A Novel Framework for the Utilisation of Dynamic Relays in Cellular Networks

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***Abstract*—Cooperative diversity has recently attracted the attention as it is promising for boosting performance of future wireless systems without compromising the desired high spectral efficiency. However, utilisation of dynamic relays in a cellular network (user terminals act as relay nodes) is very challenging since it comes together with resource constraints, increased signaling overhead and complexity. In this contribution a novel framework is presented which exploits dynamic relays in a cellular network under the presence of inter-cell interference while keeping overheads at an affordable level. It is shown that under the proposed framework, relay assisted transmission significantly improves performance. Furthermore, global power constraints are met while low signaling overhead and complexity are maintained with the use of thresholds.**

I. Introduction

Relay utilisation is well acknowledged as an effective means of increasing capacity, robustness, fairness and coverage of wireless systems without consuming extra bandwidth [1]. The transmitting source is aided by one or more relay nodes which together with the source node form a virtual antenna array. The destination node benefits from receiving multiple copies of the transmit signal by performing appropriate diversity combining. The deployment of relaying enabled systems however, is constrained by resource limitations, the need for coordination and increased complexity; therefore their utilisation in practice still remains challenging [2].

In cellular systems, for exploiting cooperative diversity, static or dynamic relay stations (RSs) can be considered. The former implies that fixed relay nodes are deployed in specific positions of a cell [3],[4] whereas the latter implies that Mobile Stations (MSs) act as relays and their position changes in time as users move [5]. Furthermore, RS selection and MS scheduling can be performed in a centralised [5],[6] or a distributed fashion [7]. Dynamic RS deployment is very cost effective since it does not require extra infrastructural costs and also provides many degrees of freedom that can be leveraged for boosting performance. However it entails higher complexity and signaling overhead since user mobility renders RS selection rather complicated.

For exploiting cooperative diversity several relaying techniques have been proposed, with the most fundamental ones being amplify-and-forward (AF) and decode-and-forward (DF) [1]. The triangular cooperative model has been taken into account, where there is one source, one relay and one destination. According to AF, the RS amplifies the received signal from the source node and forwards it to the destination node without decoding it (non-regenerative scheme). The amplification factor is properly adjusted in order for the power constraints of the RS to be met. Nonetheless this relatively simple scheme comes with the detrimental side-effect that the RS apart from the received signal it amplifies its thermal noise together with its received inter-cell interference (ICI), a factor which limits performance. In DF, the RS decodes and retransmits the received message conditioned that it is able to decode it (regenerative scheme). The capacity of both schemes is limited by the source-relay link.

In this contribution we focus on leveraging dynamic RSs in a cellular network with centralised RS selection and MS scheduling under the existence of ICI. In this setting the Base Station (BS) makes the decisions on MS and RS scheduling. The optimal strategy for maximising performance is that all MSs of the cell are considered as potential relay nodes or destinations. This inevitably entails high feedback overhead and scheduling complexity since the BS needs to know all the BS-MS and MS-MS channel coefficients and perform exhaustive search in order to identify the best MS-RS pair with respect to the considered metric. Therefore the aforementioned overhead and complexities need to be alleviated. In this respect, a novel framework focusing on the downlink is presented enabling the use of dynamic RSs while reducing the signaling and the relay selection complexity of [5]. Each MS does not feedback to the BS the channel coefficients between itself and the rest of cell MSs but only a subset of them determined by a threshold. The considered relaying techniques are the AF and DF whose performance is compared on an interference limited environment.

The paper is structured in the following way: In section II the signal and system model are presented. In section III the algorithms for relay selection with signaling and complexity reduction are described and in section IV numerical results are presented and discussed. In section V the paper is concluded.

Notation: Boldface symbols denote matrices, $(.)^H$ denotes the transpose conjugate and $\det(.)$ denotes the determinant operator. Furthermore $|.|$ represents the cardinality of a set and $\mathbb{C}^k$ the complex space with k dimensions.

