Multihop Relay Techniques for Communication Range Extension in Near-Field Magnetic Induction Communication Systems

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***Abstract*—In this paper, multihop relaying in RF-based communications and near field magnetic induction communication (NFMIC) is discussed. Three multihop relay strategies for NFMIC are proposed: Non Line of Sight Magnetic Induction Relay (NLoS-MI Relay), Non Line of Sight Master/Assistant Magnetic Induction Relay1 (NLoS-MAMI Relay1) and Non Line of Sight Master/Assistant Magnetic Induction Relay2 (NLoS-MAMI Relay2). In the first approach only one node contributes to the communication, while in the other two techniques (which are based on a master-assistant strategy), two relaying nodes are employed. This paper shows that these three techniques can be used to overcome the problem of dead spots within a body area network and extend the communication range without increasing the transmission power and the antenna size or decreasing receiver sensitivity. The impact of the separation distance between the nodes on the achievable RSS and channel data rate is evaluated for the three techniques. It is demonstrated that the technique which is most effective depends on the specific network topology. Optimum selection of nodes as relay master and assistant based on the location of the nodes is discussed. The paper also studies the impact of the quality factor on achievable data rate. It is shown that to obtain the highest data rate, the optimum quality factor needs to be determined for each proposed cooperative communication method.**

***Index Terms*—NFMIC; propagation model; relay; cooperative communication; MI-Relay; magneto inductive waveguide; multihop communications; body area networks; range extension**

I. INTRODUCTION

The number of applications for wireless communication technologies continue to grow rapidly [1]–[4]. However, the availability of frequency spectrum is limited. In many situations, multiple users and/or networks need to share the same spectrum, leading to increased interference. In many communication networks, such as in public safety communications, different frequency-hopping and other spread-spectrum methods have been adopted to mitigate interference due to the spectral overlaps, and to make the existence of radio transmissions less obvious [5].

Most existing wireless devices use radiative electromagnetic (EM) waves for data transmission between personal electronic devices. While EM-RF based systems are well suited to long range data exchange, they are not the best possible solution for communications over very short distances (such as personal area networks). EM waves are capable of traveling very long distances, and received power decays with the square of communication distance [5], [6]. Therefore, the transmitted signal can be received at distances far away from the source. Although this characteristic of the EM waves is beneficial for long range communications, it may be problematic for communications over very short distances. For instance, a transmitted signal which conveys confidential information within a battlefield may be detected by unauthorised parties. Even if the information cannot be decrypted, the detection of the transmitted signal may reveal the location of the transmitter.

Recently, a new technology called Near Field Magnetic Induction Communications (NFMIC) has emerged as a promising solution for short range communications [6]. While conventional radio communication systems use an antenna to propagate EM waves into free space for data transmission, NFMIC communications occurs through the magnetic coupling of two compact coils [5]–[13]. The resulting magnetic field does not propagate far into free space, which allows the communication to be established and retained within short distances. This class of transmission is known as *near field* communications, while communication using radiating electromagnetic waves may be referred to as *far field* communications.

The boundary between the near field and far field, i.e. the maximum possible communication range in near field, is a function of frequency. The distance from the source into which the magnetic field is radiated into free space is generally considered to equal $\lambda/2\pi$ [6]. This point in space is considered the end of near field region and the beginning of the far field. Therefore, to maintain NFMIC, the distance between the source and destination needs to be less than $\lambda/2\pi$.

NFMIC offers advantages over conventional EM-RF communications when it is used for short proximity communications. It can provide better signal quality since its behaviour is much more predictable than RF [5], [6], [10], [12], [13]. RF communications often suffer from frequency spectrum contention, reflection, shadowing and fading resulting from the surrounding environment and the presence of objects such as vehicles, buildings and the human body. By contrast, NFMIC is mainly affected by the magnetic permeability of the channel and is more robust to reflection, shadowing and diffraction. Therefore, it can be an appropriate physical layer for Body Area Networks (BAN). A BAN refers to the low

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power communications between smart sensors, within close proximity to the human body, and its potential applications may be categorised as follows:

Medical and health care: A BAN can be used for different purposes at hospitals such as automatic medical diagnosis, treatment and dosing to improve the quality of treatment and management efficiency in hospitals [14]–[16]. It is also useful for remote patient monitoring. In medical ICT (MICT), the main purpose of using a BAN is to collect the vital information regarding a patient's condition such as blood pressure, body temperature, glucose level, heartbeat and brain or cardiac signals and transmit the data to a command unit (action unit) or a central controller, which can be a smart device located in hospital and controlled by a doctor or nurse. It also may be a digital device controlled by the patients themselves [14]–[16]. BAN devices used for medical purposes are often in the form of implants and need to be located inside the human body. In such an environment, the transmitted EM signal is highly attenuated by the body tissue since communication channel is in fact the human body and contains body tissues and water.

Assisting people with disabilities: In this usage model, BAN devices may be used for object detection such as detecting stairs and vacant seat in trains also to provide guidance for routing and positioning [14]. As an example, a BAN can be used to assist a speech-impaired person [14], in which sensors may be located on the person's fingers to collect information such as the movement of fingers and relative position of fingers in respect to each other and also to the hand and communicate the gathered information to a central node to be further interpreted as vocal language [14].

Entertainment: A BAN may be used by a person for entertainment purposes such as gaming, music and video playing and so on [14], [16]. The typical devices in such networks are mobile phones, laptop computers, music players and headsets [16]. This usage scenario requires the highest data rate among all the applications discussed here, since the real time video streams require data rates in range of 384 kbit/s up to 20 Mbit/s [16]. Since the cost and power consumption needs to be minimised, it is very challenging to achieve required data rates for this category of BAN application.

Personal fitness monitoring: BAN for fitness monitoring typically consists of a music player and some sensors collecting the information relevant to the exercise, such as sensors to monitor heart rate, speed, body temperature, oxygen level and rate of glucose consumption [16]. The collected information may be further sent through a gateway, to a central data base or to a coach, monitoring the athlete [16]. This can highly improve the training of professional athletes.

Public Safety: A BAN may be used by firefighters, police, ambulance officers, emergency service or military personel for public safety purposes. Vital information from individuals and the ambient environment may be collected in order to detect an emergency situations which may require quick actions from outside [16]. Information such as the level of toxic gas in the air and the temperature can be collected and the sensor may warn the person or the action unit [15], [16]. One example of BAN usage model in military is a U.S Army program known as *warfighter physiological status monitoring* (WPSM) [17]. This programs aims to address two issues. Firstly, to reduce injuries caused by environmental factors such as high temperature and altitude sickness [17]. Authors of [17] discuss that having access to WPSA data enables the commanders at different levels to effectively have access to their troops and enhance their performance. According to [17], the second purpose of WPSM program is to increase the chance of survival for casualties. WPSM information can help the combat medic to quickly access the wounded person.

To improve the reliability of RF communication systems, higher transmission power may be used. However, increasing the transmission power may lead to interference, intersystem frequency contention and higher power consumption. Increasing the transmission power to achieve higher signal to noise ratio also results in security risks. By increasing the power, the chance of the signal being detected by unauthorised parties increases. By contrast, NFMIC not only achieves higher reliability but also reduces the required power consumption. This is due to the inherent properties of near field MI waves. A MI signal attenuates with the sixth power of distance, or about -60 dB per decade of distance [6], [9], [18]. Although this property of MI makes it unsuitable for transmission over long distances, it allows efficient communication over a short range. It also results in less interference with other communication systems and reduces frequency spectrum contention [5]–[7], [10], [12], [13], [18].

