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DEVELOPMENT OF NOVEL BACKSCATTER COMMUNICATION SYSTEMS USING A MULTI-HOP FRAMEWORK AND DISTRIBUTED BEAMFORMING

by

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A THESIS

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ABSTRACT

The goal of this thesis it to develop a wireless networking framework for battery-free devices based on passive, backscatter communication. In contrast to traditional, active communication systems, where the radio signal has to be generated using large amount of energy from batteries, the passive systems reflect the RF signal. The information is encoded by modulating the reflected signal, which consumes significantly less energy than active transmission. The existing passive, backscatter systems have limited communication capabilities. For example, the Radio Frequency Identification (RFID) systems support short-distance, direct communication between active reader and passive tags. The communication range is limited due to power and sensitivity limitations of transmitters and receivers respectively. Moreover, in contrast to a multi-hop ad hoc and sensor networks, the traditional backscatter systems limit themselves to a single-hop topology due to limited capabilities of passive tags and different challenges in passive communication. Existing literature lacks of understanding how such multi-hop, passive, and asymmetric networks can be realized and what are their theoretical limits.

This thesis aims at understanding the communication and coverage challenge in backscatter systems and addressing them through: (a) a distributed beamforming that increases the transmission range to a specific tag/location (PAPER I), and (b) a multi-hop framework for the backscatter communication that increases effective communication range (PAPER II). The proposed beamforming methodology employs spatially distributed, passive scattering devices located between transmitter and receiver to increase the RF signal strength. The theoretical limits of such scheme are analyzed mathematically and in simulations with two beamforming approaches being proposed. Furthermore, a novel architecture is proposed for multi-hop backscatter-based networking for a passive RF communication that is not currently present. The paper presents the generic analysis of the system capabilities and demonstrates the feasibility of such multi-hop network. Furthermore, the connectivity models are studied in terms of k-connectivity of such a network of tags.

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PAPER I

1. INTRODUCTION

1.1. OBJECTIVE

The main goal of this work is to study and improve an effective range of a wireless communication based on passive backscatter transmission. First, a distributed beamforming methodology is proposed that increases effective transmission range between transmitting/backscattering device and a receiver. Second, a novel multi-hop framework is proposed for the backscattering communication that extends the range of communication by relaying information via intermediate passive devices toward the intended destination.

1.2. MOTIVATION

Elimination of batteries: Traditional wireless networks assume that each device generates the radio frequency (RF) signal in order to communicate. Consequently, they require disposable batteries to operate. This increases (a) size of devices, (b) cost of deployment and maintenance, (c) pollutes environment with harmful chemical from disposed batteries. In contrast, a passive communication based on backscatter of RF signal, for example RFID, eliminates the need for batteries.

Communication range extension of battery-free devices: Existing backscatter-based communication systems are limited to a short range, one-hop exchange of information. Consequently, in order to realize the battery-free wireless sensor network those limitations have to be overcome. This work focuses on two types of scenarios:

Double-pathloss: The RF signal has to travel to and from the remote, battery-free device. Hence, the communication range for backscatter system decreases at least twice as fast as for traditional, active RF transmission. Simple increase of transmission power at the main base station is not sufficient since this power is limited (e.g .by FCC, power source limits, health concerns). Also, static antenna designs, for example directional antenna, might not be desirable due to reduced beam width (more antennas/base stations might be needed to cover an area). On the other hand, active antenna arrays would provide desirable gain improvement while being flexible in terms of coverage angle. However, traditional beamforming that employs centralized antenna arrays is costly. Hence, a more desirable solution is required in form of low cost, distributed beamforming.

Asymmetric up- and down-links: The backscatter communication realizes downlink by modulating the original signal generated by the base station (reader) which provides high signal-to-noise ratio, high data rates and potentially long range of transmission. In contrast, the uplink from the remote devices modulates the backscattered signal, which is much weaker than the original one. Consequently, the data rate and potential communication range is also lower. Moreover, the signal strength reduces with distance from the base station. As a result, a remote device at sufficient distance would be able to receive request and attempt response, but the return signal would be too weak to reach the far-away base station. However, an intermediate device could potentially receive the weak response and in turn relay it thus extending effective communication range by forming a multi-hop network.

1.3. BACKGROUND

Active beamforming is widely used technique for extending communication or sensing range. Beamforming involves phase adjustment of multiple transmitted copies of a signal such that in a particular direction or location the individual transmissions combine coherently. The copies, when received with the same phase, will increase the signal strength and quality of signal (signal-to-noise ratio). In contrast, when the phases of the received copies vary, the combined signal strength will be lower and interference is introduced. Traditionally, the active beamforming is realized by designing an integrated antenna array where each antenna element has a desired phase shift introduced. The signal is either transmitted or received through each element and the combined signal is amplified for the particular direction (beam). Most of the previous works focus on synchronizing the phase shifts (offset) of each element to maximize the signal gain. More recent designs consider a distributed beamforming where the individual transmitting elements are spatially separated and lack direct synchronization (e.g. are not tethered for precise phase shift synchronization). The main challenge is such a system is achieving desired synchronization among the distributed transmitters, or selection of the particular ones that will improve the beam formation.

For RF based communication systems a multipath propagation causes signal fading. A multipath RF propagation results in reception of a combined signal containing several components including direct, line-of-sight signal, and its reflected and scattered copies. These components may either increase quality of the received signal by constructive interference or decrease it by destructive ones. In the best case scenario, the multiple copies interfere constructively at the receiver thus increasing signal strength and quality. However, more often the interference will be destructive thus reducing signal strength and quality. In a random environment the scattering, a type of multipath propagation, results in signal fading due to the mutual interference. As a result, the average power of the received signal is reduced.

Adaptive beamforming is often employed to reduce or eliminate negative effects of scattering of an original signal when passing through a random environment. However, we discovered that the same multipath phenomenon could be utilized to boost received signal without the need of complex antenna arrays.

Let’s consider that the scattering properties of the scattering objects can be controlled, for example as it is achieved in RFID passive tags through changes in antenna impedance. In general, such scattering devices can be divided in two groups: (a) the devices that cause the constructive interference, and (b) the ones that cause only destructive interference. Now the received signal strength can be increased when only the devices from the former group are scattering RF signal. The devices from the latter group should absorb the RF signal to avoid fading. Moreover, the devices can dynamically change their impedance to either match or mismatch the RF signal thus controlling the scattering effect. By appropriately selecting the devices that scatter the received signal can be boosted. As a result a distributed beamforming is realized.

1.4. THE PROPOSED APPROACHES

This work focuses on two general approaches to improving the effective communication range

- Distributed beamforming using passive backscatter devices
- Multi-hop framework for passive devices using backscatter signal

1.5. DISTRIBUTED BEAMFORMING

Since the tags can control backscatter the incoming signal by changing their impedances, it is possible to utilize particular tags to redirect the rf signal to and from the passive devices. The proposed approach aims to improve the communication capabilities of backscatter-based rf systems by carefully selecting the subset of scattering devices. When the phase shift of those devices aligns at the receiver the signal strength increases thus virtually realizing a distributed beamforming. The improved signal strength and its quality may allow higher transmission rates. The scenario where the scattering devices are randomly distributed between the transmitting and receiving nodes is considered. The propagation mechanism is analyzed mathematically to derive the theoretical limits of such a system. A methodology is proposed for the scattering characteristics of the devices and the results are studied using the mathematical simulations.

The approach of selection of scattering devices for distributed beamforming is realized using two proposed methods: Taguchi-based scheme and learning automata (LA) based approach. Learning automata based algorithm [12] can be used to address the receiver based conflict using the feedback from the receiver portion. There are various types of learning automaton used in various works such as F-model learning automata [13] etc. Here, these learning automata based scheme are proposed such that they are used for selection of perfect device sets used for scattering to achieve improved signal strength at the receiver. The scheme using the learning automata randomly chooses the appropriate set of devices based on the periodically updated probabilities that describe how likely the particular device set contributes to the received output power. The correctly selected device sets will increase the probability value for these sets while lowering for others. Consequently, over time, the best sets of devices emerge as the ones with the largest probabilities.

The proposed Taguchi-based method utilizes carefully selected orthogonal array that dictates the subsequent sets of devices that should scatter the signal. The resulting signal strengths are then analyzed to discover the correct set that contributes positively to the beamforming. The Taguchi-based scheme benefits from using the orthogonal array to minimize the set of learning experiments thus providing quicker convergence to the right device set that contributes the most to beamforming. Moreover, the Taguchi-based scheme discovers correlations among the devices such that more accurate selection can be realized when compared to a simplistic approach where each device is analyzed individually.

1.6. MULTI-HOP NETWORK OF PASSIVE DEVICES

The asymmetric links to and from the passive device result in situations where the passive device received the signal generated by the active base station (reader) though the backscatter signal is too weak to reach the base station. The strength of the backscatter signal is lower than the received signal strength and decreases with the distance from the reader. Consequently, for far away nodes the scattered signal is very weak and can be effectively received only near the passive device. Traditionally, the backscatter systems, for example an rfid system, require a direct communication over single hop. Consequently, the device in above described scenario cannot be reached.

The proposed framework will utilize intermediate devices to receive and decode the weak signal from the far-away nodes and relay it in a multi-hop approach. In a homogenous scenario the intermediate nodes will forward the message by modulating the scattered signal from the reader (not the signal received from the far-away node). The closer the relay node is to be base station the stronger the backscatter signal is and the larger hops can be achieved. By employing the proposed multi-hop network model, the effective communication range of the tag with the reader can be improved. Hence, the performance of the RF network can be maintained by utilizing less number of tags for the propagation.

The paper 2 analyses the proposed multi-hop model to discover the theoretical limits of such system. The performance characteristics of the backscatter-based network is described in terms of the antenna orientation, the receiver sensitivity level, maximum communication range, network connectivity. The connectivity issues are analyzed mathematically in both one-dimensional and two-dimensional network scenarios.

1.7. ADVANTAGES

The proposed work introduces novel methodologies to reduce the power requirements of the devices in the RF propagating environment and improve the connectivity of the multi-hop network. The proposed methodology for distributed beamforming network is used to analyze the device selection for optimum power transfer between the transmitter and receiver. For example a set of five devices are selected based on their coherent contribution to the power using the proposed schemes. This is the first step in implementing the multi-hop networks in RF environment and can be extended to address the issues of multi-hop RFID systems in the future.

1.8. CONTRIBUTIONS

Paper I:

- Development of a model that describes RF signal propagation between two nodes in the presence of scattering devices distributed in one and dimensional cases.
- Development of a scheme for distributed beamforming using Taguchi method that learns to achieve the maximum power possible using individual scattering devices.
- Comparison of the schemes using Taguchi method and learning automata approach that learns to achieve the maximum power using sets of devices.
- Studying the performance of both the schemes with a large number of device sets.

Paper II:

- Development of a network model that describes the multi-hop propagation between the reader and a tag in the presence of multiple tags on the line of propagation.
- Analysis of such network model in one-dimensional and two-dimensional types of tag distribution.
- Analysis of the orientation sensitivity of tag antenna for a simple scenario of propagation.
- Study of their performance with varying parameters such as number of nodes, density and area of the network.

1.9. FUTURE WORK

The proposed distributed beamforming methodology has to be further analyzed to understand the effects of mobility and by considering the environmental factors. Also, the Taguchi-based and brute-force schemes could be integrated in order to combine theirs individual advantages. Moreover, the future work should include the analysis of the propagation model in more realistic scenarios that relax some assumptions including the passive antennas orientation, channel fading, and power requirements of passive devices (tags). Additionally, specific protocols have to be developed to realize the proposed multi-hop framework. Finally, the passive devices have to be designed to support features necessary for both the beamforming and multi-hop network.

PAPER

I. DISTRIBUTED BEAMFORMING FOR RF PROPAGATION USING A SCATTERING NETWORK

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Abstract—This paper proposes a novel beam-forming methodology that employs passive RF devices in order to enhance the received signal. This paper demonstrates the feasibility of such beamforming and the realization methodology for a randomly placed set of passive devices. Typically a beam forming is realized by employing an antenna array at a receiver or transmitter. The signals from antenna elements are processed in order to eliminate negative effects of multipath fading. In contrast, the proposed methodology employs spatially distributed, passive scattering devices located between transmitter and receiver in order to realize the beamforming. The proposed scheme assumes that these RF devices may change their impedance to increase or reduce scattering effect. The paper demonstrates that signal strength at the receiver can be increased by carefully selecting the devices that should scatter the RF signal,. The theoretical limits of such scheme are analyzed mathematically and in simulations. The paper presents two approaches that learn the best set of scattering nodes and utilizes it to realize the beamforming.

Index Terms—Beamforming, Learning automata, Taguchi method, scattering

1. INTRODUCTION

Active beamforming is widely used technique for extending communication or sensing range. Adaptive beamforming is often employed to reduce or eliminate negative effects of scattering of an original signal when passing through a random environment. However, the same multipath phenomenon can be utilized to boost received signal without the need of complex antenna arrays. A multipath RF propagation results in reception of a signal containing several components including direct, line-of-sight signal, and its reflected and scattered copies. These components may either increase quality of the received signal by constructive interference or decrease it by destructive one.

For RF based communication systems a multipath propagation causes signal fading. In best case, the multiple copies can interfere constructively at the receiver thus increasing signal strength and quality. However, more often the interference will be destructive thus reducing signal strength and quality. In a random environment the scattering, a type of multipath propagation, results in signal fading due to the mutual interference. As a result, the power of the received signal is reduced.

Now consider that the scattering properties of the scattering objects can be controlled, for example as it is achieved in RFID passive tags through changes in antenna impedance. In general, such scattering devices can be divided in two groups: (a) the devices that cause the constructive interference, and (b) the ones that cause only destructive interference. Now the received signal strength can be increased when only the devices from the former group are scattering RF signal. The devices from the latter group should absorb the RF signal to avoid fading. Moreover, the devices can dynamically change their impedance to either match or mismatch the RF signal thus controlling the scattering effect. By appropriately selecting the devices that scatter the received signal can be boosted. As a result a distributed beamforming is realized.

