Bringing Mobile Relays for Wireless Access Networks into Practice– Learning When to Relay

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Abstract

Adding fixed relay nodes (RNs) to wireless access networks requires additional costly infrastructure. Utilising mobile RNs, i.e., user terminals that relay signals intended for other users being the destination nodes (DNs), is an appealing cost-effective solution. However the changing node topology increases the required signalling for relay selection (RS). The signalling overhead consists of control signals that need to be exchanged between the RNs, the source node (SN) and the DN, in order to achieve the objectives of cooperation. To reduce signalling without penalizing performance we propose a three-step approach exploiting statistical knowledge on the likelihood of attaining performance gains by using RNs as a function of the node position (position of DNs and RNs). In the first step only the cell DNs that are likely to gain from relaying request the assistance of RNs. In the second step, for each DN that requests relaying, a limited set of RN candidates is formed. These decisions are made with the aid of thresholds applied to inter-node distances whose values are based on the acquired statistical knowledge. In the final step, RN candidates feed back the relevant channel state information to the SN which performs RS. Furthermore we investigate the attained gains from mobile RNs as a function of the fading environment and we show that mobile RNs can help overcome the effects of severe fading.

Index Terms

Mobile relays, cooperative diversity, wireless access networks, relay selection, limited signalling.

I. Introduction

Multiple-Input Multiple-Output (MIMO) is a key technology for modern wireless systems as it can provide the necessary quality-of-service (QoS) and cover user requirements through diversity, spatial multiplexing, array gains and/or co-channel interference rejection [1], [2]. However the gains of point-to-point MIMO come at an expense as the complexity and the cost of a transceiver device is proportional to its number of antennas [2]. Furthermore the size constraints of conventional mobile stations (MSs) often prohibit the addition of extra antennas [3]. Therefore it is of great practical interest to investigate ways of realising some of the MIMO gains while circumventing the stringent constraints described above.

Cooperative relaying, also known as cooperative diversity, is a very promising technique that can achieve the diversity gains of MIMO without requiring collocated antennas [3]. The communication between a transmitting source node (SN) and a destination node (DN) is assisted by one or more relay nodes (RNs), that together with the SN form a virtual MIMO array. These nodes receive the SN message, process it and relay it to the DN [3], [4]. The DN benefits from receiving multiple copies of the transmit signal by performing appropriate diversity combining [3], [5]. Therefore cooperative relaying can exploit the spatial diversity inherent in wireless systems that offers additional advantages compared with point-to-point MIMO. The use of RNs can increase the coverage of wireless networks and provide a uniform QoS across the cell area [3]–[6].

Although cooperative relaying can realise some of the potential of MIMO without requiring extra antenna elements, it comes with significant overheads that ought to be addressed in order to bring this technology into practice. More specifically the use of RNs is constrained by resource limitations, e.g., battery life, and it requires high signalling which makes practical RN deployment challenging [7], [10]. The signalling overhead consists of control signals that need to be exchanged between the RNs, the SN and the DN, in order to achieve the objectives of cooperation. These control signals are necessary for example in order for the involved nodes to agree upon a specific mode of operation[1], to select the RNs that will assist transmission and to achieve node synchronization.

In wireless access networks two types of RNs can be deployed, *fixed* or *mobile*. The former implies that static RNs are deployed in specific positions of a cell [8]–[13], whereas the latter implies that MSs

[1]This refers to different types of relaying, involving one or more RNs, or schemes that do not rely on relay-assisted communication.

act as RNs [14]–[17]. Fixed RNs are a part of the system infrastructure, hence their deployment requires financial investments from the mobile operators. Utilizing mobile RNs is a cost effective alternative that can exploit multi-user diversity for relay selection (RS). However it comes with higher signalling and complexity, as the changing user topology complicates the process of RS; large amounts of channel state information (CSI) need to be fed back from the MSs to the SN for the RS to take place [7], [14], [15], [18].

The achievable performance and the required signalling of an RS scheme depends on the number of RN candidates. The limiting case where all cell MSs are RN candidates results in maximum performance as well as signalling overhead [19], [20]. Focusing on *dual-hop* transmission, where the transmitting SN can be assisted at most by one RN, most contributions in the literature consider that all available MSs are RN candidates that are equally likely to be selected for relaying [21]–[34]. In these works, however, both pathloss and shadowing were not taken into account. Considering all MSs as RN candidates inevitably results in maximum signalling and scheduling complexity as the SN needs to gather information on all SN to MS and MS to MS channels and perform exhaustive search in order to identify the best RN with respect to the considered metric. This burden is prohibitive for real systems with many MSs and it needs to be alleviated to make mobile relaying practical. One way to achieve this is by taking into account that relaying does not always provide performance gains as the pathloss and shadowing that affect real systems render most of the available RN candidates useless [14], [15]. Hence the number of RN candidates, and thus signalling, can be significantly reduced by considering only the MSs that are likely to provide performance gains when acting as RNs [35].

In this paper we present a three-step approach that maintains the gains of relaying and keeps the signalling overheads for RS at a low level. In *step 1*, the DNs of the cell that are likely to profit from relaying are identified and, in *step 2*, the cell nodes that will act as RN candidates for the previously identified DNs are determined. The first two steps are performed in a distributed fashion, i.e., users decide independently about whether they will request the assistance of RNs or be RN candidates for other DNs in the cell. These actions are based on knowledge obtained during a network training phase, through numerical experiments or measurements, about the statistical relaying patterns in a cell. This knowledge reveals which nodes are likely to benefit from relaying as DNs and which nodes are likely to bring benefit when acting as RNs as a function of their geographical positions.

In *step 3* the selected RN candidates feed back to the SN the relevant CSI that is necessary for RS. The signalling overhead of this step is greatly reduced by limiting the number of RN candidates in the second step. We conclude that our algorithm can reduce signalling overhead to only 10% of its maximum value while achieving a very good performance. Therefore the proposed algorithm has the potential to drastically minimize the needed CSI feedback overhead and RS complexity. In addition to this we investigate the gains brought by mobile RNs in different wireless access environments under the presence of inter-cell interference (ICI) as modelled with the aid of the versatile Nakagami-m fading distribution [36]. We conclude that the gains resulting from the use of mobile RNs become more significant as multipath fading becomes more severe.

The rest of the paper is structured as follows: In Section II, the system and channel models are presented and in Section III our considered RS schemes are discussed. Section IV contains our proposed three-step RS algorithm which is based on learning when to relay, and Section V presents and discusses numerical results. Finally, Section VI concludes this paper.

Notations: Throughout this paper, vectors and matrices are denoted by boldface lowercase letters and boldface capital letters respectively. The transpose conjugate and the determinant of a matrix are denoted by ^{H} and $\det(\cdot)$ respectively. $|\mathcal{A}|$ represents the cardinality of the set $\mathcal{A}$ and $\mathbb{C}^k$ the complex space with k dimensions. $\mathbb{E}[\cdot]$ denotes the expectation operator, $\Pr\{\cdot\}$ denotes probability and $X \sim \mathcal{CN}(\mu, \sigma_v^2)$ represents a random variable (RV) following the complex normal distribution with mean μ and variance σ_v^2.

