SISO and MIMO Analog Network Coding Relay Architectures for the Uplink of LTE-Advanced

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***Abstract*—Analog network coding has been successfully employed in conventional two way relaying systems. However, analog two way relaying is successful when the two sender and destination nodes are symmetric. In practical cellular-based mobile communication systems of the likes of Long Term Evolution (LTE), the system is composed of several powerful base-stations and low power users' equipment. Applying classical two way relaying will cause unbearable interference. In this paper we propose applying network coding between two user equipment in the same cell in the uplink direction. We investigate Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) models for this scenario. We also study the effect of interference of other nodes in surrounding cells.**

***Index Terms*—LTE-Advanced, analog network coding, uplink model**

I. INTRODUCTION

Relays play a major role in the design and deployment of cooperative networks. The concept of inserting helping nodes to better deliver the data is very appealing in fading environments. In digital communication system, if the bit error rate (BER) of the signal falls below a certain threshold, decoding is not possible. Hence, reliability of the system is essential for proper operation. Fading channel conditions along with shadowing effects affect the signal strength and reliability. Sending the signal over an alternate path, through the relay comes as a legitimate solution to address reliability. Improving the sender message chances to be delivered to the destination can also tempt the system designers to opt for higher bit rate which is also desirable for modern communication channels [1-4]. The ability of employing the relays to act as virtual MIMO systems relieves the implementation and size limitation that hinder mounting several antennas in the currently small transmitters and receivers.

Another paradigm shift in the communication scene is the concept of network coding. The pioneering concept introduced by Ahlswede [5] in his seminal paper, promise the ability to multiplex messages and reduce the required transmission slots.

LTE-A targets relaying as one of its strategic improvements [6-9]. In this paper, we propose a system model that seeks to utilize relaying to multiplex the data from two user equipment in the uplink direction. In addition, using network coding concept, it is possible to decrease the required time slots to transfer data between the base station and mobile stations. Our proposed network coding relaying structure differs from two-way relaying in preserving a separate uplink and downlink transmission. In our work, we assume that the transmitted power is included in the gain of channels and that the transmitted message has a unity power. In addition, all channels are symmetric and quasi-static.

The rest of the paper is organized as follows: Section II is dedicated to review the background and related work. Section III discusses the system model of the proposed algorithm. Simulation parameters and results are detailed in Section IV. Finally, the conclusion and future work is presented in Section V.

Notations: It should be noted that during the rest of the paper, a bold uppercase letters, e.g. **A**, represent matrices, bold lower case letters, e.g. **a**, represent vectors, and lower case letters, e.g. a, represent scalar values. The identity matrix is denoted as **I.** The inverse of a matrix A is denoted $\mathbf{A}^{-1}$, $(.)^T$ denotes the transpose and $(.)^H$ denotes the conjugate transpose.

II. BACKGROUND AND RELATED WORK

The discussion in this paper assumes half-duplex transmission mode. Although few recent publications have addressed inband full duplex relaying [10], we adopt the half-duplex transmission, which is the most widely known transmission mode in practical communication systems.

Considering a communication system, delivering the signal stream from the mobile station (MS) to the base station (BS) and vice versa, can be done through several structures. In the following we review these traditional transmission methods.

A. Conventional Transmission

In the simplest form of communications, the conventional transmission model uses neither relays nor network coding in the transmission process from the mobile to the base station. In

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this model, the MS transmits its signal directly to the base station BS. One of the main drawbacks of this transmission mode is that users at the cell edge suffer from large attenuation and high interference due to the large distance to the parent basestation especially in the uplink direction where the limited power MS transmits its signal.

