Cognitive Incremental Relaying Networks with Spectrum Sharing and Hardware Impairments

Samuel Borges Ferreira Gomes, Daniel Benevides da Costa, Ugo Silva Dias, and Rafael Timóteo de Sousa Jr.

Abstract— **In this paper, we investigate the outage performance of underlay cognitive amplify-and-forward incremental relaying networks with multiple relays and subject to hardware impairments. Unlike regular cooperative diversity networks, which make an inefficient use of the channel resources because relays always forward the source signal regardless the channel conditions, incremental relaying exploits limited feedback from the destination terminal, and sends a single bit to indicate success. If the destination provides a negative bit via feedback, the relay retransmits an amplified version of the source signal. The end-to-end signal-to-noise-and-distortion ratio (SNDR) of incremental relaying over independent non-identical Rayleigh fading channels is formulated for partial relay selection (PR) and opportunistic relay selection (OR) schemes, based on which the respective outage probabilities are evaluated. Our simulation results show that the incremental relaying protocol can achieve maximum diversity with a more efficient channel utilization and better performance compared to fixed cooperation.**

Keywords— **Incremental relaying, cognitive radio, cooperative networks, hardware impairments, multiple relays, spectrum sharing.**

I. Introduction

In recent years, the number of wireless systems and services has grown exponentially. The emergence of new applications, new services, and growing consumer interest in mobile devices and networks have been driving the evolution of wireless networks to ultra-high speed data networks. This widespread acceptance of wireless technologies has triggered a huge demand for bandwidth, and in the coming years it is expected that this spectrum demand radio shows an even bigger growth. Cooperative diversity networks technology is one of the promising solutions for high data rate coverage required in future wireless communication systems and has gained considerably attention as an efficient way to mitigate fading in wireless networks due to its capability of emulate a multi-antenna system without the need of multiple antennas implemented at the terminals. Some of its advantages are the low RF power transmission requirements and the spatial diversity gain [1]. The basic idea is that in addition to the direct transmission from the transmitter to the receiver, there are other cooperative nodes in the system, which can be used to enhance the diversity by relaying the source signal to the destination. In a multi-relay cooperative scenario, there are several different cooperation schemes studied in the literature based on the availability of channel side information (CSI) of the source-relay links and source-destination link, such as partial relay scheme (PR) [2] and opportunistic relay selection (OR) [3], [4]. Another promising technology for meeting the demands of the next generation of wireless networks is cognitive radio [5], which aims to provide a more efficient use of the radio spectrum. In particular, cognitive radio technology provides the ability to share the spectrum opportunistically, alleviating therefore the problem of spectrum scarcity and underutilization by allowing unlicensed users to access portions of the spectrum initially allocated to a licensed user with assistance of a single or multiple relay nodes.

Although a regular cooperative diversity network can achieve spatial diversity gain, it wastes the channel resource because the relay always forwards to the destination the signal received from the source, even when it is not necessary, using therefore additional resources. Due to this fact, incremental relaying cooperative networks try to save channel resources by restricting the relaying process to the necessary conditions [1]. If the source-destination signal-to-noise ratio (SNR) is sufficiently high, the feedback indicates success of the direct transmission, and the relay does not need to transmit. However, if the source-destination SNR is not sufficiently high for successful direct transmission, the destination requests the relay to amplify and forward what has been received from the source. In the latter case, the destination may combine the two signals using a maximal-ratio combining (MRC) technique [1], [6].

Incremental cognitive relaying networks have been studied in literature for amplify-and-forward (AF) [7], [8] and decode-and-forward (DF) [9], [10] relaying systems. However, common to these works is that they have considered an ideal hardware structure. In practice, hardware suffers from several types of impairments, such as phase noise, I/Q imbalance, and high power amplifier (HPA) nonlinearities [11]. The impact of hardware impairments on single-hop systems was analyzed in [11], while a dual-hop cooperative scenario was investigated in [12]. Nevertheless, none of these works considered the direct link between source-destination.