Due to its low power consumption, reliability and the inherent difficulty of long-range detection, NFMIC is considered to be a good solution for short range military communication applications [5], [6], [18]. NFMIC can also be used in a wide range of non-military applications such as contactless payment cards, medical implants and monitoring devices, personal wireless electronics and so on. NFMIC is also a promising solution for underwater and underground communications in which signal transmission is difficult, inefficient or impossible [19]–[21]. While EM waves are severely attenuated by soil, water, body tissues and rocks, MI waves are capable of penetrating more deeply in such environments [19]–[21]. These benefits are countered by the limited data rate achievable through MI communications systems.

The contribution of this paper is to study the application of cooperative communications to NFMIC systems in order to extend the achievable communication range and enhance the channel capacity. In this paper, three cooperative communication techniques are proposed to enhance system performance where there is no line of sight (NLoS) between the source and the final destination. Methods whereby idle NFMIC devices can be utilised as cooperative relay nodes to ensure good signal quality at the final receiver are discussed. The propagation model in such scenarios is evaluated for the three different multihop relaying techniques.

The reminder of this paper is structured as follows: Section II discusses related works on the topic, Section III presents the proposed relaying strategies, in Section IV simulation results are discussed, and finally a summary of contributions is given in Section V.

II. BACKGROUND

To improve achievable communication range and to enhance capacity without increasing transmission power or receiver sensitivity, multihop relaying has been added to wireless communication system such as cellular networks [22]–[26], UWB [27], ZigBee [28] and many more [29]–[31]. In general, multihop relaying refers to a communication technique in which data is routed to the destination through one or more intermediate nodes located between the source and destination. Multihop relaying can achieve higher capacity or provide extended coverage and consequently higher reliability and throughput with lower cost and less complexity compared to conventional peer-to-peer communication systems [3], [4].

A number of different types of multihop networks have been proposed. The first is *multihop infrastructure-based* systems [1]–[4], [22], which consist of one or more fixed relaying station that are used along with the main base station to relay the data between a source (which could be a base station, user station or another relay) and a destination (base station, user station or another relay) [1]–[4]. This type of multihop relay is appropriate for long range cellular networks to cover dead spots (areas that are out of direct communication range of a base station) or to enhance network capacity in highly crowded area such as cities, shopping malls and amusement parks.

Multihop ad hoc is another multihop method which is suitable for both short range and long range communications [22], [25], [29], [32], [33]. In multihop ad hoc, there is no need for fixed infrastructure. Electronic devices such as mobile phones and laptops can be connected in a peer-to-peer fashion and relay the transmitted data from a source node to other nodes until the destination is reached. Multihop ad hoc can be used for inter and intra vehicle communications, personal area networks, local area networks, underground communications as well as communications in the battlefield. Multihop ad hoc is also useful in the event of natural disasters such as floods and storms, where fixed infrastructure may be damaged or destroyed as a result of the disaster [22], [25], [29], [32], [33].

Where multihop ad hoc networks are used in combination with fixed infrastructure networks, the resulting network is known as *multihop hybrid* [25], [34]. In such systems, traffic can be relayed by other devices to allow communication with a user far away from the source and without the need to hop through a single base station. This can be useful in busy and populated areas, where the base station is heavily loaded by data traffic. It also can enhance system coverage when a user is located outside the coverage range of a base station (for example, in dead spots). In this paper, only the multihop ad hoc technique is considered since it is the most suitable for short range communication systems and body area networks in particular.

Ad hoc networks are classified into two categories, based on the architecture of the network; centralised (cluster-based) and decentralised (distributed) networks [22], [30]. A centralised network consists of a number of nodes and only one cluster head, which is periodically elected by the other nodes in the network. The cluster head is in possession of all of the information about the entire network and should be located in the best-connected position amongst all other nodes [30]. By contrast, in distributed ad hoc networks, all nodes have the same amount of information about the network.

While centralised networks have complex architectures and limited flexibility, distributed networks are simpler to implement [30]. However, distributed networks suffer from larger end-to-end delay and higher rates of packet collision. Distributed networks are less prone to network failure, because if a node fails, there are connections to other nodes which can provide alternate paths to a destination [30]. Therefore distributed networks are suitable for multihop communications. Since they are more robust to network failure, decentralised multihop ad hoc networks work well for military communications and disaster recovery applications, since robustness is a critical factor in such scenarios [30].

Another factor that makes distributed networks more suitable for military applications is their lower transmission power requirements. Since each node is not required to transmit the traffic through a central controller, the individual transmission power can be lower. Each node can communicate with a destination through its neighbours; therefore, communication is performed via multiple shorter links instead of one link with higher transmission power. High transmission power in military communications poses security risks through location disclosure [30]. Thus low transmission power is highly desirable for military communications.

Multihop ad hoc has been considered for range extension and increased robustness in different short range communications systems such as wireless local area networks (WLANs) [22], ZigBee [28] and ultra wide band (UWB) [27]. In [28], the authors have developed a prototype system for home security and automation which uses ZigBee-based multihop sensor networks. Authors of [28] claim that it can theoretically achieve unlimited coverage range. Achieving a large coverage area through single hop peer to peer networks for such applications requires long range devices, which are often expensive and power-hungry [28].

In UWB networks, the coverage range is also limited and high data rates may not be achievable through a conventional single hop method. In [27], a simulation environment is proposed which can simulate both the physical and MAC (medium access control) layers of OFDM-based UWB multihop network. Using this simulation environment, the authors have evaluated the performance of a multihop relay UWB network to determine whether it improves system performance measures such as end to end delay and packet loss [27]. It is concluded that the IEEE 802.15.3 TDMA MAC layer can perform adequately in multihop UWB networks if proper scheduling and routing methods are precisely defined and implemented. However, further study is required into more efficient scheduling schemes such as Self-organised Time Division Multiple access (S-TDMA), to enhance the capacity and frequency reuse in such communication systems [27].

Although extensive studies have been conducted in multihop RF communication systems, this concept has not been widely investigated for near field magnetic induction communication systems. As mentioned earlier, NFMIC is limited to very short communication distances. Different techniques used in RF

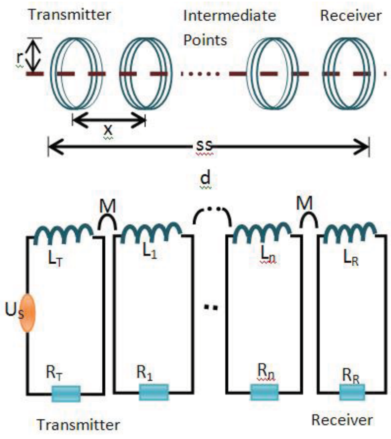

Fig. 1. Magnetic waveguide and circuit model (adopted from [19])

communications for range extension can be used in NFMIC to overcome the limited communication range. However, since the nature of signal transmission in NFMIC differs from RF communications, it is important to study range extension methods which are most applicable to NFMIC. In this paper, three different multihop methods to be applied in a NFMIC system are proposed.