II. System and Channel Model

The network consists of B single antenna BSs and K single antenna MSs per cell with MSs being uniformly distributed in the cell area. All network BSs are assumed to transmit on the same frequency (full frequency reuse). Downlink communication is taken into account although similar ideas can be applied on the uplink. The communication from a BS to a MS can either be direct (single-hop transmission) or assisted by another MS acting as an RN (dual-hop transmission). In the case of single-hop communication, the received signal at a DN k, with $k = 1, 2, \ldots, K$, assigned to BS i can be expressed as

$$y_k = h_{k,i} \sqrt{p_i}\, u_i + z_k + n_k \tag{1}$$

where $h_{k,i}$, with $i = 1, 2, \ldots, B$, denotes to the channel coefficient between DN k and the ith BS, u_i is the unit variance transmit symbol from the ith BS with transmit power p_i, $z_k = \sum_{n=1, n\neq i}^{B} h_{k,n} \sqrt{p_n}\, u_n$ corresponds to the ICI and $n \sim \mathcal{CN}\left(0, \sigma^2\right)$ represents the zero mean circularly symmetric additive white Gaussian noise (AWGN) with variance σ^2. Using (1), the mutual information for DN k is given by

$$\mathcal{I}_k = \log_2 \left(1 + \frac{\left|h_{k,i}\right|^2 p_i}{\left|\chi_k\right|^2}\right). \tag{2}$$

where $\chi_k = z_k + n_k$. Another important performance metric regarding the transmission towards DN k is the outage probability (OP) for a given SN transmit rate R_s which is expressed as

$$P_{\text{out}}^{k} = \Pr\left\{\mathcal{I}_k < R_s\right\}. \tag{3}$$

A. Dual-Hop Relaying Schemes

To further enhance the achievable rates of a SN-DN transmission, MSs in the cell area experiencing more favourable channel conditions than the direct link are assigned to relay SN's signal to DN. Let $\mathcal{M}$ with $|\mathcal{M}| = K$ be the set comprising the users of a cell. In the case of dual-hop relaying, transmission towards a DN $k \in \mathcal{M}$ can be assisted by one or more nodes acting as RNs. In this paper we assume that only one RN $r \in \mathcal{M} - \{k\}$ can aid the transmission towards a DN[2]. RNs are assumed to transmit in half-duplex mode according to which an RN cannot receive and transmit simultaneously; transmission occurs in two time slots. Our considered relaying protocol can be summarized as follows:

- *Time slot 1*: SN transmits symbol $u_i^{(1)}$; the selected RN r is in listening mode and receives the signal y_r; DN is also in listening mode and receives $y_k^{(1)}$.
- *Time slot 2*: The RN r transmits symbol u_r which is a function of the RN's received signal y_r and the employed relaying scheme. Two options exist for SN during this slot:

  a. *Orthogonal transmission*: SN remains silent.

[2]This corresponds to the well known triangular cooperative model where there is one SN, one RN and one DN. Henceforth the terms SN and BS will be used interchangeably.

b. *Non-orthogonal transmission*: SN transmits another symbol $u_i^{(2)}$ to the DN; DN k receives signal $y_k^{(2)}$ which is appropriately combined with $y_k^{(1)}$.

In this paper we assume that maximal ratio combining (MRC) is performed at the DN. Under non-orthogonal transmission, the received signals at DN k and RN r can be expressed as

$$\text{Time slot 1}\begin{cases} y_k^{(1)} = h_{k,i}^{(1)}\sqrt{p_i^{(1)}}\,u_i^{(1)} + z_k^{(1)} + n_k^{(1)} \\ y_r = h_{r,i}\sqrt{p_i^{(1)}}\,u_i^{(1)} + z_r + n_r \end{cases}$$
$$\text{Time slot 2}\begin{cases} y_k^{(2)} = h_{k,r}\,u_r + h_{k,i}^{(2)}\sqrt{p_i^{(2)}}\,u_i^{(2)} + z_k^{(2)} + n_k^{(2)} \end{cases} \tag{4}$$

where $h_{r,i}$ and $h_{k,r}$ denote the SN-RN and RN-DN channel coefficients while $h_{k,i}^{(j)}$ with $j = 1$ and 2 represent the SN-DN channel coefficient for the jth transmission time slot. In addition $n_k^{(j)}$ and $z_k^{(j)}$ denote the AWGN and the received ICI at DN respectively during the jth time slot whereas n_r and z_r denote the AWGN and the received ICI at RN respectively. For the SN-DN channel $h_{k,i}$ we assume that it remains constant during the two time slots of transmission. Furthermore it is assumed that in each time slot the total power emanating from a cell is constrained to P_c, hence

$$\begin{aligned} p_i^{(1)} &\le P_c \\ p_i^{(2)} + p_r &\le P_c \end{aligned} \tag{5}$$

where $p_i^{(j)}$ represents the transmit power of SN in the jth time slot and p_r is the power stemming out of RN.

Next, we consider the well-known decode-and-forward (DF) and amplify-and-forward (AF) [3], [4] schemes for relaying.

1) Decode-and-Forward: With DF the RN decodes and retransmits SN's signal to DN conditioned that it successfully decodes it. Therefore, during the second time slot, DN k receives

$$y_k^{(2)} \;=\; h_{k,r}\sqrt{p_r}\,u_i^{(1)} + h_{k,i}^{(2)}\sqrt{p_i^{(2)}}\,u_i^{(2)} + \chi_k^{(2)} \tag{6}$$

where $\chi_k^{(j)} = z_k^{(j)} + n_k^{(j)}$ with $j = 1$ and 2 denotes the received interference-plus-noise (IpN) at DN during the jth time slot. To obtain the capacity region for the non-orthogonal DF (NDF) we utilize the equivalent channel matrix approach presented in [5]. Following this approach the considered system can be described as a 2×2 MIMO channel whose capacity is a bound for the system's maximum achievable rate. The equivalent channel matrix for NDF can be expressed as

$$\mathbf{Q}_{\mathrm{DF}} = \begin{bmatrix} Q_{11} & 0 \\ Q_{21} & Q_{22} \end{bmatrix} \tag{7}$$

where $Q_{jj} = h_{k,i}^{(j)} \sqrt{\frac{p_i^{(j)}}{\left|\chi_k^{(j)}\right|^2}}$ for $j = 1, 2$ while $Q_{21} = h_{k,r} \sqrt{\frac{p_r}{\left|\chi_k^{(2)}\right|^2}}$. Under NDF transmission the channel can be seen as a multiple-access channel. Since RN needs to correctly decode SN's signal, the capacity of the DF scheme is limited by the SN-RN link. Therefore the following set of constraints should be met [5]