In this paper, we investigate the outage performance of underlay cognitive AF incremental relaying networks with multiple relays and subject to hardware impairments. For comparison purposes, the fixed cooperation protocol is also considered. In addition, since a multi-relay scenario is assumed, both partial relay selection and opportunistic relay selection techniques are employed to select one of the available relays for assisting in the information transmission. The end-to-end signal-to-noise-and-distortion ratio (SNDR) is then

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formulated, based on which the respective outage probabilities are evaluated. Our simulation results show that the incremental relaying protocol can achieve maximum diversity with a more efficient channel utilization and better performance comparing to fixed cooperation. Also, our simulation results examine the impact of the number of relays, hardware impairments coefficients, and outage thresholds on the overall system performance. To the best of the authors' knowledge, the proposed system setup has not been investigated in the technical literature yet and this paper aims to fill partly this gap that exists in the literature.

The remainder of the paper is organized as follows. In Section II, the signal and system models are described. Both incremental and fixed cooperation schemes subject to independent and non-identically distributed Rayleigh fading are considered. In Section III, the system outage probability is mathematically formulated. Simulation results are presented in Section IV based on which some fundamental guidelines are highlighted. Finally, Section V concludes the paper and points out some potential future works.

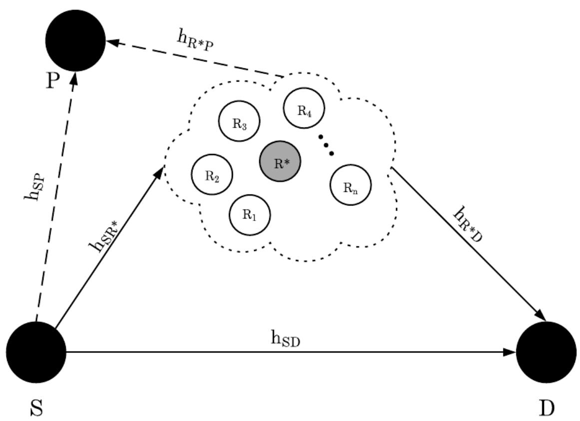

Fig. 1. Underlay cognitive relaying network with multiple relays.

II. System and Signal Models

A. System and Signal Descriptions

Consider an underlay cooperative cognitive scheme, where a secondary communication coexists with a primary transmission in the same frequency band and at the same time, as shown in Fig. 1. Specifically, the secondary nodes coexist in the same band with primary licensees, but are regulated to cause interference below the prescribed limits. The secondary network is composed by one secondary source S, multiple AF relays, and one secondary destination D. Note that a number of potential secondary relaying nodes K are available to retransmit the signal and only one of these relays (called R^*) will be selected to offer to the destination another copy of the original signal. It is assumed that the primary transmitter is far from the secondary network so that the primary communication does not cause any interference to the secondary one. In this case, only the primary receiver P will be taken into consideration in our analysis. The channel coefficients h_{ij} between two ordinary nodes in the set $\{S, D, R^*, P\}$ are mutually independent and non-identical, and follow a Rayleigh fading distribution.

Hardware impairments create a mismatch between the intended signal s and what is actually generated and emitted. This calls for the inclusion of additional distortion noise sources that are statistically dependent on the signal power and channel gains [12]. Distortion models are available for different sources of impairments (e.g., I/Q imbalance, phase-noise and amplifier non-linearities). In this scenario, the received signal at a given flat-fading subcarrier is given by

$$y = h(s + \eta_t) + \eta_r + \nu, \quad (1)$$

where s symbolizes the transmitted signal over the flat-fading wireless channel h, and ν denotes the additive white Gaussian noise (AWGN) term with zero mean and equal variance N_0. These parameters are statistically independent. In addition, η_t and η_r are defined as the distortion noises from impairments at the transmitter and receiver, respectively. In (1), $\eta_t \sim \mathcal{CN}(0, k_t^2 P)$ and $\eta_r \sim \mathcal{CN}(0, k_r^2 P|h|^2)$ where $x \sim \mathcal{CN}(a, b)$ denotes a circularly-symmetric complex Gaussian distributed random variable with mean a and variance b. The average signal power is represented by $P = \mathbb{E}\{|s|^2\}$, with $\mathbb{E}\{\cdot\}$ indicating expectation, and k_t, $k_r \geq 0$ stand for the design parameters, characterizing the level of impairments at the transmitter and receiver hardware, respectively, also interpreted as error vector magnitudes (EVMs).