Such scenario can be utilized to improve communication capabilities of RF systems. The increased signal strength and quality may allow for higher transmission (modulation) rates. Alternatively, the power control can be used in concert with the beam forming to reduce power consumption.

This paper considers such a scenario where scattering devices are randomly distributed between transmitting and receiving nodes. The mathematical analysis derives theoretical limits of such a system. Next, the methodology for controlling the scattering devices is proposed and the results analyzed mathematically and in simulations.

The main contributions of this paper are:

- Development of a model that describes RF signal propagation between two nodes in the presence of scattering devices distributed in one and dimensional cases.
- Development of a scheme for distributed beamforming using Taguchi method that learns to achieve the maximum power possible using individual scattering devices.
- Comparison of the schemes using Taguchi method and learning automata approach that learns to achieve the maximum power using sets of devices.
- Studying the performance of both the schemes with a large number of device sets.
- *Note:* Preliminary analysis of this work has been published in IEEE Computer Society with title "Distributed Beamforming Using a Scattering Network". This work focuses in more detail with other contributions.

2. RELATED WORKS

There are several related works [1][2][3][4] that discuss the methods of synchronization in a distributed beamforming. The method of random phase adjustment at the transmitter is discussed in [1] a feedback signal is sent indicating whether the signal-to-noise ratio has improved or worsened and the transmitters adjust their phases accordingly. The concept of division of nodes into master and slave nodes is discussed in [2] where the slave nodes estimates the distance from the master node and calculate the delay and phase. The problem is addressed in [3] by using a 1-bit feedback register at the receiver and the phase adjustment is done according to the feedback from it. The work in [4] starts with the correlation of noise and the design of the relay gains based on the addition of copies of desired signal. It is found that on an average correlation is beneficial regardless of the presence of the knowledge of it.

Most of the previous works focus on synchronizing the transmitted signals, which leaves phase offsets because of delays in propagation. Instead of correcting phase errors, it is possible to measure the output power at different time instants and knowing the set of nodes, which provide the maximum and minimum power. Scattering occurs at different nodes other than the transmitter and receiver and contributes to the output power.

The analysis discussed in this paper is implemented in a scattering environment. The devices present in the network, which do not seem to be involved in the propagation between two different devices, affect the value of the received power. This is due to the property of a device to scatter a signal component received from the transmitting device in the network. As the transmitter sends a signal destined to the receiver, the components of the same signal travel in different directions to other devices in the network. The signal components are scattered by those devices and the process of distributed beamforming occurs at the receiver by the direct ray and the scattered ray components.

The property of scattering has been discussed in [8] and [9] which deal with the scattering phenomenon in random media with mathematical analysis on the propagation and the propagation through spherical particles. The positioning of nodes has been described in [10] where a novel algorithm is proposed in extreme multi-path conditions. The range extension of a case where a cluster of nodes transmit to a remote receiver has been studied in [11] which helps to extend the range of a propagation in multi-path environment. In this work, the propagation between two nodes is considered in a scattering environment and the cases where other nodes act as scattering devices of their propagation are studied. This phenomenon is analyzed using two methods, Learning automata and Taguchi.

The scheme based on learning automata chooses the appropriate set of devices that contribute to the received output power using a derived algorithm. Whereas the scheme based on the Taguchi method chooses the right device that contributes more among a given set of devices. The latter scheme does a minimal number of experiments when compared to the LA-based scheme.

Learning automata based algorithm discussed in [12] proposes an algorithm to the receiver-based conflict. The probability distribution is updated after every time interval at the transmitter station. There is a discussion about the F-model learning automata in [13] where the mathematical description of the F based model is analyzed. Dynamic routing algorithm has been described in [14]. It proves the wavelength assignment technique using learning automata reduces the call set-up time by taking only small wavelengths. In this work, the learning automaton is used to select the set of scattering nodes which contributes to the output power. The Taguchi method is used to study the similar technique but to select single scattering node. Learning automaton selects the nodes as triplets according to its own algorithm of updating the probabilities.

3. PROBLEM STATEMENT

The concept of scattering phenomenon among multiple devices is shown in Fig 1. The device *a* is assumed to be the transmitter and *b* the receiver. In between, there are *n* scattering devices. They create scattered signal components that interact with the direct, line-of-sight (LOS) RF signal. As a result, the receiver experiences a multipath fading where the scattered signal interferes with the LOS one. Note, that due to different propagation path and scattering gain, the non-LOS components are attenuated. Let's denote k_i as a relative attenuation of the scattered signal from device *i*. when compared to the LOS component.

Each component has a specific delay τ_i and phase difference θ_i due to difference in propagation paths. Consequently, when compared to the LOS signal alone, the combined signal may become stronger when the phases are aligned or degrade otherwise. On average, such scenario results in reduced signal strength and quality in terms of received power and signal-to-noise ratio.

Now consider that the scattering effect of the devices can be controlled, for example by varying the antenna impedance. In such a scenario, it is possible to enable scattering only for devices that have a positive effect on the signal reception. As a result, the received power and quality can be maximized. The main challenge is in how to efficiently determine the best set of the scattering devices for a random scenario.

There are several approaches that allow learning the effect of the scattering devices on the received signal strengthen and quality. In this paper, the learning automata (LA) and Taguchi approach are considered. The proposed LA-based scheme randomly selects combinations of devices and analyses the corresponding outcomes (signal strength and quality). Subsequently, this scheme learns which sets are more suitable and increases probability of their selection.

Another scheme uses Taguchi approach, where for subsequent periods carefully selected sets of devices are involved in scattering. The Taguchi method determines the particular sets that maximize amount of information learned about the system from each test case. Consequently, this method reduces a time required to select the best set of scattering devices. Moreover, the Taguchi approach provides additional information about interactions between the individual devices. These interactions often result in non-linear terms in the overall signal model.

In another scenario, an intermediate device set is considered for a transmitter-receiver communication and the receiver is moved in a one dimensional path as shown in the figure 1(ii). Received power is calculated for different positions of the receiver and the position where the maximum power is achieved is noted. This preliminary analysis helps in better understanding the scattering phenomenon of the distributed beamforming network.

4. ANALYSIS OF SCATTERING BASED BEAMFORMING

To analyze the property of scattering and the problem of synchronizing of the signal components, the propagation model is assumed as shown in Fig 2 which show the propagation between transmitter *a* and receiver *b*. Another device *n* is placed at a distance of a_n from the propagating path. For the analysis of the propagation the following corollary is introduced.

Corollary 1: **When a device transmits a signal in a scattering environment, the power received at the receiver varies with the phase difference between the direct ray and the scattering components and is given by**

$$P'_{rntags} = \frac{1}{T'} \int_0^{T'} |C_0 z(t) + C_1 z(t - \tau_1{}') \cos\theta_1{}' + C_2 z(t - \tau_2{}') \cos\theta'_2 + \cdots|^2 \, dt$$

Proof: Let us consider communication between two devices *a* and *b* in a scattering environment. It is assumed that there are *n* scattering devices as shown in the figure.

Without losing generality, let's assume that the *n* scattering devices are positioned on a plane perpendicular to the LOS path (straight line connecting nodes *a* and *b*). Denote the distance of these devices from the LOS as *a1, a2, a3, …, an*. Then the signal received at receiver would be the sum of the direct, LOS signal component and the *n* scattered components:

$$w(t) = C_0 z(t) + C_1 z(t-\tau_1) cos\,\theta_1 + C_2 z(t-\tau_2) cos\,\theta_2 + \cdots$$

For nth device, the distance b_n is calculated as

$$b_n = 4.\sqrt{\frac{d^2}{4} + {a_n}^2} \qquad (2)$$

$$b_n = \frac{d}{cos\,\alpha_n} \qquad (3)$$

where b_n is the distance between device *a* and n^{th} device on the perpendicular, n is the angle made by the direct ray component with the scatter travelling from device *a* to nth device:

$$\tau_n = \frac{b_n - d}{c} \qquad (4)$$

$$\theta_n = 2\pi f_c \tau_n \qquad (5)$$

where τ_n, θ_n are the delay and phase of the nth scattered component. Now, the power received at device b can be expressed as

$$P_{rsumn} = \frac{1}{T}\int_0^T |C_0 z(t) + C_1 z(t-\tau_1)\cos\theta_1 + \cdots|^2\, dt \qquad (6)$$

$$P_{rsumn} = P_{th} + P_{sn} \qquad (7)$$

$$x_{ntags} = \sqrt{\frac{P_{th}+P_{sn}}{P_{th}}}.\,d \qquad (8)$$

If the device n is moved such that it is x_n units from device a then for nth device,

$$s_n = \sqrt{a^2 + (x_n - d/2)^2}$$

$${\tau_n}' = \frac{b + s_n - x_{ntags}}{c} \qquad (9)$$

Now the signal arrived at device n can be written as

$$w_n'(t) = C_0 z(t) + C_1 z(t-{\tau_1}')\cos\theta_1' + C_2 z(t-{\tau_2}')\cos\theta_2' + \cdots \qquad (10)$$

where $\theta' = 2\pi f_c \tau'$ is the phase of the signal. The power of the received signal at device n is given by

$$P'_{rntags} = \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_1 z(t-{\tau_1}')\cos{\theta_1}' + C_2 z(t-{\tau_2}')\cos\theta_2' + \cdots|^2\, dt \qquad (11) \blacksquare$$

In this case the scattered signal interacts with the LOS signal resulting in fading. In case of multiple scattering devices the interference analysis becomes more complex due to interactions between the scattering components. This introduces non-linearity into the model. Lemma 1 states that the scattering devices can be divided into two groups: (1) the one which increases received signal strength and quality, and (2) another that reduces it. Lemmas 2 and 3 express this non-linear relationship.

Lemma 1: **The received signal strength can be maximized in presence of scattering devices by carefully selecting scattering devices based on their relative contribution to the total received signal strength.** ■

The particular set of scattering devices may increase or decrease received signal strength when compared to the LOS signal alone (PLOS). The devices can be grouped as contributing and non-contributing based on the received power greater than or less than PLOS.

Lemma 2: **The received power when a particular set of devices contributes is always greater than the maximum power that can be achieved with any device in the particular set.■**

Lemma 3: **The sum of powers contributed by two individual devices considered one at a time is greater than the power contributed by both of the devices.** ■

The received powers when devices A and B are considered separately as scattering devices are respectively

$$P'_{rA} = \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_1 z(t-\tau_1')\cos\theta_1'|^2\, dt \tag{12}$$

$$P'_{rB} = \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_2 z(t-\tau_2')\cos\theta_2'|^2\, dt \tag{13}$$

The sum of individual received powers is given by

$$\begin{aligned} P'_{rsum} &= \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_1 z(t-\tau_1')\cos\theta_1'|^2\, dt \\ &+ \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_2 z(t-\tau_2')\cos\theta_2'|^2\, dt \end{aligned} \tag{14}$$

The received power when the combined effect of devices A and B is considered,

$$P'_{rtwo} = \frac{1}{T'}\int_0^{T'} |C_0 z(t) + C_1 z(t-\tau_1')\cos\theta_1' + C_2 z(t-\tau_2')\cos\theta_2'|^2\, dt \tag{15}$$

As the signals sum up in (15) there might be a decrease in the total amplitude of the combined signal, where as in (14) as the powers are calculated individually there is no effect of one scattered signal on the other. Hence, the signal power will be higher in the first case.

$$\frac{1}{T'}\int_0^{T'}|C_0z(t)+C_1z(t-\tau_1')\cos\theta_1'|^2\,dt+\frac{1}{T'}\int_0^{T'}|C_0z(t)+C_2z(t-\tau_2')\cos\theta_2'|^2\,dt > \frac{1}{T'}\int_0^{T'}|C_0z(t)+C_1z(t-\tau_1')\cos\theta_1'+C_2z(t-\tau_2')\cos\theta_2'|^2\,dt \qquad (16)$$

$$P'_{rsum} > P'_{rtwo}$$

Hence, the received power is higher in the first case.□ ■

5. THE PROPOSED BEAMFORMING SCHEMES

In this section, the three proposed approaches to a distributed, scattering-based beamforming are discussed in details: Taguchi-based scheme, a simple brute-force methodology, and learning automata (LA) based one. The proposed Taguchi-based scheme has an advantage over the other two schemes since it considers interactions between the multiple scattered copies thus ensuring higher maximum received signal strength. These schemes are presented next.

5.1. PROPOSED TAGUCHI-BASED SCHEME

This scheme is used to determine relative effect of the scattering devices on the received power. In this approach, a number of device subsets are selected. Experiments for each set are conducted where only the selected nodes are scattering the RF signal. Next, all the results are analyzed in terms of correlation with each device. The signal to noise ratio is calculated in order to provide relative contribution of each device to the total received signal strength.

The Taguchi approach is employed in this scheme to select the suitable sets of devices for the experiments. The main advantage of the Taguchi-based scheme is that it reduces the number of required experiments. The output power is measured with selected interactions between the scattered components of devices. In the proposed beamforming scheme each experiment is repeated a predefined number of times. Next, a variance and signal-to-noise ratio for the trials of each device-set is calculated. Finally, the results are compared among the device-sets thus providing the measure of the effect of each device on the received power. The device that contributes the most to the received signal strength will have higher average SN value for different combinations with other devices. Conversely, the ones having the least effect will have lower average SN value. Moreover, by comparing the SN values of the experiments where a particular device is involved, the correlation with other devices can be discovered. Consequently, the Taguchi scheme can overcome issue of interactions between scattered signals as discussed in Section 4.

The ranks are computed according to the SNP values calculated from the SN values of each experiment. The parameter with highest rank has the largest effect and vice versa. Next, an example calculation is presented for a scenario with three experiments conducted for each device-set.