$$\begin{aligned} R_i^{(1)} &\leq \min\left\{\log_2\left(1 + \frac{|h_{r,i}|^2 p_i^{(1)}}{|\chi_r|^2}\right),\ \log_2\left(1 + |Q_{11}|^2 + |Q_{21}|^2\right)\right\} \\ R_i^{(2)} &\leq \log_2\left(1 + |Q_{22}|^2\right) \\ R_{\max} &\leq \log_2\left(\det\left(\mathbf{I} + \mathbf{Q}_{\mathrm{DF}}\,\mathbf{Q}_{\mathrm{DF}}^H\right)\right) \end{aligned} \tag{8}$$

where $R_i^{(j)}$ represents the transmit rate of SN during the jth time slot, $\chi_r = z_r + n_r$ denotes the received IpN at RN and $R_{\max}$ represents the maximum achievable rate of the equivalent multiple-access channel. Hence the mutual information for the NDF transmission is given by

$$\mathcal{I}_{k,r} = \begin{cases} \frac{1}{2} R_{\max}, & R_i^{(1)} + R_i^{(2)} \geq R_{\max} \\ \\ \frac{1}{2}\left[R_i^{(1)} + R_i^{(2)}\right], & R_i^{(1)} + R_i^{(2)} < R_{\max} \end{cases}. \tag{9}$$

For the orthogonal DF (ODF) transmission the mutual information expression reduces to

$$\mathcal{I}_{k,r} = \frac{1}{2} \min\left\{\log_2\left(1 + \frac{|h_{r,i}|^2\, p_i^{(1)}}{|\chi_r|^2}\right),\ \log_2\left(1 + |Q_{11}|^2 + |Q_{21}|^2\right)\right\}. \tag{10}$$

2) Amplify-and-Forward: With the AF scheme the RN amplifies its received signal and forwards it to DN without decoding it. This relatively simple scheme comes with the detrimental side-effect that the RN apart from the received signal amplifies its thermal noise together with the ICI; this fact limits the performance of AF. The received signal at RN is amplified by a factor α_r which is adjusted so that to ensure that the RN's power constraints p_r are met. Hence the signal transmitted by the RN can be expressed as

$$u_r = \alpha_r \sqrt{p_r}\left[h_{r,i}\sqrt{p_i^{(1)}}\, u_i^{(1)} + \chi_r\right]. \tag{11}$$

In order to meet p_r the amplification factor takes the following value

$$\alpha_r = \sqrt{\left[|h_{r,i}|^2 \, p_i^{(1)} + |\chi_r|^2 \right]^{-1}}. \tag{12}$$

Therefore, during the second time slot, DN k receives

$$y_k^{(2)} = h_{k,r} \, \alpha_r \, h_{r,i} \sqrt{p_i^{(1)}} \, u_i^{(1)} + h_{k,r} \, \alpha_r \, \chi_r + h_{k,i}^{(2)} \sqrt{p_i^{(2)}} \, u_i^{(2)} + \chi_k^{(2)}. \tag{13}$$

Similar to the derivation of the mutual information of NDF, the equivalent channel matrix for the non-orthogonal AF (NAF) transmission can be obtained using the approach in [5] as

$$\mathbf{Q}_{\mathrm{AF}} = \begin{bmatrix} Q'_{11} & 0 \\ Q'_{21} & Q'_{22} \end{bmatrix} \tag{14}$$

where $Q'_{11} = h_{k,i}^{(1)} \sqrt{\frac{p_i^{(1)}}{\left|\chi_k^{(1)}\right|^2}}$, $Q'_{21} = \frac{h_{k,r} \, \alpha_r \, h_{r,i} \sqrt{p_i^{(1)}}}{\sqrt{|h_{r,i}|^2 \, \alpha_r^2 \, |\chi_r|^2 + \left|\chi_k^{(2)}\right|^2}}$ and $Q'_{22} = h_{k,i}^{(2)} \sqrt{\frac{p_i^{(2)}}{\left|h_{k,r}\right|^2 \alpha_r^2 |\chi_r|^2 + \left|\chi_k^{(2)}\right|^2}}$. Thus the mutual information for the NAF transmission is given by

$$\mathcal{I}_{k,r} = \frac{1}{2} \log_2 \left(\det \left(\mathbf{I} + \mathbf{Q}_{\mathrm{AF}} \mathbf{Q}_{\mathrm{AF}}^H \right) \right). \tag{15}$$

For the orthogonal AF (OAF) transmission where $p_i^{(2)} = 0$, the expression for the mutual information reduces to

$$\mathcal{I}_{k,r} = \frac{1}{2} \log_2 \left(1 + |Q'_{11}|^2 + |Q'_{21}|^2 \right). \tag{16}$$

For the remainder of the paper we assume that the SN-DN channel and the IpN power remain constant during the two transmission slots, i.e., $h_{k,i}^{(1)} = h_{k,i}^{(2)}$ and $\left|\chi_k^{(1)}\right|^2 = \left|\chi_k^{(2)}\right|^2$. Moreover, based on [14] where it has been shown that, in wireless access environments, non-orthogonal transmission does not result in substantial performance gains compared with the orthogonal one, we focus on studying the ODF and OAF schemes. For such schemes, the end-to-end OP between SN and the DN k through the assistance of the RN r, when SN transmits with constant rate R_s, is obtained as

$$P_{\mathrm{out}}^{k,r} = \Pr \left\{ \mathcal{I}_{k,r} < R_s \right\}. \tag{17}$$

B. Channel Model

A frequency non-selective fading channel model incorporating antenna power gain, pathloss, shadowing and multipath fading with different fading statistics is taken into account. In particular, the channel coefficient between the ℓth and the nth node[3] of the network is assumed to be given by

$$h_{\ell,n} = \sqrt{G\,\beta\,D_{\ell,n}^{-\mu}\,\gamma_{\ell,n}}\,\zeta_{\ell,n}\exp\left(j\,\theta_{\ell,n}\right) \tag{18}$$

where G is the product of the power gains of the transmit and receive antennas of nodes ℓ and n while β and μ are the pathloss constant and exponent respectively of the (ℓ, n) link with $D_{\ell,n}$ being its length. In addition $\gamma_{\ell,n}$ is the shadowing coefficient of the link, $\zeta_{\ell,n}$ and $\theta_{k,\ell}$ are the envelope and random phase respectively of the multipath fading complex coefficient and $j^2 = -1$. For G it is assumed that all MSs have antennas with unit power gain whereas BSs can have omnidirectional antennas with a 9 dB gain on the elevation. It is noted that the transmit power is determined by the system signal-to-noise ratio (SNR) which is defined as the average SNR at the edge of the cell without accounting for ICI. The 3GPP Long Term Evolution (LTE) evaluation parameters [37] are considered for β and μ, i.e., $\beta = 10^{-14.81}$ and $\mu = 3.76$, while $\gamma_{\ell,n}$ is assumed to be a log-normal RV with $\gamma_{\ell,n}$ in decibels (dBs), $\gamma_{\ell,n}^{(\mathrm{dB})}$, being normally distributed such that $\gamma_{\ell,n}^{(\mathrm{dB})} \sim \mathcal{N}(0, 8)$.