II. Signal and System Model

The network consists of N Base Stations with one antenna each and K single antenna Mobile Stations (MSs) per cell uniformly distributed in the cell area. It is assumed that all BSs communicate at the same frequency (full frequency reuse).

A. Relay assisted transmission

Downlink communication towards a MS can be assisted by the use of another MS as a relay partner (triangular cooperative model). Let h_{sd}, h_{sr} and h_{rd} be the source-destination, source-relay and relay-destination channel coefficients respectively. When relay assisted communication is enabled, communication between source and destination takes place in two time slots. In the first time slot the source transmits a symbol u_{s1} and the relay receives the signal y_r. If diversity is enabled, during the same time slot, not only the relay is listening but also the source, receiving the signal y_{d1}. During the second time slot the relay transmits a symbol $u_r = f(y_r)$ which is a function of its received signal y_r and the employed cooperative protocol. In the same time slot there is the possibility that the source also transmits another independent symbol u_{s2}. If during the second time slot only the relay transmits, the communication protocol is called *orthogonal*, otherwise it is called *non-orthogonal*. In the more general case of non-orthogonal transmission and when diversity is enabled, the destination node and the relay node receive during the first time slot

$$\begin{aligned} y_{d1} &= h_{sd}\sqrt{p_{s1}}u_{s1} + \chi_{d1} \\ y_r &= h_{sr}\sqrt{p_{s1}}u_{s1} + \chi_r \end{aligned} \tag{1}$$

and the destination node receives during the second time slot

$$y_{d2} = h_{rd}\alpha_r u_r + h_{sd}\sqrt{p_{s2}}u_{s2} + \chi_{d2} \tag{2}$$

where α_r is the amplification factor whose value depends on the communication protocol and it ensures that the RS power constraints are met. Furthermore

$$\begin{aligned} \chi_{d1} &= z_{d1} + n_{d1} \\ \chi_r &= z_r + n_r \\ \chi_{d2} &= z_{d2} + n_{d2} \end{aligned} \tag{3}$$

where $n \sim \mathcal{CN}(0, \sigma^2)$ represents the zero mean circularly symmetric additive Gaussian noise with variance σ^2. z_i represents the received inter-cell interference at the i-th node. It is assumed that in each time slot the total power emanating from a cell is constrained to P. Therefore $p_{s1} \le P$ and $p_{s2} + p_r \le P$, where p_{s1} and p_{s2} represent the transmit power of the source node (BS) in the first and second time slot respectively and p_r is the power stemming out of the relay node.

1) Amplify-and-Forward: With AF the relay node just amplifies its received signal y_r by using an amplification factor α_r which ensures that the relay power constraints p_r are met. Therefore in (2), $u_r = y_r$ and

$$\alpha_r = \sqrt{\frac{p_r}{|h_{sr}|^2 p_{s1} + \chi_r^2}} \tag{4}$$

where $\chi^2 = |\chi|^2$ for notational simplicity. There are two modes of operation for the AF protocol, the orthogonal (OAF) and the non-orthogonal one (NAF). In the case of NAF transmission ($p_{s2} \neq 0$), the equivalent channel matrix is

$$\mathbf{H}_{AF} = \begin{pmatrix} h_{sd}\sqrt{\frac{p_{s1}}{\chi_{d1}^2}} & 0 \\ \frac{h_{rd}\alpha_r h_{sr}\sqrt{p_{s1}}}{\sqrt{|h_{rd}|^2\alpha_r^2\chi_r^2 + \chi_{d2}^2}} & h_{sd}\sqrt{\frac{p_{s2}}{|h_{rd}|^2\alpha_r^2\chi_r^2+\chi_{d2}^2}} \end{pmatrix}. \tag{5}$$