The magneto-inductive waveguide method has been studied as a possible solution for multihop communications in NFMIC [19]–[21], [35]–[39]. A magneto-inductive waveguide communication system consists of a number of NFMIC nodes, where the transmitter sends the data to a receiver via multihop relay. Each node receives the data from its nearest neighbour on one side and transmits to the next neighbour on its other side via magnetic field coupling. Multihopping is performed until the data is delivered to the final destination. A typical waveguide system model can be seen in Fig. 1. As can be seen from the figure, all the cooperative nodes are passively powered and there is no need for an individual power source at each relaying node.

In [19]–[21], the magneto-inductive waveguide approach is studied for underground communications, where RF systems perform poorly due to the adverse channel conditions. In such an environment, the communication channel consists of rock and soil, possibly containing water and organic matter. Underground RF communications suffer from three major problems: high path loss, large antenna size and dynamic and unpredictable channel conditions. The authors of [19]–[21] suggest that by using NFMIC, the problems of large antenna size and dynamic channel condition may be mitigated. MI waves are not significantly affected by humidity, soil and rock since they all have nearly the same magnetic permeability as air [19]–[21]. However, the high path loss is still a problem and leads to limited coverage.

To overcome the limited range, authors in [19], [20] have investigated how a magneto inductive waveguide can be used to extend the communication distance. The performance of the improved magneto-inductive model is compared with the conventional MI and EM communication techniques. The authors conclude that by implementing a waveguide system, lower path loss can be achieved regardless of the level of water content in the soil [19], [20].

In [21], Triangle Centroid (TC) deployment algorithms for underground MI sensor networks are proposed. In this algorithm, a Voronoi diagram is used to partition the network into non-overlapping triangular cells and a three pointed star topology in each trianglular cell is used to obtain a *k-connected* network ($k > 3$) [21]. The authors show that this algorithm is more robust to network failure than the Minimum Spanning Tree (MST) algorithm which is only *1-connected*. The MST algorithm connects the entire network together with the optimum number of relaying nodes; however, nodes have only one connection, therefore the network is not robust to node failure [21]. Although this topology is well suited for underground communications, it is not realistic for a body area network. In a body area network, nodes may be randomly located and might frequently change their location. Therefore, in this paper different multihop methods in a three dimensional environment are proposed which are more applicable to a body area network.

III. PROPOSED NFMIC COOPERATIVE RELAY ALGORITHMS (NLoS)

A. Network Model

In this section, cooperative communication methods applicable to a personal area network are proposed. Three different relaying methods will be evaluated using a simple network model to show how the idle intermediate nodes can be used to extend the coverage range. The three techniques are denoted NLoS-MI Relay, NLoS-MAMI Relay1 and NLoS-MAMI Relay2. The network consists of a number of wireless nodes; however, for simplicity it is assumed that only 4 nodes contribute to the communication: a transmitter (source), a receiver (destination) and two intermediate nodes which function as cooperative relay nodes. The source and destination are separated from each other by a distance d. However, there is no direct link between them; the target receiver is out of the communication range of the transmitter. It is assumed that there are two idle devices between the source and the sink, which can be utilised to assist the communication by providing an indirect path from the transmitter to the receiver over which information may be relayed. The transmitter is separated from the relay 1 and 2 by distance (x-component of the distance) $x_{Tx,R1}$ and $x_{Tx,R2}$ respectively, and the receiver is located at a distance $x_{R1,Rx}$ and $x_{R2,Rx}$ from relay 1 and 2 respectively. Relay R1 is assumed to be closer to the transmitter and R2 is located closer to the receiver such that any distance-dependent differences in performance may easily be evaluated. Both the source and sink have a direct link with R1 and R2. To avoid spectrum contention, the network uses Time Division Multiple Access (TDMA). As is usual in single-channel wireless systems half duplex transmission is used, meaning that a node can either transmit or receive data during a specific time slot, but cannot do both simultaneously. A relay node receives the signal from the transmitter, amplifies it and then forwards it to the next hop, which could either be the final receiver or another relay node (this is known as the Amplify and Forward cooperative relaying technique) [40].

B. Relay node selection metric

Different relay selection criteria can be considered to choose either of intermediate nodes as relay node such as signal to interference and noise ratio, angle of arrival (AoA), time difference of arrival (TDoA) and separation distance between the nodes. In NFMIC, communication distance has a critical impact on the received signal strength and on the achievable data rate. Since signal attenuation is proportional to the sixth power of distance rather than the square as in the case of RF communications, it is the dominant factor in determining achievable system performance. Furthermore, since in an NFMIC personal area network, communication occurs over very short distances, shadowing and multipath effects are not as critical as in RF communications. Hence, the separation distance between the nodes is the most appropriate criterion for optimum performance achievement. This paper studies the impacts of distance of relaying nodes with respect to transmitter/receiver on the system performance, in order to show the optimum selection of the relaying nodes. The performance is measured according to the received signal strength at the target receiver as well as the maximum end to end throughput capacity.

C. Physical Channel Model

In this section, a peer to peer communication model is described. Fig. 3 illustrates an ideal near field magnetic induction communication system, in which there is no angular or lateral misalignment between the transmitting and receiving antenna coils. The system consists of a transmitter and a receiver separated from each other by distance d. The circuit model of such a system is also shown in Fig. 3.

According to [41], the power transfer function for this scenario is:

$$\frac{P_{Rx}}{P_{Rx}} = \frac{\mu_0^2 N_T^2 N_R^2 A_R^2 \omega^2}{16\pi^2 R_{Tx} R_{Rx}} H_{INT}^2 \tag{1}$$

where the magnetic field strength is [41]:

$$H_{INT} = \int_0^{\pi} \frac{\mathrm{dI_{Tx}} \times \mathrm{x}}{\mathbf{x}^3} = \sqrt{\frac{r_T^4 \pi^2}{\left(r_T^2 + d^2\right)^3}} \tag{2}$$

The cross sectional area of the receiving coil is:

$$A_R = 2 \cdot \pi \cdot r_R^2 \tag{3}$$

The total resistances of the receiving and transmitting circuits are:

$$R_{Rx} = (2 \cdot \pi \cdot r_R \cdot N_R \cdot R_0) + R \tag{4}$$

$$R_{Tx} = (2 \cdot \pi \cdot r_T \cdot N_T \cdot R_0) + R_S \tag{5}$$

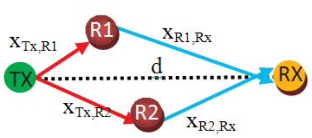

Fig. 2. NLoS-MI Relay

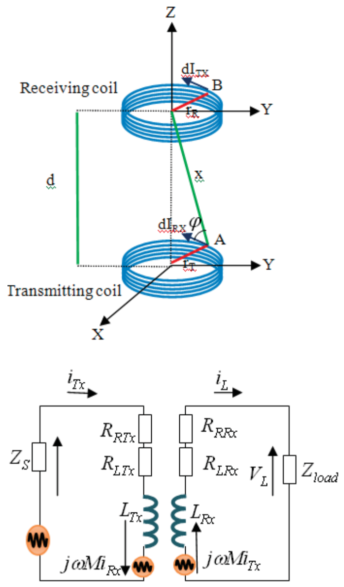

Fig. 3. Ideal transmitting and receiving coil configuration and the circuit model (adapted from [41])