Generally, the signal received u at the BS from the MS is

$$u = h_{MB}x + n + \mathbf{h}^{T}{}_{MB_{int}}\,\mathbf{x}_{int} \quad (1)$$

Where h_{BM} is the gain of the channel from the MS to the BS. x is the transmitted signal with unit power, n is the noise at the BS with variance σ_n^2. The interference channels are denoted by the vector $\mathbf{h}_{MB_{int}}$ between the interfering mobile users in other cells and the MS parent basestation BS. The interfering signals $\mathbf{x}_{int}$. The interference signal is assumed Gaussian with variance $\sigma^2_{MB_{int}}$. Consequently, the capacity can be calculated as:

$$\mathrm{C} = \log_2(1 + \frac{|h_{MB}|^2}{\sigma_n^2 + \sigma^2_{MB_{int}}}) \quad (2)$$

B. One way relaying

Relays have been introduced in the communication systems to aid the communication between the MS and the BS. The low capacity at the edge users can be solved by introducing relays to strengthen the signal transmitted from the MS to the BS. In the one way relaying, the MS transmits its signal to the RS in the first time slot and then the RS forwards the received signal to the BS in the second time slot. In our analysis of the one way relaying we constrain ourselves to the two-hop one way relaying which does not involve the direct link. We thereafter call it directly one-way relaying.

Several structures for one way relaying exist in literature including Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF).

The capacity of the channel between the MS and the RS is:

$$\mathrm{C}_1 = \log_2(1 + \frac{|h_{MR}|^2}{\sigma_n^2 + \sigma^2_{MR_{int}}}) \quad (3)$$

Where h_{MR} is the channel between the MS and the RS. $\sigma^2_{MR_{int}}$ is the interference of other MSs of neighboring cells to the RS.

And the capacity of the channel between the RS and the BS is

$$\mathrm{C}_2 = \log_2(1 + \frac{|h_{RB}|^2}{\sigma_n^2 + \sigma^2_{RB_{int}}}) \quad (4)$$

Where h_{RB} is the channel between the RS and then BS and $\sigma^2_{RB_{int}}$ is the interference of interfering RSs cells to the BS. Then, the overall capacity of the transmission, in case of DF-relaying can be expressed as [11], [12]:

$$\mathrm{C_t} = \frac{\mathrm{C_1} * \mathrm{C_2}}{\mathrm{C_1} + \mathrm{C_2}} \quad (5)$$

C. Two way relaying

One way relaying involves two non-overlapping time slots for the transmission of the signal from the source to destination. This greatly reduces the overall capacity. The idea of network coding appeared to reduce the number of required time slots and consequently increase the capacity [13-17].

One of the most commonly discussed model in Network Coding is the TWRC (Two-Way Relay Channel), where two transceiver nodes communicate with each other through a relay in overlapping time slots, which is illustrated in Fig. 1.

In this case, the number of required time slots is reduced to two time slots for both the uplink and downlink transmission. This is achieved through making use of the interference property of the channel. The two sending nodes transmit their messages at the same time in the first time slot, and then the relay node retransmits its received signal at the second time slot. The signal transmitted by the relay is the combination of the two messages. Each one of the communicating nodes can then eliminate its own message from the combination assuming channel state information is known at all nodes. This is called Analog Network Coding (ANC) [13], [16], [17].

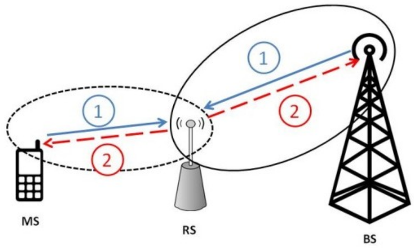

Fig. 1. Conventional Two Way Relaying Model

In TWR, the signal received at the RS at the first time slot can be expressed as

$$u_R = h_{MR}x_1 + h_{BR}x_2 + n_1 + R_{int} \quad (6)$$

Where, h_{MR} is the channel between the MS and the RS, h_{BR} is the channel between the BS and the RS, and the interference at the relay R_{int} with the variance $\sigma^2_{R_{int}}$comprises the interference caused by interfering BSs and interfering MSs at the relay. The RS scales the received signal by a normalization factor β where,

$$\beta = \frac{1}{\sqrt{|h_{MR}|^2 + |h_{BR}|^2 + \sigma^2_{n_1} + \sigma^2_{R_{int}}}}$$

Where $\sigma^2_{n_1}$ is the variance of the noise n_1.The scaled signal is broadcast again to the BS and the MS. So the received signal at the BS is

$$u_B = h_{RB} * \beta * u_R + n_2 + B_{int} \quad (7)$$

The base station already knows its own signal, $\beta h_{RB} h_{BR} x_2$. It subtracts it from the received signal to retrieve the desired uplink signal from the MS, so its signal can be expressed as

$$u_B = \beta h_{RB} h_{MR} x_1 + \beta h_{RB}(n_1 + R_{int}) + n_2 + B_{int} \quad (8)$$

