bi-static and Multi-static to find the best in terms of BER, outages and data transfer. The data provided is very useful for deciding while implementing different types of network topologies in a given area. It also brings to notice the factors that can enable extended range for these devices.

2.2 Efficient Rectenna Configuration

Rectenna is a combination of antenna and rectifier with the primary task to convert RF to DC voltage and is heart of any energy harvester circuit to convert the incedent electromagnatec waves. An important parameter of rectenna is the rectenna efficiency which is described as the ratio of DC power output to the RF incident power input i.e. amount of DC power generatedwith a given RF incident energy. Considerable research work has been done to increase the efficiency even for 0 dbm levels as the ambient energy available is in the range of few dBms. Summary of rectenna efficiency in different frequency bands achieved by prior research is given in table 1. In [14] an antenna array was used while in [15] the rectenna was designed with closed form expression. In [16] and [17] substrates with low losses were used in [16] the rectenna used was a multiband one and in [17] it was a single band. In[18] again a dual band rectenna was utilized while [19] and [20] emphasized on impedance matching circuit.

S No	Prior Work	Efficiency	Input Power (dbm)	Frequency (MHz)
(a)	[14]	65 %	25	2450
(b)	[15]	40 %	0	2450
(c)	[16]	44.5 %, 34.5 %	-8.77, -16.27	900, 1750
(d)	[17]	33 %	-10	900
(e)	[18]	15 %	-20	850, 1850
(f)	[19]	17 %	-20	868
(g)	[20]	20.5 %	-20	868

DC output voltage that is generated by rectenna is to be further enhanced by means of voltage multiplier circuits or by increasing the number of diodes in order to manipulate the output voltage. Here an important relation is highlighted that as we increase the number of diodes, the output voltage increases but at the cost of efficiency. Also in order to tackle the problem of large number of diodes, following approaches can be used.

- One branch of diodes used for startup of energy harvester and another for boost conversion.

- Combining multiple rectennas operating at same or different frequency band into one single module, thus enhance the DC power output.

RF to DC efficiency of a rectenna is given as below :

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\frac{V_R^2}{R}}{P_{in}} \tag{2.1}$$

Where P_{in} and P_{out} are the power input and output respectively, and V_R is the voltage across resistance R.

2.3 Wireless System Model

SWIPT as a matter of fact has found its most prominent application in Backscatter communication and passive RFIDs. In Fig 2.1 a passive RFID is seen and the figure enumerates how the communication is being carried out through reflection. The basic principle of communication by reflection requires two impedance Z_0 and Z_1 with the former for absorbing state and the later for reflection state. A RFID has single antenna for both energy harvesting and communication. When the RFID is in absorbing state and harvests energy than it is working in downlink mode and otherwise while communicating it works in uplink mode, however both the links are prone to large scale fading and are separated by a distance d with the path gain model [21] is given as:

$$L \equiv L(d) = \left(\frac{\lambda}{4\pi d_0}\right)^2 \left(\frac{d_0}{d}\right)^v \tag{2.2}$$

where d_0 is the reference distance ,λ is propagation wavelength and path loss exponent (PLE) is v. As the communication bandwidth between the tag and reader is small thus we can assume it to be flat fading. Passive RFIDs transmit and receive very less data and thus it is described as small scale fading and the coefficient for same is given as $h = ae^{-j\phi}$. It is also known that there is an existing line of sight communication between reader and RFID due to the small ranges involved and thus we will be assuming it to be Nakagami small scale fading with $E[a^2] = 1$ and Nakagami parameter as $M \geq 1/2$. In case of no line of sight communication Rayleigh fading model may be utilized or Rican model which have $M = 1$ and $M = \infty$.

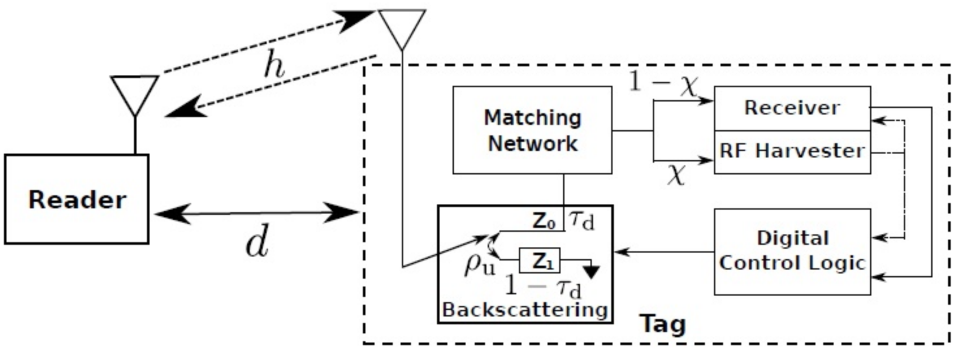

Figure 2.1: A Passive RFID where an interrogator is acting as CE and as a reader to receive reflected information from RFID tag.

Received signal and the tag is given as follows :

$$x = \sqrt{P_T T_s G(d)}\boldsymbol{hs} + z \tag{2.3}$$

$$c_T(t) = \sqrt{2LP_R} R\{he^{j2\pi F_c t} \tag{2.4}$$

while the received power at tag is given as follows:

$$P_R^{(n)} = E\left[|s^2|\right] P_T L(d) \left|h^{(n)}\right|^2 = \mathrm{P}(d)\gamma^{(n)} \tag{2.5}$$

$$P_{in} = LP_R|h|^2 = LP_R a^2$$

where $\mathrm{E}[\boldsymbol{s}] = 0$ and $E[|s^2|] = 1$, P_R is transmit power. F_c is the frequency, T_s is the symbol duration, $P_R^{(n)}$ is a function of $\gamma^{(n)}$, i.e. $P_R^{(n)} \equiv P_R^{(n)}(\gamma^{(n)})$.

$$f_{\gamma^{(n)}}(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m}{\Omega}x}, x \geq 0 \tag{2.6}$$

$$F_{\gamma^{(n)}}(x) = 1 - \int_x^\infty f_{\gamma^{(n)}}(y)dy = 1 - \frac{\Gamma\left(m, \frac{m}{\Omega}x\right)}{\Gamma(m)}, x \geq 0 \tag{2.7}$$

Where m = 1 and m = ∞, Rayleigh and no-fading is obtained, respectively.

$$P_{har}^{(n)} \equiv P_{har}^{(n)}\left(P_R^{(n)}\right) = p\left(P_R^{(n)}\right) \tag{2.8}$$

where

$$p(x) \triangleq \left\{ \begin{array}{cc} 0 & x \in [0, P^{sen}], \\ e(x).x, & x \in [P^{sen}, P^{sat}], \\ e\left(P^{sat}\right).P^{sat} & x \in [P^{sat}, \infty] \end{array} \right\} \tag{2.9}$$

Harvesting function e$(\cdot)$ is defined over the interval $P \triangleq [P^{sen}, P^{sat}]\,.P^{sen}$ represents sensitivity; In case the input power is below the senstivity mark than the harvested power is zero.

2.4 RF Harvesting Models

Passive RFIDs work on communication using reflection and rather than the Marconi radio system where there is requirement of Amplifiers, Mixers and other components. In order to attain communication Binary modulation is used in which there are two different termination loads Z_0 and Z_1 being varied for modulation which modulates Tag data over the illuminating signal reflected back to the reader in an ultra low power scenario. The primary and only source of power available to the RFID tag for operation is the reader generated signal which has to be harvested for any kind of communication. Energy harvesters have limited sensitivity and quite less than communication receivers, for successful operation the incident power must be greater than the RFIDs harvester sensitivity i.e. $P_{in} > P_{sen}$. In previous semester and also work carried out in [2] prescribed that a high order polynomiall can be considered as groound truth model for calculation of harvesting efficiency function. A couple of Linear and Non Linear models were compared with through analysis to find the impact of linearity, saturation and sensitivity effects in energy harvesting and to calculate harvested power and its dependence on input power. Harvested power from these models are shown in Fig 2.2.

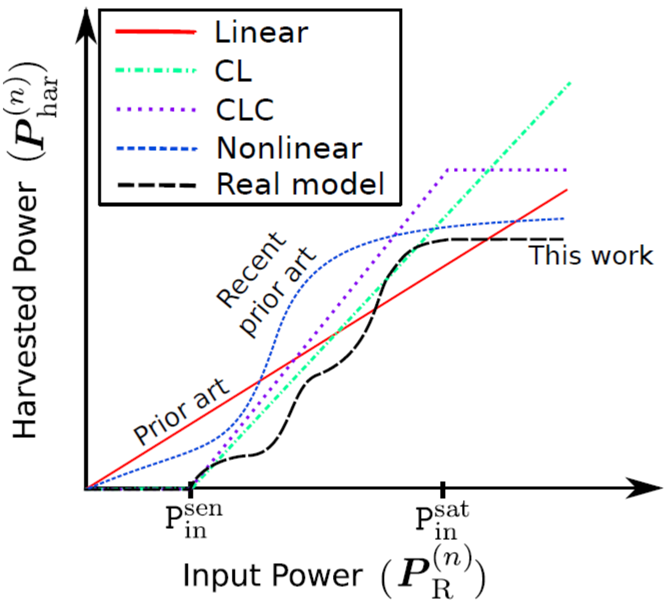

Figure 2.2: Work in previous semester which includes comparison of different linear models with Saturation and sensitivity effects.

Using the previously established model in last semester harvested power generated by the harvester can be represented as :

$$p(x)\left\{\begin{array}{cc} 0 & x \in [0, P_{sen}], \\ (w_0 + \sum_{i=1}^{W} w_i(10\log_{10}(x))^i\ ).x, & x \in [P_{sen}, P_{sat}], \\ \mathrm{p}(P_{sat}) & x \geq P_{sat} \end{array}\right\} \tag{2.10}$$

Where W is the degree of polynomial and w_i is the corresponding coefficients from $i = 1$ to W. The harvesting efficiency function is as listed:

$$(w_0 + \sum_{i=1}^{W} w_i(10\log_{10}(x))^i \tag{2.11}$$

For analysis the function described in Eq. 2.12 is assumed to be continious and increasing in the interval $[P_{sen}, P_{sat}]$, also the ultra sensitive rectenna is used here for modeling purpose along with convex optimized fitting methods.