Assuming a time division multiple access (TDMA) scheme for information transmission, it follows that the secondary communication takes place in two time slots. In the first phase, S broadcasts the signal x to both R^* and D with transmit power P_S. The destination sends an one-bit acknowledgment (ACK) to the relay and to the source if it is able to decode reliably the source signal. This means that if the direct transmission is good enough, there is no need of retransmission and the source can transmit new information in the next time slot. The received signals at the destination and at the selected relay can be written, respectively, as

$$y_{SD} = h_{SD}x + \nu_D, \quad (2)$$

$$y_{SR^*} = h_{SR^*}x + \eta_r + \nu_{R^*}, \quad (3)$$

where $\eta_r \sim \mathcal{CN}(0, k_r^2 P_S |h_{SR^*}|^2)$ and $P_S = \mathbb{E}\{|x|^2\}$.

If the secondary communication through the direct link in the first phase fails, the destination sends a negative acknowledgment (NACK) to the relay to indicate this. In such a case, a second phase starts and the selected relay forwards to the destination an amplified version of the source information y_{SR^*} with the following gain

$$G = \sqrt{\frac{P_{R^*}}{P_S|h_{SR^*}|^2(1+k_r^2)+N_0}}, \quad (4)$$

where P_{R^*} means the relay power and N_0 denotes the noise variance. Under hardware constraints, the selected relay introduces additional distortion noise in the transmitted signal. Hereby, the received signal in the second phase by the destination can be written as

$$y_{SR^*D} = (Gy_{SR^*} + \eta_t)h_{R^*D} + \nu_D, \quad (5)$$

where $\eta_t \sim \mathcal{CN}(0, k_t^2 P_{R^*})$.

B. End-to-End SNDR

Underlay cognitive radio systems encompass techniques that allow the cognitive communication to be aware of the interference caused by their transmitters to the receivers of all non-cognitive users. In this paradigm, unlicensed radios coexist in the same band with primary licensees, that is, secondary users can transmit their data in the licensed frequency range when the primary users are also transmitting as long as they regulate their transmit powers to cause interference below the prescribed limits.

In our scenario, the transmit powers P_S and P_{R^*} need to be carefully designed to ensure that the interference caused at P remains below the maximum tolerable interference power I_p [13]. More specifically, under the underlay paradigm, the transmit power must be set according to the radio environment, i.e.,

$$P_S = \frac{I_p}{|h_{SP}|^2}, \tag{6}$$

$$P_{R^*} = \frac{I_p}{(1+k_t^2)|h_{R^*P}|^2}. \tag{7}$$

By combining (2), (3), (4), (5), (6), and (7), and defining $\varrho = I_p/N_0$ as the average SNDR of the system, it can be shown that the resulting instantaneous SNDR at the destination via direct link, via relay links, and end-to-end link can be, respectively, expressed as

$$\gamma_{SD} = \frac{\varrho|h_{SD}|^2}{|h_{SP}|^2}, \tag{8a}$$

$$\gamma_{SR^*} = \frac{\varrho|h_{SR^*}|^2}{|h_{SP}|^2}, \tag{8b}$$

$$\gamma_{R^*D} = \frac{\varrho|h_{R^*D}|^2}{\delta|h_{R^*P}|^2}, \tag{8c}$$

$$\gamma_{SR^*D} = \frac{\gamma_{SR^*}\gamma_{R^*D}}{\alpha\gamma_{SR^*}\gamma_{R^*D} + \beta\gamma_{SR^*} + \delta\gamma_{R^*D} + 1}, \tag{8d}$$

where α, β and δ denote the impairments parameters [13], being defined as

$$\begin{cases} \alpha = k_r^2 + k_t^2 + k_r^2 k_t^2 \\ \beta = 1 + k_r^2 \\ \delta = 1 + k_t^2 \end{cases}$$

It is assumed a relay clustered structure,and thereby experience the same scale fading. As the links undergo Rayleigh fading, the channel gains $|h_{SD}|^2$, $|h_{SR^*}|^2$, $|h_{R^*D}|^2$, $|h_{SP}|^2$ and $|h_{R^*P}|^2$ are exponential random variables with variances σ_{SD}^2, σ_{SR}^2, σ_{RD}^2, σ_{SP}^2, and σ_{RP}^2, respectively.

C. Relay Selection Techniques

In cooperative relaying, the relay selection procedure requires special attention, since it has a strong impact on network and transmission performance [14]. In this work, we consider two relay selection strategies: opportunistic relaying technique (OR) and partial relay selection (PR), under the presence of transceiver hardware impairments.