Where the interference at the base-station B_{int}, with variance $\sigma^2_{B_{int}}$, is caused by the interfering relays transmission in the neighboring cells. The uplink capacity is [12]:

$$\mathrm{C_{UL}} = \log_2(1 + \frac{\beta^2 |h_{RB}|^2 |h_{MR}|^2}{\beta^2 |h_{RB}|^2 (\sigma^2_{n_1} + \sigma^2_{R_{int}}) + \sigma^2_{n_2} + \sigma^2_{B_{int}}}) \quad (9)$$

Where, $\sigma^2_{n_2}$ is the variance of the thermal noise n_2 at the BS and $\sigma^2_{B_{int}}$is the variance of the interference at the BS.

In particular, the above model is studied in [12] under realistic LTE parameters, including realistic channel models and power levels for the BS, RS and MS. The analog network coding two way relaying scenario is compared to one way relaying and shared relaying. The main conclusion in [12] is that two way relaying suffers from unacceptable interference.

This can be easily deduced by analyzing the cellular LTE structure and taking into account the following facts:

(i) The transmission power of the BS is much larger compared to the transmission power of the MS.

(ii) When sending the uplink signal and the downlink signal at the same time, the uplink signal, undergoes interference at the relay coming from other mobile equipment and more importantly from other transmitting basestations.

III. PROPOSED UPLINK SYSTEM MODEL

From the analysis in Section II, it is clear that having the base station and the mobile equipment transmitting at the same time leads to high interference and more importantly, unbalanced interference that will act against the uplink signal.

Using analog network coding in its classical two way form is not suitable for the LTE-A system, we provide in the following section a new structure to make use of the network coding in the LTE-A to avoid the above shortcomings. In our analysis, we assume that all the channels are complex normal distributed $C(0,\sigma^2)$ and also the noise at either the RS or the BS is complex normal of the same value $C(0,\sigma_n^2)$.

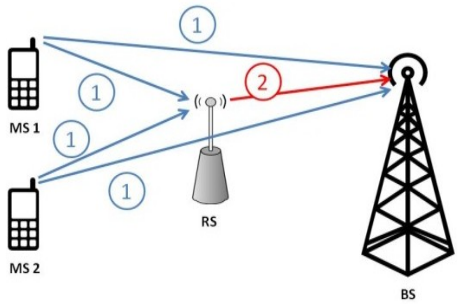

Fig. 2. Proposed Analog Network Coding Relaying

1) *The First Uplink Scenario (SISO):*

In this model, the BS and the RS have only one antenna each. The channel between the first mobile station and the relay is denoted as h_{1r} and the channel between the second one and the relay is called h_{2r}, while the channel between MSs and the BS are named h_{1b}, h_{2b} respectively.

The transmission scenario is illustrated in Fig. 2. At the first time slot the two MSs will transmit their symbols x_1, x_2 at the same time. The analog network coded signal that consists of the two signals of the mobile stations is received by the RS and the BS in the same time slot.

The signal received at the RS, u_r can be expressed as:

$$u_r = h_{1r}x_1 + h_{2r}x_2 + n_1 + \mathbf{h}_{MR_{int}}{}^T\,\mathbf{x}_{int} \qquad (10)$$

Where, $\mathbf{h}_{MR_{int}}{}^T\,\mathbf{x}_{int}$ is the interference of other MSs of neighboring cells to the RS propagated through the channels $\mathbf{h}_{MR_{int}}$ between the interfering mobile stations and the relay and will be further denoted as $\varepsilon_{MR_{int}}$.

While, the received signal at the base station u_b can be expressed as

$$u_b = h_{1b}x_1 + h_{2b}x_2 + n_2 + \mathbf{h}_{MB_{int}}{}^T\,\mathbf{x}_{int} \qquad (11)$$

Where, $\mathbf{h}_{MB_{int}}{}^T\,\mathbf{x}_{int}$ is the interference of other MSs of neighboring cells to the BSs propagated through the channels $\mathbf{h}_{MB_{int}}$ between interfering mobile stations and the basestation and will be further denoted as $\varepsilon_{MB_{int}}$.