5.2. EXAMPLE OF THE TAGUCHI-BASED SCHEME

Consider a scenario with five scattering devices placed at a random distance to LOS between transmitter and receiver. In such case, the Taguchi-based approach would render an orthogonal array that defines 8 device-sets, as show in Table 1. The value ‘1’ indicates the device that will scatter the RF signal during the particular experiment, and value ‘0’ indicates the inactive device.

Three trials are conducted for each experiment and SN values for each experiment are calculated as follows:

$$Sm1 = (P11 + P12 + P13)^2/3$$

$$St1 = P11^2 + P12^2 + P13^2$$

where P11, P21, P31 are the outputs for each trial of experiment 1. The difference of *Sm1* and *St1* is calculated as $\mathrm{Se1} = \mathrm{St1} - \mathrm{Sm1}$.

The variance for the particular experiment is determined by dividing Se1 with N-1 where N is the number of node considered here.

$$Ve1 = \frac{Se1}{N-1} \qquad (17)$$

Finally, the signal-to-noise ratio is calculated using the following expression

$$SN_1 = 10\,log\frac{\left(\frac{1}{N}\right)(Sm1 - Se1)}{Ve1} \qquad (18)$$

where N is the number of trials for each experiment and Ve1 is the variance of the particular experiment. In general P_{ij} is the output for the i^{th} experiment and j^{th} trial.

For each device averages of the SN values for the experiments with the presence and absence of the device are calculated and the difference is obtained as SNP. The responses are tabulated and ranked accordingly. The node with the highest rank contributes more to the output and the one with the least rank contributes the least or in other words it has a negative effect on the output.

5.3. BRUTE-FORCE SCHEME

The brute-force scheme calculates the received powers when each of the given set of devices is considered as a scattering device and ranks them based on their contribution to the power output. This scheme takes less time as it doesn't learn like the schemes using the Taguchi and learning automata methods do.

5.4. LEARNING AUTOMATA-BASED SCHEME

For the learning automata approach, a learning automaton is defined by a set of 4-tuple {A, B, P, T}. A and B are the set of actions and set of responses respectively. Depending on the values of B, different values of A are defined. If B is a set of binary values {0, 1}, the model is known as P-model. If B is a set of distinct values, it is called Q-model and if B has values in the interval [0, 1] it is called S model.

Beamforming Algorithm

The transmitter is given a set of distances of 'a' from, as shown in the figure. Let G(t) be the set of distances of *a*. A learning automaton is placed at transmitter node. For each time instant *t* an element from the set G(t) is chosen and the output, i.e., the power is calculated. For each element *i* of G, there is a basic transmission probability Pj(t) which is updated after each time slot according to the feedback from the network.

Updating Scheme

Each time the transmitter selects an element from the set G(t) and the signal is sent to the receiver. The receiver in turn leaves a feedback i.e., penalizing or rewarding the network. The whole process takes a propagation delay of τ. This feedback information from the network is used by the automata at the transmitter node to update the probability of selecting distance a_i for new transmission.

The following probability updating scheme is used:

If there is a penalty or if the output is a destructive interference during (t-τ) time interval.

$$P_i(t+1) = P_i(t) - \beta \times P_i(t) \qquad (19)$$

If there is a reward or if there is a constructive interference at the output (t-τ) time interval:

$$P_i(t+1) = P_i(t) + \varepsilon \times \beta \times (1 - P_i(t)) \qquad (20)$$

where $\beta \in$ □(0,1) and ε is a small number $0 < \varepsilon << 1$

The values of β and ε have a great impact on the network performance. The value of the parameter ε must be as small as possible to guarantee the convergence of the automaton. The value of β is used to determine the probability updating. If β is high, the automaton is adapted to the changes of the network state. The automaton is not accurate in this case. Low value of β means the network is more accurate but less adaptive. Hence the value of β should be selected to achieve the combination of accuracy and speed which maximizes network performance.

Action probabilities are initialized as a uniform distribution and the convergence criterion determines the completion of any learning stage:

$$max\{p_i(k)\} > \eta \qquad (21)$$

The reference level of acceptable performance is given by

$$P_{ref} = (1 + \partial)P_{th} \qquad (22)$$

If the response is favorable the action is rewarded or if its is unfavorable it is penalized.

Each action α_i has a probability $p_i(k)$ where *k* is a discrete-time variable for the automaton which increments after λ sec. If action is chosen at time k, the penalty-reward scheme updates action probabilities as β=0 for success and β=1 for failure.

In this simulation η is taken as 0.5, λ as 16 seconds. Each element of action vector takes 3random tags placed at random distances.

For the simulation the value of a is taken as 0.02 b as 0.01 where $0<b<a<<1$.

6. RESULTS AND DISCUSSION

The proposed schemes and the appropriate propagation models have been implemented in the Matlab. Several scenarios have been simulated in order to verify and analyze the performance of the proposed schemes. Unless otherwise specified the following parameter values have been used: Transmission power equal to 36.0206 dBm, propagation exponent $3x10^{-4}$, distance between transmitter and receiver 3m, frequency 2 GHz.

6.1. SINGLE SCATTERING NODE SCENARIO

The first scenario considers a pair of nodes whose position in reference to the LOS is varied. This scenario illustrates that the received power varies with the position of the scattering node, and can potentially provide increased signal strength.

Figures 4(i) and 4(ii) show the plot of power received 'P_r' at the device 'b' vs the perpendicular distance 'a' of scattering device from the direct ray path with the device on a single dimension and on a two-dimensional plane respectively. It can be observed that the power fluctuates between minimum and corresponding maximum values -37.75 dBm to -40.75 dBm with change in 'a'. It is because of the phase difference between direct ray and scattered component that leads to constructive and destructive interferences. Also, the maximum values of 'P_r' for various 'a' also varies because as the scattering device moves away from device 'a', the attenuation also increases.

The plot in the figure 8(i) shows the variation of received power for the device set {2.51, 1.45, 0.47, 1.34} when the receiver is moved along a one-dimensional path relative to the transmitter. As shown above, the beamforming occurs effectively at only some positions of the receiver and have a maximum when it is moved 0.6m from the original position.

The figure 8(b) shows the BER performance when ASK type of modulation is used at the transmitter. As shown in the figure BER decreases with increasing E_b/N_o for this particular device set.

6.2. MULTIPLE SCATTERING NODE SCENARIO

Second scenario analyzes the limits of the performance gain for a varying number of scattering nodes. This illustrates how multiple nodes can potentially improve the received signal strength.

The Fig shows the plot of the power received ‘P_r’ vs the number of devices contributing maximum and minimum peak powers. The curve of maximum peaks grows exponentially staring above ‘P_{th}’ which is -40.2 dBm and the minimum peak curve almost maintains the same value. There is a slight increase for higher values of ‘n’ due to the addition of more number of scattering devices. The third curve shows the plot for power received ‘P_r’ for random device selection. It shows that the power values stay in the limits defined by curve 1 and 2.

The received power is calculated for two device sets: (i) group of contributing devices and (ii) group ofnon-contributing devices. The two curves are plotted for each of the two cases with increasing number of devices. As shown in the figure 9, the received power for the contributing devices increases as *n* increases, whereas there is only a slight increase in the received power for the non-contributing devices and this is due to addition of more number of devices. The figure 10 shows the received power versus the number of devices selected from a set of both contributing and non-contributing devices. The power increases as *n* increases with slight fluctuations due to the non-contributing devices.

6.3. CORRELATION EFFECT IN A COMBINED SIGNAL

Next, a scenario with 10 randomly located devices is considered. The particular devices are configured to either enable or disable scattering of the RF signal. The seven sets of with the highest received power are shown in Fig . The maximum combined signal strength is contrasted with the simple summation of individual contributions from each device alone.

The observed maximum for the actual signal strength is different from the maximum when simple summation of individual contributions is used. This illustrates that the signal interference from multiple scattering devices result in non-linear outcome. Hence, in order to maximize the received power the interactions between the scattering signals have to be taken into account. A simple selection of all devices that individually increase LOS signal strength may result in suboptimal solution.

6.4. COMPARISON OF BEAMFORMING SCHEMES

The final simulation scenario considers a randomly located 5 nodes that can scatter the RF signal. The proposed schemes are employed and the performance in terms of signal strength, signal-to-noise ratio, and learning time are compared. The beamforming schemes learn which scattering nodes do increase signal strength through a set of experiments. As the schemes learn about the impact of the scattering nodes, they select the hitherto best configuration in order to increase the received signal strength. The results for the Taguchi-based scheme are shown in Tables 2 and 3.

Each experiment is repeated for three trials and SNR is calculated. The SN value for each device is calculated and tabulated. The device which has highest value has largest effect on output power and is given the highest rank. The other devices are ranked accordingly. From the above result, the device at 2.51m improves the power more than any other device and the device at 1.6m attenuates the power most.

It can be observed that in experiment 4 where the device at a=2.51m is considered, has an average received power of -34.5496 dBm. As the second case, in experiment 7 with device at a=0.57m, the average output power is found to be -35.9914 dBm. For the experiments 2 and 3, where the device in the first case is considered with two more devices have average output powers of -31.3402 dBm and -31.6143 dBm respectively which are about 3 dBm higher than that in the first case. In other words, the output power when multiple devices are considered differs by a small number compared to the case with a single device. Hence, the combined output power will be less than the sum of powers with single devices considered, thus explaining the correlation.

The plot of SN values for each device is shown in Fig for both Taguchi-based and brute-force methods. Although the Taguchi method attained different values, the magnitude of the SN values show that the effect of each tag is the same when compared to the brute-force methods.

The scheme using learning automata approach is designed to achieve the best set of triplet devices that contribute power from a set of devices placed at different distances. The result showed the following triplets gave a significant combined power.

Tables 4 and 5 show the results from the LA-based scheme when the devices are placed in single dimension and two-dimensional plane respectively. It shows that the highest achievable power is -33.89 dBm from the triplets for the first case and -34.22 dBm for the second. The LA approach took more time to analyze the method and to select the best set.

The Fig shows the time taken for different experiments to finish the analysis of selecting the best devices from a set of 50 devices. The learning automata based approach takes longer time as it has to do many permutations to calculate the best set of devices whereas the Taguchi method takes lesser time because it only does few selected combinations to obtain the value.

7. COMPARISON OF THE PROPOSED SCHEMES

From the results it can be observed that the scheme using Taguchi method performs better.

- Less learning time 31.21s compared to 44.80s for the scheme using LA-based scheme
- Higher learning rate for the scheme using Taguchi method. It is calculated as the mean value of $\Delta P(k)=P(k+1)-P(k-1)$ and it is observed the value is 0.5916 for scheme using Taguchi method and 0.4774 for the scheme using Learning Automata.

8. CONCLUSION AND FUTURE WORKS

The theoretical and simulation analysis of the scattering based beam-forming scenarios showed that by carefully controlling scattering characteristics of intermediate devices the received signal strength and quality can be improved. The paper introduced and studied three beam-forming schemes that can maximize the signal strength. The proposed Taguchi-based scheme has been shown to render the optimal beam-forming configuration. It was contrasted in simulation with other two schemes: brute force and learning automata based approaches. Both of these schemes achieved suboptimal performance of the beam forming. However, the brute-force method provides a relatively fast convergence to the suboptimal solution.

The main benefits of using the Taguchi based scheme are reduced power requirements and shorter learning time than the LA-based scheme. By using five scattering devices the received power improves by 10.6%. It achieves a higher SINR ratio of 93.5753 which is 2.1% higher than for LA-based scheme and 1.41% higher than for the brute-force scheme.

The proposed distributed scattering-based beamforming scheme can potentially be employed in various applications including passive RFID systems, and communication with nano-devices. For example, the passive RFID tags can utilize the other surrounding tags to increase signal strength and quality thus increasing communication speed and read range. Also, the proposed schemes can be applied in RFID system to discover device's location.

The future work includes more research on varying position of the receiver case and also the simulations of combined taguchi and brute-force schemes.