The achievable capacity associated with the equivalent channel matrix is,

$$C_{NAF} = \frac{1}{2}\log_2\left(\det\left(\mathbf{I} + \mathbf{H}_{AF}\mathbf{H}_{AF}^H\right)\right). \tag{6}$$

The factor $\frac{1}{2}$ is related to fact that transmission takes place in two time slots. In the case of OAF ($p_{s2} = 0$) the equation above reduces to

$$C_{OAF} = \frac{1}{2}\log_2\left(1 + \frac{|h_{sd}|^2 p_{s1}}{\chi_{d1}^2} + \frac{|h_{rd}|^2|h_{sr}|^2\alpha_r^2 p_{s1}}{|h_{rd}|^2\alpha_r^2\chi_r^2 + \chi_{d2}^2}\right). \tag{7}$$

2) Decode-and-Forward: In the case of DF, the relay node fully decodes its received signal, if decoding is possible, and retransmits it to the destination. Therefore $u_r = u_s$ and $\alpha_r = \sqrt{p_r}$ in (2). It can operate in two modes like the AF protocol, the orthogonal (ODF) and the non-orthogonal one (NDF). If the signal is decoded correctly, the equivalent channel matrix for NDF transmission is

$$\mathbf{H}_{DF} = \begin{pmatrix} h_{sd}\sqrt{\frac{p_{s1}}{\chi_{d1}^2}} & 0 \\ h_{rd}\sqrt{\frac{p_r}{\chi_{d2}^2}} & h_{sd}\sqrt{\frac{p_{s2}}{\chi_{d2}^2}} \end{pmatrix}. \tag{8}$$

Under the DF framework the channel can be seen as a multiple-access channel. The capacity of the DF scheme is limited by the source-relay link, since the relay node needs to correctly decode its received signal. Therefore the following set of constraints need to be met [8],

$$\begin{aligned} &R_{t1} \le \min\left\{\log_2\left(1 + \frac{|h_{sr}|^2 p_{s1}}{\chi_r^2}\right), \log_2\left(1 + \frac{|h_{rd}|^2 p_r + |h_{sd}|^2 p_{s1}}{\chi_{d2}^2}\right)\right\} \\ &R_{t2} \le \log_2\left(1 + \frac{|h_{sd}|^2 p_{s2}}{\chi_{d2}^2}\right) \\ &R_{max} \le \log_2\left(\det\left(\mathbf{I} + \mathbf{H}_{DF}\mathbf{H}_{DF}^H\right)\right) \end{aligned} \tag{9}$$

where R_{t1}, R_{t2} refer to the encoding rates of the source during the first and the second time slot respectively. R_{max} refers to the maximum achievable rate of the equivalent MAC channel. With respect to (9) the capacity of the NDF cooperative protocol when diversity is enabled is

$$C_{NDF} = \begin{cases} \frac{1}{2}R_{max}, & R_{t1} + R_{t2} \ge R_{max} \\ \frac{1}{2}\left(R_{t1} + R_{t2}\right), & R_{t1} + R_{t2} < R_{max}. \end{cases} \tag{10}$$

If transmission takes place in an orthogonal manner, the capacity expression reduces to

$$C_{ODF} \leq \frac{1}{2}\min\left\{\log_2\left(1+\frac{|h_{sr}|^2 p_{s1}}{\chi_r^2}\right),\right. \left.\log_2\left(1+\frac{|h_{rd}|^2 p_r + |h_{sd}|^2 p_{s1}}{\chi_{d2}^2}\right)\right\}. \quad (11)$$

B. Non-relay assisted transmission

In the case there is absence of cooperation, the Signal to Interference plus Noise Ratio (SINR) of the i-th MS γ_i, when k is its associated BS, is

$$\gamma_i = \frac{|h_{ik}|^2 p_k}{\sum_{j\neq k}|h_{ij}|^2 p_j + \sigma^2} \quad (12)$$

where $|h_{ik}|^2$ corresponds to the channel gain of the useful signal and $\sum_{j\neq k}|h_{ij}|^2$ corresponds to the detrimental ICI and p_k and p_j correspond to the respective power allocation levels. In this paper equal power allocation is considered for simplicity. Each MS is assigned to the BS that provides the strongest received average SNR.