For multipath fading, it is assumed that $\zeta_{\ell,n}$ follows the Nakagami-m distribution [36] and $\theta_{\ell,n}$ is uniformly distributed over the range $[0, 2\,\pi)$. The Nakagami-m distribution is an empirical though versatile statistical distribution that describes multipath scattering with relatively large delay-time spreads and with different clusters of reflected waves [34], [38]. Its advantage is that it incorporates some physical characteristics of realistic wireless channels and can therefore model different wireless access environments. The probability distribution function (PDF) of the Nakagami-m distributed $\zeta_{\ell,n}$ is given by [36, eq. (11)]

$$f_{\zeta_{\ell,n}}(x) = \frac{2\,m_{\ell,n}^{m_{\ell,n}}\,x^{2\,m_{\ell,n}-1}}{\Gamma\left(m_{\ell,n}\right)\,\Omega_{\ell,n}^{m_{\ell,n}}}\exp\left(-\frac{m_{\ell,n}\,x^2}{\Omega_{\ell,n}}\right)\,U(x) \tag{19}$$

where $m_{\ell,n} \geq 1/2$ is the fading parameter, $\Omega_{\ell,n} = \mathbb{E}\left[\left|\zeta_{\ell,n}\right|^2\right]$ is the average fading power, $\Gamma(\cdot)$ is the Gamma function [39, eq. (8.310/1)] and $U(\cdot)$ is the unit step function. The Nakagami-m PDF is very general as it can describe other well-known distributions, e.g. for $m_{\ell,n} = 1$ the Rayleigh and for $m_{\ell,n} = 0.5$

[3] A network node can be either a BS or a MS, i.e., $\ell, n = 1, 2, \ldots, K + B$.

the one-sided exponential distribution. Moreover, it can approximate the Ricean distribution with sufficient accuracy by setting [40], [41]

$$m_{\ell,n} = \left[1 - \left(\frac{\mathcal{K}_{\ell,n}}{\mathcal{K}_{\ell,n}+1}\right)^2\right]^{-1} \tag{20}$$

where $\mathcal{K}_{\ell,n}$ denotes the Rice factor of the (ℓ, n) link [42]. The fading parameter $m_{\ell,n}$ can also describe different line-of-sight (LOS) and non-LOS (NLOS) conditions of the (ℓ, n) link for $m_{\ell,n} > 1$ and $0.5 \leq m_{\ell,n} \leq 1$ respectively. Moreover, extensive measurement campaigns have shown that the relationship between a signal and its direction of arrival can be embodied by $m_{\ell,n}$ [43]. Hence, varying degrees of fast fading and local scattering can be approximated for any BS-MS and MS-MS channel with the correct choice of $m_{\ell,n}$'s leading to accurate modelling of different channel conditions. Wireless access environments can be divided into two main categories: *macrocells* and *microcells*.

- In macrocells the cell radius is usually $1 - 10$ km and the BS antennas are mounted on high towers. BS-MS and MS-MS channels for such environments are usually NLOS ones with $0.5 \leq m_{\ell,n} \leq 1$.
- For microcells the cell radius is $0.2 - 1$ km and the antenna height of the BSs is a few meters. In such environments, there usually exist some LOS BS-MS and/or MS-MS channels with $m_{k,\ell} > 1$.

For both macrocells and microcells, ICI channels are usually NLOS ones, i.e., for any MS node ℓ parameter $m_{\mathrm{ICI},\ell}$ of all its ICI channels are such that $0.5 \leq m_{\mathrm{ICI},\ell} \leq 1$.

III. Relay Selection Approaches

In this paper two approaches are considered for RS: a *proactive* and a *reactive* one inspired by [21]. In [21] where no direct link between SN and DN is assumed, RS is performed based on measurements at the RNs. In this paper it is assumed that there is direct link between the SN and DN[4] and RS takes place at the SN based on CSI fed back by the involved nodes. In the proactive approach, it is the SN that gathers all the relevant system CSI and selects an RN before transmission commences; SN selects the RN that maximizes mutual information and transmits at a rate equal to this, therefore eliminating OP. Our employed evaluation metric for proactive RS with CSI is the maximum attained mutual information, i.e., the achievable capacity. In the reactive approach, RS takes place after SN's transmission. The SN transmits at a constant rate and the best RN, which results in the minimum end-to-end OP, is selected

[4]This is a valid assumption for urban wireless access networks.

amongst the ones that have successfully decoded SN's signal. As the SN lacks CSI before transmission, the OP is our considered metric for reactive RS.

A. Proactive RS

Let $\mathcal{F}$, with $\mathcal{F} \subseteq \mathcal{M}$, be the set of DNs that request the aid of an RN. For a DN $k \in \mathcal{F}$, a set of RN candidates $\mathcal{G}_k \subseteq \mathcal{M} - \{k\}$ is formed. Although some MSs do not request assistance from an RN, they might themselves act as RNs for other MSs. It is noted that in the limiting case $\mathcal{G}_k$ comprises all the cell users apart from MS k. Then, SN gathers the $2\,|\mathcal{G}_k|$ coefficients describing CSI between SN and RNs as well as between RNs and DN. In addition SN needs to collect the $|\mathcal{G}_k|$ coefficients for the IpN power at each RN. Thus, in total, SN requires $3\,|\mathcal{G}_k|$ coefficients to perform RS for DN k. The best RN r_k to assist the transmission towards DN k is selected by the SN according to

$$r_k = \arg\max_{r \in \mathcal{G}_k} \mathcal{I}_{k,r}. \tag{21}$$

It is possible that the single-hop direct transmission from SN to DN achieves superior mutual information than the RS-based one [14], [15], [33], [44]. Thus SN compares the mutual information resulting from the single-hop transmission with that of the transmission through the best RN and decides whether to use the RN or not. Therefore the final capacity is obtained as

$$C_k = \max\left\{\mathcal{I}_k,\, \mathcal{I}_{k,r_k}\right\}. \tag{22}$$

Our considered evaluation metric for the aforementioned scheme that opportunistically utilizes proactive RS is the average system capacity (ASC) given by

$$\overline{C} = \frac{1}{K}\mathbb{E}\left[\sum_{k=1}^{K} C_k\right] \tag{23}$$

where the expectation is taken over all channel realizations and DN positions. We aim to devise an RS algorithm that reduces the cardinality of $\mathcal{F}$ and $\mathcal{G}_k$ for a given DN $k \in \mathcal{F}$ without significantly sacrificing potential performance gains achieved from relaying. We thus define the average percentage of a cell's MSs that become RN candidates for all DNs as

$$\overline{P} = \frac{1}{K\,(K-1)}\,\mathbb{E}\left[\sum_{i=1}^{|\mathcal{F}|} |\mathcal{G}_i|\right]. \tag{24}$$

This percentage is directly proportional to the percentage of CSI coefficients that need to be acquired by the SN and represents the signalling overhead of RS. In the limiting case where $\overline{P} = 1$, all MSs in the cell are always RN candidates for all DNs, thus $|\mathcal{G}_k| = K - 1$ for $k \in \mathcal{M}$, corresponding to the maximum signaling overhead.