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10. APPENDIX

The device set considered for the Leaning automata-based scheme are {a=1.6m, a=1.70m, a=0.41m, a=0.57m, a=0.73m, a=0.58m, a=0.89m, a=1.03m, a=1.45m, a=0.96m, a=2.47m, a=2.6m, a=2.51m}

11. FIGURES

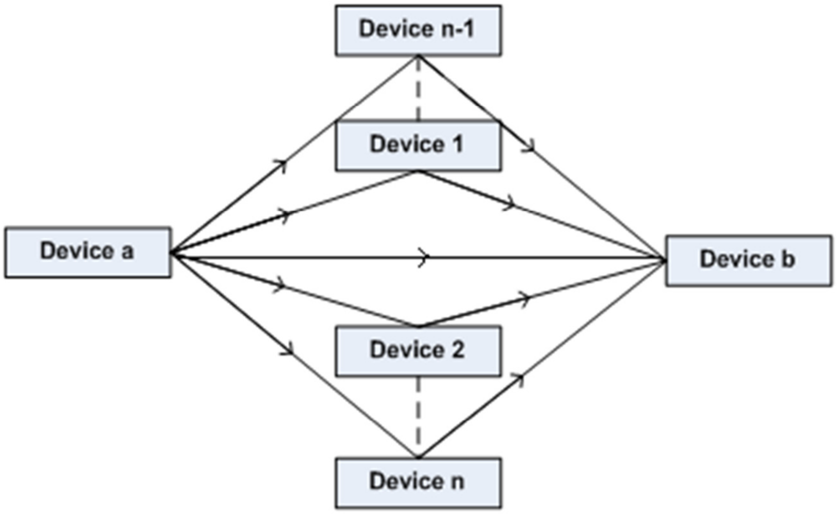


Fig 1. Communication in a scattering environment

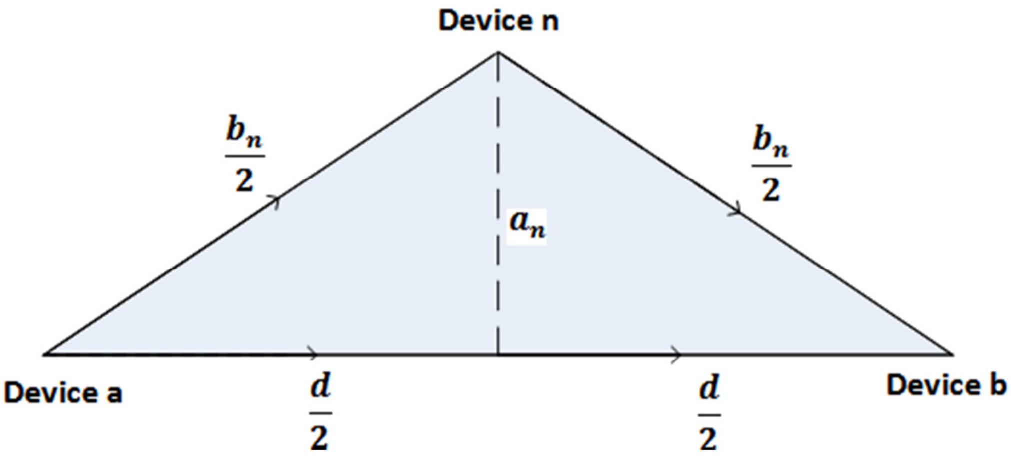


Fig 2. Scattering signal component of nth device

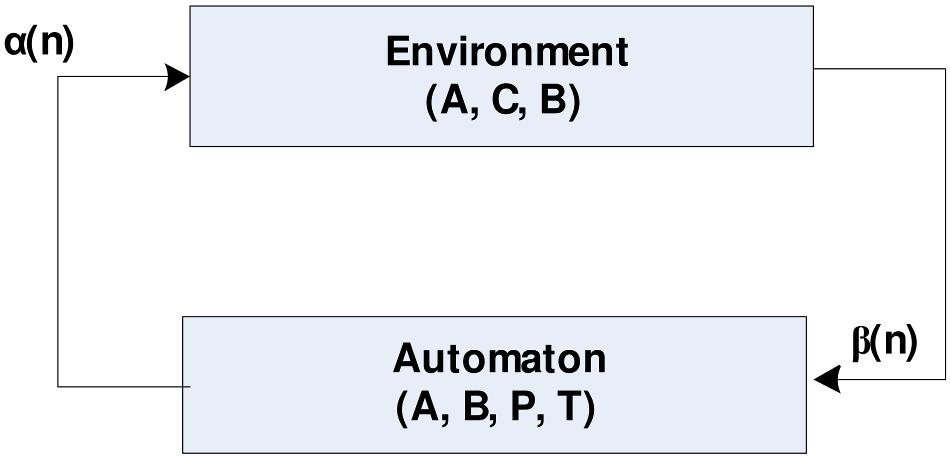
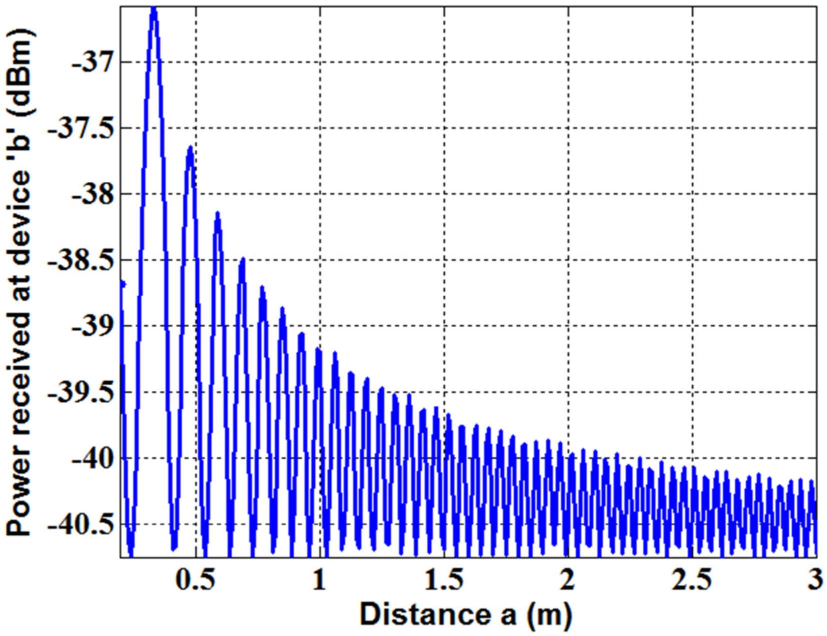
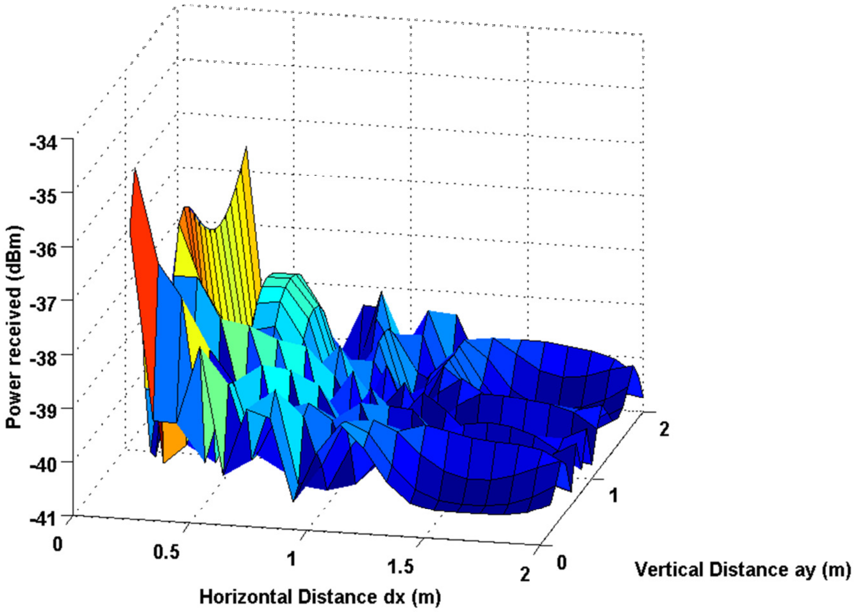


Fig 3. Learning automaton



(i)



(ii)

Fig 4. Power received Pr which is sum of direct and scattered rays versus distance ‘a’ [m] varied in (i) single dimension and (ii) two dimensional plane respectively

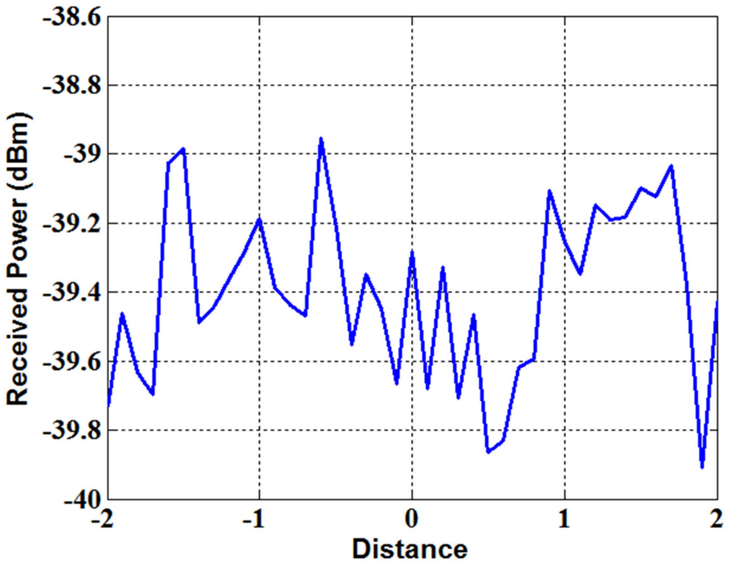


Fig 5(i). Received Power for different positions of the receiver

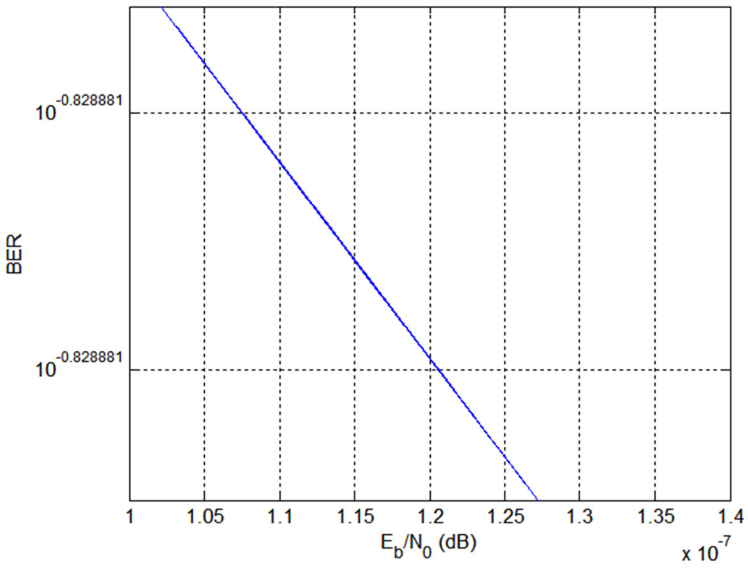


Fig 5(ii) BER variation for different positions of receiver

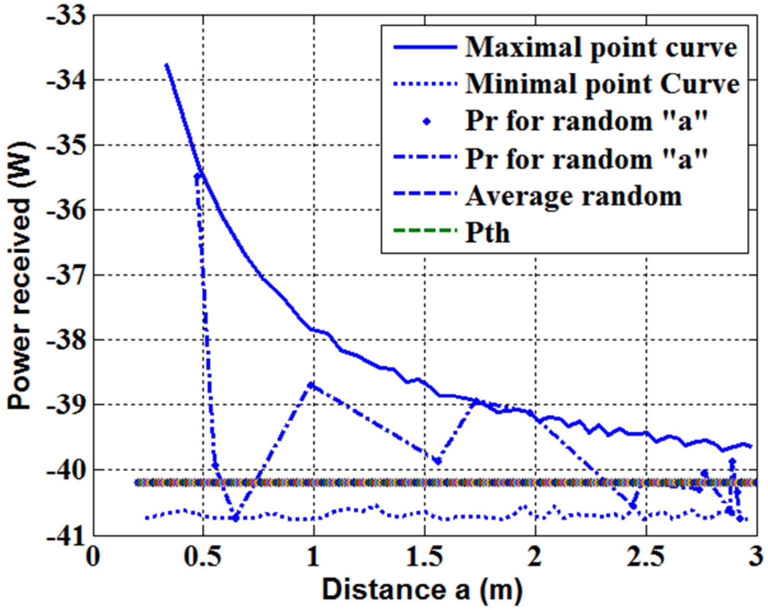


Fig 6. Maximum and minimum received power Pr vs total number of devices

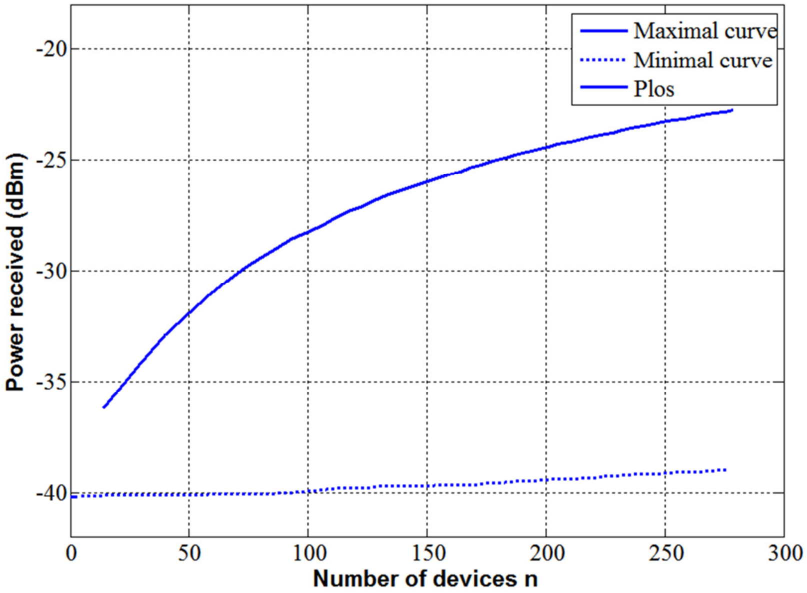


Fig 7. Maximal and minimal power curves by selecting contributing and non-contributing device set