2.4.1 Linear Model

This model have been used in maximum energy harvesting prior publications, and only has one parameter model for modelling of harvested power, Mathematically represented as :

$$p_1(x) = \eta_L.x, x > 1, \tag{2.12}$$

The model does not take into account the harvesters sensitivity, saturation effect i.e when the input power is above a threshold power or below the minimum required power.

2.4.2 Constant Linear Model

This model is more realistic in nature and uses sensitivity setting and its factual implication on the harvester. It provides information on harvester and the situation in which it is not able to harvest any energy when the input power reaches the minimum threshold level, while no modifications are made to account for saturation effect. The model is described as follows :

$$p_2(x) \triangleq \left\{ \begin{array}{cc} 0 & x \in [0, P_{sen}] \\ \eta_{CL}.(x - P_{sen}), & x \in [P_{sen}, \infty] \end{array} \right\} \tag{2.13}$$

η_{CL} is constant harvesting eff.

2.4.3 Nonlinear Normalized Sigmoid

There were two models proposed in [11] and [22] in which the former one used a sigmoid to describe the harvested energy without sensitivity and the later one also used a sigmoid but accounts for sensitivity. First one is expressed as p_3 and the later one as p_4. The shape of both p_3 and p_4 are governed by the real numbers a_0, b_0 and c_0. Models are given as follows :

$$p_3(x) \triangleq \frac{\frac{c_0}{1+\exp(-a_0(x-b_0))} - \frac{c_0}{1+\exp(a_0 b_0)}}{1 - \frac{1}{1+\exp(a_0 b_0)}} \tag{2.14}$$

$$p_4(x) \triangleq \max\left\{ \frac{c_0}{\exp(-a_1 P_{sen} + b_1)} \left(\frac{1 + \exp(-a_1 P_{sen} + b_1)}{1 + \exp(-a_1 x + b_1)} - 1 \right), 0 \right\} \tag{2.15}$$

2.4.4 Second Order Polynomial Model

In [7] a mathematical model which was based upon quadratic polynomial was proposed, the model was in milliWatt domain. It is presented in two forms i.e one without sensitivity and one which includes sensitivity of the harvester. Harvested power in both the models is described as follows:

$$p_5(x) \triangleq a_2 x^2 + b_2 x + c_2 \tag{2.16}$$

$$p_6(x) \triangleq a_3(x - P_{sen})^2 + b_3(x - P_{sen}) \tag{2.17}$$

2.4.5 Piece-wise Linear Model

Piece wise model can be used to model energy harvesting from RF as well as other sources like harvesting from ambient light or sunlight done by photo-diodes described as a function of illuminiance. Saturation and sensitivity is are modeled as $q_J = P_{sat}$ and $q_0 = P_{sen}$. Harvested power is give by $p_7(x)$ and is described as follows:

$$p_7(x) \triangleq \left\{ \begin{array}{cc} 0 & x \in [0, q_0] \\ l_j(x - q_{j-1}) + v_{j-1}\ , & x \in (q_{j-1}, q_j), \forall j \in [J] \\ v_J & x \in [0, \infty] \end{array} \right\} \tag{2.18}$$

where input and harvested power points are given as $\{q_j\}_{j=0}^{J}$ and $\{v_j\}_{j=0}^{J}$ while slope as $l_j \triangleq \frac{v_j - v_{j-1}}{q_j - q_{j-1}}$

2.5 Non Linear Energy Harvesting in Passive Tags

Passive RFID tags works on backscatter scenario where task of RFID tag is to bifurcate the incident RF energy for harvesting purpose and also for wireless communication simultaneously i.e. Non duty cycled operation. The RFID tags comprises of a transistor that acts as a reflector while an interrogator incidents the energy on it. A schematic of a mono-static back-scatter architecture (non duty cycled) is depicted in Fig 2.3. The SDR Reader antenna emits electromagnetic waves to the Tag in the vicinity of reader and than also performs the function of receiver when it receives reflected signal from passive RFIDs,

The RFID tag antenna has two impedance which are defined as Z_0 and Z_1, when the antenna is terminated at Z_0, the tag absorbs power from the incident signal and when the antenna is terminated at Z_1, the tag reflects the incoming signal, i.e. it scatters back information (up-link), provided that it has sufficient amount of energy. It is further assumed that the overall round-trip communication among the interrogator and the tag lasts a single coherence time period. τ_d denotes the fraction of time the antenna is at Z_0, while $1 - \tau_d$ corresponds to the time at load Z_1. In Mono-static architecture, the incident input power at tag antenna is $P_R = P_T L(d)\gamma = P(d)\gamma$. Since, only a part of p_u input incident power is back-scattered (i.e.$p_u P_R$), the received power at the Reader due to the round trip nature of back-scattering operation is given as :

$$g_{\text{int}}(P_R) \triangleq p_u P_R L(d)\gamma = p_u \frac{(P_R)^2}{P_T} \tag{2.19}$$

Following events are required for successful reception:

A=Bit error rate at reader is below a specified threshold β

$$= \left\{ 2Q\left(\frac{\sqrt{g_{\text{int}(P_R)}}}{\sigma_u}\right)\left(1 - Q\left(\frac{\sqrt{g_{\text{int}}(P_R)}}{\sigma_u}\right)\right) < \beta \right\} \tag{2.20}$$

and

B=Power harvested by Tag is larger than tag's power consumption P_c

$$= \{p(\zeta_{har} P_R) > P_C\} \tag{2.21}$$

Where $Q(x) = \frac{1}{\sqrt{2\pi}} \int\limits_0^\infty e - \frac{t^2}{2} dt$ represents the Q-function and Eq.(2.20) is the probability of BER under coherent maximum-likelihod detection, while $\beta \in (0, \frac{1}{2})$ is the BER threshold. Parameter ${\sigma_u}^2$ is given as variance of thermal AWGN noise which is measured at the receiver circuit of SDR.

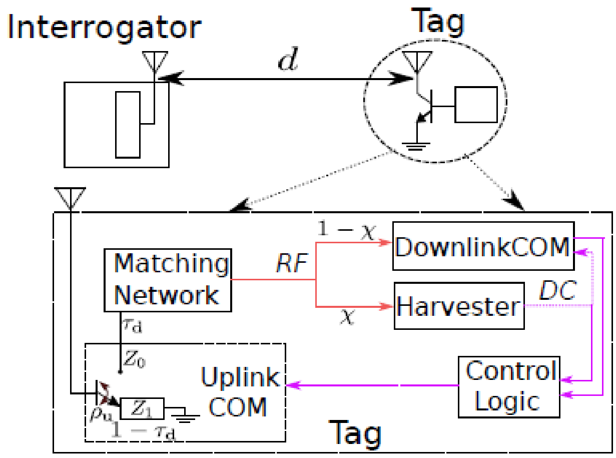

Figure 2.3: A Passive RFID architecture consisting of an SDR based interrogator.

Tag antenna is either connected to Z_0 or Z_1 as per the requirement state of harvesting. It is also highlighted that for tag to operate effectively the total harvested power must be greater than tags overall power demand. Passive RFIDs do not have any kind of storage capability like battery or capacitors. The backscatterd signal for for a N tag bits is given as $b(t) = \sqrt{Lp_uP_R}h(A_s - \Gamma_0 + \Delta\Gamma \sum_{n=1}^{N} Sb_n(t-(n-1)T))$ where $\Delta\Gamma = (\Gamma_0 - \Gamma_1)$ and $b_n \in \{0,1\}$ while b_n is the nth bit transmitted. For successful interrogation and to avoid misinterpretations following is carried out :

- Balance time between absorbing and reception states.
- line coding scheme to avoid thermal noise as legitimate communication
- FM0 line coding scheme is utilized.
- It observes for 2T signal duration for each bit of size T.

Coherent detection is carried out in a $T/2$ shifted waveform and s_{b_n} is represented in two parts as follows:

$$s_0(t) \triangleq \begin{Bmatrix} 1, 0 \le t < \frac{T}{2} \\ \hline 0, otherwise \end{Bmatrix} \tag{2.22}$$

and

$$s_1(t) \triangleq \begin{Bmatrix} 1, \frac{T}{2} \le t < T \\ \hline 0, otherwise \end{Bmatrix} \tag{2.23}$$

Near perfect synchronization is assumed and the received signal is projected upon the basis function subspace with the help of two correlates and the base-band signal at the output is given as :

$$y_n = gs_n + w_n, n = 1, 2, 3.......N \tag{2.24}$$

where $g \triangleq L\sqrt{p_uP_R}h^2(\Gamma_0 - \Gamma_1)$ and s_n is vector representation of nth trasmitted signal. In Passive RFIDs which use FM0 as line coding scheme s_n is represented as $s_n \in \{[1,0]^T, [0,1]^T$ while w_n is the noise.

2.6 Outage scenarios and BER

The error probability for base-band signal in previous section with channel g and of duration $2T$ is given as

$$\mathrm{P}(BER|g) = 2Q(\frac{|g|}{\sigma})(1 - Q(\frac{|g|}{\sigma})) \tag{2.25}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int\limits_{x}^{\infty} e^{-\frac{t^2}{2}dt}$ is the Q function.

Passive RFIDs do not have any storage capability and for an interrogator to successfully extract tags information following must be satisfied :

- Power received at the RFID antenna is greater than the harvesters sensitivity.
- RFID power consumption must be less than the harvested power.
- BER remains below a pre decided level.

Different outage scenarios are as listed below:

2.6.1 Moderate Harvesters Sensitivity in Comparison to Communication Receiver

Input power which is also the received power at tag is defined as :

$$P_{in} = LP_R|h|^2 = LP_R a^2 \tag{2.26}$$

Taking into account the input power mentioned in Eq. (2.26), RFIDs harvesting ability metric is given as follows :

$$\mathbf{P}(\mathrm{A}) \triangleq \mathrm{P}(P_{in} \leq P_{sen}) = \mathbf{F}_{P_{in}}(P_{sen}) \tag{2.27}$$

Where the cumulative distribution function of P_{in} is given as $\mathbf{F}_{P_{in}}$. Above equation gives the probability of P_{in} at tags antenna is below P_{sen} i.e. Harvesters senstivity. It basically describes the amount of time in which RFID is not able to harvest energy due to low input power, as in past we have considered Nakagami fading thus the Nakagami outage of same is described as follows :

$$\mathbf{F}_{P_{in}}(P_{sen}) = 1 - \int\limits_{P_{sen}}^{\infty} f_{P_{in}}(y)dy = 1 - \frac{\Gamma(M, \frac{M}{LP_R}P_{sen})}{\Gamma(M)} \tag{2.28}$$

Sensitivity of a communication receiver generally available over the shelf is around -40dbm while for harvesters it is -80dbm and thus almost half in comparison to communication one. It can be safely concluded that all available electromagnetic signals may not fit for energy harvesting.