An important metric apart from the achievable capacity is the probability of outage,

$$P_o = \Pr\{C < R\} \quad (13)$$

where C represents the achievable rate between the source node and the destination node and R represents the transmission rate of the source.

III. Proposed Framework

It is assumed that users are served in a round-robin fashion in order to guarantee fairness. For the utilisation of dynamic relay nodes in order to aid the transmission to specific users, RS candidates need to be specified for each MS respectively. Each MS k needs to be associated with a set $\mathcal{R}(k)$ containing the indices of other MSs that are potential RS. The choice of the relay node can be based on different criteria.

A. Full Overhead Case

In the optimal case, the set of RS candidates for a specific MS destination comprises all the MSs of the cell apart from the destination MS [5]. Let $\mathcal{S}$ be the set comprising all the MSs of the cell, $|\mathcal{S}| = K$. If the target is the maximisation of the achievable rate when MS d is being served, the RS selection algorithm is,

$$r_s = \arg\max_{\substack{r\in\mathcal{S}\\ r\neq d}} C(r,d) \quad (14)$$

where r_s represents the RS index which aids the transmission towards destination node d. $C(r_s,d)$ is the achievable rate when the target node is d and communication is assisted by node r_s which acts as a RS. The achievable rate is also a function of the employed cooperation protocol. This implies that the BS which performs the RS selection needs to possess the full CSI of the BS-MS channels and also the MS-MS channels. Therefore each MS needs to estimate and feed back to the BS K channel coefficients overall in the case of single antenna BSs and MSs. This results to the feedback of K^2 channel coefficients per cell. The selected RS r_s of (14) will be utilised by the BS if the provided achievable rate $C(r_s,d)$ is greater than the case without the use of cooperation $C(d)$ (direct transmission). Therefore the final achievable rate is

$$C_{final}(d) = \max\{C(r_s,d), C(d)\}. \quad (15)$$

The BS needs to perform K calculations in order to select the best RS for the selected destination node and also calculate the capacity of the direct transmission. Therefore it is desirable that both feedback overhead and computational complexity at the BS are reduced.

B. Reduced Overhead Case

The size of the RS candidates set for each MS, and therefore signaling and complexity, can be substantially reduced without compromising performance. A reasonable criterion for choosing relay node candidates is based on the inter-user distance since it is likely that a relay node situated far from the destination node will not provide substantial gains. Algorithm 1 chooses relay node candidates for all cell MSs based on a distance threshold d_{th} and this leads to a substantial reduction of feedback load and complexity. By increasing this threshold the number of relay candidates per MS increases together with the feedback load since the channel coefficients related to RS candidates need to be communicated to the BS. However this load can be maintained small enough in order for maximum performance to be attained as it can be seen in section IV.

Algorithm 1 Choice of Relay Node Candidates

Require: Define distance threshold d_{th}
Require: In each time window all MSs broadcast a training signal and hear the training signals of the other MSs
  for all MSs $k \in \mathcal{S}$ **do**
    for all MSs $m \in \mathcal{S}, m \neq k$ **do**
      Step 1 Estimate the distance d_{km}
      if $d_{km} \leq d_{th}$ **then**
        MS m is a relay candidate for MS k and its index is added to $\mathcal{R}(k)$, where $\mathcal{R}(k) \subseteq \mathcal{S}$. h_{km} is estimated.
      end if
      Step 2 Feed back to the BS all indices $\mathcal{R}(k)$ and channel coefficients h_{kn}, $n \in \mathcal{R}(k)$
    end for
  end for

Under this framework each MS k feeds back instead of K channel coefficients $|\mathcal{R}(k)|$ channel coefficients, where $|\mathcal{R}(k)| \leq K$. Therefore the BS needs to perform $|\mathcal{R}(k)|$ calculations per MS in order to identify the best relay partner and decide whether to use it or not. Thus, apart from feedback load reduction, this framework mitigates the computational complexity at the BS side.