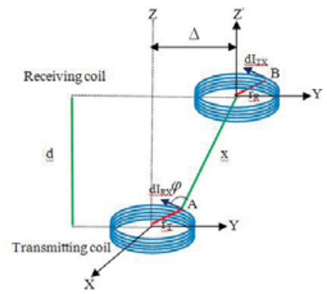

Fig. 4. Lateral Misalignment (adapted from [41])

where R_L and R_S are the resistance of load and source respectively and r_R ,r_T , N_R and N_T are the radius and number of turns of the receiving and transmitting circuit respectively. R_0 is the per unit resistance of the wires used to build the coils (copper wire in this case). Therefore the power transfer function for the ideal communication link becomes [41]:

$$\frac{P_{Rx}}{R_{Tx}} = \frac{\mu_0^2 \cdot N_T^2 \cdot N_R^2 \cdot r_R^4 \cdot \omega^2 \cdot r_T^4}{16.R_{Tx} \cdot R_{Rx} \cdot \left(r_T^2 + d^2\right)^3} \tag{6}$$

According to [42], [43] the power transfer function can be also expressed as:

$$\frac{P_{Rx}}{R_{Tx}} = Q_T Q_R k^2 \tag{7}$$

k is the coupling coefficient and Q_T and Q_R denote the quality factor of transmitting and receiving antennas [43]:

$$Q_T = \frac{\omega L_T}{R_{Tx}} = \frac{\omega\left(\mu_0 \pi N_T^2 r_T^2\right)}{l_T R_{Tx}} \tag{8}$$

$$Q_R = \frac{\omega L_R}{R_{Rx}} = \frac{\omega\left(\mu_0 \pi N_R^2 r_R^2\right)}{l_R R_{Rx}} \tag{9}$$

L_T and L_R are the inductance of the transmitting and receiving coils respectively and l_T and l_R are the length of the two coils. Thus by substituting Q-factor into the power equation, the power transfer function reduces to:

$$\frac{P_{Rx}}{R_{Tx}} = Q_T Q_R \frac{r_T^2 r_R^2 l_T l_R}{16(r_T^2 + d^2)^3} \tag{10}$$

Hence the coupling coefficient can be expressed as:

$$k = \sqrt{\frac{r_T^2 r_R^2 l_T l_R}{16(r_T^2 + d^2)^3}} \tag{11}$$

In reality, achieving a perfect antenna alignment is difficult and this results in some degree of performance reduction in terms of achievable communication range or data rate. There are two main sources of performance degradation: angular and lateral misalignment. To simplify the model, it is assumed in this work that there is no angular misalignment and only lateral misalignment exists. When there is lateral misalignment, the receiver antenna coil plane is parallel to the transmitting antenna coil plane. Therefore, they make no contribution in flux cutting through the receiving coil. In fact, the dominant component will be the z-direction [41]. According to [41], the power transfer function in this case is,

$$\frac{P_{Rx}}{R_{Tx}} = \frac{\mu_0^2 \cdot N_T^2 \cdot N_R^2 \cdot r_R^4 \cdot \omega^2 \cdot m^2}{64.R_{Tx} \cdot R_{Rx} \cdot r_T \cdot \Delta^3} \cdot \left[\Delta \cdot K + \frac{(r_T \cdot m) - (2-m)\Delta}{2-2m} \cdot E\right]^2 \tag{12}$$

where K and E are the complete elliptic integrals of the first and second kind respectively and m is the elliptic modulus and is always a positive value between 0 and 1 [41].

$$K(m) = \int_0^{\pi/2} \frac{d\gamma}{\sqrt{1 - m^2 \sin^2\gamma}}; \; 0 \le m \le 1 \tag{13}$$

$$E(m) = \int_0^{\pi/2} \sqrt{1 - m^2 \sin^2\gamma} \cdot d\gamma \, ; 0 \le m \le 1 \tag{14}$$

$$m = \left[\frac{4 \cdot r_T \cdot \Delta}{(r_T + \Delta)^2 + d^2}\right]; 0 \le m \le 1 \tag{15}$$

To simplify the power transfer function, the Q-factor is substituted in the power equation and therefore it becomes $P_{Rx} = R_{Tx} Q_T Q_R k^2$, which implies that in the case of lateral misalignment the coupling coefficient is

$$k^2 = \frac{r_R^2 \cdot \Delta^2 \cdot l_T \cdot l_R}{16.\pi^2 \cdot \left((r_T + \Delta)^2 + d^2\right)^2 \cdot r_T \cdot \Delta^3} \cdot \left[\Delta \cdot K + \frac{(r_T \cdot m) - (2-m)\Delta}{2-2m} \cdot E\right]^2 \tag{16}$$

The following three sections discuss the NFMIC cooperative communications methods being proposed to enhance the communication distance and data rate.

D. NLoS-MI Relay

Data transmission to the target receiver is achieved in two phases:

Phase 1: the transmitter broadcasts its signal to all nodes and the nodes within its transmission range receive the signal (R1 and R2 in this case).

Phase 2: the receiving relay (R1 or R2) which has direct line of sight with the target receiver and the best expected received signal strength (RSS) is selected, and amplifies and forwards the data to the destination. According to the following theoretical analysis (validation through simulation results in Section IV), it will be shown that the relay node which achieves higher RSS will provide a higher end to end throughput.

During the first phase, the transmitting antenna coil (which has a quality factor Q and efficiency η) sends the data to relays R1 and R2 through magnetic field coupling with transmission power P_T. The transmitting antenna gain is defined as [8], [9],

$$G_{Tx} = Q_{Tx} \eta_{Tx} \tag{17}$$

The gain of the relaying antennas is defined as:

$$G_{Ri} = Q_{Ri} \eta_{Ri} \tag{18}$$

where the index Ri stands for the relay node i. According to model described in Section III-A, the received signal power at R1 from the transmitter is:

$$P_{R1}^{Tx} = P_{Tx} G_{Tx} G_{R1} k_{Tx,R1}^2 (x_{Tx,R1}) \tag{19}$$

where k is the coupling coefficient at distance $x_{i,j}$ and is defined as [8], [9]:

$$k_{i,j}^2(x_i) = S_{i,j}.W_{i,j} \tag{20}$$

where

$$S_{i,j} = \frac{r_j^2 \cdot \Delta_{i,j}^2 \cdot l_i \cdot l_j}{16.\pi^2 \cdot \left((r_i + \Delta_{i,j})^2 + x_{i,j}^2\right)^2 \cdot r_i \cdot \Delta_{i,j}^3} \tag{21}$$

$$W_{i,j} = \left[\Delta_{i,j} \cdot K + \frac{(r_i \cdot m_{i,j}) - (2 - m_{i,j})\,\Delta_{i,j}}{2 - 2m_{i,j}} \cdot E\right] \tag{22}$$

In this case $m_{i,j}$ is (for agiven transmitting node i and receiving node j):

$$m_{i,j} = \left[\frac{4 \cdot r_i \cdot \Delta_{i,j}}{(r_i + \Delta_{ij})^2 + x_{i,j}^2}\right]; 0 \le m_{i,j} \le 1 \tag{23}$$

$\Delta_{i,j}$ is the lateral misalignment between node i and j and $x_{i,j}$ is the separation distance between node i and j on the x axis. Similarly, the received power at R2 will be:

$$P_{R2}^{Tx} = P_{Tx} G_{Tx} G_{R2} k_{Tx,R2}^2 (x_{Tx,R2}) \tag{24}$$

In the second phase, based on the relay selection criterion (the separation distance between the relay and transmitter/receiver), one of the intermediate nodes is selected to forward the data to the final receiver.