2.6.2 Limited Harvested Power

If the energy harvested by the tag is not enough for communication or is below the RFIDs power consumption P_c than limited power consumption outage will occur. Mathematically it can be described as :

$$\mathbf{P}(p(\zeta_{har}P_{in}) \leq P_c) \tag{2.29}$$

Function p(.) is continious and increasing, thus the above Eq 2.29 can be described as :

$$\mathbf{P}(\beta) \triangleq \mathbf{P}(P_{in} \leq \frac{p^{-1}(P_c)}{\zeta_{har}}) = \mathbf{F}_{P_{in}}(\frac{p^{-1}(P_c)}{\zeta_{har}}) \tag{2.30}$$

Where $p^{-1}(P_c)$ represents inverce function of p(.). It will be worth mentioning here that the above equations depend on

- Quality of RF energy harvester used.
- Fading effects.
- Amount of time RF harvested energy is not enough for RFID consumption as there is no ability for storage of energy.

2.6.3 Outage due to BER below Threshold

At the reader detection is carried out by ML differential detection and the error probability is :

$$\mathrm{P}(error|g) = 2Q(\frac{|g|}{\sigma})(1 - Q(\frac{|g|}{\sigma})) \tag{2.31}$$

The predefined threshold is set as β and with it the even can be defined mathematically as :

$$\mathbf{P}(C) \triangleq \mathbf{P}\left(P_{in} \leq \frac{\sqrt{P_R}\sigma R^{-1}(\beta)}{|\Gamma_0 - \Gamma_1|\sqrt{p_u}}\right) = \mathbf{F}_{P_{in}}\left(\frac{\sqrt{P_R}\sigma R^{-1}(\beta)}{|\Gamma_0 - \Gamma_1|\sqrt{p_u}}\right) \tag{2.32}$$

In case the Interrogator is not able to successfully read the data from tag than the same is attributed to occurrence of any of these events :

- Incident signal is not in the range of energy harvester i.e. limited harvester sensitivity.
- If the harvested power is not enough for communication.
- If BER is below the required levels.

With the above mentioned conditions the probability of an unsuccessful reception by interogator is as follows:

$$\mathbf{P}(F) = 1 - \mathbf{P}(F^C) = 1 - \mathbf{P}(A^C \cap B^C \cap C^C) \tag{2.33}$$

$$= 1 - \mathbf{P}(P_{in} > \theta_F) = \mathbf{F}_{P_{in}}(\theta_F) \tag{2.34}$$

where $\theta_F \triangleq \max\left\{P_{sen}, \frac{p^{-1}(P_C)}{\zeta_{har}}, \frac{\sqrt{P_R}\sigma R^{-1}(\beta)}{|\Gamma_0-\Gamma_1|\sqrt{P_u}}\right\}$ and the above described even can find out the chances of a failed reception. It is also required that the chances of successful reception be enumerated after taking into account the effects of Nakagami fading. $\mathbf{P}(ReaderSuccess) \equiv \mathbf{P}(F^C) = \frac{\Gamma\left(M, \frac{M}{LP_R}\theta_F\right)}{\Gamma(M)}$

Chapter 3

Network of RFID Tags based on Nonlinear Energy Harvesting

In the last chapter we have studied about nonlinear models for energy harvesting in passive RFID tags and the mechanism of a single RFID. We also studied about energy outage and information outage in RFID and there comparision based upon different nonlinear models. In this chapter rather than deliberating on a single tag, the way ahead will be to apply the system model on a network of RFIDs and thus bring about a complete network of RFID for a larger general area. A scatter radio network is comprised of multiple passive RFID tags, being interrogated by a single reader. It may also consist of a number of Carrier Emitters (CE) to cater for illumination of tags for energy harvesting and to cover a large area deprived of an ambient energy sourse[23]. A comparative analysis is also carried out for passive RFID tags in a large area served by single reader configuration and with CE or without CEs[24]. The topology and network architecture of Mono-static and Multi-static schemes is shown in Fig 3.1.

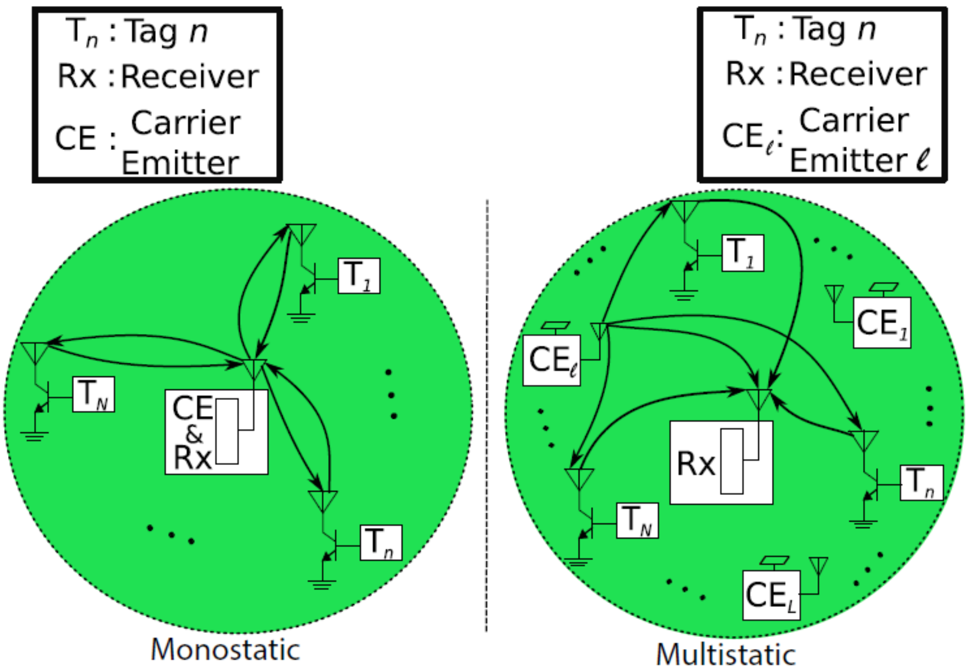

Figure 3.1: RFID tags in different network topology with Mono-static architecture on left and Multi-static on right.

3.1 Channel Model and Network Architecture

A Passive RFID WSN comprise of N tags at different locations that backscatter their data to a single reader which can be a software defined radio (SDR). All these scatter radios can be classified in a set denoted by N =1,2,.....N. It has been described in previous chapters that a mono-static architecture consist of a single emitter and reader to interrogate a number of passive RFIDs, however in a multi-static architecture there are a number of carrier emitters and a single reader to interrogate the passive RFIDs. Going forward for a multistatic archetecture we assume a set of carriers denoted as L= 1,2.....L. These CEs are are all spread distinctively and have no relation with the reader. CEs transmit a continious wave (CW) which can be a anything based upon any multiplexing scheme i.e. Time division multiple access (TDMA) or frequency division multiple access (FDMA). The transmission channel for communication between Tag and Reader is considered to be changing with time and frequency i.e. Quasi-static. FDMA and TDMA methodology for simultaneous transmission over a given channel is managed by distributing it into time slots and frequency slots, in TDMA the l^{th} time slot and in FDMA the l^{th} frequency spot will develop $2N + 1$ links in a number of configurations :

- N number of RFID to Interrogator links.
- N number of CE to RFID links.
- N number of CE to Interrogator links.

Let us define the distance between l_{th} emitter and n_{th} RFID as $d_{C_l T_n}$, distance between n_{th} RFID and Interogrator as $d_{T_n R}$ and between the n_{th} emitter and Interrogator as $d_{C_l R}$. In Fig 3.2 a multi-static topology is shown as well as access of time slots in case of FDMA and TDMA.

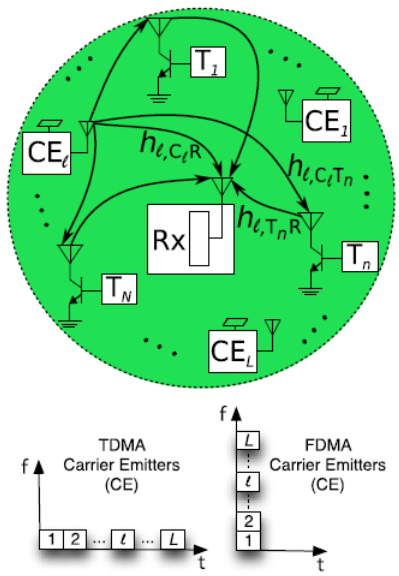

Figure 3.2: Multi-Static topology with N Tags and L CEs, access of time slots represented in TDMA and FDMA multiple access schemes.

3.1.1 Monostatic RFID Architecture

There is a single Interogator and RFID configuration and Reader is itself responsible for illumination of Passive RFID in full duplex mode. In mono-static architecture the signal of Interrogator is incident upon the RFID which then harvests it as per the energy content and than reflects the same signal back to the reader. There are two links in function when communication is underway between a transmitter and receiver i.e RFID to reader and reader to RFID denoted as $k = T_nR, RT_n$ under a common distance of d_k. Position of different RFID tags is classified by denoting, n_{th} RFID as u_{T_n}, l_{th} emitter as u_{C_l} and reader as $u_{R,}$. For Simulation purpose we consider N tags and there are N links deployed between tag and Interrogator and the following path loss model is adopted :

$$L_k = \left(\frac{\lambda}{4\pi d_0}\right)^2 \left(\frac{d_0}{d}\right)^{v_k} \tag{3.1}$$

where d_0 is the reference distance and is taken as unity, λ as carrier wavelength, v_k as path loss exponent for a link k where k belongs to the set $k = T_nR, RT_n$ for monostatic and $k = C_lR, C_lT_n, T_nR$ for multi-static. It is known that the communication between a RFID and reader will be of very less bits and will occupy a small bandwidth, keeping the same in mind we assume small fading i.e. frequency non selective flat fading. Channel gain for TDMA in time slots and for FDMA in frequency spots is denoted as $h_{l,k} = a_{l,k}e^{-j\phi_{l},k}$ where $k \in C_lR, C_lT_n, T_nR$ for multi-static and $k \in T_nR, RT_n$ for mono-static.

