The Benefits of Relay Selection in WiMAX Networks

Albert Bel, Jose Lopez Vicario, Gonzalo Seco-Granados
Group of Signal Processing for Communications and Navigation (SPCOMNAV),
Universitat Autònoma de Barcelona (UAB), Bellaterra, 08193, Spain
Tel: +34935813843, Fax: +34 935814031, Email: albert.bel@uab.cat

Abstract: In this work, we study the viability and potential gains of using a cooperative scheme in WiMAX networks. In particular, an opportunistic relay selection strategy is analyzed in a realistic scenario where the available channel state information is in general outdated. The analysis is performed in terms of outage probability, defined as the probability that instantaneous capacity is lower than a target rate. In particular, an analytical expression is derived in order to theoretically show under what conditions the cooperative scheme is advantageous. It is demonstrated that cooperation is not always beneficial unlike it is usually assumed. Cooperation causes a performance loose when the available channel state information is not sufficiently accurate and the number of relays is low. Simulation results corroborate these conclusions.

Keywords: cooperative communications, opportunistic relay selection, outdated CSI, WiMAX.

1. Introduction

During the last decade, most efforts in wireless communications have been aimed to improving spectral efficiency. The proposals have centered on using one or more of the following approaches: MIMO (Multiple-Input Multiple-Output) transceivers [1], large increase in signals bandwidth (Ultra Wide Band communications) [2] and cross-layer optimizations [3]. The underlying motivation for improving spectral efficiency was the continuous need to evolve the cellular communication systems, from the 2G systems (e.g. GSM) to 3G (e.g. UMTS or W-CDMA), LTE-UMTS, etc. All these examples use an infrastructure-centered architecture; that is to say, the core of the access network is a deployment of base stations (BS) or access points, and the communication is always established between the user equipment and a base station.

The advent of ad-hoc networks and the widespread use of Wi-Fi routers (which can also be configured in ad-hoc mode) hinted that a change in paradigm in wireless networks was possible by implementing them using a mesh-network topology. In a mesh-network topology, each node is connected and communication protocols are shared across the nodes. Mesh networks automatically learn and maintain dynamic path configurations; and wireless devices in a mesh-network topology create a seamless data path to one another [4].

Mesh networking is sometimes referred to as multi-hop networking. Mesh topologies provide a flexible architecture that can move data between nodes efficiently. Within the mesh network, small nodes act as simple routers. Each node then transmits a low power signal capable of reaching neighbouring nodes, each of which in turn transmits the signal to the next node, with the process being repeated until the data arrives at its destination. An advantage of this topology is the ability for greatly improving coverage and adapting to changes in network topology. Nodes can be readily added and removed, and their location changed. As people become more mobile and wireless capabilities are included in new classes of devices, future business need to adapt or self-configure to these changes.

Summing up, the benefits of mesh networking include lower deployment and infrastructure costs, enhanced availability and the improved ability to balance traffic and to support mobility. These benefits are captured by the new system WiMAX [5]. WiMAX is a wireless metropolitan-area network (WMAN) technology, based on the IEEE 802.16 standard, which provides interoperable broadband wireless connectivity to fixed, portable and nomadic users. It provides up to 50 kilometers of area service, allows users to get broadband connectivity without the need of direct line-of-sight to the base station, and provides total data rates up to 75Mbps (large enough to simultaneously support hundreds of business and homes). More importantly, allegedly WiMAX offers the WSPs (Wireless Service Providers) a lower-cost alternative to deploy broadband WMAN and it represents a serious competitor to the evolution of 3G cellular systems.

The relevant conclusion drawn for the discussion above is that, thanks technological advances, wireless metropolitan-area communication systems using mesh networking (as exemplified by IEEE 802.16j) seem to provide many advantages compared to existing cellular systems. This represents a change in the paradigm of mobile communications since it shows that their evolution relies on using smart terminals that can communicate with one another whereas the volume and, possibly complexity, of central infrastructure is reduced or at worst maintained. By itself, the change is already known among the research community and it has given rise to research topics such as cooperative communications [6, 7].