If R1 is selected as the cooperative relay, the received signal power at the receiver will be:

$$P_{Rx}^{R1} = P_{R1}^{Tx} G_{Rx} G_{R1} k_{Rx,R1}^2; \quad P_{Rx}^{R1} = \left(P_{Tx} G_{Tx} G_{R1} k_{Tx,R1}^2\right) G_{Rx} G_{R1} k_{Rx,R1}^2 \tag{25}$$

which may be further simplified to:

$$P_{Rx}^{R1} = P_{Tx}G_{Tx}G_{Rx}G_{R1}^2 k_{Tx,R1}^2 k_{Rx,R1}^2 \quad (26)$$

However, if R2 is selected, the received signal power is:

$$P_{Rx}^{R2} = P_{Tx}G_{Tx}G_{Rx}G_{R1}^2 k_{Tx,R2}^2 k_{Rx,R2}^2 \quad (27)$$

In general the received power at the destination through relay i will be:

$$P_{Rx}^{Ri} = P_{Tx}G_{Tx}G_{Rx}G_{Ri}^2 k_{Tx,Ri}^2 k_{Rx,Ri}^2 \quad (28)$$

The signal power seen by the receiver can be used to determine the channel capacity. According to the Shannon-Hartley capacity theorem (Equation 29), the channel capacity at the receiver through relay i is:

$$C_{Rx}^{Ri} = B_f f_0 \log_2\left(1 + \frac{P_{Rx}^{Ri}}{N}\right) \; ; \; B_f = \frac{B}{f_0} \quad (29)$$

In Equation 29 B_f is the 3 dB fractional bandwidth, f_0 is the operating frequency and N is the received system noise power. The 3 dB fractional bandwidth can be estimated if the quality factor of the antennas are known [43]:

$$B_f = \frac{B}{f_0} = \frac{\sqrt{-\left(Q_i^2 + Q_j^2\right) + \sqrt{\left(Q_i^2 + Q_j^2\right)^2 + 4Q_i^2 Q_j^2}}}{\sqrt{2}Q_i Q_j} \quad (30)$$

In RF communications, interference from other spectrum users is frequently the main source of noise. However, such interference is not as severe in short-range NFMIC. Thus in the analysis of noise in the NFMIC relay network, it is assumed that the noise affecting the system is principally thermal noise, and its power may be calculated using the well know Johnson noise equation:

$$N_{Power}(watts) = kTB \quad (31)$$

where k is Boltzmann's constant (1.38×10^{-23}) and B is the communication bandwidth. The system is assumed to be operating on a person's body therefore the temperature will be around 37°C (310°K).

E. NLoS-MAMI (Master-Assistant Magnetic Induction) Relay1

A different technique can be deployed to utilise both intermediate nodes in cooperative communication. The system is shown in Fig. 5. Transmission of information is now achieved in three phases:

Phase1: The transmitter broadcasts the signal to all nodes in its communication range. Both idle devices (which are in the listening state) can receive the data from the transmitter.

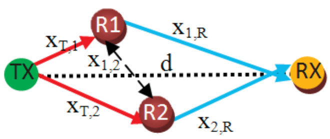

Fig. 5. NLoS- MAMI Relay1

Phase2: R1 and R2 receive the data; one of the relay nodes (Relay Assistant) amplifies and forwards the data to the other relay (Relay Master) as well as to the final destination. In Section IV it will be shown by simulation that for this scenario it is optimum to choose the node closest to the transmitter as relay assistant (Ra) and the node located closer to the receiver as relay master (Rm).

Phase3: The relay master receives the data, amplifies it and forwards it to the final receiver. The receiver (Rx) receives the signal and combines it with the previously received copy of the same signal and decodes it.

Therefore, in this scenario, the receiver receives the same signal from two different paths via the two relay nodes. In phase 1, the strength of the signal received by each relay node is as given in Equations 19 and 24. However, in stage 2, where the signal is transmitted from the relay assistant to the relay master and the destination, the received signal power at the relay master via the relay assistant is:

$$\begin{aligned} P_{Rm}^{Ra} &= P_{Ra}^{Tx}G_{Ra}G_{Rm}k_{Ra,Rm}^2; \\ P_{Rm}^{Ra} &= P_{Tx}G_{Tx}G_{Ra}^2 G_{Rm}k_{Tx,Ra}^2 k_{Ra,Rm}^2 \end{aligned} \quad (32)$$

Similarly, the received power at the final destination through the relay assistant is:

$$\begin{aligned} P_{Rx}^{Ra} &= P_{Ra}^{Tx}G_{Rx}G_{Ra}k_{Rx,Ra}^2(x_{a,Rx}); \\ P_{Rx}^{Ra} &= P_{Tx}G_{Tx}G_{Ra}^2 k_{Tx,Ra}^2 G_{Rx}k_{Rx,Ra}^2 \end{aligned} \quad (33)$$

The relay master now combines the signal received directly from the transmitter with the signal from the relay assistant and forwards the combined signal to the final receiver. Therefore, the power at the relay master during this phase is:

$$\begin{aligned} P_{Rm-total}^{S2} &= P_{Rm}^{Ra} + P_{Rm}^{Tx}; \\ P_{Rm-total}^{S2} &= P_{Tx}G_{Tx}G_{Rm}\left(G_{Ra}^2 k_{Tx,Ra}^2 k_{Ra,Rm}^2 + k_{Tx,Rm}^2\right) \end{aligned} \quad (34)$$

In the third phase, the relay master combines the two versions of the same signal received during phase 1 and 2, and sends the combined signal on to the final destination. The received signal power at this stage at the final receiver is:

$$\begin{aligned} P_{Rx}^{total} &= \left(P_{Rx}^{Ra} + P_{Rx}^{Rm}\right); \\ P_{Rx}^{Rm} &= P_{Rm-total}^{S2}G_{Rx}G_{Rm}k_{Rx,Rm}^2 \end{aligned} \quad (35)$$

By substituting Equation 34 into 35, it can be simplified to:

$$\begin{aligned} P_{Rx}^{total} &= G^t\left(k_{Tx,Ra}^2 k_{Rx,Ra}^2 G_{Ra}^2 + k_{Rx,Rm}^2\beta\right) \\ G^t &= P_{Tx}G_{Tx}G_{Rx} \\ \beta &= G_{Rm}^2\left(G_{Ra}^2 k_{Tx,Ra}^2 k_{Ra,Rm}^2 + k_{Tx,Rm}^2\right) \end{aligned} \quad (36)$$

The capacity can also be calculated using the final power equation, resulting in:

$$C_{Rx}^{MAMI1} = B_f f_0 \log_2\left(1 + \frac{P_{Rx}^{total}}{N}\right) \quad (37)$$

F. NLoS-MAMI (Master-Assistant Magnetic Induction) Relay2

The final cooperative technique proposed for such systems is denoted NLoS-MAMI Relay2. This method is suitable where there is no direct link between one of the intermediate nodes and the target receiver, although it still works in the case where there is a direct line of sight between the receiver and both relay nodes. However, even if there is a direct LoS between the relay assistant and the receiver, Ra does not transmit to the receiver; transmission is performed only through the relay master. Transmission is achieved in three phases:

Phase 1: The transmitter broadcasts the signal to the idle intermediate nodes. Both R1 and R2 receive the signal. The received power at Ra is given by:

$$P^{Tx}_{Ra} = P_{Tx} G_{Tx} G_a k^2_{Tx,a}(x_{T,a}) \tag{38}$$

while at the relay master (Rm), it is

$$P^{Tx}_{Rm} = P_{Tx} G_{Tx} G_m k^2_{Tx,m}(x_{T,m}) \tag{39}$$

Phase 2: The relay assistant, which is the relay with no direct link with the receiver, forwards the received data to Rm. The difference between NLoS-MAMI Relay1 and NLoS-MAMI Relay2 is that in stage 2 in NLoS-MAMI Relay2, the relay assistant does not transmit to the final destination, while in NLoS-MAMI Relay1, both receiver and relay master receive data from the relay assistant. The received signal power at the relay master via relay assistant during this stage is:

$$P^{Ra}_{Rm} = P_{Ta} G_a G_m k^2_{a,m}(x_{a,m}); \;\; P_{Ta} = P^{Tx}_{Ra} \tag{40}$$

Since the transmission power at this stage is equal to the signal power received by the relay assistant at the previous stage, Equation 40 can be rewritten as:

$$P^{a}_{Rm} = P_{Tx} G_{Tx} G_m G_a^2 k^2_{Tx,a} k^2_{a,m} \tag{41}$$

Phase 3: The relay master combines the same signal received through Tx and Ra in stage 1 and 2 and forwards it to the final destination. The total signal power received by the relay master at this stage is:

$$\begin{aligned} P^{S2}_{Rm} &= P^{Tx}_{Rm} + P^{Ra}_{Rm}; \\ P^{S2}_{Rm} &= P_{Tx} G_{Tx} G_m \left(k^2_{Tx,m} + G_a^2 k^2_{Tx,a} k^2_{a,m}\right) \end{aligned} \tag{42}$$

The target receiver receives the signal relayed by the relay master and decodes it. The received signal power at the target destination at this stage is:

$$\begin{aligned} P^{total}_{Rx} &= P^{m}_{Rx} = P_{Tm} G_{Rx} G_m k^2_{m,Rx}(x_{m,Rx}); P_{Tm} = P^{S2}_{Rm} \\ P^{total}_{Rx} &= \left(P_{Tx} G_{Tx} G_m^2 G_{Rx} k^2_{m,Rx} \left(k^2_{Tx,m} + G_a^2 k^2_{Tx,a} k^2_{a,m}\right)\right) \end{aligned} \tag{43}$$

From the expression for received signal power, the capacity can be determined using:

$$C^{MAMI2}_{Rx} = B_f f_0 \log_2 \left(1 + \frac{P^{total}_{Rx}}{N}\right) \tag{44}$$

The propagation model has been simulated in Matlab for each of the three methods. Results are shown in the following section.

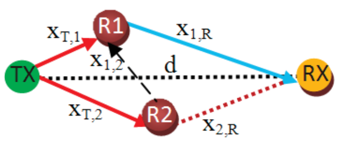

Fig. 6. NLoS- MAMI Relay2

IV. SIMULATION :

A. Methodology

Matlab has been used to implement the propagation model for each of the three proposed multihop methods. The transmission power is set to 200 μW, which is sufficient for short range communications such as for a sensor network. The receiver sensitivity is 10 nW, which leads to a communication range of 18 cm for the point to point, line of sight scenario in this study. The antenna coils have a radius of 0.5 cm and the number of turns is 10. The operating frequency is set to 13.56 MHz, and the 3 dB fractional bandwidth is 10 kHz (see Equation 29). The system is assumed to be homogenous and all nodes use identical antennas with identical quality factors. The coil quality factor is 830, which is typical for when a high permeability material is used for the core of the coils (such as ferrite or manganese zinc). The permeability of ferrite is 0.0008 H.m^{-1}. However, the location of each node is chosen such that the transmitter and received have no direct link with each other and have no angular and lateral misalignment with respect to each other. The transmitter is located at the reference location $(x, y, z) = (0, 0, 0)$. The two relay nodes are located at a distance between transmitter and receiver and have the same lateral misalignment in respect to Rx and Tx. In this analysis, identical lateral misalignment are chosen to measure the performance of each relaying method based on their distance only and to allow comparison of the performance of the three relaying strategies. R1 is located close to transmitter $(5, 2, 5)$ and R2 is located at the edge of the communication range of the transmitter at $(-5, -2, 18)$. The position of receiver is varied in the horisontal (x) direction to determine the maximum achievable distance using each relaying strategy (from $(18, 0, 0)$ to $(60, 0, 0)$).

B. Relay Selection

Using this scenario, the three multihop techniques are simulated to determine the extent of performance improvement achieved and hence to determine which multihop technique is the most effective. The results are shown in Fig. 7 to 11.

Fig. 7 shows the achieved received signal strength and communication distance for the NLoS-MI Relay case where the relaying node is located at three different distances (1,10 and 18 cm) from the original transmitter. The horizontal line shows the receiver sensitivity threshold which is -50 dBm. In other words, to be able to decode the transmitted signal with minimal bit error rate, the final receiver requires the received signal strength to be at least -50 dBm. The dotted line shows the received signal power versus the communication range for the final receiver where there is no cooperative relay. As can be seen form Fig. 7, at distances above 18 cm, the receiver would not be able to decode the transmitted signal with an acceptable bit error rate; therefore it is considered to be out of communication range of the original transmitter. The other three lines in the plot show the received signal strength at the out of range receiver if an idle intermediate node is used to relay the data from the source to destination. It is observed that a relay node can be used to enhance the communication range. Depending on the location of the relaying node, the communication range can be improved to a maximum of 65 cm. However in the worst case scenario (where the relay is located at the edge of the communication range) the maximum achieved range is 37 cm (still a significant improvement). Since the location of the relaying node has a very significant role to play in range extension, the relay node is placed at a variety of distances from the transmitter to observe the optimum location of the relay node with respect to the transmitter and receiver. It can be seen from the graph that as the relaying node moves toward the transmitter, longer distances can be achieved. Therefore, if there are more than one node between the transmitter and the out of range receiver, the node closer to the transmitter as the relay will achieve greater range and/or higher data rate. For instance, using R1 (the relay closer to the transmitter (5 cm)) results in an additional 20 kb/s of channel capacity at distance 30cm in comparison with relaying through R2 (18 cm) (see Fig. 10).

Fig. 8 shows the performance of the NLoS-MAMI Relay1 strategy. Here the graphs showing the two cases of $Rm = R1$ and $Rm = R2$ tend to overlap as the receiver is moved away from the transmitter toward the receiver. This implies that in MAMI Relay1, the achievable communication range and data rate is almost identical for both cases ($Rm = R1$ and $Rm = R2$). However, when $Rm = R2$, a slightly higher RSS is achieved in comparison to the case where Rm is closer to the transmitter ($Rm = R1$). It also can be seen that by using this strategy, the communication distance can be enhanced to 48 cm. Therefore by applying this relaying strategy to the communication system, the range can be dramatically extended. When the final receiver is located close to the edge of its transmission range, using the NLoS-MAMI Relay1 technique, the capacity can be improved from 292 kb/s to more than 400 kb/s ($Rm = R2$) and up to 412 kb/s ($Rm = R1$).

In Fig. 9, it can be seen that unlike NLoS-MAMI Relay1, in NLoS-MAMI Relay2, if the relay master is selected to be closer to the transmitter, longer ranges can be achieved. Relaying through R1 as the relay master improves the range by 8 cm in comparison with the case when the relay master is R2.