B. *Reactive RS*

Reactive RS entails that SN transmits at a constant rate R_s towards a DN k. RNs that decode SN's message form the set $\mathcal{C}_k \subseteq \mathcal{M} - \{k\}$. For RS to take place, all RNs belonging to $\mathcal{C}_k$ feed back to SN the channel coefficients describing the CSI between them and DN k. The best RN r_k for this DN is the one minimizing the end-to-end OP given by (17), i.e.,

$$r_k = \arg\min_{r \in \mathcal{C}_k} P_{\text{out}}^{k,r}. \tag{25}$$

Choosing between direct single-hop or RS-based dual-hop transmission, the final end-to-end OP between SN and DN is given by

$$P_{\text{O}}^k = \min\left\{P_{\text{out}}^k,\, P_{\text{out}}^{k,r_k}\right\}. \tag{26}$$

The considered evaluation metric for our scheme that utilizes reactive RS in an opportunistic manner is the average OP (AOP) given by

$$\overline{P}_{\text{O}} = \frac{1}{K}\,\mathbb{E}\left[\sum_{k=1}^{K} P_{\text{O}}^k\right] \tag{27}$$

where the expectation is taken over all channel realizations and DN positions. It must be noted that this scheme requires that only the nodes that have decoded SN's message ($r_k \in \mathcal{C}_k \;\forall\, k$) feed back their SN-RN CSI to SN. This feedback overhead is less than that of the proactive scheme; the proactive scheme requires that both the SN-RN and RN-DN channel coefficients of all the RN candidates are fed back to the SN.

IV. Learning when to relay

In this section we present a three-step algorithm that exploits the mobility of RNs and keeps the signalling overhead below a prescribed average level. As described in Section III, the required signalling for RS is directly proportional to the number of RN candidates per DN. It can therefore be mitigated by reducing the number of RN candidates per DN. This can be achieved through learning the statistical relaying patterns in a cell, i.e., learning which DNs are likely to benefit from relaying as a function of their position in the cell and which MSs can provide gains while relaying signals intended for other MSs. Our three-step algorithm exploits this statistical knowledge and reduces the number of RN candidates per DN without severely compromising performance. Although our approach can be utilized with either proactive or reactive RS, we focus hereinafter on proactive RS which has greater potential.

A. Statistical Relaying Patterns

To investigate the statistical relaying patterns in a cell, i.e., the likelihood of attaining performance gains with RS as a function of the MS nodes position (MSs can be either DNs or RNs), we conduct numerical experiments. Let us consider a two-tier cell network consisting of $B = 19$ cells each with radius $\rho_c = 1$ km. We assume a macrocellular environment with Rayleigh multipath fading for the useful and ICI links and focus on the central cell which fully captures the effect of ICI. The network is assumed to operate in the ICI-limited regime and the system SNR = 20 dB. As an indicative metric of the statistical relaying patterns in a cell we calculate the probability $P_{\text{rel},k}$ that DN k achieves greater mutual information by using RN r_k than by receiving signals directly from SN. This probability can be expressed as a function of the DN k position p_k as

$$P_{\text{rel}}\left(\mathrm{p}_k\right) = \Pr\left\{\mathcal{I}_{k,r_k} > \mathcal{I}_k\right\}. \tag{28}$$

Fig. 1 plots P_{rel} as a function of the DN k position p_k in the two dimensional (2D) space for a densely populated cell. The ODF relaying scheme is considered where for every MS serving as a DN all other MSs of the cell are assumed to be RN candidates. To gain insights on when relaying is beneficial, full signalling overhead is allowed and we assume that the SN has full CSI for all the SN-RNs and RNs-DN channels. As it can be clearly seen from Fig. 1, the further away a DN is from the SN (BS is assumed to be in the centre of the cell), the more likely it is to choose dual-hop relaying for alleviating the effect of high pathloss to the SN. In addition DNs near the cell edge experience high ICI originating from neighbouring cells, thus they are likely to choose an ICI resilient RN for enhancing the achievable mutual information. It should also be noted that the antenna gain of the BS provides a strong direct SN-DN channel to DNs near SN rendering dual-hop transmission less likely to be preferred.

For a cell with a more moderate number of MS nodes than that of Fig. 1, P_{rel} is expected to be lower, as the fewer RNs are available, the lower is the probability that a RN is preferred for assisting transmission; the diversity order offered from MSs diminishes. In Fig. 2, for the same channel conditions as in Fig. 1, the empirical cumulative distribution function (CDF) of the distance from the SN of MS nodes for three different cases is illustrated. *i*) Case 1: MSs being DNs and choosing an RN, *ii*) Case 2: MSs acting as RNs and *iii*) Case 3: MSs being DNs and preferring non-relay assisted single-hop transmission. In this figure 30 nodes in total are assumed for the cell and all MS distances are measured from its centre. It can be observed that for nodes being no further than 0.5 km from the BS, the probability that a DN chooses an RN is only 0.1, the probability that a node becomes an RN is 0.5 and that the probability that a DN prefers single-hop transmission is 0.5. Consequently, nodes that are located near the BS are not likely to profit from dual-hop transmission while being DNs, although they are more likely to be good RNs assisting transmission towards DNs at the edge of the cell.

B. The Three-Step Algorithm

In order to exploit the observations made before we propose a three-step algorithm that limits the signalling needed for relaying without sacrificing the performance gains of proactive RS. Our algorithm relies on the application of inter-node distance thresholds, d_1 and d_2, in order to identify which MS nodes can benefit from RNs while being DNs and which ones are suitable to act as RNs for other MSs being DNs. We assume that cell MS nodes know their distance to the BS and to the DN; for example this can be achieved with the use of global positioning system (GPS) receivers [17], [45].

Step 1: We first form the set $\mathcal{F} \subseteq \mathcal{M}$ of DNs that request the aid of RNs. A threshold d_1 is applied on the distance between a DN and SN such that only DNs that are highly likely to gain from relaying belong to $\mathcal{F}$. Therefore for all K cell DNs, if $D_{k,i} \geq d_1$ ($k = 1, 2, \ldots, K$ and node i is the SN), $k \in \mathcal{F}$ and DN k requests the aid of an RN.

Step 2: For every DN $k \in \mathcal{F}$ we form the set $\mathcal{G}_k \subseteq \mathcal{M} - \{k\}$ of MS nodes that act as RN candidates for this DN[5]. For every cell node $r \in \mathcal{M} - \{k\}$, MS r acts as an RN candidate for DN k if $D_{r,i} \leq d_2$ and $D_{r,i} \leq D_{k,i}$. To limit the number of RN candidates per DN we apply the threshold

[5]It is noted that sets $\mathcal{F}$ and $\mathcal{G}_k$ are not mutually exclusive, $\mathcal{F} \cup \mathcal{G}_k \neq \emptyset$.

d_2 on the distance between the DN and the rest of MSs; we thus further reduce the number of RN candidates by selecting only the nodes located between DN and SN.