Among the set of cooperative techniques, opportunistic relay selection (ORS) is a useful strategy for practical implementation [8]. This is because ORS is a low complexity strategy consisting in only activating the best relay (in accordance with the performance metric). Apart from the inherent simplicity of the proposed technique, this strategy avoids the need of synchronization (needed by most distributed space-time coding schemes) and reduces the power consumption of the terminals. When ORS is implemented in a real system, however, there may exist a delay between the instants when the selection process is encompassed and the actual transmission of data from the selected relay takes place. In other words, the channel state of the selected relay considered at the selection decision can substantially differ from the actual one and, as a result, system performance is affected.

The study of the impact of outdated channel state information (CSI) on ORS has been addressed by few authors. For instance, it was shown in [9] that a selection relaying mechanism based on localization knowledge can outperform an opportunistic scheme with instantaneous information. Although it was not explicitly discussed, the reason for that being that available CSI was subject to delays. As a consequence, the selection scheme proposed in [9] may work better when decisions are made based on location information instead of instantaneous but outdated CSI (localization variations are considerably slower than those induced by the wireless channel).

Our intention here is to analyse how WiMAX can be improved by using ORS in realistic conditions of delayed CSI. We focus our attention on studying the outage probability of a two-hop cooperative scheme, where the probability of outage is defined as the probability that the instantaneous capacity of the system is below a predefined value R. As we will show later, there may be situations where using a cooperation scheme does not provides benefits for the network.

2. Objectives

The main objectives of this work have been presented in the previous section and can be summarized as follows:

1. To obtain an analytical expression of the impact of outdated CSI on relay selection.
2. To investigate the viability of using a cooperative scheme in WiMAX networks.

3. System model

Consider a WiMAX network where one mobile subscriber unit (SU) sends information to the BS. In order to improve system performance, a cooperative mechanism is considered. In particular, an ORS strategy is adopted in a scenario with K mobile SUs of the network working as relays. In figure 1, we present an example of the proposed scenario. Notice that we have considered a network topology where relays are linearly placed in a segment of distance d halfway between the SU and the BS, being d also the distance of the SU-BS link.

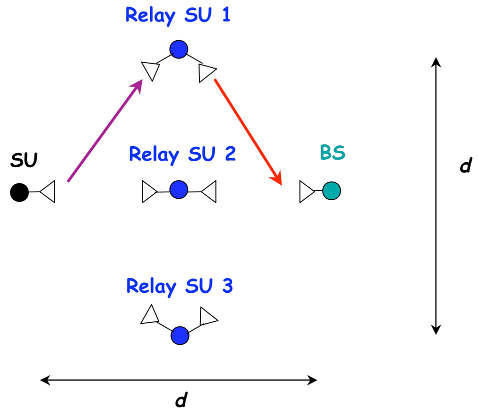

Figure 1: Scheme of the proposed relaying strategy.

3.1.– Signal Model

For the sake of notation simplicity, we define an arbitrary link A-B between two nodes A and B. Node A can be the source ($A=S$) or the k-th relay ($A=k$), whereas node B can correspond to the k-th relay ($B=k$) or to the destination ($B=D$). With this model in mind, the received signal can be written as follows:

$$r_B = h_{A,B} x_A + n_B$$

where x_A is the transmitted symbol from node A with power $P_A = E\left[|x_A|^2\right]$, n_B is AWGN noise with zero mean and variance σ_n^2 (independent of the value of B), $h_{A,B}$ is the channel response between nodes A and B modelled as $h_{A,B} \sim CN\left(0\ ,\ \sigma_{A,B}^2\right)$ (Rayleigh fading), being $\sigma_{A,B}^2$ the channel strength depending on the simplified path-loss model, $\sigma_{A,B}^2 = (\lambda_c / 4\pi d_o)^2 (d_{A,B}/d_o)^{-\mu}$, with λ_c standing for the carrier wave-length, d_o is a reference distance, $d_{A,B}$ is the distance of the link and μ is the path-loss coefficient (being $\mu=3$ in this work). We assume a block-fading channel where the channel response remains constant during one time-slot and that the different channels (for changing A or B) are independently distributed. Concerning power allocation, we consider that total transmit power is evenly distributed among the source and the selected relay, k^*, i.e., $P_S=P_{k^*}=P/2$. We denote by $\gamma_{A,B} = P_A |h_{A,B}|^2 / \sigma_n^2$ the instantaneous signal-to-noise ratio (SNR) experienced in the link A-B in a given time-slot and by $\bar{\gamma}_{A,B} = P_A \sigma_{A,B}^2 / \sigma_n^2$ its long-term average. Also, we define $\hat{\gamma}_{A,B}$ as the SNR employed by the relay selection mechanism, which can differ from the actual SNR $\gamma_{A,B}$ but both of them have the same long-term average $E\left[\hat{\gamma}_{A,B}\right] = E\left[\gamma_{A,B}\right] = \bar{\gamma}_{A,B}$ (further details can be found in the Subsection 3.3.). Finally, it is worth pointing out that the main scope of this work is to show the impact of outdated CSI on relay selection decisions and, for the sake of mathematical tractability, we will be considering the capacity of single carrier in each hop. The study can be easily extended to OFDM by applying the same analysis to each subcarrier simultaneously and, hence, it is applicable to WiMAX on a subcarrier per subcarrier basis.