In this contribution MS scheduling is performed in a round-robin fashion in order to ensure fairness, although the proposed framework can be extended for the case of max-SNR scheduling. For the selected MS to be served, the relay selection procedure is given by the following algorithm.

Algorithm 2 Relay Node Selection

if MS k is selected to be served **then**
  Find $r_s = \arg\max_{\substack{r \in \mathcal{R}(k) \\ r \neq k}} C(r,k)$
  if $C(r_s,k) > C(k)$ **then**
    Utilise relay node r_s, $C_{final}(k) = C(r_s,k)$
  else
    Transmit directly to destination k, $C_{final}(k) = C(k)$
  end if
end if

After the best relay partner for each MS is identified, it is utilised if the provided achievable rate is greater to the case of direct transmission (no cooperation).

IV. Numerical Results

A network comprising two tiers of cells with a radius of 1 km has been considered (19 cells overall) where BSs are located in the cell centre. Each cell has K single antenna Mobile Stations (MSs) which are uniformly distributed in the cell area. It is assumed that all BSs have one omni-directional antenna and they communicate on the same frequency (full frequency reuse). We assume that MS selection is done in a round-robin fashion. The channel coefficient between the i-th MS and the j-th BS is,

$$h_{ij} = \Gamma_{ij}\sqrt{G\beta d_{ij}^{-\mu}\gamma_{ij}} \tag{16}$$

where d_{ij} is the distance of the i-th MS and the j-th BS. μ is the path-loss exponent and β the path-loss constant. γ_{ij} is a log-normal coefficient which models shadowing, $\gamma_{dB} \sim \mathcal{N}(0\,dB, 8\,dB)$, and Γ is the complex Gaussian coefficient which models small-scale fading, $\Gamma \sim \mathcal{NC}(0,1)$. G is the BS antenna power gain which is assumed to be 9 dB (gain on the elevation). For the pathloss, the 3GPP Long Term Evolution (LTE) model has been used. The channel coefficient between the MSs of the network is given by equation (16) and the antenna gain is one according to the LTE specifications for MSs.

In figure 1 it is plotted the average percentage of cell users considered as relay candidates per MS as a function of the distance threshold (algorithm 1). This percentage also corresponds to the average percentage of the total number of channel coefficients per cell fed back; this represents the feedback overhead. It can be seen that a distance threshold set to 0.5 km corresponds to considering about 20 per cent of the cell users as potential relay partners per MS.

In figure 2 it is plotted the average achievable rate performance for the proposed overhead reduction scheme against the distance threshold for the two modes of DF and AF

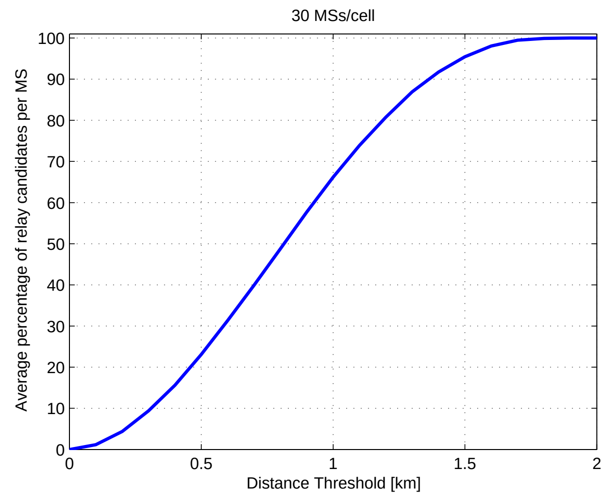

Fig. 1. A plot of the average percentage of considered relay candidates per MS as a function of the distance threshold.