At the second time slot of that model, the RS will transmit a scaled version of u_r to the base station.

Consequently, the received signal at the BS in the second time slot is,

$$u_{rb} = \beta h_{rb}\left(h_{1r}x_1 + h_{2r}x_2 + n_1 + \varepsilon_{MR_{int}}\right) + n_3 + \varepsilon_{RB_{int}} \; (12)$$

Where β is the normalization factor of the RS that normalizes its power to the unity, while h_{rb} is the channel between the RS and the BS and $\varepsilon_{RB_{int}}$ is the interference of other RSs of neighboring cells to the BS.

$$\beta = \frac{1}{\sqrt{|h_{1r}|^2 + |h_{2r}|^2 + \sigma_n^2 + \sigma_{\varepsilon MR_{int}}^2}} \qquad (13)$$

At the end of the second time slot, the BS obtains two equations of two unknown transmitted signals by the mobile stations. One of these equations is received directly through the direct channels and the other received through the RS. Hence, the BS can retrieve the original symbols of the MSs by solving these two independent equations using recovery process like the zero forcing technique [18].

We can express our equations in the matrix form as

$$\begin{pmatrix} u_b \\ u_{rb} \end{pmatrix} = \underbrace{\begin{bmatrix} h_{1b} & h_{2b} \\ \beta h_{rb}h_{1r} & \beta h_{rb}h_{2r} \end{bmatrix}}_{\mathbf{H}} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \underbrace{\begin{pmatrix} n_2 + \varepsilon_{MB_{int}} \\ \beta h_{rb}\left(n_1 + \varepsilon_{MR_{int}}\right) + n_3 + \varepsilon_{RB_{int}} \end{pmatrix}}_{\mathbf{n}} \qquad (14)$$

We can write it as,

$$\mathbf{u} = \mathbf{H}\,\mathbf{x} + \mathbf{n} \qquad (15)$$

Where $\mathbf{u} = [u_b \; u_{rb}]^T$, $\mathbf{x} = [x_1 \; x_2]^T$. Hence, the original sent signals by the two mobile stations can be recovered.

Defining the noise covariance matrix $\sum$ and the covariance matrix of the useful received signal is $\mathbf{HH}^H$, where $\mathbf{H}$ is the overall channel matrix. Then, the overall capacity of our proposed system is [19]:

$$C = \frac{1}{2}E\{log\,\det(I + \mathbf{H}^H\textstyle\sum^{-1}\mathbf{H})\} \; (16)$$

2) *The Second Uplink Scenario (MIMO):*

In this model, we investigate the effect of having 2-antennas relay station and 2-antennas base station. The antenna elements are mounted sufficiently apart to assume independent channels. We suppose that the channels between the first mobile station and the two antennas of the RS are h_{1r1} and h_{1r2} but the channels between the second MS and the relay are h_{2r1} and h_{2r2}, while the direct channels between the MSs and the BS are $h_{1b1}, h_{1b2}, h_{2b1}$ and h_{2b2}.

At the first time slot the two MSs transmit their signals x_1, x_2 at the same time to the base station's antennas over the direct channels so that the BS will get its first two equations. At the same time, the RS will receive also two equations over its two antennas in the same two unknowns, which are the transmitted symbols. The interference terms on each antenna element can be calculated according to the SISO case and will be denoted $\varepsilon_{MR_{int1}}$ and $\varepsilon_{MR_{int2}}$ for the relay antennas and $\varepsilon_{MB_{int1}}$ and $\varepsilon_{MB_{int2}}$ for the BS antennas.