3.2.– Relaying mechanism

In this work, we consider a half-duplex two-hop decode and forward (DF) protocol as relaying strategy. When using half-duplex DF, the transmission is divided in two time-slots. In the first time-slot, the source transmits the information to the relays, which attempt to demodulate and decode this information. In the second time-slot, the relays encode again the information and retransmit it to the destination [7].

In an ORS scheme, only the best relay is allowed to cooperate with the source. More specifically, the subset of relays able to decode the information is named as the decoding subset $\mathcal{D}$ and, from that subset, the relay with the best relay-destination channel quality retransmits the information. Unlike other approaches, the scheme proposed in this work selects the relay with the largest normalized SNR instead of the largest absolute SNR because of practical considerations. In other words, the selected relay k^* is such that:

$$k^* = \arg\max_{k \in \mathcal{D}} \left\{ \frac{\hat{\gamma}_{k,D}}{E\left[\hat{\gamma}_{k,D}\right]} \right\} = \arg\max_{k \in \mathcal{D}} \left\{ \frac{\hat{\gamma}_{k,D}}{\bar{\gamma}_{k,D}} \right\}$$

The reason why we propose this selection strategy is to use all relays with the same probability. Thus, the power consumption of the different terminals is uniformly distributed, while diversity gains can still be efficiently extracted. This can help to improve the acceptance by the different users of cooperation mechanism since all of them contribute to common welfare with the same amount of battery. If the selection were based on the absolute SNR, some users may be reluctant to participate since they may experience battery consumption faster than the average. Notice that the relay selection approach makes its decision based on the estimated version of the SNR, $\hat{\gamma}_{k,D}$. Concerning the accuracy of this estimate, it will depend on the way that CSI is provided. Here, we propose and discuss two methodologies according with the adopted duplexing mode (FDD or TDD):

1. FDD: since uplink and downlink channels operate at different frequency bands, feedback mechanisms are required. First of all, relays belonging to the decoding set send a signalling message to the destination (i.e., BS) indicating that they are able to relay the message. This signalling message can be, for instance, a pilot sequence used by the BS to estimate the instantaneous SNRs of the different relays. Once the different SNRs are estimated, the BS selects the relay with the best quality and broadcasts this decision via a selection command (only $\log_2 K$ bits required).
2. TDD: in this scheme channel reciprocity between the uplink and downlink holds. Then, each of the relays is able to know its own CSI. With this information, a possible selection strategy is that proposed in [10]. Those relays belonging to the decoding set start a timer. The timer of each relay adopts as initial value a parameter inversely proportional to its instantaneous SNR. Then, the timer that first expires is that belonging to the best relay. In order to avoid collision, this relay signals its presence to the rest of relays via a flag packet before the relaying procedure is started.

As can be observed in both strategies, there exists a time delay, T_D, between decision and relay transmission instants that may affect system performance.