In a RFID, Reader configuration the distance is very less between them as there are no marconi radio components in the same, keeping that as a consideration we can plan the link to be based on strong line of sight (LoS) with NAkagami small scale fading described as :

$$f_{al,k}(x) = 2(M_k)^{M_k} \frac{x^{2M_k-1}}{\Gamma(M_k)} e^{-M_k x^2}, x \geq 0 \tag{3.2}$$

where $M_k \geq 1/2$ is as per the Nakagami fading and Gamma function is described as $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt$. In case there is no fading than the value of $M_k = \infty$ and in case there is no LoS existing between the transmitter and receiver than put up as $M_k = 1$.

An advantage of Monostatic architecture is that the emitter and Reader are served with the same oscillator this leads to carrier frequency offset (CFO) ΔF_l and phase offset $\Delta\phi_l$ to be zero. For a time slot l the received signal for a RFID n at a particular time slot l is given by the following expression :

$$r_{l,n}^{[m]} = h_{l,n}^{[m]} \sqrt{\frac{M_n}{M_n+1} E_n^{[m]}} x_n + w_{l,n}, n \in N \tag{3.3}$$

$$a_{l,n}^{[m]} = (a_{l,T_nR})^2, \phi_{l,n}{}^{[m]} = 2\phi_{l,T_nR} + \angle\Gamma_{n,0} - \Gamma_{n,1} \tag{3.4}$$

For a RFID getting illuminated by a Reader in monostatic system the average received power per bit given as :

$$E_{l,n}^{[m]} = \frac{E\left[\left(a_{l,n}^{[m]}\mu_{l,n}^{[m]}\right)^2 T\right]}{2} = \frac{1+M_n}{2M_n}\left(\mu_{l,n}^{[b]}\right)^2 T \tag{3.5}$$

$$E\left[\left(a_{l,n}^{[m]}\right)^2\right] = E\left[(a_{l,T_nR})^4\right] = (M_n+1)/M_n \tag{3.6}$$

$$\mu_n^{[m]} = \sqrt{2P_R} L_{T_nR} \left|\Gamma_{n,0} - \Gamma_{n,1}\right| \frac{2}{\pi} S_n \tag{3.7}$$

With the above mathematical expression SNR of monostatic architecture can be expressed as

$$SNR_n^{[m]} = E_n^{[m]}/N_0 \tag{3.8}$$

3.1.2 Multistatic RFID Architecture

In multistatic architecture there are a number of emitters and tags while only single reader, the task of these CEs is to illuminate the RFIDs in a larger area compared to monostatic architecture. l^{th} CE depending on it being on FDMA or TDMA transmits a CW on the l^{th} frequency or time slot. In multistatic systems there is also an issue of different oscillators on the emitter and Reader, let us define the same as $\Delta F_l, \Delta\phi_l$ carrier frequency offset (CFO) and phase offset respectively. with complex baseband signal defined as :

$$q_l^{[b]}(t) = \sqrt{2P_{C_l}}e^{-j(2\pi\Delta F_l t+\Delta\phi_l)} \tag{3.9}$$

where P_{C_l} is the l^th CE transmit power. In case of multistatic RFID network each tag is illuminated by the carrier wave $q_l^{[b]}(t)$. For successful transmission and reception, RFIDs data is binary modulated on the CW by switching the antenna load impedance frm between two coefficients. To transmit '0', $\Gamma_{n,0}$ is used and to modulate bit '1', $\Gamma_{n,1}$ is used. In scatter radio communication, there are no mixers, amplifiers or signal conditioners and thus the transmission takes place only on the basis of switching of frequencies and consonant to the reflection coefficients the sub-carrier frequencies are designated as $F_{n,0}$ for $\Gamma_{n,0}$ and $F_{n,1}$ for $\Gamma_{n,1}$ with 50 percent duty cycled square waveform of duration T working on binary FSK. Phase is set as $\Phi_{n,i}$ and fundamental frequency as $F_{n,i}$. A backscattered FSK signal from the tag utilizes a total of four frequencies, $\pm F_{n,i_n} i_n \in \mathrm{B}$. Thus to demodulate the signals from RFID would require four matched filters [25] and not two. Coherent FSK is used RFID communication and frequencies used by all tags must be orthogonal to each other, i.e four frequencies must satisfy the orthogonality principle as mentioned below:

$$\{\pm F_{n,i_n} i_n\}, \forall(i_n, n) \in \mathrm{B} \times \mathrm{N} \tag{3.10}$$

$$|F_{n,i} - F_{j,m}| = \frac{k}{2T}, F_{n,i} \gg \frac{1}{2T} \tag{3.11}$$

For Noncoherent FSK $1/2T$ is replaced by $1/T$ and

$$\forall(i,n),(m,j) \in \mathrm{B} \times \mathrm{N} : m \neq i, k \in \mathrm{N} \tag{3.12}$$

Eq (3.11) gives an insight that in case of large area served by a number of RFIDs say N tags transmitting at the same time the transmission will be divided into N channels which are orthogonal to each other and thus impede any probability of collision[26].

Eq (3.12) the tag topography is multistatic and in a TDMA environment. With the above mentioned assumptions received base-band signal at the interogator for tag n and a time period T is as follows :

$$r_{l,n}^{[b]} = h_{l,n}^{[b]}\sqrt{E_{l,n}^{[b]}x_n + w_{l,n}}, n \in N \tag{3.13}$$

and the vector x^n is described as

$$x_n \triangleq \sqrt{\frac{1}{2}}\left[e^{+j\Phi_{n,0}}e^{-j\Phi_{n,0}}e^{+j\Phi_{n,1}}e^{-j\Phi_{n,1}}\right]^T \odot v_{i_n} \tag{3.14}$$

where the symbol transmitted by the RFID corresponding to the bit i_n is $v_{i_n} = [(1-i_n)\,(1-i_n)\,i_n i_n]^T$ is a four dimensional signal. As the communication between RFID and Reader is a radio transmission and prone to some phase changes i.e. for a tag n and reader in the bit $(0,1)$ phase mismatch represented as $\Phi_{n,0}, \Phi_{n,1}$ corresponding to bit $0,1$

may be received in an erroneous way. Formulating for frequencies and bandwidth the baseband bandwidth of Reader which is in-turn an software defined radio is denoted as W_{SDR}, for $F_{n,i_n} + 20/T < W_{SDR}$[27]

$$h_{l,n}^{[b]} \triangleq a_{l,n}^{[b]} e^{-j\phi_{l,n}^{[b]}} \tag{3.15}$$

$$a_{l,n}^{[b]} = a_{l,C_l T_n}, a_{l,T_n R}, \tag{3.16}$$

$$\phi_{l,n}^{[b]} = \phi_{l,C_l T_n} + \phi_{l,T_n R} + \Delta\phi_l + \angle\Gamma_{n,0} - \Gamma_{n,1} \tag{3.17}$$

$$w_{l,n} \sim C\mathrm{N}(\theta_4, N_0 I_4) \tag{3.18}$$

With $N_0 = K_b T_\theta / 2$ and K_b is the Boltzman constant and T_θ is temperature of the receiver, also the average energy for each bit of n^{th} RFID over a designated l^{th} slot is further given as follows :

$$E_{l,n}^{[b]} = \frac{E\left[\left(a_{l,n}^{[b]} \mu_{l,n}^{[b]}\right)^2 T\right]}{2} = \frac{\left(\mu_{l,n}^{[b]}\right)^2 T}{2} \tag{3.19}$$

Where $\mu_{l,n}^{[b]}$ is defined as $\mu_{l,n}^{[b]} = \sqrt{2P_{C_l} L_{C_l T_n} L_{T_n R}} \, |\Gamma_{n,0} - \Gamma_{n,1}| \, \frac{2}{\pi} S_n$ and S_n is a constant assumed as scattering efficiency. As we progress further we need to find the SNR associated with the n_{th} tag at l_{th} slot already described in above equations and given as :

$$SNR_{l,n}^{[b]} = E_{l,n}^{[b]} / N_0 \tag{3.20}$$

The SNR of multi-static and mono-static can be compared upon and it can be seen that there main dependence is on energy per bit i.e. $E_{l,n}^{[b]}$ and $E_n^{[m]}$. It is further highlighted that $E_n^{[m]}$ for mono-static case is do not depend upon time index l as the emitter and reader are same and are fuction of path loss i.e. $L_{T_n R}$ which remains same during the L time slots while in case of multi-static $E_{l,n}^{[b]}$ is a function of $L_{C_l T_n}$ and also as there are a number of emitters it is imperative that they correspond to slots L in index l. The above analysis shows that for mono-static, the link is dependent upon $T_n R$ and for multi-static on $C_l T_n$ and $T_n R$.