In OR scheme, a single relay based on instantaneous global CSI (i.e., from both hops) of the network is selected to assist the source communication. Thus, the relay R^* is chosen based on the maximization of γ_{SRD}, i.e., the relay which provides the maximum γ_{SRD} will be selected. On the other hand, in PR scheme only a local information (i.e., from first hop) is used for the selection, i.e., the relay which maximizes γ_{SR} will be chosen for assisting the source transmission. Note that there is a tradeoff between these two relay selection scenarios. Although OR outperforms PR, the complexity of the former is higher than the latter since the number of required channel estimations increases due to the necessity of estimating the channel gains of both hops, while in the latter only the estimation of the first-hop channel gains is needed.

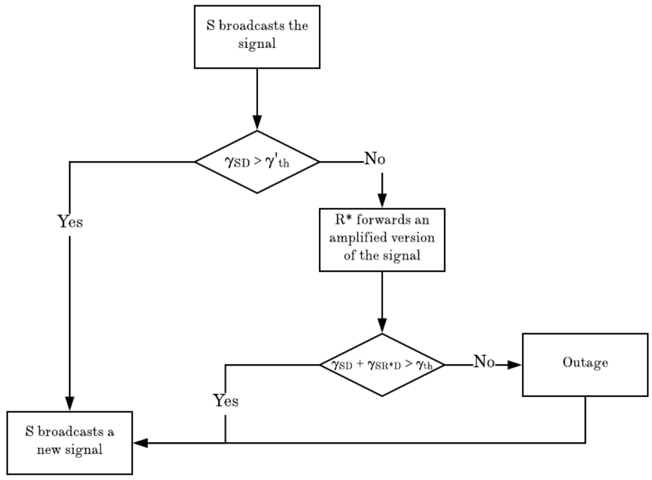

Fig. 2. Flowchart of AF incremental relaying protocol with MRC.

III. Performance Analysis

In this section, we examine the outage performance of the incremental relaying protocol under the considered system setup. As shown in Fig. 2, if the instantaneous SNDR of direct link at the destination γ_{SD} is less than a threshold value γ'_{th}, the destination D will need assistance from relay cooperation over a best relay R^*. Note that the transmission rate is random in incremental relaying. If the first phase was successful, the transmission rate is $\mathcal{R}$ bps/Hz, while if the first transmission was in outage, the transmission rate becomes $\mathcal{R}/2$ as in fixed relaying. Keeping in mind that the incremental relaying communication occupies two time slots, we set γ_{th} = $2^{2\mathcal{R}} - 1$ to attain the corresponding necessary conditions for achieving an ergodic capacity. The destination will combine both signal from D and R^* using a MRC technique. The outage probability can be formulated as

$$P_{\text{out}}(\gamma_{th}) = \Pr\{(\gamma_{SD} < \gamma'_{th}) \cap (\gamma_{SR^*D} + \gamma_{SD} < \gamma_{th})\}, \tag{9}$$

where $\Pr\{\cdot\}$ represents a probabilistic event with $\gamma'_{th} = 2^{R} - 1$.

For comparison purposes, we also examine the fixed cooperation scheme, as illustrated in Fig. 3. Unlike incremental relaying, the relays in fixed cooperation scheme will always cooperate. In this case, the source node broadcasts the signal to relays and destination node, which combine these two signals

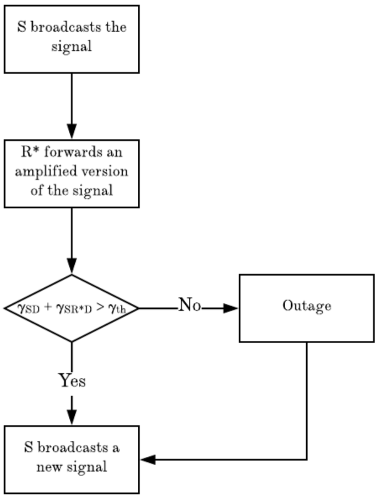

Fig. 3. Flowchart of AF fixed relaying protocol with MRC.