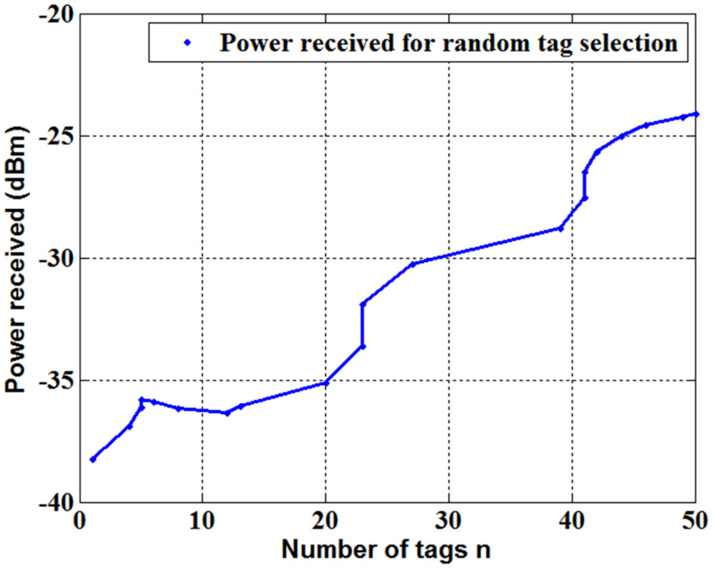


Fig 8. Received power for random tag selection

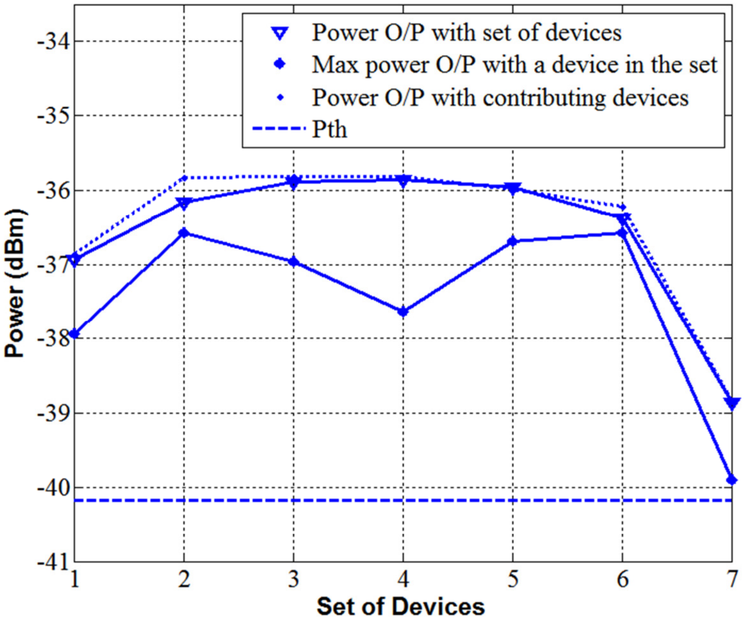


Fig 9. Received power for the best device-sets

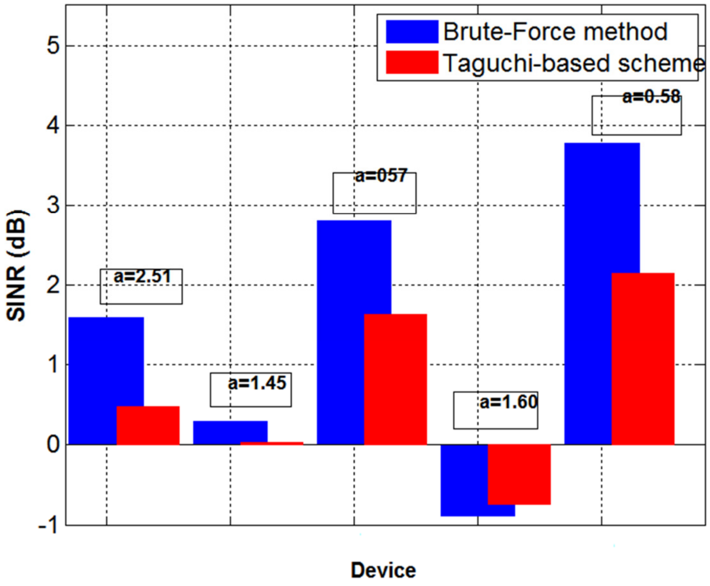


Fig 10. Per-device SNR for Taguchi method

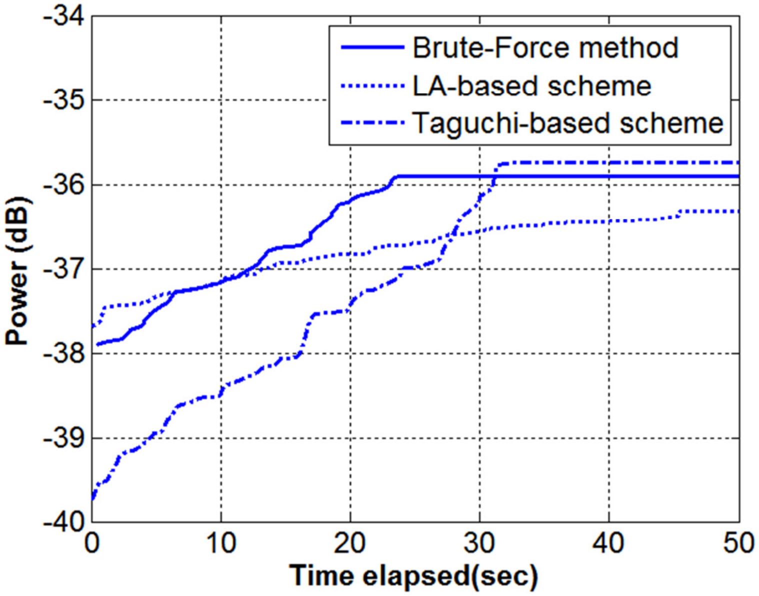


Fig 11. Plot of time elapsed to reach threshold value of power

12. TABLES

TABLE 1. DEVICE-SETS FOR THE TAGUCHI-BASED SCHEME

Exp	**Device**	**Device**	**Device**	**Device**	**Device**
1	1	1	1	1	1
2	1	1	1	0	0
3	1	0	0	1	1
4	1	0	0	0	0
5	0	1	0	1	0
6	0	1	0	0	1
7	0	0	1	0	0
8	0	0	1	0	1

TABLE 2. RESULTS FOR THREE TRIALS OF EACH EXPERIMENT

Received Power (dBm)			**SN**
Trial 1	**Trail 2**	**Trial 3**	
-29.1909	-29.6922	-29.5725	107.7421
-31.2396	-31.9320	-30.8491	107.3877
-31.3723	-32.0439	-31.4269	116.2389
-34.3136	-34.8035	-34.5317	105.0714
-38.5513	-38.3778	-38.1682	120.1829
-33.8195	-34.5770	-34.4298	103.7198
-35.7030	-36.1404	-36.1308	114.5174
-32.0943	-31.7769	-32.4336	104.3731

TABLE 3. ARRAY FOR SCHEME USING TAGUCHI APPROACH

Exp	**Device a=2.51**	**Device a=1.45**	**Device a=0.57**	**Device a=1.6**	**Device a=0.58**
SNP	1.5883	0.2921	2.7982	-7.7074	3.7714
Rank	3	4	2	5	1

TABLE 4: RESULTS FROM LEARNING AUTOMATA BASED SCHEME

Set	Device 1	Device 2	Device 3	Power (dBm)
1	2.470000	0.590000	1.700000	-37.405008
2	0.770000	1.450000	0.720000	-37.433624
3	0.330000	0.960000	1.190000	-35.774063
4	1.190000	0.330000	0.960000	-35.774063
5	0.960000	0.590000	1.450000	-37.232877
6	0.720000	0.590000	1.190000	-36.902710
7	0.330000	0.590000	0.980000	-33.891142
8	0.330000	0.890000	2.470000	-35.989157
9	0.330000	1.190000	2.470000	-35.960924
10	0.720000	1.190000	0.590000	-36.902710
11	0.330000	0.980000	0.770000	-34.229565
12	0.770000	1.450000	0.720000	-37.433624

TABLE 5: RESULTS FROM LEARNING AUTOMATA BASED SCHEME WITH DEVICE IN A 2D PLANE

Device 1		Device 2		Device 3		Received power
X1	Y1	X2	Y2	X3	Y3	
0.98	0.96	1.7	1.19	1.45	0.98	-37.52
2.47	1.7	1.22	0.33	0.33	1.19	-36.22
0.72	0.33	2.47	1.45	0.96	2.47	-37.54
0.33	0.77	0.89	0.89	0.72	0.59	-37.38
0.77	0.89	0.72	0.59	1.45	0.77	-36.55
0.59	0.72	0.33	0.89	1.22	0.96	-37.24
0.72	1.19	1.19	0.89	1.22	0.33	-35.38
1.70	0.98	0.59	2.47	0.72	0.77	-37.42
0.96	0.89	1.70	2.47	0.77	0.33	-36.30
1.19	0.77	1.22	0.33	0.96	0.89	-34.48
1.70	0.98	0.96	0.59	1.22	0.77	-37.15
2.47	0.59	0.33	1.45	0.96	0.33	-36.37
0.96	0.72	1.70	0.77	1.22	0.33	-34.22

PAPER

II. MULTI-HOP FRAMEWORK FOR BATTERY-LESS DEVICES USING PASSIVE RF COMMUNICATION

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Abstract— Typical wireless multi-hop networks employ active communication where RF signal has to be generated by a sending node. In contrast backscatter communication modulates backscattered RF signal that requires significantly less energy to operate than the active one. This paper proposes a novel architecture for multi-hop backscatter-based networking for a passive RF communication that is not currently present. Such a system consists of a powerful reader and small, battery-less nodes. The reader generates the original RF signal, while the passive devices backscatter this signal among themselves thus enabling multihop communication from far-away nodes. The paper presents the generic analysis of the system capabilities and demonstrates the feasibility of such multi-hop network. It also investigates the connectivity models in terms of k-connectivity of such network with uniformly distributed tags.

Key words— Radio Frequency Identification (RFID), backscattering, passive tag, orientation sensitivity

1. INTRODUCTION

Typical wireless communication systems require active generation of RF signal to transmit messages. This results in high-energy requirements and reduced life of battery powered devices. In contrast, the passive backscattering systems modulate reflected RF signal to transmit information. As a result, such passive communication has several advantages over traditional sensor networks. The main benefits are: (a) reduced size and weight of devices since battery is not required and (b) elimination of battery waste which is harmful to environment. The most well-known backscatter system is the passive Radio Frequency Identification (RFID) system. In recent years, it has received much attention in the fields of security, logistics, tracking and supply. An RFID system consists of multiple tags and a reader. Passive RFID tags are used in many applications as they do not use battery and utilizes the electromagnetic energy of the signal from the reader.

However, such a passive communication is currently limited to one-hop, direct communication between an active reader and passive devices. The communication distance is limited by two main factors: (a) minimum required energy that has to be harvested by the passive device in order to operate, and (b) the sensitivity level of the reader at which the reflected, modulated backscatter signal can be decoded. The former depends on the efficiency of the harvesting circuitry and energy-efficiency of the device. In the past, the passive devices had to be very close to the source of the RF signal. However, advancements in in integrated circuits (ICs) fabrication improved both effectiveness of energy harvesting and energy-efficiency of the ICs. Consequently, such passive chips can be powered much further away from reader than the backscatter signal can be decoded, as shown in Figure 1. The proposed solution employs intermediate nodes to decode the message from far-away device, and forward the data by modulating the backscatter signal.

In a passive RFID system if the tag is far away from the reader, it is difficult for the tag to generate backscattered signal that can reach the reader. By employing multiple tags in between the reader and the farthest tag it is possible to make the backscatter reach the reader.

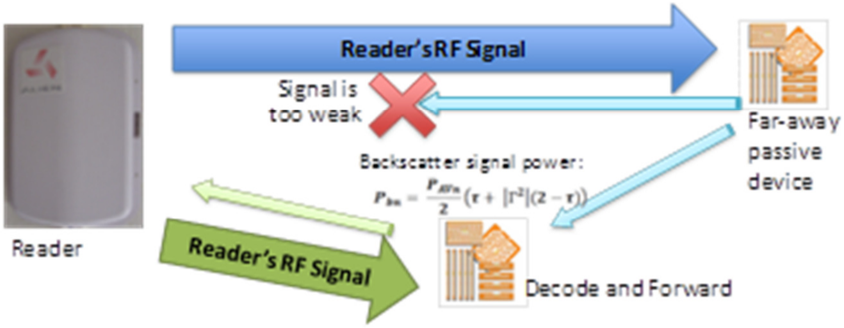

Fig. 1. Overview of the multi-hop, backscatter communication

The backscattered signal hops between multiple tags that are in the propagating path. This is called as Multi-hop RFID system. There is no need to generate a backscatter signal of high power from the tag. The effective range can be improved by employing multiple tags.

Each tag has a particular transmission range which is much smaller than that of the reader. In a uniform RFID passive network the tags have the same transmission range r, which is much smaller than that of the reader R where $r<R$. The distance between the reader and the destination tag is d', which is considered to be less than R and greater than r. Since the transmission range is r is less than the distance d', the tag cannot transmit the backscatter information to the reader. By placing particular number of tags in the path, the backscatter signal can reach the reader.

In general, multi-hop networks are classified into one-dimensional and two-dimensional networks depending on the type of distribution of the nodes, which are tags in this work, on a single line or over an area. They are further sub-divided into homogenous and non-homogenous networks based on the type of range assignments to each node. If the transmission ranges of all the nodes are same, the network is called homogenous and if they are different the network is called non-homogenous.

The number of neighbors of a node is termed as degree d. The minimum node degree of the network is the smallest node degree over all the nodes. A connected network has always $d_{min}>0$ but the reverse implication is not sufficient. A network is said to be *k-connected* if for each node pair there exist at least k mutually independent paths connecting them.

The source and the destination are to be connected by the network using *N* intermediate nodes. Two nodes in the network are said to be connected if the distance between them is less than or equal to the radio transmission range d. The location of the nodes follows different probability distributions in different works. For example, in a one dimensional network, the location of the i^{th} node can be assumed to follow Gaussian distribution with mean $\mu_i=i/(N+1)$ and variance σ^2 independent of all other nodes.

The connectivity of a network can be estimated using k-connectivity probability. A network path is said to be *k-connected* if and only of no set of *(k-1)* nodes exists whose removal would disconnect the path. In other words, the path should be connected even if (*k-1)* nodes fail. For a wireless multi-hop network where n nodes are randomly distributed in a plane according to homogenous two-dimensional Poisson process with average density λ, the minimal number of neighbors that a node has a connection is denoted by d_{min}. The probability that the network is k-connected is given by

$$P(network\ is\ k - connected) \approx P(d_{min} \geq k)$$

where k is a predefined value for connectivity.

For k=1, i.e., if the probability that each node has one neighbor *P(1-conn)=1* then it is said that *P(1-conn)* would the *P(conn)*, the probability the network is connected. In most works, if the probability that the network is *k-connected P(k-conn)>0.95*, the network is said to be almost surely connected.