In Fig. 10 and 11, the performance of all proposed relaying techniques are compared to each other. Fig. 10 and 11 show the communication range versus the received signal strength and achieved data rate respectively for the three methods. It is observed that MAMI-Relay1 outperforms the other two multihop methods (MI-Relay and MAMI-Relay2). Although the MI-Relay strategy enhances the achieved data rate and the communication range, its performance is highly dependent to the location of the relaying node. For example if the node close to the edge is selected, it results in minimal range and data rate enhancement, while if the relay is in close proximity to the transmitter it can achieve almost the same performance improvement as MAMI Relay2 (where $Rm = R1$).

Similarly, optimum placement of the relay master and relay assistant in MAMI-Relay2 leads to considerable performance. For instance, when the target receiver is located 40 cm away from the transmitter, the achieved data rate is 18 kb/s higher if the relay master is closer to the transmitter (Fig. 11).

Based on the simulation results and the above discussion, it is evident that the location of each relaying node and selection of the nodes to act as master or assistant can impact the achieved data rate and the communication range significantly. Table I describes how the position of each node impacts the NLoS-MAMI Relay 1 and 2 strategies. To obtain the optimum location of each node, two approaches have been taken. First, the relay master was placed as close as possible to the transmitter and the relay assistant progressively moved from the transmitter toward the receiver for each method. The master is placed at the edge of the communication range while the assistant is placed at different distances form the transmitter. Secondly, the relay assistant is fixed at 2 cm and 18 cm from the transmitter and the master is moved to different locations (2,10 and 18 cm from the transmitter). The results show that in NLoS-MAMI Relay1, very similar performance is achieved if either of the nodes act as a master or assistant. However, the best result is obtained in both methods when both master and assistant are located as close as possible to the transmitter. As they move toward the edge of transmission range, performance degrades. In comparison with NLoS-MAMI Relay1, NLoS-MAMI Relay2 is strongly affected by the selection of the master and assistant. As described earlier, where the two nodes have different distances from the transmitter, if the node closer to the edge is selected as master, the system performance can be improved considerably. In NLoS-MAMI Relay1 as Ra moves toward the edge of transmission range, the location of Rm becomes more critical. For example if Ra is located 2 cm away from the transmitter and Rm is located at 2 cm to 18 cm from the original source, the achieved range varies from 58 to 64.6 cm while if Ra is located at the communication edge (18 cm), the achieved range varies from 40 cm to 60 cm as Rm moves from 2 cm to 18 cm. In the later scenario, the achieved range differs by 20 cm, while in the former case the difference is less than 7 cm. This implies that in NLoS-MAMI Relay1, if the node closer to the edge acts as the relay master, not only greater range is achieved but also more consistent system performance can be obtained.

In contrast, MAMI-Relay2 achieves the best range with greater robustness as the relay master becomes closer to the transmitter. For instance, when Rm is located 2 cm away from the transmitter, the achieved distance varies from 56.6 cm to 59 cm if the relay assistant is moved from the source to the communication edge (see Table I). Almost the same variation is observed when the relay master is located at the edge but the achieved distance is reduced to 20cm.

C. Quality Factor

From the power equations discussed in Section III, it can be seen that to increase the received signal strength and subsequently the achieved communication range, antennas with higher quality factor should be designed. However, Equation 29 suggests that higher quality factor does not necessarily result in a higher data rate. For a homogenous system, with identical quality factors, the equation simplifies to $B_f = (0.644/Q)$. Therefore to achieve the highest data rate, the optimum Q-factor must be determined. Fig. 12 to 14 shows the optimum Q-factor for different communication distances at

TABLE I
MAMI RELAY1 AND 2 COMPARISON-MASTER/ASSISTANT SELECTION

dis. between Tx and Ri (cm)		**Rm=2cm**			**Rm=18cm**			**Ra=2cm**			**Ra=18cm**		
		Ra(cm)=			**Ra(cm)=**			**Rm(cm)=**			**Rm(cm)=**		
		2	10	18	2	10	18	2	10	18	2	10	18
Achieved dis.	MAMI Relay1	65	44	40	65	59	58	64.6	59	58	60	44	40
	MAMI Relay2	59	58.8	56.6	39	38	36.8	56	41	39	37	42	59

operating frequency 13.56 MHz, for the three multihop relay techniques.

As can be seen from Fig. 12, if the optimum Q-factor (120) is obtained, a data rate of up to 870 kb/s is achieved where the receiver is located at 25 cm away from the source (NLoS-MI Relay method). As distance increases the optimum Q-factor also increases. For example at 45 cm, in NLoS-MI Relay via R1, Q-factor 191 is required to achieve 525 kb/s, while a Q-factor 243 is needed to achieve a data rate of 397 kb/s if relaying is performed via R2. The same trend can be seen for MAMI-Relay1 and 2 in Fig. 13 and 14. The graphs also suggest that as the Q-factor increases, the achieved data rate tend to decrease and asymptotically approaches the same data rate for all the cases.

Fig. 13 suggests that for NLoS-MAMI Relay1, a specific Q-factor at a given communication distance results in very similar data rates regardless of which node is selected to act as master or assistant. However, in MAMI-Relay2 (Fig. 14) and MI-Relay (Fig. 12) the selection of each node as master and assistant impacts the optimum Q-factor to achieve the highest data rate. Optimal selection of each node as relay master and relay assistant in each method results in a reduction on the value of required Q-factor to obtain the best data rates. The size of antenna coil is one of the important factors which determines the value of the Q-factor. A smaller Q-factor means the possibility of smaller antennas, hence smaller devices. Therefore, by choosing the most suitable multihop method according to the scenario, and selecting the optimal node as relay master and assistant, the size of the device can be reduced without degrading the data rate. However, the optimum Q-factor to achieve highest data rate does not automatically lead to greater communication range. Therefore, in every application it is important to determine the most critical requirement, whether it is the data rate or the communication range extension. The optimum Q-actor, data rate and the communication range can then be determined.

V. CONCLUSION

In this paper, the differences between communication systems using EM and MI are discussed in the context of far field and near field effects. In this paper, three multihop relay schemes are proposed for NFMIC, where there is no direct link between the source and the destination. The proposed methods, denoted as NLoS-MI Relay, NLoS-MAMI Relay1 and NLoS-MAMI Relay2 are studied theoretically and evaluated using Matlab simulations. The performance of each technique is measured in terms of the RSS and channel data rate. It has been shown that MAMI-Relay1 outperforms the other techniques and is most effective if the relay master is located closer to the transmitter. The achievable RSS and channel capacity for each method is affected by the distance between the transmitter and the relay nodes, and this relationship is quantified.

It is discussed that in NLoS-MI Relay as the relay node moves toward edge of the communication range, the overall range decreases. In NLoS-MAMI Relay2, the selection of the node which are to perform as relay master and assistant will strongly affect the achieved range and this method is more effective if the node closer to the source is selected as relay master.

The impact of the Q-factor on achievable data rate in each method is discussed. The study shows that while higher Q-factor (larger antennas, higher frequency and higher permeability core material) leads to longer communication distances, it does not directly result in higher data rates. It is discussed that for any given scenario, there is an optimum Q-factor which results in the highest achievable channel data rate. In the future, the authors intend to extend the study to model and analyse the impact of different misalignment (lateral and angular misalignment) on the proposed cooperative communication methods and the relay selection strategies discussed in this paper.