Thus, the signals received at the RS u_{r1} and u_{r2} can be expressed as:

$$u_{r1} = h_{1r1}x_1 + h_{2r1}x_2 + n_1 + \varepsilon_{MR_{int1}} \qquad (17)$$

$$u_{r2} = h_{1r2}x_1 + h_{2r2}x_2 + n_2 + \varepsilon_{MR_{int2}} \qquad (18)$$

While, the received signals at the base station u_{b1} and u_{b2} can be expressed as

$$u_{b1} = h_{1b1}x_1 + h_{2b1}x_2 + n_3 + \varepsilon_{MB_{int1}} \qquad (19)$$

$$u_{b2} = h_{1b2}x_1 + h_{2b2}x_2 + n_4 + \varepsilon_{MB_{int2}} \qquad (20)$$

Then, at the second time slot, the RS will transmit its network coded signals to the base station using spatial multiplexing. The received signals at the BS through the second slot are

$$u_{rb1} = Gh_{11}u_{r1} + Gh_{21}u_{r2} + n_5 + \varepsilon_{RB_{int1}} \qquad (21)$$

$$u_{rb2} = Gh_{12}u_{r1} + Gh_{22}u_{r2} + n_6 + \varepsilon_{RB_{int2}} \qquad (22)$$

Where G is the normalization factor of the RS and $h_{11}, h_{21}, h_{12}, h_{22}$ are the channels between the RS and the BS. The interference terms $\varepsilon_{RB_{int1}}$ and $\varepsilon_{RB_{int2}}$ are the interference of other relays in neighboring cells on the BS antennas 1 and 2 respectively.

Thus, we can express the system as

$$\begin{bmatrix} u_{b1} \\ u_{b2} \\ u_{rb1} \\ u_{rb2} \end{bmatrix} = \underbrace{\begin{bmatrix} h_{1b1} & h_{2b1} \\ h_{1b2} & h_{2b2} \\ Gh_{11}h_{1r1} + Gh_{21}h_{1r2} & Gh_{11}h_{2r1} + Gh_{21}h_{2r2} \\ Gh_{12}h_{1r1} + Gh_{22}h_{1r2} & Gh_{12}h_{2r1} + Gh_{22}h_{2r2} \end{bmatrix}}_{\mathbf{H}_{MIMO}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} n_3 + \varepsilon_{MB_{int1}} \\ n_4 + \varepsilon_{MB_{int2}} \\ Gh_{11}(n_1 + \varepsilon_{MR_{int1}}) + Gh_{21}(n_2 + \varepsilon_{MR_{int2}}) + n_5 + \varepsilon_{RB_{int1}} \\ Gh_{12}(n_1 + \varepsilon_{MR_{int1}}) + Gh_{22}(n_2 + \varepsilon_{MR_{int2}}) + n_6 + \varepsilon_{RB_{int2}} \end{bmatrix}}_{\mathbf{n}_{MIMO}}$$

(23)

Consequently, the system can be represented as:

$$\mathbf{u} = \mathbf{H}_{MIMO}\mathbf{x} + \mathbf{n}_{MIMO} \qquad (24)$$

The overall capacity of our proposed system using the log determinant equation [17], [21] is

$$C_{MIMO} = \frac{1}{2} E\{log\det(I + H^H \Sigma^{-1} H)\} \qquad (25)$$

IV. Simulation Results

In this section, we simulate the performance of the system under specific channel conditions and interference model between each of user equipment, relay node, and the base station. We applied the IEEE 802.16j channel models [12], [21], [22] with the parameters shown in TABLE I.

We used these parameters to generated channel models for BS-RS link, the two MSs-RS links, and the two MSs-BS links. In our simulations, we assume that the two mobile stations are at the cell edge (the furthest point of the base station) where it experiences the lowest SINR. The relay is at 2/3 of the cell radius away from the base station. We also assume that the noise level at the receiver of each node is the same. The exact positions of communication nodes are depicted in Fig.3. To simplify simulations, we neglected the effect of shadowing.