3.2 ML detection of Scatter Network Communication

To estimate the power distribution in a reflection based signal from Tag and also to accommodate small scale fading for both topologies i.e. mono-static and multi-static we need to find the PDF of RV $(a_{l,k})^2$ given as :

$$f_{a_{l,k}^2}(x) = (M_k)^{M_k} \frac{x^{M_k - 1}}{\Gamma(M_k)} e^{-M_k x}, x \geq 0 \tag{3.21}$$

3.2.1 Coherent Mono-static and Multi-static

Mono-static

In Mono-static environment there is only one Reader cum CE and the BER for a RFID designated n over a time slot given as l and channel characteristics and phase paramaters as $h_{l,n}^{[m]}$ and $\Phi_{n,0}, \Phi_{n,1}$ is dependent upon amplitude and will follow following expression :

$$\mathrm{P}\left(e_{l,n}^{[m]} \middle| a_{l,n}^{[m]}\right) = Q\left(\frac{a_{l,n}^{[m]}\sqrt{\frac{M_n}{M_n+1}}E_n^{[m]}\|x_0 - x_1\|_2}{\sqrt{2N_0}}\right) \tag{3.22}$$

$$= Q\left(a_{l,n}^{[m]}\sqrt{\frac{M_n SNR_n^{[m]}}{M_n+1}}\right) \tag{3.23}$$

Where $Q(x) = \frac{1}{\sqrt{2\pi}}\int\limits_x^\infty e^{-\frac{t^2}{2}dt}$ and $\|x_0 - x_1\|_2 = \sqrt{2}$, also for simplicity $M_{C_l T_n} = M_{l,n}$ and $M_{T_n R} = M_n$ has been taken. Random variable $a_{l,n}^{[m]} = (a_{l,T_n R})^2$ for small scale fading is expressed by gamma distribution with parameters $(M_n, 1/M_n)$ and the error rate is as follows :

$$\mathrm{P}\left(e_{l,n}^{[m]}\right) = \underset{a_{l,n}^{[m]}}{\mathrm{E}}\left[\mathrm{P}\left(e_{l,n}^{[m]}|a_{l,n}^{[m]}\right)\right] \tag{3.24}$$

$$= \frac{1}{2}\left(\frac{M + M_n^2}{2SNR_n^{[m]}}\right)^{\frac{M_n}{2}} \cup \left(\frac{M_n}{2}\frac{1}{2}\frac{M_n + M_n^2}{2SNR_n^{[m]}}\right) \tag{3.25}$$

Dependence of Bit error rate is on Signal to noise ratio of the n_{th} RFID i.e. SNR_n^m which is dependent upon the energy per bit for mono-static topology, it is imperative to mention that the BER is dependent upon the topology used for scatter network.

Multi-static

Multi-static topology used in scatter radio network has BER given as follows for a particular n^{th} tag over l^{th} time slot :

$$\mathrm{P}\left(e_{l,n}^{[b]}|a_{l,n}^{[b]}\right) = Q\left(a_{l,n}^{[b]}\sqrt{SNR_{l,n}^{[b]}}\right) \tag{3.26}$$

which can be further simplified and upperbounded as

$$\mathrm{P}\left(e_{l,n}^{[b]}\right) = \underset{a_{l,n}^{[b]}}{\mathrm{E}}\left[\mathrm{P}\left(e_{l,n}^{[b]}|a_{l,n}^{[b]}\right)\right] \tag{3.27}$$

$$= \frac{1}{2}\left(\frac{M_{l,n}M_n}{SNR_{l,n}^{[b]}}\right)^{M_n} \cup \left(M_n, 1 + M_n - M_{l,n}\frac{2M_{l,n}M_n}{SNR_{l,n}^{[b]}}\right) \tag{3.28}$$

$SNR_{l,n}^{[b]}$ and energy per bit per slot described above in Eq() concludes that the BER is dependent upon the network topology used like the same in mono-static case.

3.2.2 Non Coherent Mono-static and Multi-static

Detection of a RFID backscattered signal is done using ML detection technique for orthogonal signaling, in order to mathematically express non-coherent detection let us take the n_{th} RFID operating over the l_{th} slot, channel amplitudes as $a_{l,n}^{[m]}$ and $a_{l,n}^{[b]}$ unknown angles $\phi_{l,n}^{[m]}$, $\phi_{l,n}^{[b]}$ and phases as $\Phi_{n,0}$ and $\Phi_{n,0}$ the received vector $r_{l,n}$ in ML detection can be represented as :

$$\left| r_{l,n}^{[x]}[1] + e^{2j\Phi_{n,0}} r_{l,n}^{[x]}[2] \right| \frac{\geq^{i_n=0}}{<_{i_n=1}} \left| r_{l,n}^{[x]}[3] + e^{2j\Phi_{n,1}} r_{l,n}^{[x]}[4] \right| \tag{3.29}$$

In case of square law method for detection the same signal $r_{l,n}$ can be represented as:

$$\left| r_{l,n}[1] \right|^2 + \left| r_{l,n}[2] \right| \frac{\geq^{i_n=0}}{<_{i_n=1}} \left| r_{l,n}[3] \right|^2 + \left| r_{l,n}[3] \right|^2 \tag{3.30}$$

Where for mono-static x=[m] and for multi-static x=[b] and also the phases are taken as $\Phi_{n,0}$ and $\Phi_{n,0}$. It can be seen and verified that that the conditional probabilities given in earlier part for coherent detection of Mono-static and Multi-static signal also uses the same bounds as seen in the ML detection.

3.3 Proposed detection methodology for N-LOS

Proposition 1

In N-LoS scenario the RFID and Reader do not share a direct LoS and thus Rayleigh fading is used for estimation. In case of Mono-static for N-LoS $M_n = 1$ is taken which offers diversity order of upto 1/2 for any l, n. Probablity of error over the l^{th} slot is given by:

$$\Pr(e_{l,n}^{[m]}) = \frac{1}{2} - e^{\frac{1}{SNR_n^{[m]}}} Q\left(\sqrt{\frac{2}{SNR_n^{[m]}}} \right) \tag{3.31}$$

Eq 3.31 concludes that under Rayleigh fading BER decays inversely proportional with square root of SNR.

Proposition 2

In Multi-static topology with N-LoS scenario $M_{ln} = M_n = 1$ offers diversity of 1 for any l, n.

$$\lim_{x\to\infty} \frac{\log\left(\frac{1}{x} e^{\frac{2}{x}} \Gamma\left(0, \frac{2}{x}\right)\right)}{\log(x)} \tag{3.32}$$

It can be safely said that under N-LoS scenario the multi-static BER drops faster compared to mono-static for single slot.

Chapter 4

Information and Energy Outage Probability for Passive RFIDs with RF Energy Harvesting

Wireless scatter network working in mono-static topology or in multi-static one the communication has to be multiplexed and there will be some interference on account of oscillator used in CE or reader as they are prone to some deviation in frequency and may not withstand exact orthogonal frequencies required to be generated for error free communication. The orthogonaliity cretarion already disscussed is as follwos :

$$|F_{n,i} - F_{j,m}| = \frac{k}{2T}\_and\_F_{n,i} \gg \frac{1}{2T} \tag{4.1}$$

Communication in scatter radio network is by means of reflection i.e. CE/ Reader to RFID and than RFID to CE/ Reader by means of reflection in which in case there are two adjacent tags marked as n^{th} and j^{th} Tag working on sub-carrier frequencies can have a false signal corresponding to n^{th} tag as $(F_{n,0}, F_{n,1})$ will cause interference. The above mentioned interference factor makes a strong point for careful frequency assignment as well as astute calculations before putting up a RFID in a geographic location, there are $N!$ options for allocation of frequencies to N Tags and following can be deduced mathematically :

$$g_{l,n}^{[m]} = (a_{l,n}^{[m]})^2, g_{l,n}^{[b]} = (a_{l,n}^{[b]})^2 \tag{4.2}$$

$A(n) = N/n$ denotes the RFIDs which cause interference to n Tags mentioned in Eq(4.2). In order to carry out a fair comparison between mono-static and multi-static typologies it is imperative to assume that $g_{l,n}$ and $g_{l,j}$ are independent and also $n \neq j$. Grid topology for mono-static and multi- static is shown in Fig 4.1 and 4.2.

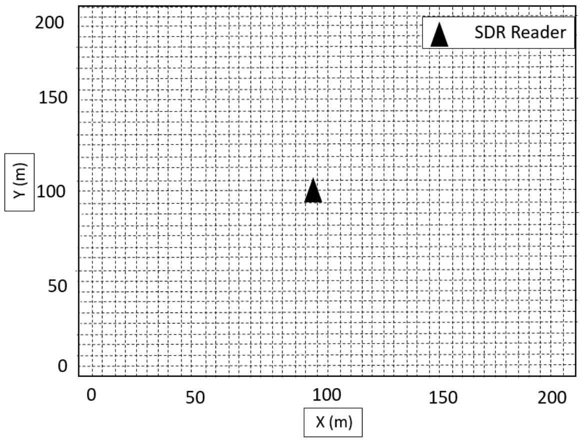

Figure 4.1: Grid topology for mono-static architecture with single SDR Reader.

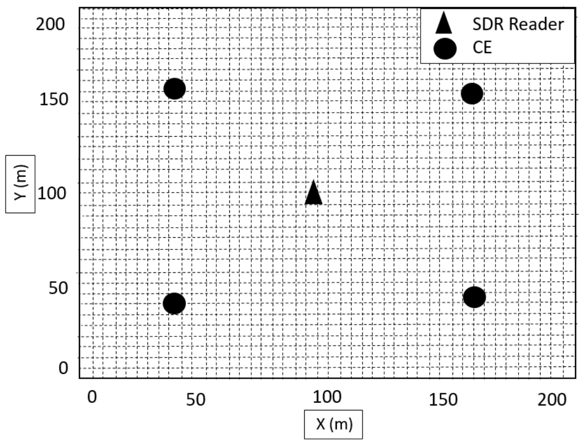

Figure 4.2: Grid topology for multi-static architecture with four CEs and single SDR Reader.