3.3.– Modelling of CSI delay

We consider that the SNR estimates available at the selection procedure were obtained from a channel state, $\hat{h}_{k,D}$, which differs from the actual channel response, $h_{k,D}$, due to the effect commented above. Indeed $\hat{h}_{k,D}$ is an outdated version of $h_{k,D}$, i.e. these two random variables are samples of the same Gaussian process. Then, $h_{k,D}$ conditioned on $\hat{h}_{k,D}$ follows a Gaussian distribution:

$$h_{k,D}\left|\widehat{h}_{k,D} \sim CN\left(\rho_k \widehat{h}_{k,D}\ ,\ (1-\rho_k^2)\sigma_{k,D}^2\right)\right. \tag{1}$$

where ρ_k is the correlation coefficient between $h_{k,D}$ and $\widehat{h}_{k,D}$. This parameter can take different values according with the channel model[1]. From the above discussion, it is straightforward to show that the actual SNR, $\gamma_{k,D}$, conditioned on its estimate, $\widehat{\gamma}_{k,D} = P_k\left|\widehat{h}_{k,D}\right|^2/\sigma_n^2$, follows a non-central chi-square distribution with 2 degrees of freedom, whose probability density function (pdf) takes the following expression:

$$f_{\gamma_{k,D}|\widehat{\gamma}_{k,D}}\left(\gamma_{k,D}\middle|\widehat{\gamma}_{k,D}\right) = \frac{1}{\overline{\gamma}_{k,D}(1-\rho_k^2)}\exp\left(-\frac{\gamma_{k,D}+\widehat{\gamma}_{k,D}\rho_k^2}{\overline{\gamma}_{k,D}(1-\rho_k^2)}\right)I_o\left(\frac{2\sqrt{\gamma_{k,D}\widehat{\gamma}_{k,D}\rho_k^2}}{\overline{\gamma}_{k,D}(1-\rho_k^2)}\right) \tag{2}$$

with $I_o(\bullet)$ standing for the zero-order modified Bessel function of the first kind and that the long-term average of $\widehat{\gamma}_{k,D}$ is equal to $E\left[\widehat{\gamma}_{k,D}\right] = E\left[\left|\widehat{h}_{k,D}\right|^2\right]P_k/\sigma_n^2 = E\left[\left|h_{k,D}\right|^2\right]P_k/\sigma_n^2 = \overline{\gamma}_{k,D}$.

4. Outage probability analysis

As commented previously, we define the outage probability as the probability that the instantaneous capacity of the system is below a predefined value R. Since we consider a two-hop DF scenario, we should start the analysis by studying the decoding subset $\mathcal{D}$, i.e. the subset of relays that are not in outage when considering the source-to-relay link:

$$\mathcal{D} = \left\{k : \log_2\left(1+\gamma_{S,k}\right) \geq 2R\right\} = \left\{k : \gamma_{S,k} \geq 2^{2R}-1\right\}$$

Note that we have considered that outage in the first hop occurs when instantaneous capacity is lower than $2R$ (as it will done in the relay-to-destination link). By doing so, the resulting end-to-end spectral efficiency is R as the proposed two-hop scheme requires two time-slots to transmit the information from the source to the destination.

By defining now $\mathcal{D}_\ell$ as an arbitrary decoding subset with l relays, we can easily compute its probability as:

$$\text{Prob}(\mathcal{D}_\ell) = \prod_{i\in\mathcal{D}_\ell}\text{Prob}\left(\gamma_{S,i} \geq y\right)\prod_{j\notin\mathcal{D}_\ell}\text{Prob}\left(\gamma_{S,j} < y\right) = \prod_{i\in\mathcal{D}_\ell}\exp\left(-y/\overline{\gamma}_{S,i}\right)\prod_{j\notin\mathcal{D}_\ell}\left(1-\exp\left(-y/\overline{\gamma}_{S,j}\right)\right) \tag{3}$$

where the second equality comes from the Rayleigh fading assumption and y has been defined as $y = 2^{2R}-1$ for the sake of notation simplicity. With this last expression, the outage probability of ORS can be written as follows [8]:

$$\text{Prob(outage)} = \sum_{l=0}^{K}\sum_{\mathcal{D}_\ell}\text{Prob}(\text{outage}\mid\mathcal{D}_\ell)\text{Prob}(\mathcal{D}_\ell) \tag{4}$$