TABLE I. Simulation Parameters

Element	Value
BS TX power	47 dBm
BS-RS channel model	IEEE 802.16j, Type H
BS-MS channel model	IEEE 802.16j, Type E
RS-MS channel model	IEEE 802.16j, Type E
Cell radius	876 m
Carrier frequency	2 GHz
Noise power	-151dBW – -144 dBW
Mobile height	1 m
Relay height	From 15 m to 30 m
BS height	30 m
Propagation environment	Urban
Roof height	15m
Street width	12 m
Distance between buildings centers	60 m

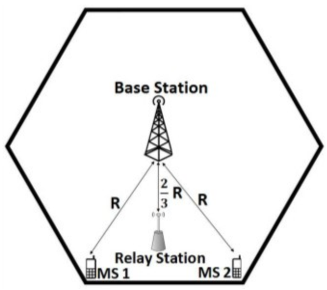

Fig. 3. Nodes distribution in the cell

In our simulation, we assumed that all nodes have the same direction and that the operating frequency band is reused between neighboring nodes. This simulation structure is shown in Fig. 4.

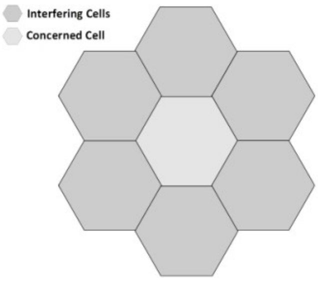

Fig. 4. Interfering cells distribution

In next figures, we compare the performance of our model with different other possible models that may be deployed. We compare the proposed ANC-relaying system with the conventional model, where no relaying nodes exist between mobile stations and the base station. i.e. the mobile station uplink transmission in the conventional case depends only on the direct path between it and the base station. The proposed structure is also compared to one way two-hop relaying, where the mobile station transmits its message to the relay, which in turn retransmits the message to the base station after decoding it to reduce the noise. However, it requires two time slots to transmit a message from the mobile station to the base station. Additionally, two-way relaying is also examined. In two way relaying both uplink and downlink transmission sessions occur in the same time slots to reduce the required time slots. However, the uplink path will suffer in this case because of unequal power distribution between the base station and the mobile stations. The performance of these different transmission strategies are compared in different transmission scenarios. In the first scenario we apply the simulation parameters in TABLE I. and the performance of different systems are plotted as a function of the relay power. The result of this scenario is illustrated in Fig. 5. and Fig. 6. In this system, the proposed architecture provides the best system capacity among different transmission architectures. Fig. 5. illustrates the performance of different uplink architectures at noise power level equal to -151 dBW. However, Fig. 6. illustrates the performance of the uplink transmission architectures against the relay power with the noise level of all nodes fixed at -144 dBW. With the increase of noise power, the capacity gain of the proposed ANC-relaying architecture decreases. The SISO ANC-relaying is below the conventional transmission. In Fig. 5. and Fig. 6. the relay is at height 15m (i.e. at rooftop level), while the base station height is 30 m. These results can be interpreted by carefully inspecting the MS-RS channel which has the same propagation properties of the direct channel MS-BS but with the BS placed at a higher level than the RS. The amplify-and-forward nature of the transmission makes it sensitive to accumulated noise in the proposed ANC relaying which involves two-hops (MSs-to-RS and RS-to-BS).

In fact, for two-hop transmissions, to provide noticeable gain, it is required that the link MS-RS and RS-BS be better than the direct link MS-BS. One way to achieve this goal is to alleviate the RS above the roof-top level.