protocols with enabled diversity (destination node listens in both time slots). In each time slot the power emanating from each cell is constrained. Consequently BS and RS share the available cell power during the second time slot (non-orthogonal schemes). Transmit power is determined by the System SNR which is the average SNR that a user experiences at the edge of the cell. It can be seen that the performance of all the considered schemes saturates when the threshold distance reaches 0.5 km (maximum performance is achieved). Therefore it can be inferred that with about 20 per cent of the total overhead, maximum performance can be attained. DF schemes outperform AF ones. More specifically, the NDF scheme achieves the greatest sum-rate performance, although the ODF performs the same when the threshold distance is greater than 0.6 km. Regarding the AF schemes, the OAF outperforms the NAF.

In figure 3 the probability of outage is plotted against the System SNR for source rate $R = 2$ bits/sec/Hz. Notably the smallest probability of outage is attained by the NDF scheme while all probabilities saturate when the System SNR exceeds 15 dB. This is due to the ICI as it becomes the limiting factor in the high transmission power regime. In figure 4 there is a plot of the achievable rate against the System SNR for the proposed scheme. It can be noticed that we attain gains with the utilisation of dynamic relays in all transmission power regimes. In figure 5 it can be seen the performance of the proposed framework as a function of the number of the cell MSs. It is clear that multi-user diversity gains can be attained in the process of dynamic relay partner selection.

V. Conclusion

Although the importance of cooperative diversity has been well recognised, utilisation of dynamic relay nodes in cellular systems remains challenging due to the high signaling load and complexity entailed. It is crucial that relay partner selection is done in an opportunistic way in order to optimise

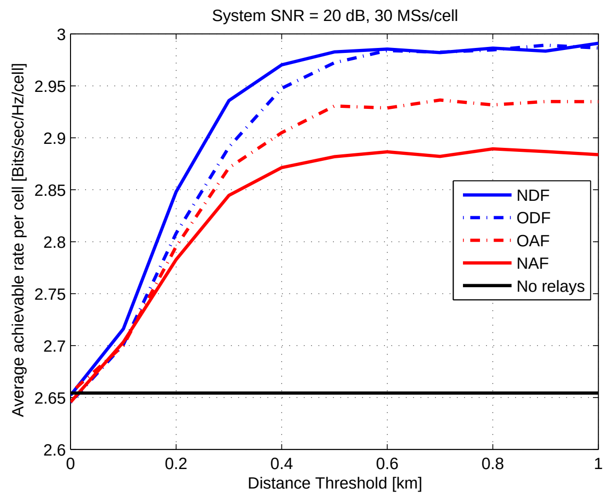

Fig. 2. A plot of the average sum-rate per cell versus distance threshold for the proposed framework.

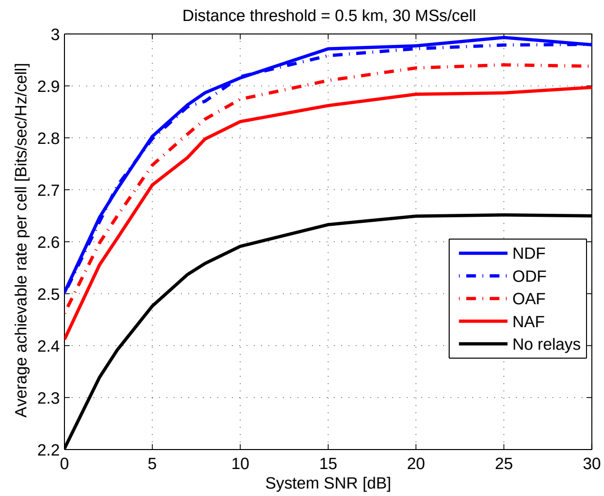

Fig. 4. A plot of the average sum-rate per cell versus system SNR.