where the second summation is over all the possible decoding subsets $\mathcal{D}_\ell$ (i.e., the $\binom{K}{l}$ possible subsets of l relays taken from the K relays). As for $\text{Prob}(\text{outage}\mid\mathcal{D}_\ell)$, this is the probability that the selected relay is in outage conditioned on the fact the decoding subset is $\mathcal{D}_\ell$. In [8], this probability was solved by assuming an ideal scenario with an absolute SNR selection. Our contribution here is to adapt the outage expression to a (realistic) scenario with outdated CSI and a max-normalized SNR strategy. Indeed, the only term in (4) affected by these two particularities is $\text{Prob}(\text{outage}\mid\mathcal{D}_\ell)$. This is because a node belongs to the decoding set if it has perfectly decoded the information, which is independent of CSI delays and relay selection decisions. Conversely, $\text{Prob}(\text{outage}\mid\mathcal{D}_\ell)$ depends on the relay selection accuracy and this clearly depends on both ρ_k and how the relay has been selected.

[1] Under the assumption of a Jakes' model, for instance, the correlation coefficient takes the value $\rho_k = J_o(2\pi f_{d,k}T_{D,k})$, where $f_{d,k}$ stands for the Doppler frequency, $T_{D,k}$ is the delay mentioned in the previous subsection, and $J_o(\cdot)$ denotes the zero-order Bessel function of the first kind.

When l=0, that probability is clearly equal to 1 as there are no active nodes to relay the transmission. For l>0, we should first define $\mathcal{A}_{k,\mathcal{D}_\ell}$ as the event that relay k is selected (i.e., $k^*=k$) under the assumption of a given decoding set $\mathcal{D}_\ell$. By doing so, we can re-rewrite $\text{Prob}(\text{outage} \mid \mathcal{D}_\ell)$ as follows:

$$\begin{aligned}\text{Prob}(\text{outage} \mid \mathcal{D}_\ell) &= \sum_{k\in\mathcal{D}_\ell} \text{Prob}\left(\gamma_{k,D} < y \mid \mathcal{A}_{k,\mathcal{D}_\ell}\right)\text{Prob}\left(\mathcal{A}_{k,\mathcal{D}_\ell}\right) \\ &= \sum_{k\in\mathcal{D}_\ell} \int_0^\infty F_{\gamma_{k,D}|\hat{\gamma}_{k,D}}\left(y\middle|\hat{\gamma}_{k,D}\right) f_{\hat{\gamma}_{k,D}|\mathcal{A}_k}\left(\hat{\gamma}_{k,D}\middle|\mathcal{A}_{k,\mathcal{D}_\ell}\right)\mathrm{d}\hat{\gamma}_{k,D}\text{Prob}\left(\mathcal{A}_{k,\mathcal{D}_\ell}\right) \\ &= \frac{1}{l}\sum_{k\in\mathcal{D}_\ell} \int_{\gamma_{k,D}=0}^{y} \int_{\hat{\gamma}_{k,D}=0}^{\infty} f_{\gamma_{k,D}|\hat{\gamma}_{k,D}}\left(\gamma_{k,D}\middle|\hat{\gamma}_{k,D}\right) f_{\hat{\gamma}_{k,D}|\mathcal{A}_k}\left(\hat{\gamma}_{k,D}\middle|\mathcal{A}_{k,\mathcal{D}_\ell}\right)\mathrm{d}\gamma_{k,D}\mathrm{d}\hat{\gamma}_{k,D}\end{aligned} \tag{5}$$

where $F(\cdot)$ stands for the cumulative density function (CDF), $\text{Prob}\left(\mathcal{A}_{k,\mathcal{D}_\ell}\right)$ is equal to $1/l$ due to the fairness property of the proposed relay selection strategy (i.e. all the normalized estimated SNRs have the same statistics) and $f_{\gamma_{k,D}|\hat{\gamma}_{k,D}}\left(\gamma_{k,D}\middle|\hat{\gamma}_{k,D}\right)$ is given by (2). Note that $f_{\hat{\gamma}_{k,D}|\mathcal{A}_k}\left(\hat{\gamma}_{k,D}\middle|\mathcal{A}_{k,\mathcal{D}_\ell}\right)$ can be easily computed since this relay selection problem is statistically equivalent to the scheduling problem observed in a multi-user broadcast channel with independently distributed Rayleigh fading channels and a max-normalized SNR scheduler. More specifically, the following equation can be obtained [11]:

$$f_{\hat{\gamma}_{k,D}|\mathcal{A}_k}\left(\hat{\gamma}_{k,D}\middle|\mathcal{A}_{k,\mathcal{D}_\ell}\right) = l\frac{\exp\left(-\hat{\gamma}_{k,D}/\bar{\gamma}_{k,D}\right)}{\bar{\gamma}_{k,D}}\left(1-\exp\left(-\hat{\gamma}_{k,D}/\bar{\gamma}_{k,D}\right)\right)^{l-1} \tag{6}$$

By plugging (6) and (2) into (5) we obtain an integral equation already solved in a work related with multi-user diversity and imperfect CSI [12] (details are omitted for brevity):

$$\text{Prob}(\text{outage} \mid \mathcal{D}_\ell) = \sum_{k\in\mathcal{D}_\ell}\sum_{m=0}^{l-1}\binom{l-1}{m}\frac{(-1)^m}{m+1}\left(1-\exp\left(-\frac{y(m+1)}{\bar{\gamma}_{k,D}(1+(1-\rho_k^2)m)}\right)\right) \tag{7}$$

Finally, by introducing (3) along with (7) in (4), the outage probability can be written as:

$$\begin{aligned}\text{Prob}(\text{outage}) &= \prod_{j=1}^{K}\left(1-\exp\left(-y/\bar{\gamma}_{S,j}\right)\right) \\ &+ \sum_{l=1}^{K}\sum_{\mathcal{D}_\ell}\sum_{k\in\mathcal{D}_\ell}\sum_{m=0}^{l-1}\binom{l-1}{m}\frac{(-1)^m}{m+1}\left(1-\exp\left(-\frac{y(m+1)}{\bar{\gamma}_{k,D}(1+(1-\rho_k^2)m)}\right)\right)\prod_{i\in\mathcal{D}_\ell}\exp\left(-y/\bar{\gamma}_{S,i}\right)\prod_{j\notin\mathcal{D}_\ell}\left(1-\exp\left(-y/\bar{\gamma}_{S,j}\right)\right)\end{aligned}$$

where the first term is related to the case that $\mathcal{D}$ is an empty set (i.e., l=0).

5. Results

In this section, we compare the outage probability of the proposed cooperative scheme with that obtained without cooperation. Special attention has been paid to carrying out a fair comparison in a realistic scenario. It has been considered that the distance of the source-to-destination link is d=100 meters, the carrier frequency is set to f_c=2.5GHz, the target rate is R=1 bits/seg/Hz and the number of relays is K=5. Finally, we define system SNR as the average received SNR of the single-hop scheme. For each value of system SNR, the cooperative schemes use the same total power P as that needed by the single-hop scenario to achieve this SNR value. By doing so, we are fairly evaluating the advantage of using cooperation as the total transmit power of the system is kept constant.

As observed in Figure 2, the proposed max-normalized SNR strategy is able to extract the diversity gains of the cooperative system (ρ=1). However, performance is quite sensitive to the value of ρ. Asymptotic performance is significantly affected when ρ moves away from 1. In particular, one can observe that only a slight improvement can be obtained by using cooperation when ρ=0.6. For the case that ρ=0.1, it is noticeable that it is better to use a single-hop (i.e. non-cooperative) strategy. This is because better results are obtained by concentrating total power and transmission time in a single-hop communication instead of dividing them between the source and the relay terminals.

On the basis of the conclusions above, it is interesting to provide system designers with tables indicating when cooperation is beneficial. In that direction, a possible example is the validity region presented in Figure 3. More specifically, it is shown the region for which it is appropriate using a cooperative scheme as a function of the number of relays and the correlation value. As observed, a high number of relays are needed to exploit cooperative diversity in scenarios with low ρ. In other words, although the diversity provided by relay selection can compensate CSI uncertainties, a large number of relays are required when the quality of the CSI estimate decreases.