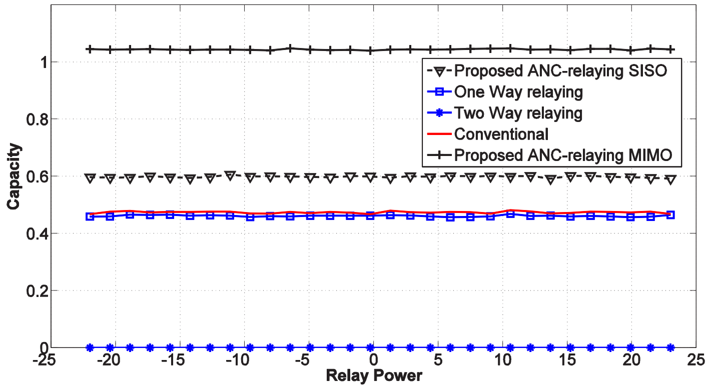

Fig. 5. Capacity vs. relay power , relay height = 15m, noise power = -151dBW

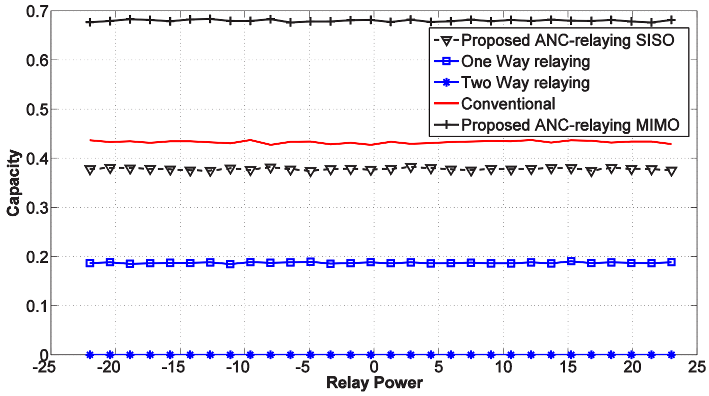

Fig. 6. Capacity vs. relay power , relay height = 15m, noise power = -144dBW

In Fig. 7. , we compare the performance of different discussed systems versus the height of the relay, as we move from rooftop to base station's height (15 m above rooftop). We note that the performance of proposed system and one-way relaying improves with the increase in the antenna height. In addition, a small increment in the relay's height near over the 15m-height till 20 m (5 meter over roof top), the proposed system improves its performance significantly.

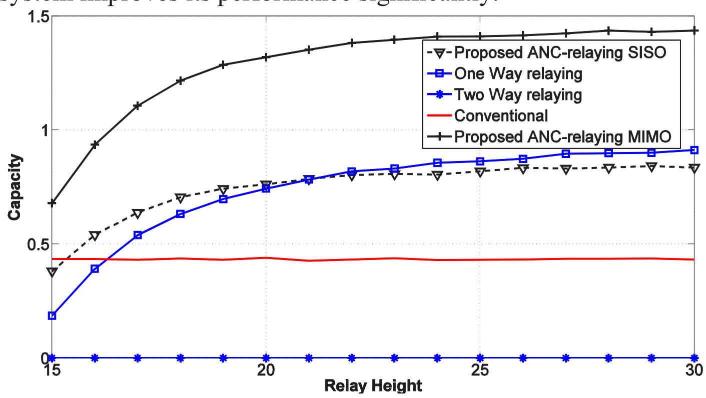

Fig. 7. Capacity vs. relay height, relay power = 5dBW, noise power = -144dBW

In Fig. 8. , the performance of the system is drawn against noise power in case of relay power level of 5dBW and at relay height of 17m.

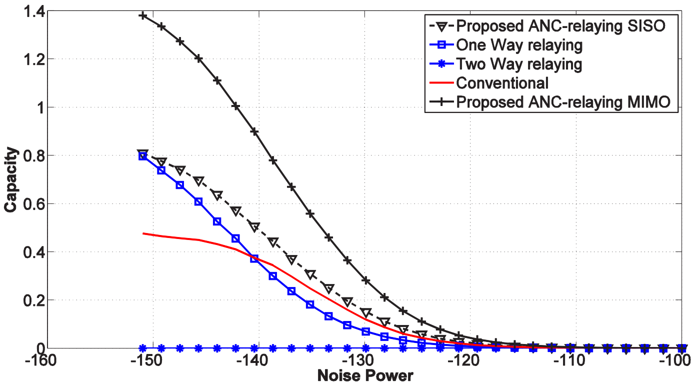

Fig. 8. Capacity vs. noise power, relay height = 17m, relay power = 5dBW

In Fig. 8. , it is shown that through increasing the RS height level, and consequently improving the links MS-RS and RS-BS, that the capacity of proposed ANC-relaying architecture greatly outperforms those of other transmission architectures over the entire inspected noise power level.

V. Conclusion and Future Work

In this paper we propose an uplink model that is capable of multiplexing two mobiles' signals and sending them over two time slots achieving similar time slot saving gain to the two way relaying case. The proposed system assumes "cheap relay" that works in half-duplex mode and does not involve decoding operation. Simulation results confirm the validity of the proposed system. For future work, an extension of the proposed work to the downlink scenario can be investigated. Moreover, introducing multiple relays and involving relay selection process is another valid extension of the work.

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