Step 3: SN gathers all CSI coefficients from all MSs belonging to $\mathcal{G}_k$ and selects the RN maximising the mutual information of transmission towards DN k , i.e., $r_k = \arg\max_{r \in \mathcal{G}_k} \mathcal{I}_{k,r}$. RN r_k is used only if $\mathcal{I}_{k,r_k} > \mathcal{I}_k$. This step necessitates that the SN receives relevant CSI feedback which represents the signalling overhead that is mitigated via the limitation of RN candidates described in the previous step.

A detailed outline of the proposed algorithm is given below.

Remarks: The actions of the first two steps of the proposed algorithm are performed in a distributed fashion; MS nodes decide independently about whether they will request the assistance of RNs or act as RN candidates for other MSs. The final step is performed centrally at the SN. To justify the second step we note that the DNs that belong to $\mathcal{F}$ are more likely to find a good RN closer to them than to the BS, i.e., the SN. This is due to the antenna gain at the BS which makes it more likely that the BS-RN link is stronger on average than the RN-DN link as the RN is in principle located between the BS and the DN. Therefore all RN candidates for a specific DN are located inside a conceptual circle whose centre is the DN (see Fig. 3 for an illustration). Inside this conceptual circle there can be MS nodes which are further away from the BS than the DN; these nodes are not likely to provide gains acting as RNs since they experience greater attenuation to the BS than the DN itself. Thus we can further reduce the number of RN candidates by selecting as final RN candidates the nodes inside this circle which are closer to the BS than DN. We finally note that the efficiency of the proposed algorithm, i.e., how good is the balance struck between performance and signalling, depends on the selection of distance thresholds d_1 and d_2. Although, in this paper, this selection is based on numerical results, it can also be based on real-world measurements.

V. Numerical Results and Discussion

This section presents performance evaluation results for the proposed RS scheme that limits signalling overhead for RS. The results presented also provide insights on how to select thresholds d_1 and d_2 for the proposed three-step algorithm. Furthermore the performance gains resulting from the utilization of mobile

Set distance thresholds d_1, d_2
for DN $k = 1, 2, \ldots, K$ **do**
  if $D_{k,i} \geq d_1$ **then**
    DN k requests the aid of RNs, $k \in \mathcal{F}$
    for MS $r \in \mathcal{M} - \{k\}$ **do**
      if $D_{r,i} \leq d_2$ and $D_{r,i} \leq D_{k,i}$ **then**
        MS r becomes RN candidate for DN k, $r \in \mathcal{G}_k$
        RN r feeds back $|h_{k,r}|^2$ and $|\chi_r|^2$ to SN
      end if
    end for
    DN k feeds back $|h_{k,i}|^2$ and $|\chi_k|^2$ to SN
    RN selection: $r_k = \arg\max_{r \in \mathcal{G}_k} \mathcal{I}_{k,r}$
    if $I_{k,r_k} > I_k$ **then**
      RN r_k assists transmission, $C_k = \mathcal{I}_{k,r_k}$
    else
      SN transmits directly to DN k, $C_k = \mathcal{I}_k$
    end if
  else
    DN k feeds back $|h_{k,i}|^2$ and $|\chi_k|^2$ to SN
    SN transmits directly to DN k, $C_k = \mathcal{I}_k$
  end if
end for

RNs as a function of the wireless access environment are investigated in order to apprehend under which fading conditions relaying is more beneficial.

A. Performance of the Three-Step Algorithm

To evaluate our opportunistic proactive RS scheme, the channel model of Section II-B is considered with Rayleigh multipath fading, i.e., $m_{\ell,n} = 1$ for every (ℓ, n) link. Fig. 4 illustrates the average percentage

$\overline{P}$ of cell MS nodes considered as RN candidates per DN as a function of threshold d_2 for different versions of the proposed algorithm, $\rho_c = 1$ km and for $K = 30$ nodes/cell. The considered versions are the following. *i*) Version 1: only threshold d_2 is applied for determining RN candidates, *ii*) Version 2: both d_2 and $D_{k,i}$ thresholds are applied and *iii*) *Version 3*: in addition to applying d_2 and $D_{k,i}$, relaying is enabled only for DNs whose distance from the BS is greater than $d_1 = 0.5$ km. As clearly shown, the latter case where all three thresholds (d_1, d_2 and $D_{k,i}$) are considered attains the minimum overhead charge. For example, it can be seen that if $d_2 = 0.5$ km and all thresholds are applied (lowermost curve) the system is charged with only $\overline{P} = 10\%$ of the potential feedback overhead.

Using (23), Fig. 5 plots $\overline{C}$ versus threshold d_2 for different versions of the proposed algorithm, $\rho_c = 1$ km, system SNR = 20 dB and for both proactive ODF and OAF relaying. As shown in this figure, for all the considered versions with opportunistic relaying, maximum $\overline{C}$ performance is achieved when threshold $d_2 = 0.5$ km. Interestingly, for $d_2 > 0.5$ the $\overline{C}$ performance saturates, thus good RN candidates for a DN are not likely to be found any further than 0.5 km from the DN. Version 1 ODF curve represents the case where only threshold d_2 is applied and this achieves the best $\overline{C}$ performance. When $d_2 > 0.5$ km, the saturated curve also represents the maximum $\overline{C}$ that can be achieved irrespective of the amount of CSI feedback overhead that is allowed. It can be also seen that the application of all three thresholds (Version 3) results in a small performance degradation as compared to the case where only d_2 is applied (Version 1) while it substantially mitigates feedback load. When $d_2 = d_1 = 0.5$ km and $D_{k,i}$ are applied (Version 3), only $\overline{P} = 10\%$ of the total available MS nodes are considered as RN candidates per DN on average as shown by lowermost red curve of Fig. 4. For 30 nodes/cell this translates to only 3 RNs per DN on average. Therefore the signalling overhead for CSI feedback can be brought down to 10% of its maximum value without greatly reducing the achievable $\overline{C}$ performance.

B. The Effect of Multipath Fading

We model different multipath fading conditions using the Nakagami-m distribution. Its fading parameter m determines the severity of small-scale fading and the degree of LOS. We evaluate the performance of both proactive and reactive RS under ODF transmission and for the ICI limited regime; system SNR = 20 dB is considered. We assume that all cell MS nodes act as RNs for every DN in order to investigate how the benefits of mobile RNs vary over different multipath fading environments. The considered environments for all channels are generally divided into LOS and NLOS ones and for the cell of interest we assume that $\rho_c = 1$ km. For LOS (ℓ, n) channels each with $m_{\ell,n} \geq 1$, two scenarios are investigated. Scenario LOS1: an environment with $1 \leq m_{\ell,n} \leq 1.5$ for each BS-MS and MS-MS as well as $0.5 \leq m_{\ell,n} \leq 1$ for each ICI (ℓ, n) link and Scenario LOS2: BS-MS, MS-MS and ICI channels are subject to Nakagami-m fading with $1 \leq m_{\ell,n} \leq 1.5$. Four scenarios are also taken into account for NLOS conditions for all channels. In particular, Scenario NLOS1: BS-MS and MS-MS channels are Rayleigh faded ($m_{\ell,n} = 1$) and for each ICI (ℓ, n) link $0.5 \leq m_{\ell,n} \leq 1$, Scenario NLOS2: a bad urban environment, where BS-MS and MS-MS channels as well as ICI ones are subject to Rayleigh fading ($m_{\ell,n} = 1$ for every (ℓ, n) link in the cell of interest), Scenario NLOS3: a macrocell where all BS-MS and MS-MS channels as well as ICI ones are subject to Nakagami-m fading with $0.5 \leq m_{\ell,n} \leq 1$ and Scenario NLOS4: an environment plagued by severe fading, where BS-MS and MS-MS channels as well as ICI channels experience exponential fading ($m_{\ell,n} = 0.5$ for every (ℓ, n) link). For all aforementioned scenarios, each assignment of $m_{\ell,n}$ to a link, when $m_{\ell,n}$ is within a region of values, is made equiprobable for all links in this region.