The main contributions of this paper are:

- Development of a network model that describes the multi-hop propagation between the reader and a tag in the presence of multiple tag on the line of propagation.
- Analysis of such network model in one-dimensional and two-dimensional types of tag distribution.
- Analysis of the orientation sensitivity of tag antenna for a simple scenario of propagation.
- Study of their performance with varying parameters such as number of nodes, density and area of the network.

2. RELATED WORK

The main challenge in multi-hop networks is achieving high network connectivity with a minimum node density. A limited work has been published on determining the range and probability distributions of the multi-hop RFID network. [1] discusses the use of RFID tags in wireless sensor multi-hop networks by attaching them to each node and whenever the data is to be transmitted the receiver's tag is activated. This setup enables radio and microcontroller to go into sleep mode when they are not active and hence there is less power consumption. Although this falls under the multi-hop mechanism it doesn't actually come under the multi-hop RFID since the reader and the tags are used only to keep the nodes active and not used to transmit data. The connectivity and transmission range of the nodes in wireless multi-hop networks has been discussed studied in [2] in terms of k-connectivity for homogenous and non-homogeneous range assignments of the nodes. Similar study is analyzed in [4] in shadowing environment. The effect of minimum hop count distribution on connectivity is discussed in [4] by deriving the exact probability distribution of minimum hop count from the density of relay nodes in the path selected. The probability distribution of the expected hop count for packet transmissions with an arbitrary node density is developed in [5]. [6] studies the one-dimensional ad hoc network as a group of clusters which presents the formula for network connectivity with approximation.

The minimum node degree and the k-connectivity characteristics are investigated in [7] assuming random uniform distribution of the nodes for a given node density ρ. The shadowing phenomenon which affects the connectivity is also explained in [8] in a log-normal shadow fading environment. The exact probability of one-dimensional network is obtained in [9] and is used to obtain some loose bounds for the probability that a finite two-dimensional network is connected.

The tags in multi-hop RFID network act as scattering devices which receives the backscatter signal from a tag and scatters it to another. The design and orientation of the RFID tag antenna plays an important role in this multi-hop propagation model. [10] and [11] discuss about the antenna design for UHF RFID tag antennas for different types of tags. [12] and [13] presents a good explanation of the propagation of the backscatter signal in different kinds of environments with different values of propagation constants.

This paper presents a new method of modeling a multi-hop RFID network in one-dimensional and two-dimensional cases using statistical analysis. The distributions function for minimum hop count and node density also is derived. Also, the analysis includes consideration for the tag orientation.

3. PROBLEM STATEMENT

The propagation model for the multi-hop RFID network consists of a reader and multiple tags in the propagation line. For the network to connected at least one tag, which participate in the multi-hop propagation, should be in its transmission range. Thereby, network connectivity can be achieved.

3.1. GENERAL FORMULATION OF THE PROPOSED MULTI-HOP SYSTEM

In the proposed approval, tags not only communicate with the reader but also read and relay information to other tags. By using this technique, the effective range can be increased.

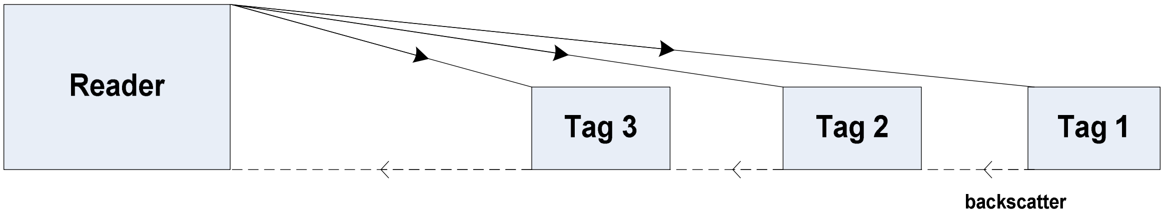

Fig. 2. Simple one-dimensional RFID network

Figure 2 shows a simple one-dimensional RFID network with tag 1 as the destination. The backscattered signal from the same tag hops between the intermediate tags (i.e., tag 1, tag 2 etc) until it reaches the reader. The intermediate tags use the electromagnetic energy from the reader to generate a copy of the received signal.

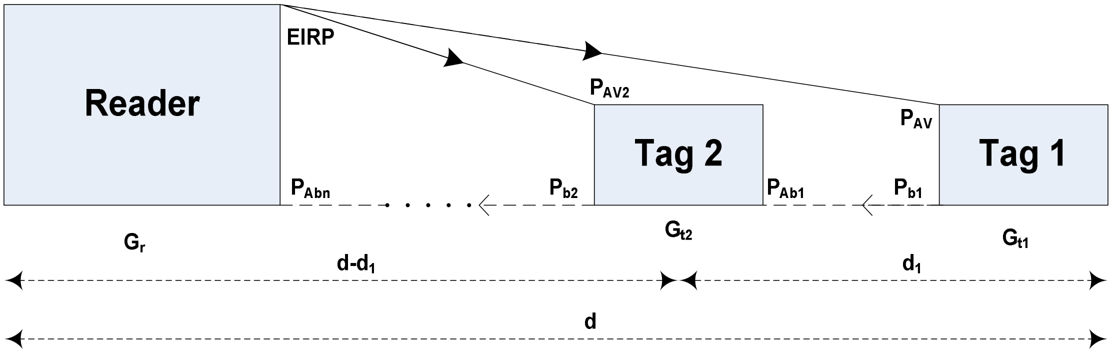

Fig. 3. Analysis of one-dimensional RFID network

Figure 3 illustrates the scenario with intermediate tag 2 relaying message information from tag 1. Each tag receives two types of signals, one from the reader which it uses for generation of backscatter and another as a backscatter from an adjacent tag. The destination tag receives a power of P_{AV} from the reader.

3.2. NOTATIONS USED IN THE ANALYSIS:

d_n – Distance between tag n and tag $n+1$

P_{AVn} – Power available at tag n's antenna from the reader signal

P_{bn} – Power of the backscattered signal from tag n

P_{Abn} – Power received at tag $n+1$ from the backscatter of tag n

λ – Wavelength of the signal

EIRP – Effective Isotropic Radiated Power

η – Propagation constant

3.3. THEORETICAL ANALYSIS OF THE BACKSCATTER SIGNAL PROPAGATION

Corollary 1: In a multi-hop passive RFID network, the distance between the tags which participate in the backscatter propagation is given by

$$\frac{d_n}{d} = \sqrt{\frac{P_{AV}}{\eta_1 . G_{t1}}}\left(\sqrt{\frac{\eta_n G_{tn}}{P_{AVn}}} - \sqrt{\frac{\eta_{n+1} G_{tn+1}}{P_{AVn+1}}}\right)$$

Proof: The farthest tag communicates with the reader using the intermediate tags. It is proved that the backscatter power from the intermediate tags increases as they get closer to the reader. For the tags closer to the reader the hop distance can be increased thus accommodating less number of tags.

Reader sends a signal to track tag 1 as shown in figure 2, the signal reaches the antenna of tag 1.

According to Frii's formula, distance between reader and tag,

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{\eta.G_{t1}.G_r.EIRP}{P_{AV}}} \qquad (1)$$

where G_{t1}, G_r are the gains of tag 1 and reader respectively, P_{AV} is the power available at tag 1, η is the fading coefficient.

The distance between the tag n and tag *n+1* considering the backscatter signal is given by

$$d_n = \frac{\lambda}{4\pi}\sqrt{\frac{\eta.G_{tn+1}.G_{tn}.P_{AVn}.\tau}{2.P_{Abn}}} \qquad (2)$$

where P_{AVn} is the power available from the reader at the antenna of tag *n*, P_{Abn} is the power received at tag *n+1* from tag *n*. From (2) we can write

$$P_{Abn} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{{d_n}^2}\frac{\eta.G_{tn+1}.G_{tn}.P_{AVn}.\tau}{2} \qquad (3)$$

$$P_{Abn} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{{d_n}^2}\frac{\eta.G_{tn+1}.G_{tn}.P_{AVn}.\tau}{2} \qquad (4)$$

Let us assume the tag 'n' is placed at a fixed distance 'x' from the reader, then 'x' is given by

$$x = \frac{\lambda}{4\pi}\sqrt{\frac{\eta.G_{tn}.G_r.EIRP}{P_{AVn}}} \qquad (5)$$

$$P_{AVn} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{x^2}\eta.G_{tn}.G_r.EIRP \qquad (6)$$

Therefore,

$$P_{Abn} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{{d_n}^2}\frac{\eta.G_{tn+1}.G_{tn}.\left(\left(\frac{\lambda}{4\pi}\right)^2\frac{1}{x^2}\eta.G_{tn}.G_r.EIRP\right).\tau}{2} \qquad (7)$$

$$d_n = \left(\frac{\lambda}{4\pi}\right)^2 \frac{\eta.G_{tn}}{xP_{Abn}}.\sqrt{\frac{G_{tn+1}.G_r.EIRP.\tau}{2}} \qquad (8)$$

The power received at tag *n+1*, P_{Abn} should be greater than the threshold value of the tag

$P_{Abn} \geq P_{th}$

$$d_n \leq \left(\frac{\lambda}{4\pi}\right)^2 \frac{\eta.G_{tn}}{x.P_{th}}.\sqrt{\frac{G_{tn+1}.G_r.EIRP.\tau}{2}}$$

The maximum value of d_n would be

$$d_n = \left(\frac{\lambda}{4\pi}\right)^2 \frac{\eta.G_{tn}}{x.P_{th}}.\sqrt{\frac{G_{tn+1}.G_r.EIRP.\tau}{2}} \qquad (9)a$$

where G_{t1} is the gain of tag 1 antenna, G_r is the gain of the reader and *EIRP* is the Effective Isotropic Radiated Power from the reader, P_{AV} is the available power from tag 1.

The minimum number of hops *n* can be found out from the equation

$$d_{n+1} \geq d - d_n \qquad (9)b$$

The above figure shows the plot of distance between tag *n* and tag *n+1* versus EIRP of the reader for various values of η. From the above figure, it is evident that by increasing the EIRP, d_n increases and the slope decreases with an increase in η.

The distance between the reader and tag 2 is given by,

$$d - d_1 = \frac{\lambda}{4\pi}\sqrt{\frac{\eta_2.G_{t2}.G_r.EIRP}{P_{AV2}}} \qquad (10)$$

where d_1 is the distance between tag 1 and tag 2, G_{t2}, G_r are the gains of tag 2 and the reader respectively.

From (1) and (2), we get

$$\frac{d_1}{d} = 1 - \sqrt{\frac{\eta_2.G_{t2}.P_{AV}}{\eta_1.G_{t1}.P_{AV2}}} \qquad (11)$$

Similarly we get,

$$\frac{d_2}{d} = \sqrt{\frac{P_{AV}}{\eta_1.G_{t1}}}\left(\sqrt{\frac{\eta_2 G_{t2}}{P_{AV2}}} - \sqrt{\frac{\eta_3 G_{t3}}{P_{AV3}}}\right) \qquad (12)$$

where d_2 is the distance between tag 2 and tag 3

In general we can write,

$$\frac{d_n}{d} = \sqrt{\frac{P_{AV}}{\eta_1.G_{t1}}}\left(\sqrt{\frac{\eta_n G_{tn}}{P_{AVn}}} - \sqrt{\frac{\eta_{n+1} G_{tn+1}}{P_{AVn+1}}}\right) \qquad (13)$$

The above equation provides the relationship between the distance between tag *n* and tag *n+1* and *d* in terms of the gains and powers available at the particular tags.

4. ORIENTATION SENSITIVITY

The transmission range of a tag in a particular direction depends on the orientation of its antenna and hence the orientation sensitivity is a parameter of importance. The orientation sensitivity of the tag antenna is the ratio of f its maximum range to the minimum. It is represented by

$$A = \frac{r_{min}}{r_{max}} \qquad 0 < A < 1 \qquad (14)$$

In general, the Frii's space transmission equation is given by

$$P_R = P_T.\frac{G_T G_R \lambda^2}{(4\pi r)^2} \qquad (15)$$

where P_R is the received power, P_T is the transmitted power, *r* is the distance between transmitter and receiver, G_T, G_R are the gains of transmitter and receiver antennas respectively. λ is the wavelength of the electromagnetic wave

In (1) the gains are not constant. They depend on the orientation of the antennas. Considering the orientations of antennas, (1) can be modified as follows

$$P_R = P_T.\frac{G_T(\theta_T,\emptyset_T).G_R(\theta_R,\emptyset_R).\lambda^2}{(4\pi r)^2}(1-|\Gamma_T|^2)(1-|\Gamma_R|^2)|\rho_T-\rho_R|^2$$

(16)

where Γ_T, Γ_R are the reflection coefficient of transmitter and receiver respectively and this is due to mismatch between the antenna and the circuitry.

ρ_T, ρ_R are the polarization vectors of transmitter and receiver respectively and reflects the loss due to mismatch of polarizations of transmitter and receiver antennas.

4.1. ORIENTATION SENSITIVITY ANALYSIS

Example:

For a half-wave dipole antenna, the gain is given by

$$G_R(\theta_R, \emptyset_R) = 1.641\left(\frac{\cos\left(\frac{\pi}{2}cos\theta_R\right)}{sin\theta_R}\right)^2 \qquad (17)$$

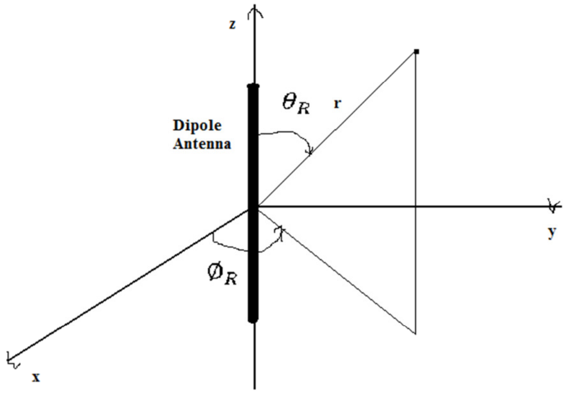

Fig. 4. Dipole antenna angle definition

$$P_R = P_T.\frac{G_T(\theta_T,\emptyset_T).G_R(\theta_R,\emptyset_R).\lambda^2}{(4\pi r)^2}(1-|\Gamma_T|^2)(1-|\Gamma_R|^2)|\rho_T-\rho_R|^2$$

(18)

From the above formula range ‘r’ is given by

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_T.G_T(\theta_T,\emptyset_T).G_R(\theta_R,\emptyset_R)(1-|\Gamma_T|^2)(1-|\Gamma_R|^2)}{P_R}}|\rho_T-\rho_R| \qquad (19)$$

Both the transmitter and receiver antennas have orientations and hence the range *r* depends on both the parameters.