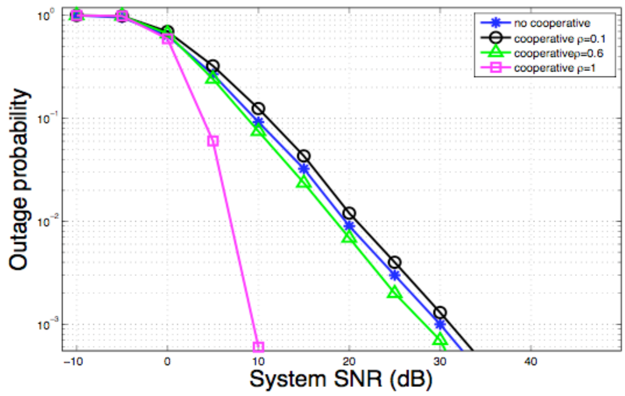

Figure 2: Outage probability vs. system SNR for cooperative and non-cooperative systems. (K=5 relays, d=100 m, symbols: simulated results, curves: analytical expression).

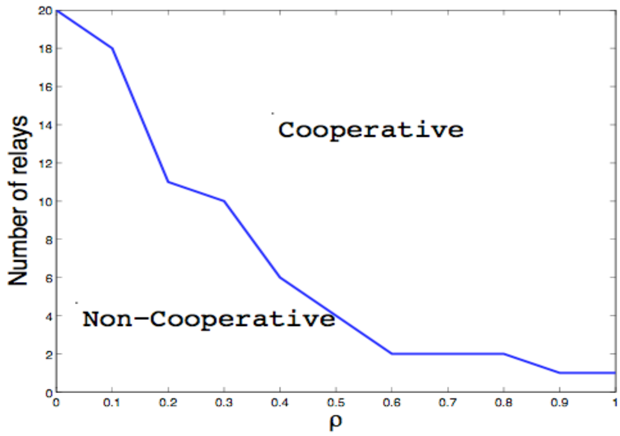

Figure 3: Validity regions for cooperative and non-cooperative systems. (K=5 relays, d=100 m, system SNR= 20dB, 1% outage probability).

Finally, it is worth noting that, although the analysis has been carried out from an information theoretic point of view, it can be readily extended to a practical scheme with adaptive coding and modulation (ACM). Notice that expressions derived in the previous section evaluates the probability of having instantaneous SNR lower than a specified value given by the Shannon capacity, y, and this value can be set equal to the different SNR thresholds of the ACM modes.

6. Business Benefits

The business benefits resulting from the study carried out in this work are enumerated below:

1. An analytical tool has been provided to assess performance of cooperative schemes. System designers can use this tool to forecast the benefits of cooperation in practical

schemes. By doing so, trade-offs in terms of increased cost vs. performance can be assessed before applying cooperative communications products.
2. The proposed max-normalized SNR relay selection strategy helps guaranteeing a fair balance between cooperation and own usage of the terminals. Actions like this are crucial for the user acceptation of cooperation strategies and, as a consequence, the commercialization of cooperative terminals.
3. It has been claimed that multi-hop communications can contribute to reduce power consumption at global level and help to fight against climate change because power efficiency is achieved by dividing a link in several shorter sections. With the study carried in this work, it can be assessed when this claim is true depending on CSI knowledge and the desired data rate.

To conclude this section, it is worth noting that the objectives of this work are in close alignment with the expected impacts of the challenge "The Network of the Future" of FP7 [13] to the extent that it contributes to define global standards for a new generation of ubiquitous and extremely high capacity network and service infrastructures, to reinforce European industrial leadership in wired and wireless networks and to create new industrial/service opportunities in Europe.

7. Conclusions

In this work, we have studied the impact of outdated CSI on cooperative systems. The analysis has been carried out in terms of the outage probability of the system. To do so, an analytical expression has been obtained for an ORS scenario where the relay selection is based on the (fair) max-normalized SNR criterion. With this analytical study, it has been proved that the benefits obtained using this cooperative scheme fade away when the number of relays decreases and the level of CSI uncertainty increases beyond certain limits. In those situations, the complexity of the system is increased without obtaining any diversity gain. In particular, we have presented the detailed conditions on CSI quality and number of relays that make ORS worthwhile. Hence, the necessity of modifying the relay selection mechanism in order to improve robustness against CSI impairments is made apparent, raising multiple open issues for further research.

Acknowledgments

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