4.1 Mono-static Outage Analysis

In mono-static topology there are a number of Tags which are being served by a single Reader cum Emitter for illumination purpose and also reading the reflection from all the tags, frequency assignment requires allotment of subcarrier frequencies which takes care of the interference issues mentioned in above sections, let the assignment be represented as C and a parameter $p_{nj}(C)$ which is inversely proportional to assigned frequencies seperation between a given RFID n and RFID j. the signal to interference to noise ratio of a RFID n at l^{th} time slot is mathematically given as :

$$SINR_{l,n}^{[m]}(C) \triangleq \frac{g_{l,n}^{[m]} \frac{M_n}{M_n+1} E_n^{[m]}}{\sum_{j\in \mathrm{A}(n)} p_{n,j}(C) g_{i,j}^{[m]} \frac{M_j}{M_j+1} E_j^{[m]} + N_0} \tag{4.3}$$

Every RFID is assigned a different subcarrier frequency F_{n,i_n}^{C} under the predefined assignment scheme C, also the binary modulation used at each tag, pulse shaping and filtering function at the reader, parameter $p_{nj}(C)$ also depends on pulse shaping and modulation scheme. there is also a variation in the clocks of different RFIDs i.e. RFID

j and RFID n may have mismatch in clock and also sub-carrier frequency difference is there due to use of FSK against MSK which is continuous phase.

$$p_{n,j}(C) = \max_{i_n, i_j \in B} \left\{ \left[\varepsilon_{n,j} \left| F^C_{n,i_n} - F^C_{j,i_j} \right| \right]^{-2} \right\}, j \in \mathrm{A}(n) \tag{4.4}$$

SINR for (l, n) received at reader

$$SINR^{[m]}_n(C) = \frac{\mathrm{E}\left[g^{[m]}_{l,n}\right] \frac{M_n}{M_n+1} E^{[m]}_n}{\sum_{j \in \mathrm{A}(n)} p_{n,j}(C) \mathrm{E}\left[g^{[m]}_{i,j}\right] \frac{M_j}{M_j+1} E^{[m]}_j + N_0} \tag{4.5}$$

$$= \frac{E^{[m]}_n}{\sum_{j \in \mathrm{A}(n)} p_{n,j}(C) E^{[m]}_j + N_0} \tag{4.6}$$

4.2 Multi-static Outage Analysis

SINR in multi-static topology for a set frequency assignment C of a particular tag n and l^{th} time slot is as follows :

$$SINR^{[b]}_{l,n}(C) = \frac{\left[g^{[b]}_{l,n}\right] E^{[b]}_{l,n}}{\sum_{j \in \mathrm{A}(n)} p_{n,j}(C) \left[g^{[b]}_{l,n}\right] E^{[b]}_{l,n} + N_0} \tag{4.7}$$

Eq(4.7) can be averaged as

$$SINR^{[b]}_{l,n}(C) = \frac{E^{[b]}_{l,n}}{\sum_{j \in \mathrm{A}(n)} p_{n,j}(C) E^{[b]}_{l,n} + N_0} \tag{4.8}$$

4.3 Proposed Model for Mono-static and Multi-static

In case of fixed mono-static topology and for calculation of SINR the following outage probablity is followed :

$$\mathrm{P}(SINR^{[m]}_{l,n}(C) \leq \theta) \leq 1 - e^{-\sqrt{\frac{2\theta}{SNR^{[m]}_n(C)}}} \tag{4.9}$$

Eq 4.9 highlights the outcome of an even will depend upon tag location and network topology and also the frequency assignment C. In case of fixed multi-static topology and frequncy assignmnet C with N-LoS M_{ln} and $M_n = 1$, the outage probablity is given as

$$\mathrm{P}(SINR^{[b]}_{l,n}(C) \tag{4.10}$$

Eq 4.10 shows that event depends upon tag location, frquency assignment C and network topology.

4.4 Scatter Network with Diversity Reception

Scatter network working in mono-static and multi-static topologies are sometimes placed an N-Los region in which Raleigh fading is used to model the signal communication, in case each tag emits the same information on L slots, than BER for mono-static drops with $1/SNR^d$ where $d \geq L$ and for multi-static also at $1/SNR^d$ where $d = l/2$. There can be two ways in which a diversity receiver is used : (a) coherent case, exploit maximum ratio combining and channel estimation over L slots. (b) Non-coherent case, select max SNR over L slots and then doing detection.

4.4.1 Diversity Reception in Mono-static

In case of mono-static with for a fixed frequency assignment represented as C the probability of n^{th} RFIDs SINR below a benchmark value θ over L slots is given as :

$$\mathrm{P}\left(\bigcap_{l=1}^{L}\left\{SINR_{l,n}^{[m]}(C) \le \theta\right\}\right) = \left[\mathrm{P}\left(SINR_{l,n}^{[m]}(C) \le \theta\right)\right]^{L} \tag{4.11}$$

$$\overset{(b)}{\le} \left(1 - e^{-\sqrt{\frac{2\theta}{SINR_{l,n}^{[m]}(C)}}}\right) \tag{4.12}$$

Above mentioned probability event is the mono-static outage event for the n^{th} tag over L time-slots and it holds true for rayleigh fading.

4.4.2 Diversity Reception in Multi-static

In case of Multi-static topology the outage probability of a certain RFID n over time slots L can be represented as following:

$$\mathrm{P}\left(\bigcap_{l=1}^{L}\left\{SINR_{l,n}^{[b]}(C) \le \theta\right\}\right) = \prod_{l=1}^{L}\left[\mathrm{P}\left(SINR_{l,n}^{[b]}(C) \le \theta\right)\right] \tag{4.13}$$

$$\overset{(b)}{\le} \prod_{l=1}^{L}\left(1 - 2\sqrt{\frac{\theta}{SINR_{l,n}^{[b]}(C)}}K_1\left(2\sqrt{\frac{\theta}{SINR_{l,n}^{[b]}(C)}}\right)\right) \tag{4.14}$$

Here also the frequency assignment has been taken as C and threshold as θ and the above equation holds only for reyleigh fading.

4.5 Energy Outage Analysis

In a mono-static or multi-static topology an energy outage at a particular RFID n will happen if for all L time slots the received input power from an ambient source at a RFID is below a level θ_h. The input power can be described as :

$$P_{h,l,n}^{[m]} = P_R L_{T_n R}(a_{l,T_n R})^2 \tag{4.15}$$

$$P_{h,l,n}^{[b]} = P_{C_l} L_{C_l T_n}(a_{l,C_l T_n})^2 \tag{4.16}$$

If in the above mentioned Eqs, the received power is below a threshold θ_h then there are two further cases that emerge out of the same : (a) RF harvesting will be zero in this case as the threshold is not breached. (b) The communication circuit used for transmission require a minimum power to operate. These events can be further followed up as :

$$\mathrm{P}(\mathrm{EO}_{L,n}^{[m]}|\theta_h) \triangleq \mathrm{P}\left(\bigcap_{l=1}^{L}\left\{P_{h,l,n}^{[m]} \le \theta_h\right\}\right) \tag{4.17}$$

$$\mathrm{P}(\mathrm{EO}_{L,n}^{[b]}|\theta_h) \triangleq \mathrm{P}\left(\bigcap_{l=1}^{L}\left\{P_{h,l,n}^{[b]} \leq \theta_h\right\}\right) \tag{4.18}$$

As we analyze the energy outage in mono-static and multi-static, the difference among both of them is due to the presence of different path gain i.e. $L_{C_lT_n}$ for multi-static and L_{T_nR} for mono-static. Mono-static outage event is given as follows with random variable $P_{h,l,n}^{[m]}$ and shapping factor $\left(M_n, \frac{P_R L_{RT_n}}{M_n}\right)$:

$$\mathrm{P}\left(\mathrm{EO}_{L,n}^{[m]}|\theta_h\right) = \left(\frac{\gamma\left(M_n, \frac{M_n\theta_h}{P_R L_{T_nR}}\right)}{\Gamma(M_n)}\right)^L \tag{4.19}$$

Energy outage event for multi-static is given as follows for random variable $P_{h,l,n}^{[b]}$ with shapping parameter $\left(M_{l,n}, \frac{P_{C_l} L_{C_lT_n}}{M_{l,n}}\right)$:

$$\mathrm{P}\left(\mathrm{EO}_{L,n}^{[b]}|\theta_h\right) = \prod_{l=1}^{L}\left(\frac{\gamma\left(M_n, \frac{M_{ln}\theta_h}{P_{C_l} L_{C_lT_n}}\right)}{\Gamma(M_{ln})}\right)^L \tag{4.20}$$

Further we can find the average energy outage by amalgamation of energy outage events of mono-static and multi-static scenarios which has been given as :

$$\frac{1}{N}\sum_{n=1}^{N}\mathrm{P}\left(\mathrm{EO}_{L,n}^{[m]}|\theta_h\right).\frac{1}{N}\sum_{n=1}^{N}\mathrm{P}\left(\mathrm{EO}_{L,n}^{[b]}|\theta_h\right). \tag{4.21}$$

Like in the previous equation we can also find out the worst case scenario by finding out the maximum energy outage from the above mentioned data, described as follows :

$$\max_{n\in N}\{\mathrm{P}\left(\mathrm{EO}_{L,n}^{[m]}|\theta_h\right)\}, \max_{n\in N}\{\mathrm{P}\left(\mathrm{EO}_{L,n}^{[m]}|\theta_h\right)\} \tag{4.22}$$

Outage probabilities given above are dependent upon the used topology and also on the placement of RFIDs in a geographical area and the same can be averaged to find out a collective probability in case a particular square area is provided.

Chapter 5

Simulation Results

5.1 Comparison of Nonlinear Models

Fig. 5.1 is a comparison of Linear and Non linear energy harvesting models with sensitivity and saturation effects. Fig 5.1 provides a conclusive comparison of all non linear energy harvesting models. It can be seen that the ground truth model here is the ultra sensitive rectenna discussed in [11] and simulations presented in previous semester. It is also highlighted that the proposed Non linear model adheres to the data provided by the Rectenna harvester and thus is the closest to it, however other non linear models such as sigmoid and second order polynomial are close to the ground truth model. Linear models discussed in previous semester were found to be out of the plot due to linearity shown. Fig 5.2 is for three linear baseline models studied in previous semester, it can be seen that the expected harvested energy computed for the baseline models is not in consonance with the data available i.e. ground truth. The three models discussed are generally with the same results however the linear model can be seen giving some deviation.