From (4) maximum and minimum values of *r* are determined and the orientation sensitivity of the particular tag is determined by using (14).

For a patch antenna, the gain is given by,

$$G_T(\theta_T, \emptyset_T) = 3.136 \left[\sin\theta_T \ \frac{\sin\left(\frac{\pi}{2}\cos\theta_T\right)}{\cos\theta_T} cos\left(\frac{\pi}{2}\sin\theta_T\, sin\emptyset_T\right)\right]^2 \qquad (20)$$

The gain of the patch antenna is dependent on both θ_R and the projection angle $\emptyset_R$.

Two tags x and y are assumed to have positioned in a two-dimensional plane and have half-wave dipoles as their antennas. Hence, for the propagation between the two, each of the antennas has some orientation with the other. It is assumed that tag x and tag y have gains G_T and G_R respectively.

The distance will be

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_T.G_T(\theta_T,\emptyset_T).G_R(\theta_R,\emptyset_R)(1-|\Gamma_T|^2)(1-|\Gamma_R|^2)}{P_R}}\,|\rho_T - \rho_R|$$

(21)

where P_T and P_R are the power transmitted by tag *x* and power received by tag *y* respectively

$$G_T(\theta_T, \emptyset_T) = 1.641\left(\frac{\cos\left(\frac{\pi}{2}cos\theta_T\right)}{sin\theta_T}\right)^2 \qquad (20)$$

$$G_R(\theta_R, \emptyset_R) = 1.641\left(\frac{\cos\left(\frac{\pi}{2}cos\theta_R\right)}{sin\theta_R}\right)^2 \qquad (21)$$

where θ_R and θ_T are the orientations of tag *y* and tag *x* antennas w.r.t each other.

5. ANALYSIS OF ONE-DIMENSIONAL AND TWO-DIMENSIONAL NETWORKS

The one-dimensional and two dimensional networks are analyzed using the distribution of minimum hop count and the connectivity probability when the tags with ominidirectional antennas are distributed according to some random distribution. The connectivity probabilities are found for both types of networks using the Poisson distribution process for the distribution of tags and assuming that not all the tags have same transmission range. [8] provides a similar analysis in the two cases of network connectivity.

Let the nearest neighbor distance for a particular tag is given by the variable *x* and *p* be the probability that no tag in the network is isolated.

For Poisson point process in two dimensions, the probability density function is given by

$$f(x) = 2\pi\rho x.e^{-\rho\pi x^2}\ for\ x > 0 \qquad (22)$$

The probability that the distance between a randomly chosen tag in the network to its neighboring tag is less than or equal to *r* given by

$$P(x \leq r) = \int_{x=0}^{r} xp(x)dx = 1 - e^{-\rho\pi r^2} \qquad (23)$$

The probability that the tag has at least one neighbor is given by

$$P(n > 0) = P(x \leq r) \qquad (24)$$

Since there are *N* tags in the network and each has different range, probability that the minimum number of neighbors for each tag is greater than zero is given by

$$P(n_{min} > 0) = P(n_1 > 0).P(n_2 > 0)\dots P(n_N > 0)$$

$$= \left(1 - e^{-\rho\pi {r_1}^2}\right)\left(1 - e^{-\rho\pi {r_2}^2}\right)\dots(1 - e^{-\rho\pi {r_N}^2}) \qquad (25)$$

Hence the probability that the network is connected is given by

$$P(connected) = \left(1 - e^{-\rho\pi {r_1}^2}\right)\left(1 - e^{-\rho\pi {r_2}^2}\right)\dots\left(1 - e^{-\rho\pi {r_N}^2}\right) \qquad (26)$$

5.1. ONE-DIMENSIONAL NETWORK MODEL

In this section, a one-dimensional RFID network with homogeneous range assignments is considered. The reader is placed at location0 and the *N* tags placed along the horizontal line as shown in the Figure 4.

Lemma 1: The k-connectivity probability of a one-dimensional multi-hop homogeneous passive RFID system varies with the transmission range *r*.

Let the length of the whole path is *L*.

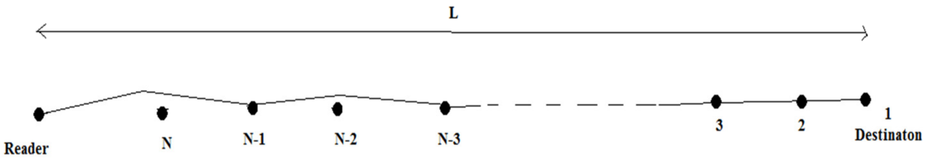

Fig. 5. One-Dimensional Network with N tags

It is assumed that the *N* tags are randomly distributed according to the Poisson process with a fixed rate λ.

Probability that a tag is placed within a range *r* is $p = \frac{r}{L}$.

Probability that *k* numbers of tags are placed in the range *r* is given by

$$P(n = k) = \frac{(Np)^k}{k!} e^{-Np} \tag{27}$$

Let us suppose the density $\rho = \frac{N}{L}$, then transforming (11) results in

$$P(n = k) = \frac{(\rho r)^k}{k!} e^{-\rho r} \tag{28}$$

The above equation also denotes the probability that a tag has *k* neighbors if the range is *r/2*.

5.2. TWO-DIMENSIONAL NETWORK MODEL

In this section, a two-dimensional multi-hop RFID network is analyzed. It is assumed that the network consists of tags distributed in an area *A* with a density ρ.

Lemma 2: The k-connectivity probability in the two-dimensional case varies with the square of the transmission range i.e., r^2.

Let us assume that *N* tags are uniformly distributed across the region according to a Poisson process with a density λ

Probability that a tag is placed within a small area 'a' is equal to $p = \frac{a}{A}$. Probability that *k* numbers of tags are placed in an area *a* is given by

$$P(n = k) = \frac{(Np)^k}{k!} e^{-Np} \tag{29}$$

Let us suppose the density $\rho = \frac{N}{A}$, then transforming (11) yields

$$P(n=k)=\frac{(\rho a)^k}{k!}e^{-\rho r} \qquad (30)$$

The area ‘a’ covers the range ‘r’ i.e., $a=\pi r^2$

Equation (14) becomes

$$P(n=k)=\frac{(\rho\pi r^2)^k}{k!}e^{-\rho\pi r^2} \qquad (31)$$

The above equation also denotes the probability that a tag has *k* neighbors.

6. RESULTS AND DISCUSSION

The proposed propagation model has been implemented in MATLAB.

6.1. SIMPLE ONE-DIMENSIONAL MULTI-HOP SCENARIO

Simple one dimensional case is considered with varying transmitted power (EIRP) and the distance d_n is calculated. The same task is repeated with varying number of nodes and results averaged.

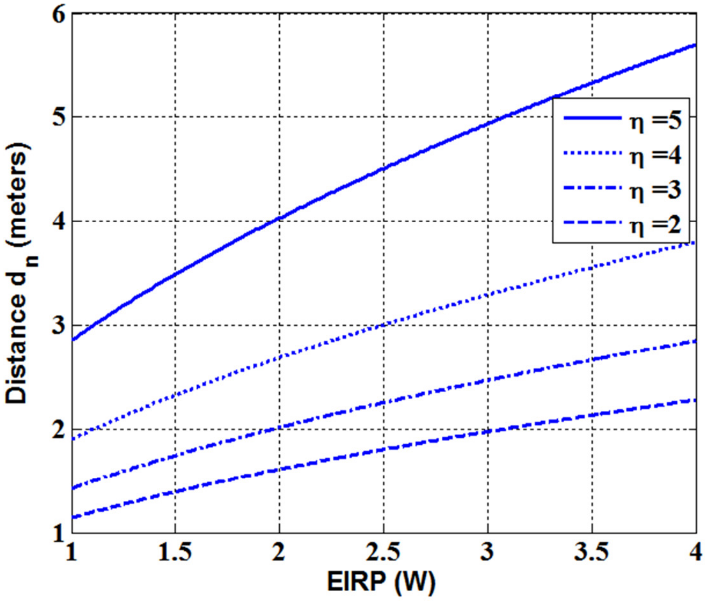

Fig. 6. Distance d_n vs. power from reader

The above figure shows the plot of distance d_n between tag *1* and tag *2* versus EIRP of the reader for various values of η according to the equation 9(a). From the above figure 6, it is evident that by increasing the EIRP, d_n increases and the slope decreases with an increase in η. The coefficient η is the parameter used in the equation 9(a).

6.2. ANTENNA RANGE

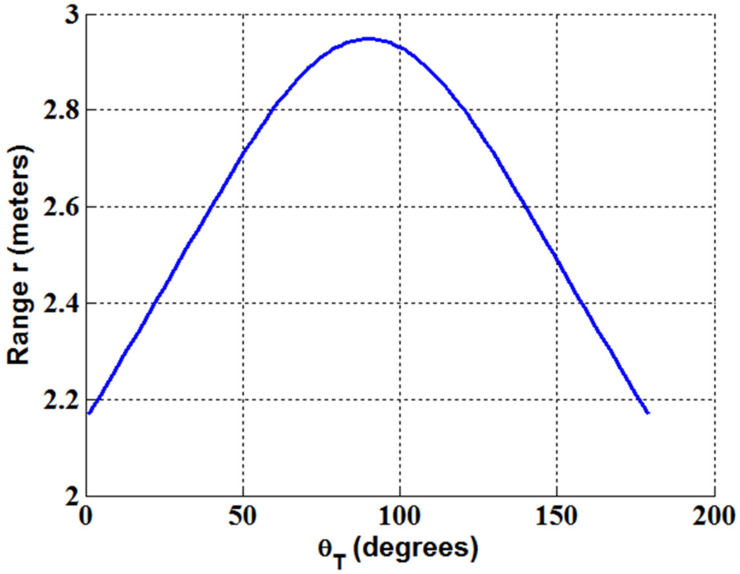

Fig. 7. Range ‘r’ vs. θ_R

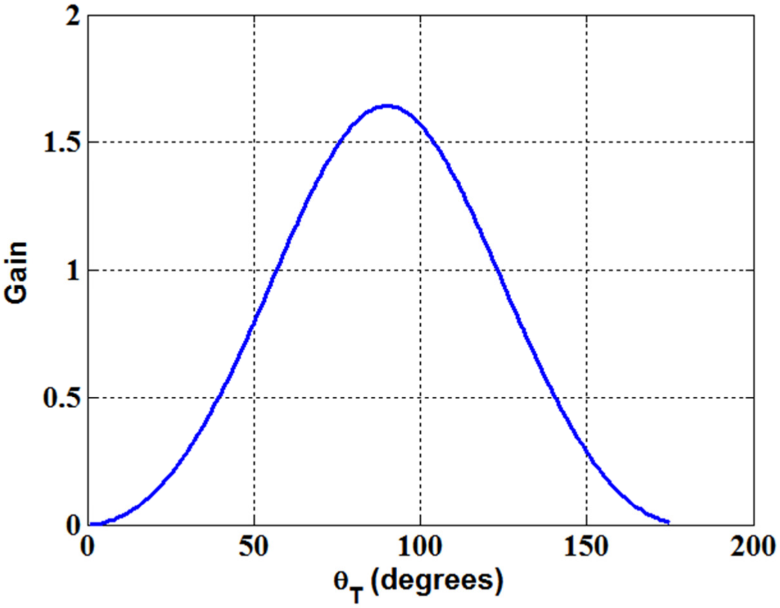

Fig. 8. Plot of G_R vs. θ_R

Figure 7 shows the plot of range r of tag vs. θ_R for a fixed output power and for a fixed orientation of reader or another tag. Hence only G_R varies as the orientation changes and hence r depends on the gain of tag, At 90 degrees of orientation, maximum range can be achieved while the minimum is achieved at 0 and 180 degrees.

The plot of gain of the reader G_R versus the orientation angle of the reader antenna θ_R is shown in the figure 8. It can be observed that the gain reaches its maximum at 90 degrees and decreases further.

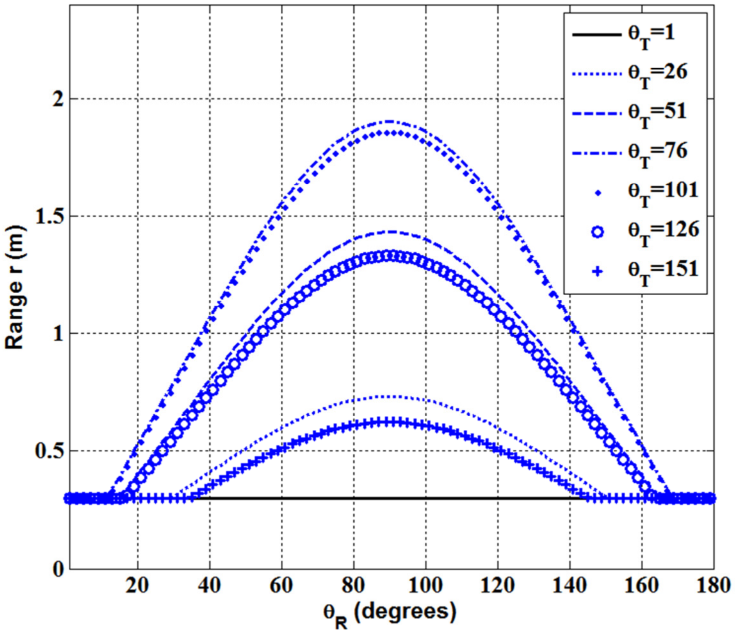

Fig. 9. θ_R Range ‘r’ vs θ_R for different θ_T

Figure 9 shows the relationship between θ_R and range r for different values of θ_T. Tag x is fixed at a certain orientation to tag y and the orientation of tag y is changed and range is calculated. Again, tag x is fixed in another position and the same procedure is repeated and the plot is taken. It shows that for any orientation of tag x, tag y goes to a maximum at 90 degrees.