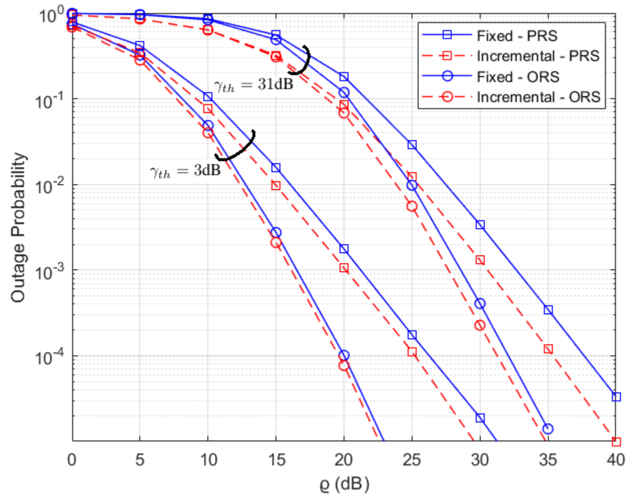

Fig. 4. Outage probability versus ϱ for incremental and fixed relaying protocols under PR and OR selection schemes and by setting different outage thresholds.

using MRC [12]. If the SNDR of the resulting signal is less than a given threshold γ_{th}, outage occurs. Thus, for fixed relaying, the outage probability can be formulated as

$$P_{\text{out}}(\gamma_{th}) = \Pr\{(\gamma_{SR^*D} + \gamma_{SD} < \gamma_{th})\}. \qquad (10)$$

IV. Simulation Results

In this section, in order to evaluate the performance of the proposed system, Monte Carlo simulation results are presented. Without loss of generality, it is considered a linear network modeling the path-loss as $\sigma_{ij} = d_{ij}^{-\varphi}$, where d represents distance between two nodes i, j in the set $\{P, S, R^*, D\}$, and φ is the path-loss coefficient. We set the coordinates of primary receiver P, source S, destination D, and selected relay R^* at (0.5,0.5), (0,0), (1,0) and (0.5,0), respectively.

In Fig. 4, assuming both PR and OR selection schemes, the outage probability versus ϱ of fixed and incremental relaying is ploted for two different thresholds (γ_{th} = 3dB and γ_{th} = 31dB) and assuming MRC at the receiver. We set the number of relays $K = 2$ and the hardware impairments levels $k_t = k_r = 0.1$. From these curves, note that incremental relaying always outperforms fixed cooperation, in addition to yield a more efficient use of the channel resources. Also, as expected, OR selection achieves better performance than PR one because it relies on the CSI of both first-hop and second-hop links for the selection process. We can also infer from the plots that the diversity gain of both incremental and fixed cooperation schemes under OR selection is $K+1$. However, assuming PR selection, the diversity gain reduces to 2, since only the quality of the first-hop link is taken into account to select the relay. Finally, when γ_{th} decreases, the system outage performance improves.

Fig. 5 illustrates the impact of hardware impairments on the system outage performance assuming different number of relays $K = 2, 3, 4$ and under OR selection scheme. We set the transmission rate as $\mathcal{R} = 1$ bps/Hz, implying γ_{th} = 3dB. Two sets of EVMs are considered: $k_t = k_r = 0.1$ and $k_t = k_r = 0.3$. Note that there is a tradeoff relationship between the parameters. More specifically, after $\varrho = 10$dB, it can be seen that is better to have a higher number of relays cooperating under high hardware impairments ($K = 4$ and $k_t = k_r = 0.3$), than a lower value of K with low hardware impairments. The same happens for $\varrho = 15$dB, in terms of system performance, when compared $K = 2$ ($k_t = k_r = 0.1$) and $K = 3$ ($k_t = k_r = 0.3$).

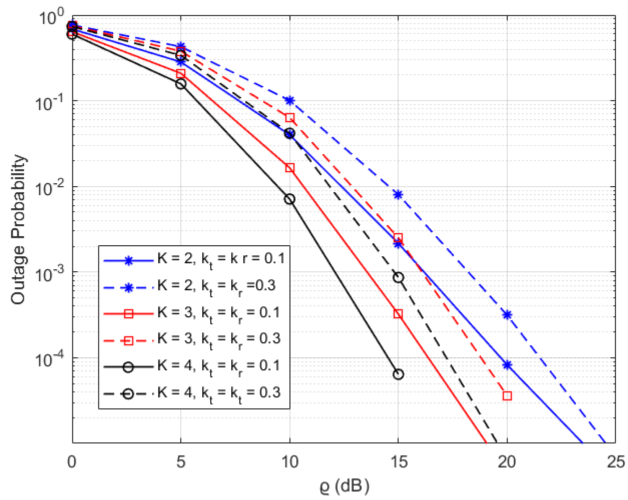

Fig. 5. Outage probability versus ϱ for different number of relays and hardware impairment levels, and assuming OR selection scheme.