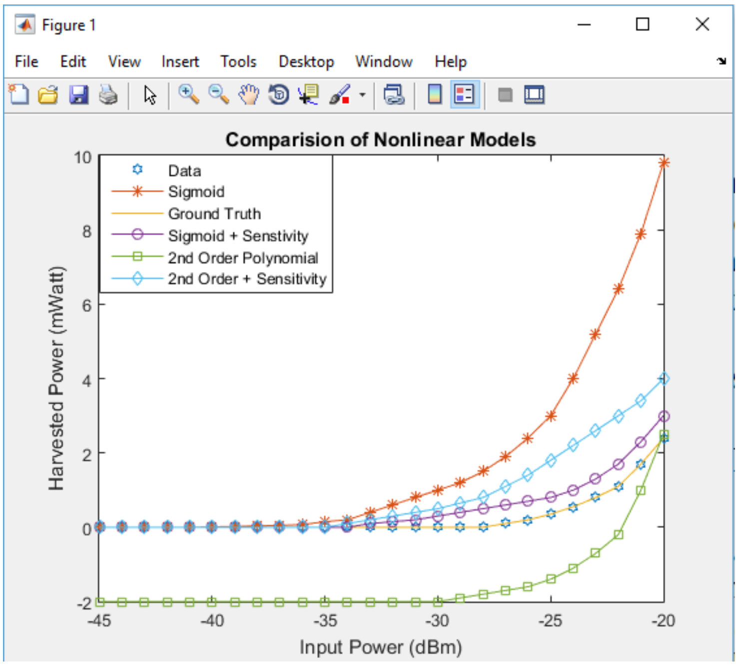

Figure 5.1: A Passive RFID where an interrogator is acting as CE and as a reader to receive reflected information from RFID tag.

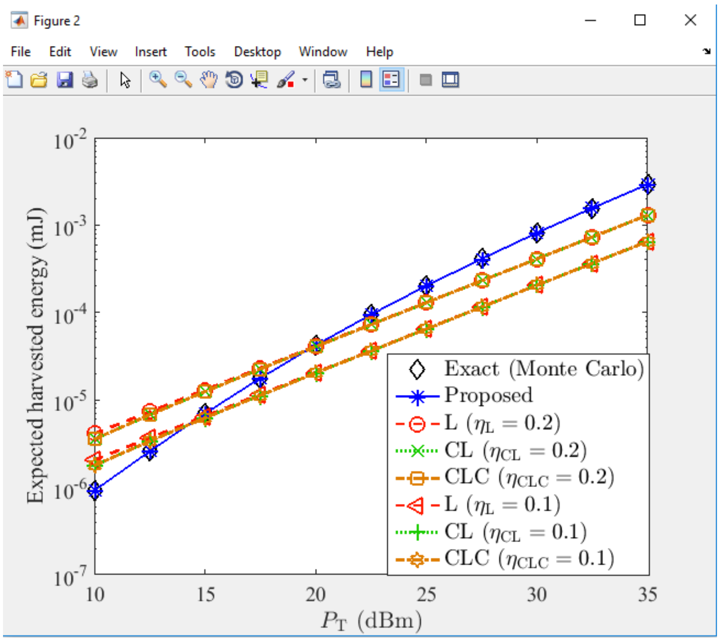

Figure 5.2: Expected Harvested Energy for a given Transmission Power.

5.2 Outage Analysis and Probability of Successful Reception

Simulation results shown in Fig 5.3 and Fig 5.4 are for probability of successful reception in LoS and NLoS scenario. Matlab Simulations have been carried out with path loss component $v = 2.3$, fr uency $\lambda = 0.3456$ i.e. UHF carrier frequency, RFID reflection coefficient Γ_0 and Γ_1, defined to be $|\Gamma_0 - \Gamma_1| = 1$. BER threshold value at $\beta = 10^{-5}$, $\tau_d = 0.5$, $X = 0.5$ and $p_u = 0.01$. Fig 5.3 provides information probablity of successful reception at SDR Reader in scenario where LoS exists. For simulations as done in LoS scenario, Nakagami fading is considered and Nakagami parameter is taken as M=10, distance $d = 7m$ and received power $P_R = 2.5Watt$, same data is used for Fig 5.4 i.e. NLoS scenario.

It is very clear from the Fig 5.3 and 5.4 that the piecewise linear model described in Eq 2.18 follows the actual data points. L and CL models totally deviate from actual figures, while it is clearly seen that both the sigmoid based models are overestimating, also the sensitivity based sigmoid model tend to be closer to the ground truth model. It is also interesting that the second order polynomial based model is underestimating the data while here also adding sensitivity to same makes it into an overestimation model.

Fig 5.5 shows the probablity of sucessful reception at SDR Reader with a given power consumption value. It can be seen from the simulation that the proposed model follows the data closely while linear and constant linear models are overestimating.

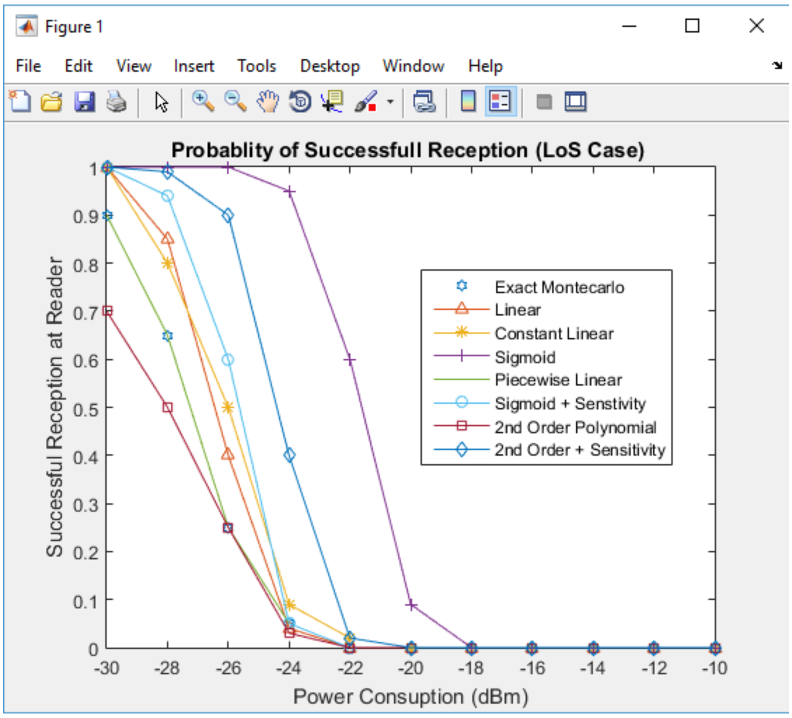

Figure 5.3: Probability of Successful reception at interrogator given power consumption parameter P_c in a LoS scenario.

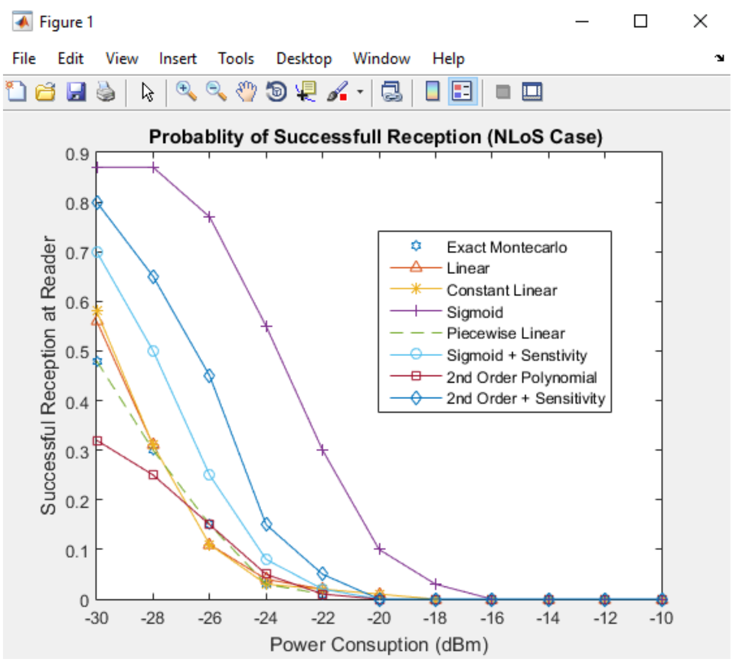

Figure 5.4: Probability of Successful reception at interrogator given power consumption parameter P_c in a NLoS scenario.

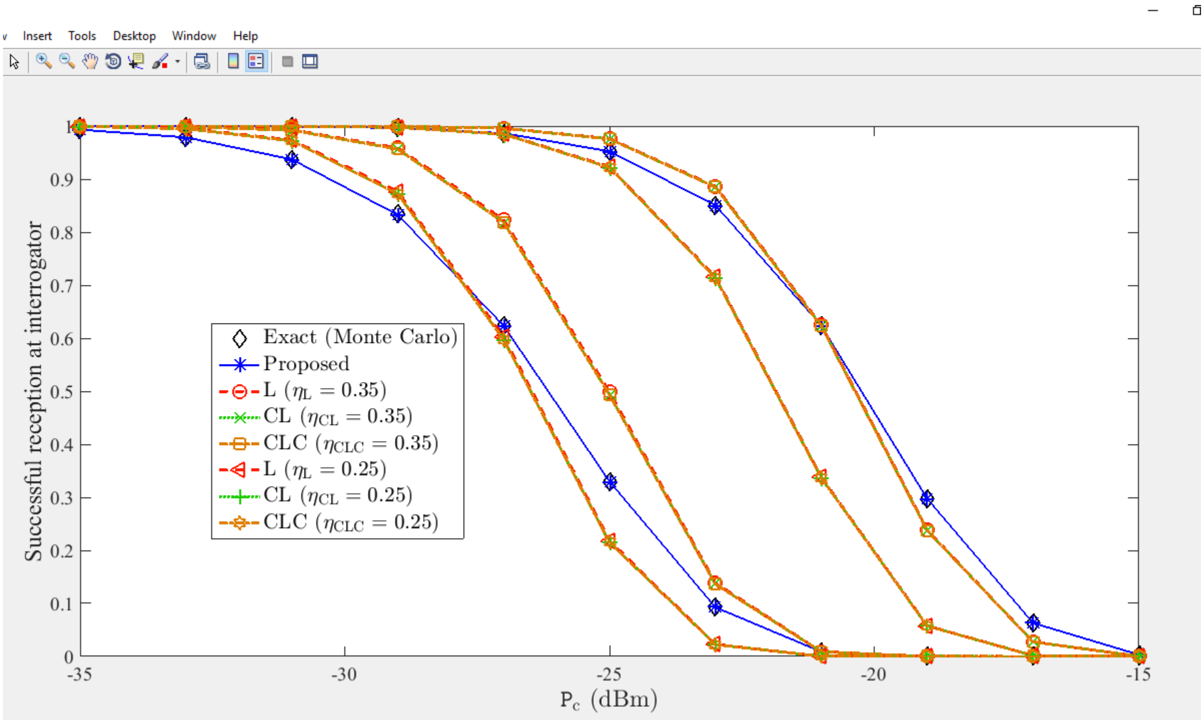

Figure 5.5: Probability of successful reception at Reader, with RFID power consumption as P_c and given RFID - Reader distance.