Fig. 6 plots $\overline{C}$ (23) as a function of the number of cell MS nodes K for our opportunistic proactive ODF RS scheme under various LOS and NLOS conditions. We observe that for NLOS fading for all channels in the cell, $\overline{C}$ improves as K increases and for large K $\overline{C}$ curves for NLOS2–NLOS4 scenarios converge; larger K results in more options for RS, thus increasing RS diversity. Notably, $\overline{C}$ performance for scenario NLOS1 outperforms all other NLOS ones indicating that its fading is less severe; this scenario serves as a lower bound for the considered LOS ones. For $K = 1$ there exists no RN to be selected (no MS diversity) and this case provides the lower bound for $\overline{C}$. More importantly it is shown that transmission with the aid of mobile RNs for NLOS2–NLOS4 scenarios results in larger increase on $\overline{C}$ for increasing K as fading conditions become more severe. Furthermore Fig. 6 illustrates $\overline{C}$ performance for various LOS conditions for the BS-MS and/or MS-MS and/or ICI channels. As shown, increasing K results in improvements on $\overline{C}$ for all LOS conditions under consideration. Clearly, the resulting $\overline{C}$ becomes larger as LOS conditions for the BS-MS and MS-MS channels become stronger.

By numerically evaluating (27) in Fig. 7, the $\overline{P}_{\mathrm{O}}$ performance versus K is plotted for our opportunistic reactive ODF RS assuming that BS transmits at a constant rate R_s = 1 bits/sec/Hz. In this figure, the trend observed in Fig. 6 is reversed; as K increases, the gain in $\overline{P}_{\mathrm{O}}$ becomes larger as LOS gets stronger whereas for different NLOS conditions the gain in $\overline{P}_{\mathrm{O}}$ remains similar. This happens mainly because as fading conditions for SN-RN channels become more severe, the probability of RNs belonging in the decoding set decreases and hence less options are available for RS.

Generally we can conclude that for all the considered multipath fading conditions, relay-assisted transmission becomes more efficient as the number of RN candidates increases. Severe fading can be efficiently mitigated by employing mobile RNs and proactive RS. However if full CSI is not available and a reactive scheme is employed, relaying is more beneficial in the LOS regime as its gains increase proportionally to the degree of LOS.

VI. Conclusions

Although the importance of cooperative relaying has been well recognized, utilisation of mobile RNs in wireless access networks remains challenging due to the required signalling and the increased complexity. In order to profit from mobile RNs when an RN selection scheme is considered, it is crucial that this selection is performed in an opportunistic manner and that signalling is mitigated. Furthermore it is important to assess under which fading conditions relaying is more beneficial. In this paper we have presented a three-step algorithm for RN selection that exploits statistical knowledge on the relaying patterns in a cell. According to this algorithm, only a subset of DNs that are highly likely to profit from relaying request the aid of RNs. Furthermore for DNs that request the aid of RNs, not all the cell nodes are considered as potential RNs. It is sufficient that a small subset of the overall nodes, the ones nearer the DN, become RN candidates. In this fashion, a very good performance can be attained while signalling overhead and complexity are drastically reduced, a fact that can bring mobile relay utilisation closer to practice. In addition to the presented algorithm we have assessed the gains of relaying in different wireless access environments using the Nakagami-m fading distribution and we have shown that mobile RNs can help overcome the effects of severe multipath fading.

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FIGURES' CAPTIONS

Fig. 1: A 2D plot of the probability $P_{\rm rel}$ of selecting an RN partner as a function of the DN position for proactive ODF relaying, $\rho_c = 1$ km and system SNR = 20 dB.

Fig. 2: CDF of the MSs distance from the cell center for MSs choosing an RN, acting as RNs and preferring non-relay assisted transmission. 30 nodes in total are considered in the cell, proactive ODF relaying, $\rho_c = 1$ km and system SNR = 20 dB.

Fig. 3: Illustration of the inter-node distance thresholds considered in the proposed three-step algorithm for determining a limited number of RN candidates for a DN.

Fig. 4: Average percentage $\overline{P}$ of RN candidates per DN versus distance threshold d_2 for different versions of the three-step algorithm, Rayleigh multipath fading, $\rho_c = 1$ km and for 30 nodes/cell.

Fig. 5: ASC $\overline{C}$ versus distance threshold d_2 for different versions of the three-step algorithm, Rayleigh multipath fading, $\rho_c = 1$ km, system SNR = 20 dB and for both proactive ODF and OAF relaying.

Fig. 6: ASC $\overline{C}$ versus the number of cell MS nodes K for proactive RS with ODF transmission, $\rho_c = 1$ km, system SNR = 20 dB and for different multipath fading conditions.

Fig. 7: AOP $\overline{P}_{\rm O}$ versus the number of cell MS nodes K for reactive RS with ODF transmission, $\rho_c = 1$ km, system SNR = 20 dB, R_s = 1 bits/sec/Hz and for different multipath fading conditions.