VI. RESULT FIGURES

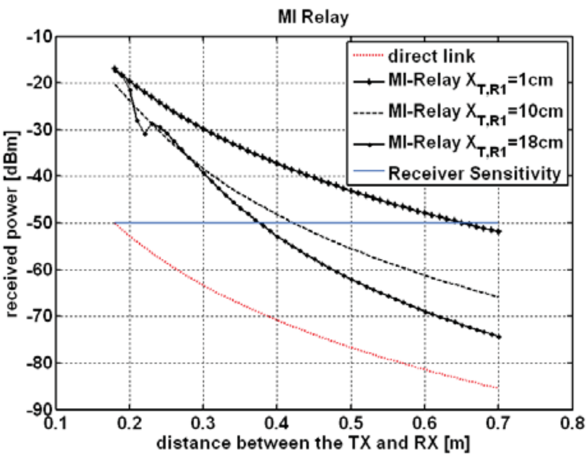

Fig. 7. NLOS-MI Relay-relay node at different distances

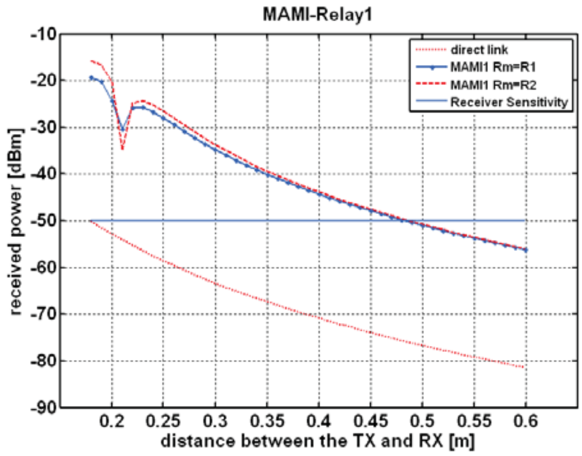

Fig. 8. NLOS-MAMI Relay1-achieved range

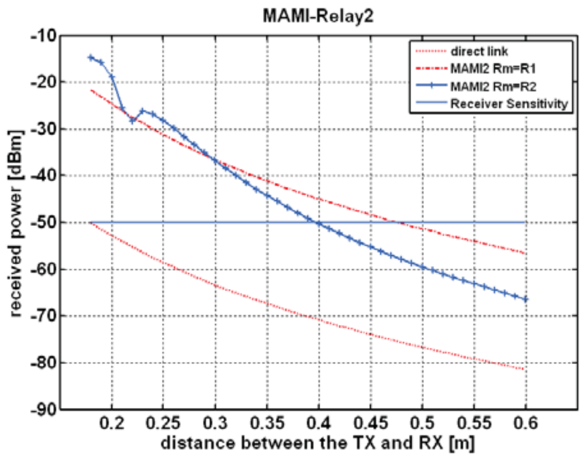

Fig. 9. NLOS-MAMI Relay2-achieved range

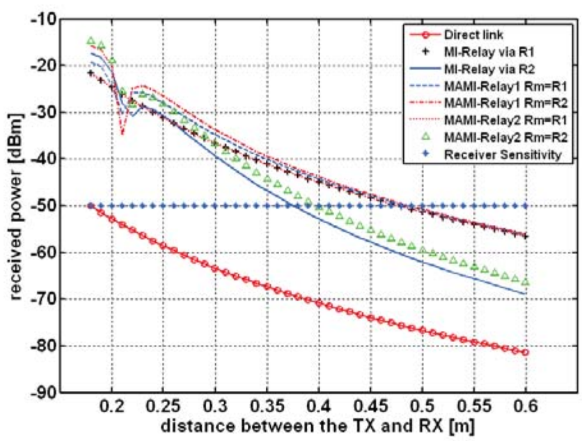

Fig. 10. RSS and achieved distance comparison between the three methods

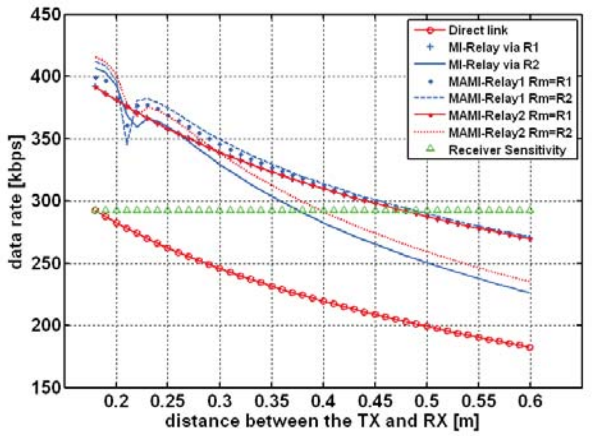

Fig. 11. data rate comparison between the three methods

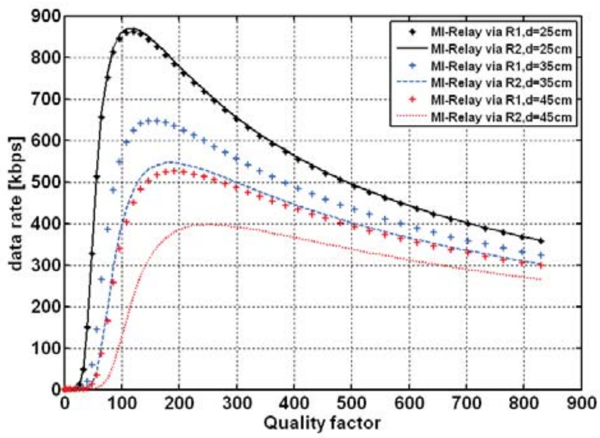

Fig. 12. NLOS-MI Relay-Optimum Q-factor

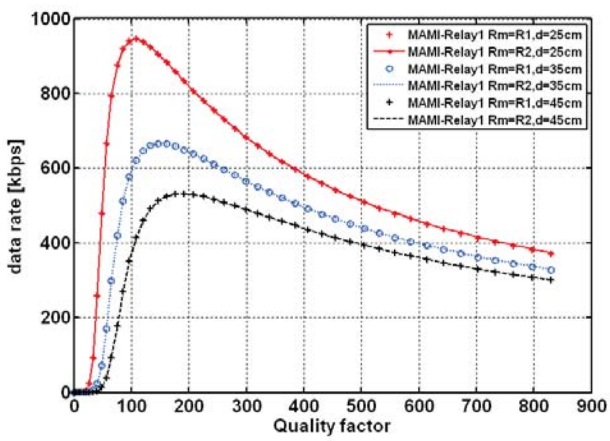

Fig. 13. NLOS-MAMI Relay1-Optimum Q-factor

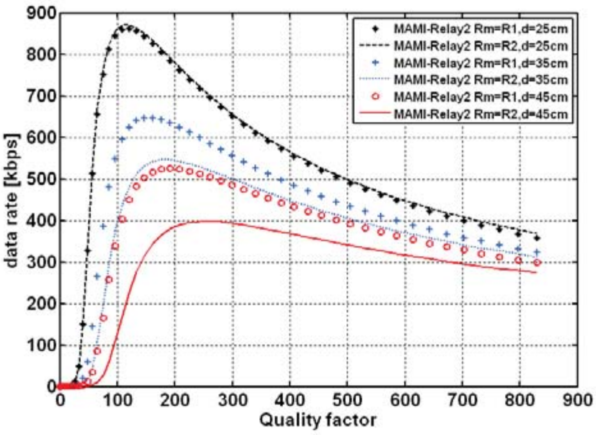

Fig. 14. NLOS-MAMI Relay2-Optimum Q-factor

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