5.3 Performance of Mono-static and Multi-static under Fading

Fig 5.6 and 5.7 examines average and max information outage performance by taking and average of Eq (4.21) and Eq (4.22) over a sample grid against harvesting threshold θ_h for Nakagami fading with $P_{tx} = 35dBm$ and $N = 8$ RFIDs. It is evident from Fig 5.6 that information outage events are more in mono-static topology and less in multi-static topology as the probability of placement of a RFID near the CE is more in later case.

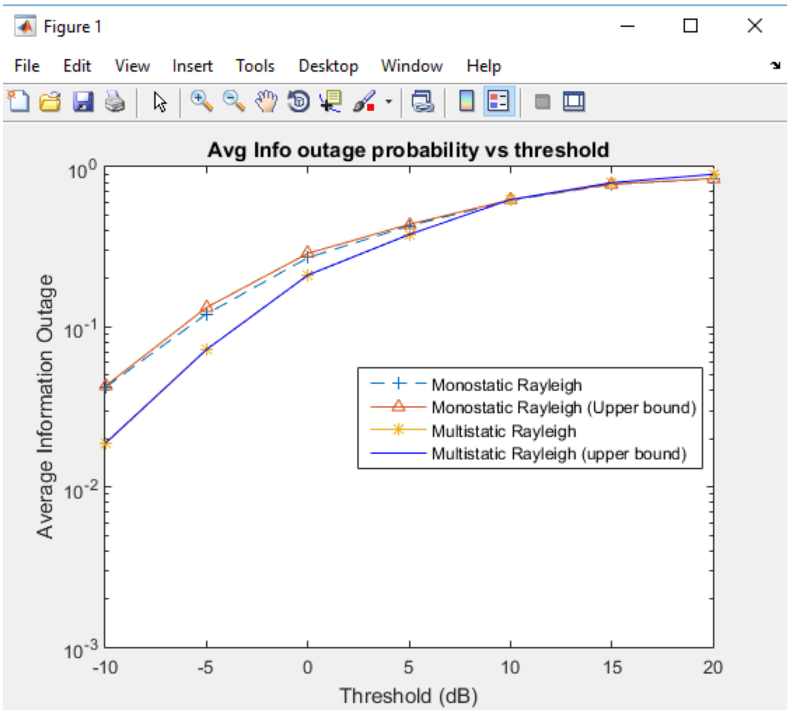

Figure 5.6: Average and maximum information outage performance for mono-static and multi-static network against threshold for Rayleigh fading case

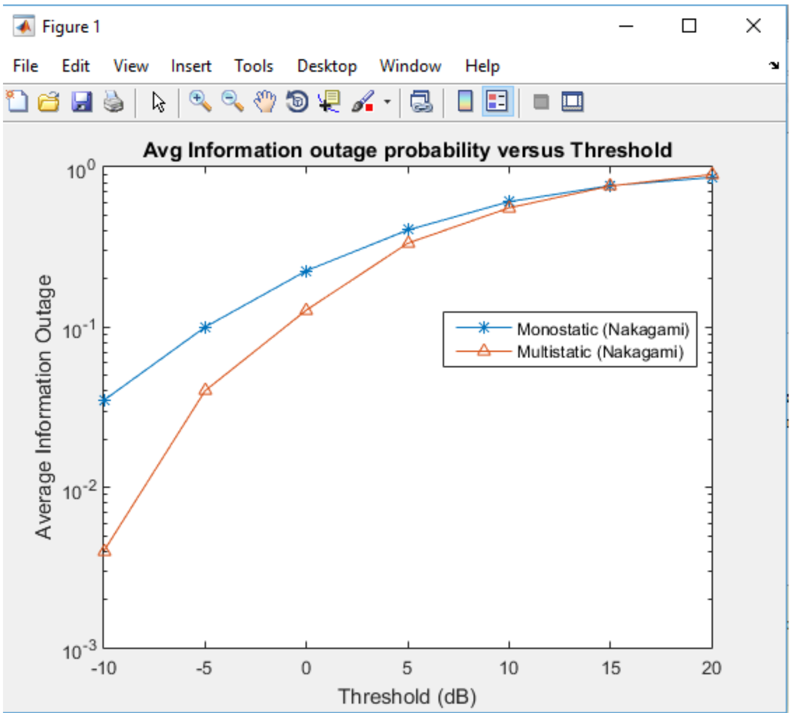

Figure 5.7: Average information outage performance for mono-static and multi-static network against threshold for Nakagami fading case

Fig 5.8 illustrates the energy outage probability under different fading schemes. It can be seen that multi-static system gives better results than mono-static one and the performance gap is seen increasing as θ decreases. Also the gap is more in Nakagami fading than in Rayleigh. Fig 5.9 gives an insight on impact of transit power on BER. It also incorporates various values of different grid configuration for measurement of BER.

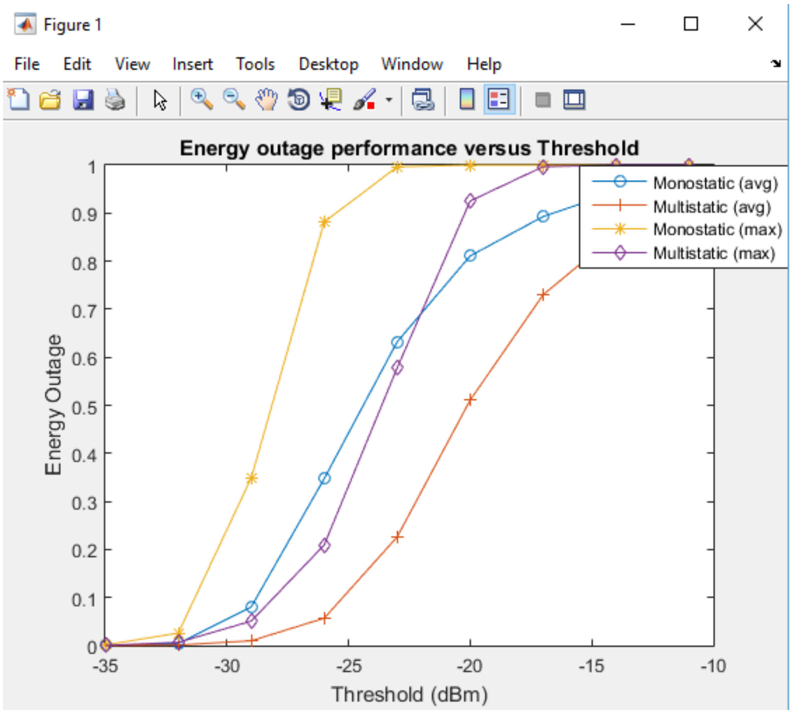

Figure 5.8: Average energy outage performance for mono-static and multi-static network against threshold for an independent location case.

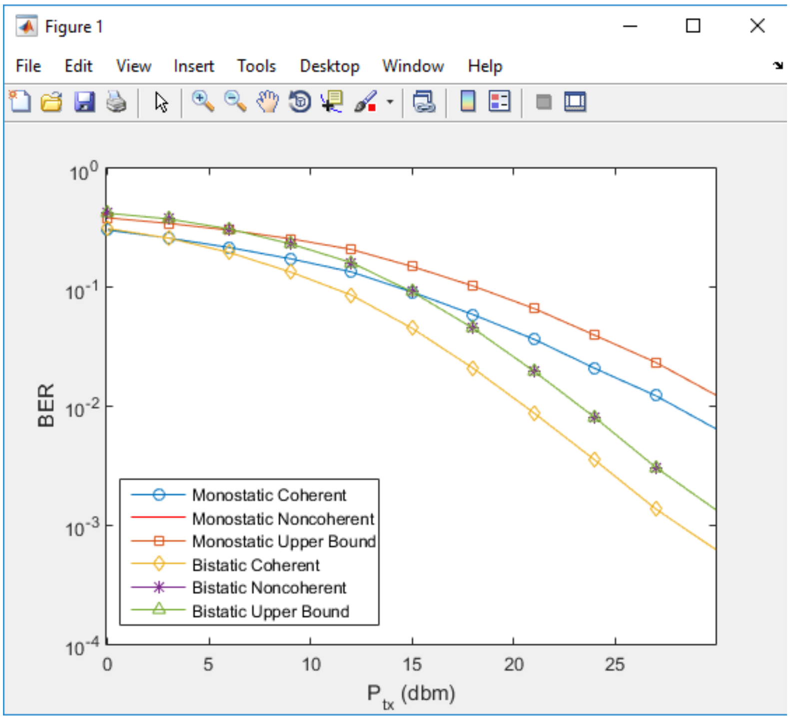

Figure 5.9: Average energy outage performance for mono-static and multi-static network against threshold for an independent location case.

Chapter 6

Conclusion and Future Scope

In the last semester realistic and efficient RF energy harvesting models were studied which were Non linear and accounted for sensitivity and saturation. This semester the same study is carried forward with in depth study of more Non linear harvesting models and there efficiency under different fading environment. Through mathematical models and simulation results it has emerged that the piece-wise linear mode studied in last semester which follows the found truth model of ultra sensitive Rectenna is the most efficient of all under LoS and N-LoS scenario with Nakagami and Rayleigh fading superimposed. A study and comparison of of different Rectenna efficiency models was also carried out to find a high efficiency Rectenna under zero dBm input power. Finally to take the work forward towards application in current environment, study of passive RFID was done. Scatter radio network which is a network architecture of many RFIDs has been discussed with emphasis on Mono-static and Multi-static topologies, there application and outage analysis in fading environment and a solution to there placement in a geographical area given the frequency assignment and quantity of such tags.

Future scope of this thesis is use of proposed models in energy harvesting where it has been concluded that all harvesters show strong non linearity. The same can be applied to passive RFIDs and backscatter radio network for current application like supply chain management, precision agriculture and Traffic management.

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