The connectivity of the homogeneous multi-hop network is investigated in two cases: one-dimensional and two-dimensional. In the one-dimensional network model, 50 tags of uniform range each with omnidirectional antenna are considered. They are spread out over a length of 500 m, hence the density oof the one-dimensional network is ρ=5X10^{-2}. The probability that a tag in the network has exactly *k* neighbors is calculated by the formula as in (28).

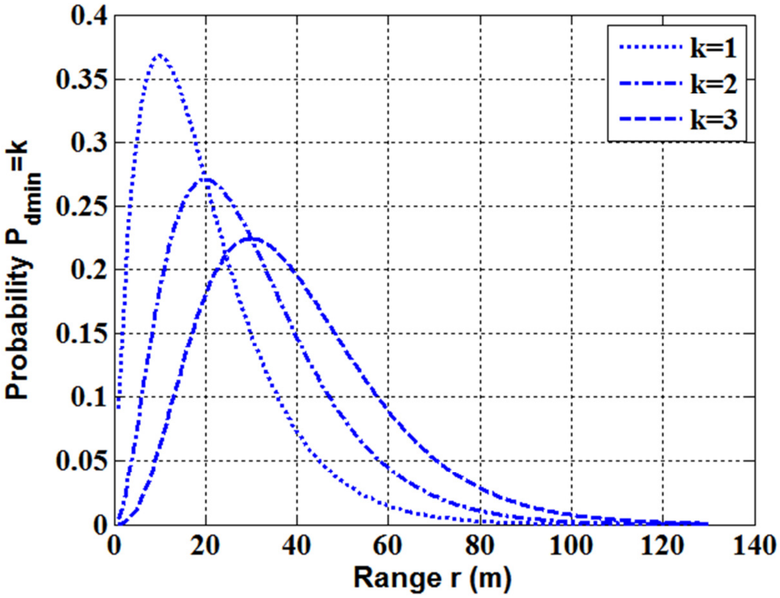

Fig10. Probability that the tag has *k* neighbors (one-dimensional case) with 50 nodes and ρ=5x10^{-2}

The figure 10 shows the probability that a tag in the network of length 500 m has exactly *k*=1,2,3 neighbors with a variation in range *r*. It is clear that the probability increases with increase in *r* up to a peak and then it comes to zero in each case. Also, the probability decreases as the number of neighbors increase.

For the second case, a two-dimensional network model is considered with 50 tags dispersed over 100 x 100 m^2. The density of the network is ρ=5x10^{-4}.

The probability that a tag in the network has *k* neighbors versus the range is shown in the figure 11. The probability is high for least for higher number of connected neighbors and is high for a single neighbor. All the probabilities decrease after the peaks in the plots.

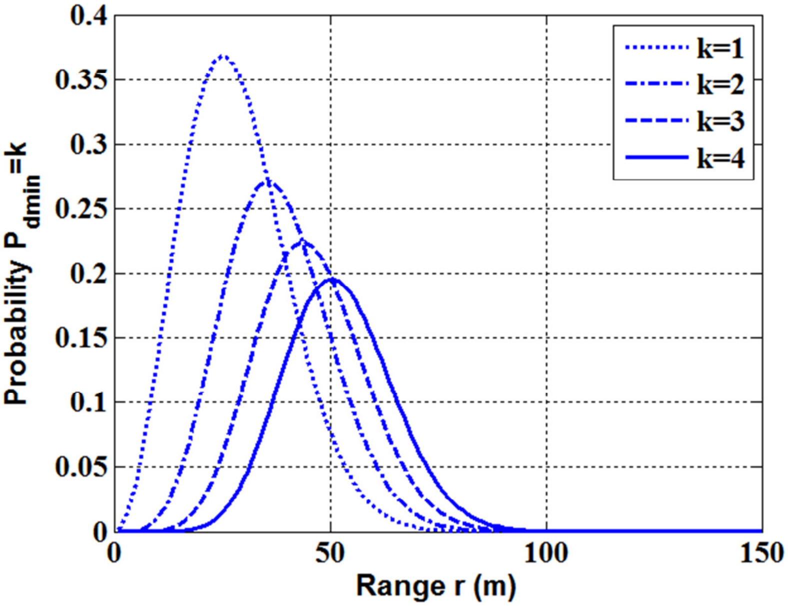

Figure 11: Probability that the tag has *k* neighbors (two-dimensional case) with 500 nodes and ρ=5x10^{-4}

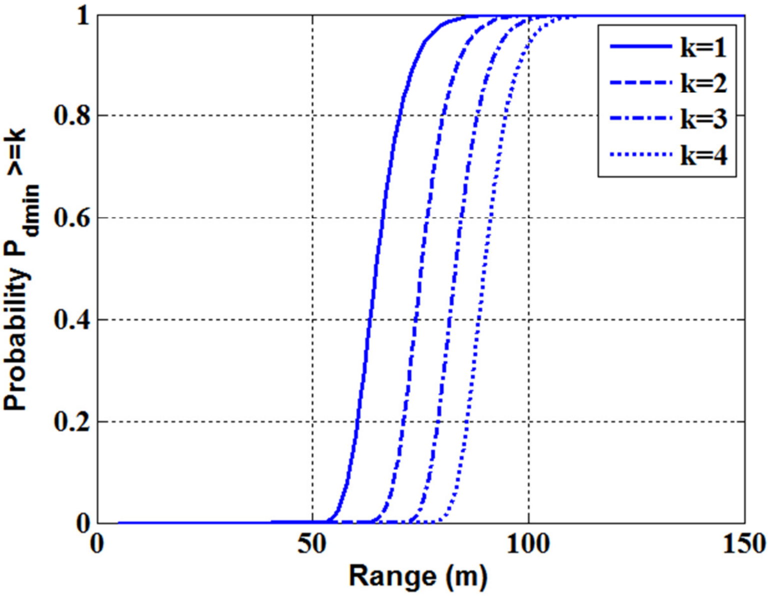

Fig 12. Probability of *k*-connectivity (one-dimensional case) with 50 nodes and ρ=5x10^{-2}

The probability of *k*-connectivity is illustrated for the one-dimensional network in figure 12. *k*-connectivity probability is the probability that each tag has at least *k* neighbors in the network. The probability starts increasing for least *k* and remains zero for higher *k*'s. As the range *r* increases the probability increases for next higher *k*. The *k*-connectivity probabilities reach 1 implying the network is connected as shown in the figure.

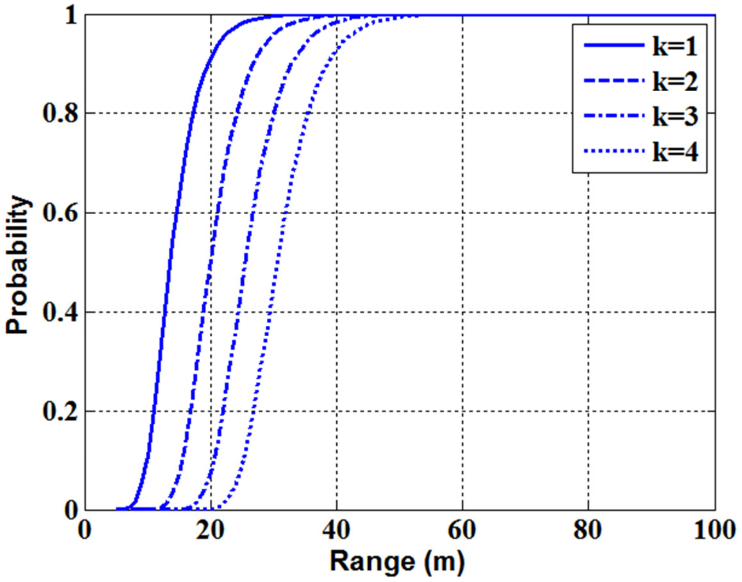

Fig 13. Probability of *k*-connectivity (two-dimensional case) 50 nodes and ρ=5x10^{-4}

The probability of *k*-connectivty for two-dimensional network model with 50 nodes distributed over an area of 100 x 100 m^2 is illustrated in figure 13. The probability for least *k* starts increasing while other probabilities remain zero. The probability for *k=2* increases after an increase in *r* and so on. The probabilities reach 1 meaning that the network is connected in the order of *k*. It is evident that the *k*-connectivity probability reaches 1 sooner for lesser *k*, that is for a single node connectivity.

The probability of connectivity versus the orientation sensitivity (r_{min}/r_{max}) of the antenna of the tags is plotted in the figure 10 for 50 devices each having half-wave dipole.

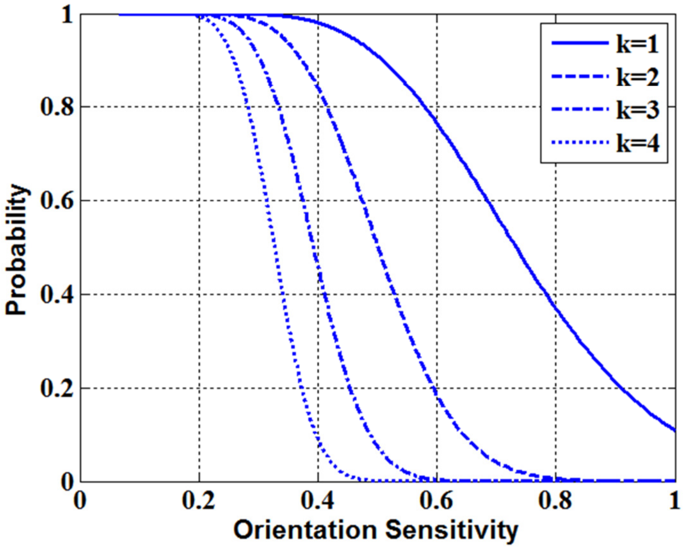

Fig 14. Probability of *k*-connectivity (one-dimensional case) vs Orientation Sensitivity.

The network is *k-connected* for lesser sensitivity and tends to reach zero for higher sensitive antennas. Since the devices are distributed on a single line, the network should be connected for number of antenna orientations. It is clear that the *k-connectivity* for *k=1* is higher than that for higher values of *k*'s.

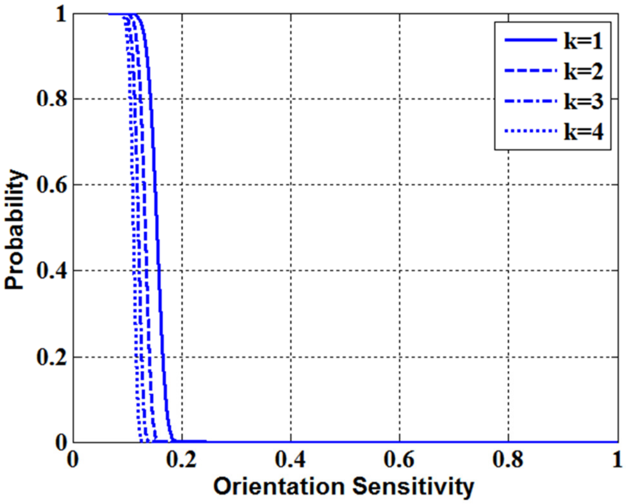

Fig 15. Probability of *k*-connectivity (two-dimensional case) vs Orientation Sensitivity.

The k-connectivity probability is plotted for the two dimensional scenario versus the orientation sensitivity. Since the tags are distributed over an area and the half-wave dipole of each tag is oriented the network is connected only for a small set of orientations.

As shown in the figure, the probability drops to zero well before when compared to the single dimension scenario. This is because the orientation of both antennas play an important role in the two-dimensional scenario and hence there are less set of orientations for which the network is *k-connected.*

7. CONCLUSION AND FUTURE WORK

The theoretical and simulation analysis of the passive multi-hop RFID network showed that by using the proposed scheme the number of tags can be reduced with a good probability of connectivity. As the tags have antennas for the reception, the orientation sensitivity of the tag antenna in a simple scenario has also been discussed. The probability of connectivity of the network has also been studied in two scenarios, one-dimensional and two-dimensional models. The main benefits of using this scheme are reduced number of tags for multi-hop communication, high probability of network connectivity in the two dimensions.

The future work includes the analysis of this propagation model in more scenarios considering the orientation, multi-path conditions and power requirements of tags.

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SECTION

2. CONCLUSION AND FUTURE WORK

This work proposes distributed beamforming methodology in a scattering environment which utilizes Taguchi-based scheme and learning automata based scheme for selection of devices. By utilizing the selected devices for scattering, the signal strength can be improved. By using five scattering devices, the received power improves by 10.6% using the Taguchi based scheme.

The brute-force scheme has the least leaning time than the other two methods but it doesn't learn the correlation between devices. The Taguchi-based scheme achieves better signal-to-noise ratio which is higher than Learning-automata based scheme by 2.1% and brute-force scheme by 1.41%. The proposed scheme can be employed in applications like passive RFID system and communication systems using nano-devices.

The work also proposes a multihop-RFID system employing passive devices for communication with the reader. This scheme uses the proved theory that the communication range can be improved using the multiple intermediate devices. The backscattering signal has been analyzed mathematically and the hop distances are calculated for the backscatter communication.

The probability of connectivity has also been studied using one-dimensional and two-imensional scenarios. The theoretical and mathematical analyses showed that number of tags can be reduced by using multi-hop communication by effectively utilizing the intermediate tags. The orientation of the tags has also been considered for the connectivity of the network.

VITA

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