Fig. 6 plots the outage probability versus ϱ for incremental relaying, by setting $\varphi = 4$, $K = 2$, $\gamma_{th} = 3$dB, and assuming a PR selection scheme. The effects of hardware impairments are investigated. Note that there is only a minor performance loss caused by transceiver hardware impairments when the hardware impairments parameter is $k_t = k_r = 0.1$, but when these parameters increase, there is a significant performance loss on the system.

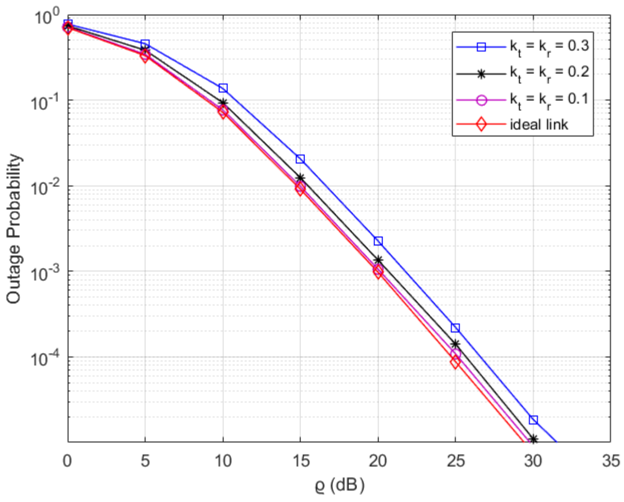

Fig. 6. Outage probability versus ϱ for incremental relaying considering PR scheme and different values of hardware impairment coefficients.

Finally, Fig. 7 plots the outage performance of incremental relaying scheme for different numbers of relays K. The EVMs were set to $k_t = k_r = 0.1$, over OR selection scheme. As expected, there is a relevant performance gain when we increase the number of relays. Also, it can be concluded that the diversity order equals to $K + 1$.

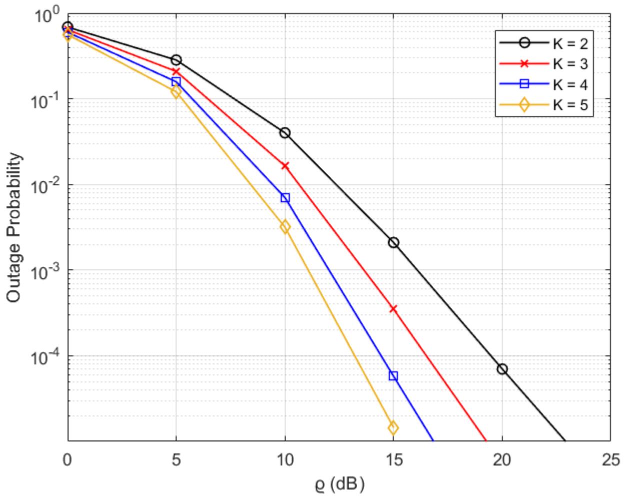

Fig. 7. Outage probability versus ϱ for incremental relaying considering OR scheme and different number of relays.

V. Conclusions and Future Works

In this paper, the outage performance of underlay cognitive incremental relaying networks with relay selection and hardware impairments was investigated. Two relay selection techniques were assumed: opportunistic relaying (OR) and partial relay (PR) selection. Our results revealed that incremental relaying is definitely an efficient technique in comparison to fixed cooperation. In addition to save the channel resources, incremental relaying always outperforms fixed cooperation in terms of outage probability. Also, we showed that OR and PR selection schemes undergo different diversity order, with the former always being better than the later.

As future works, a detailed analytical analysis can be provided for the considered system setup since our results were obtained only through simulations. In addition, the impact of imperfect CSI on the outage performance can be considered as well as the case of multiple destinations/sources. Finally, the effect of multiple antennas on the overall system performance arises as an interesting subject for investigation.

VI. Acknowledgments

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