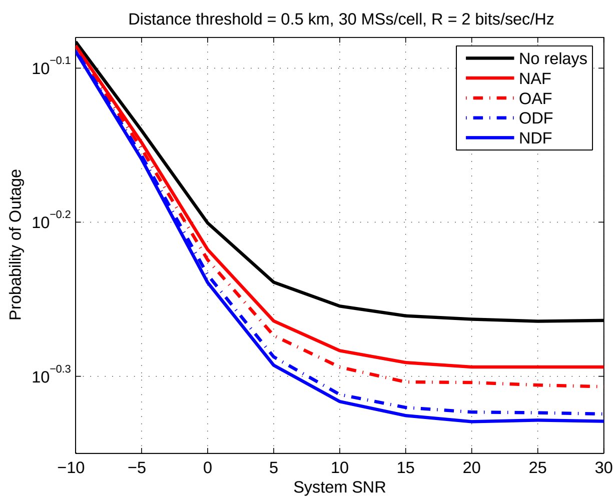

Fig. 3. A plot of the probability of outage versus the System SNR under the presence of ICI.

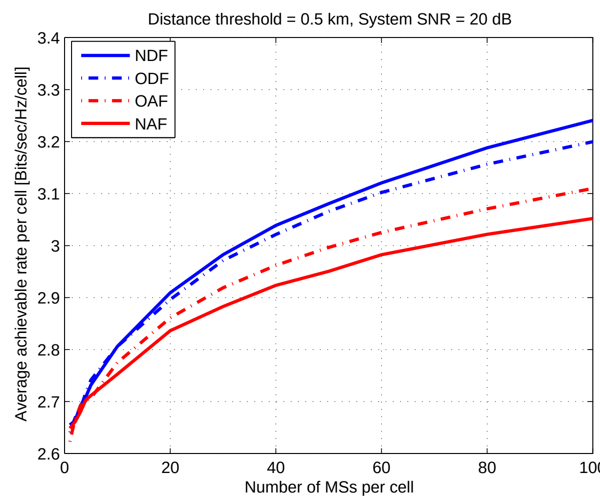

Fig. 5. A plot of the average sum-rate per cell versus the number of cell users.

network performance while keeping overheads to a minimum. In this contribution we have presented a novel framework for exploiting dynamic relays in a full frequency reuse cellular environment. For serving a specific MS of the cell, not all the cell MSs should be considered as potential relay partners. It is sufficient that a small subset of the overall MSs, the ones close to the destination node (determined by a distance threshold) become RS candidates. In this fashion, maximum performance can be attained while feedback overhead and complexity are dramatically reduced.

REFERENCES

[1] J.N. Laneman et al, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, December 2004.

[2] Y.W. Hong et al, "Cooperative Communications in Resource-Constrained Wireless Networks," *IEEE Signal Processing Magazine*, May 2007.

[3] R. Pabst et al, "Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio," *IEEE Communications Magazine*, September 2004.

[4] E. Yilmaz, R. Knopp and D. Gesbert, "Some System Aspects regarding Compressive Relaying with Wireless Infrastructure Links", in Proc. *IEEE GLOBECOM 2008*, New Orleans, USA, December 2008.

[5] S. Song, K. Son, H.W Lee and S. Chong, "Opportunistic Relaying in Cellular Network for Capacity and Fairness Improvement", in Proc. *IEEE GLOBECOM 2007*, Washington D.C, November 2007.

[6] H. Viswanathan and S. Mukherjee, "Performance of Cellular Networks with Relays and Centralized Scheduling," *IEEE Trans. on Wireless Communications*, vol. 4, no. 5, September 2005.

[7] A. Bletsas, A. Khisti, D.P. Reed and A. Lippman, "A Simple Cooperative Diversity Method Based on Network Path Selection," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, March 2006.

[8] R. Nabar, H. Boelckei, F.W Kneubuehler, "Fading Relay Channels: Performance Limits and Space-Time Signal Design," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 6, August 2004.