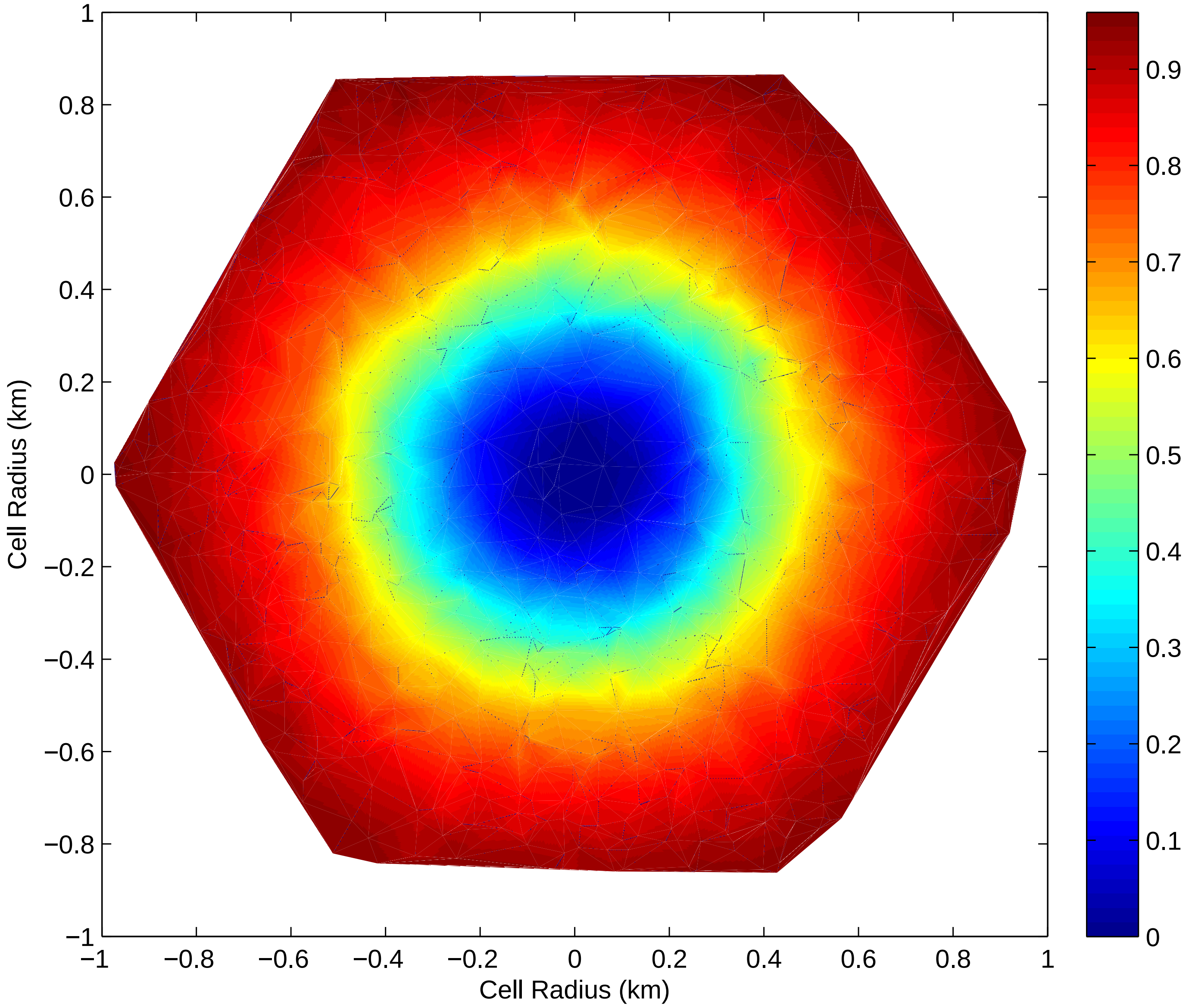

Fig. 1. A 2D plot of the probability P_{rel} of selecting an RN partner as a function of the DN position for proactive ODF relaying, $\rho_c = 1$ km and system SNR = 20 dB.

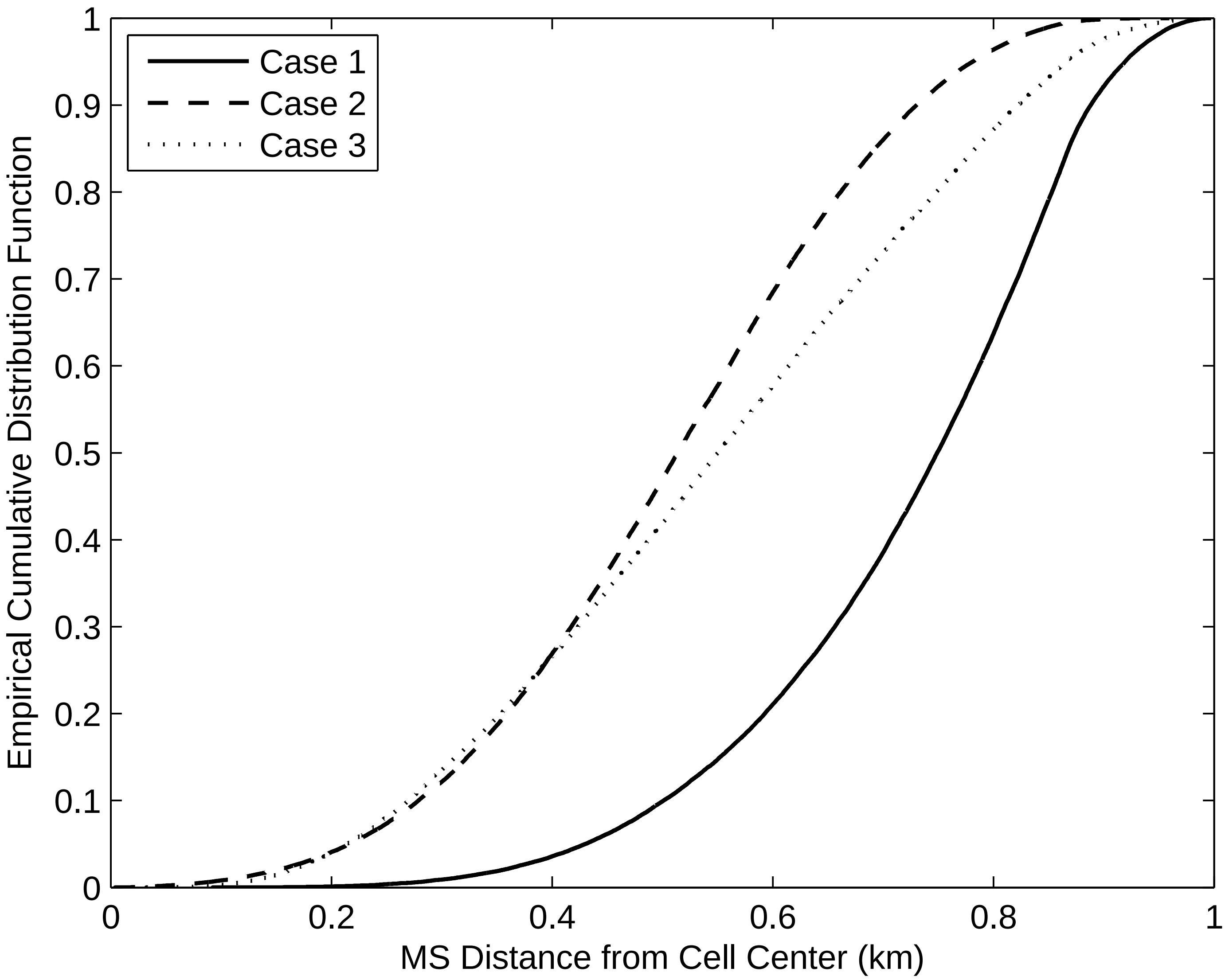

Fig. 2. CDF of the MSs distance from the cell center for MSs choosing an RN, acting as RNs and preferring non-relay assisted transmission. 30 nodes in total are considered in the cell, proactive ODF relaying, $\rho_c = 1$ km and system SNR = 20 dB.

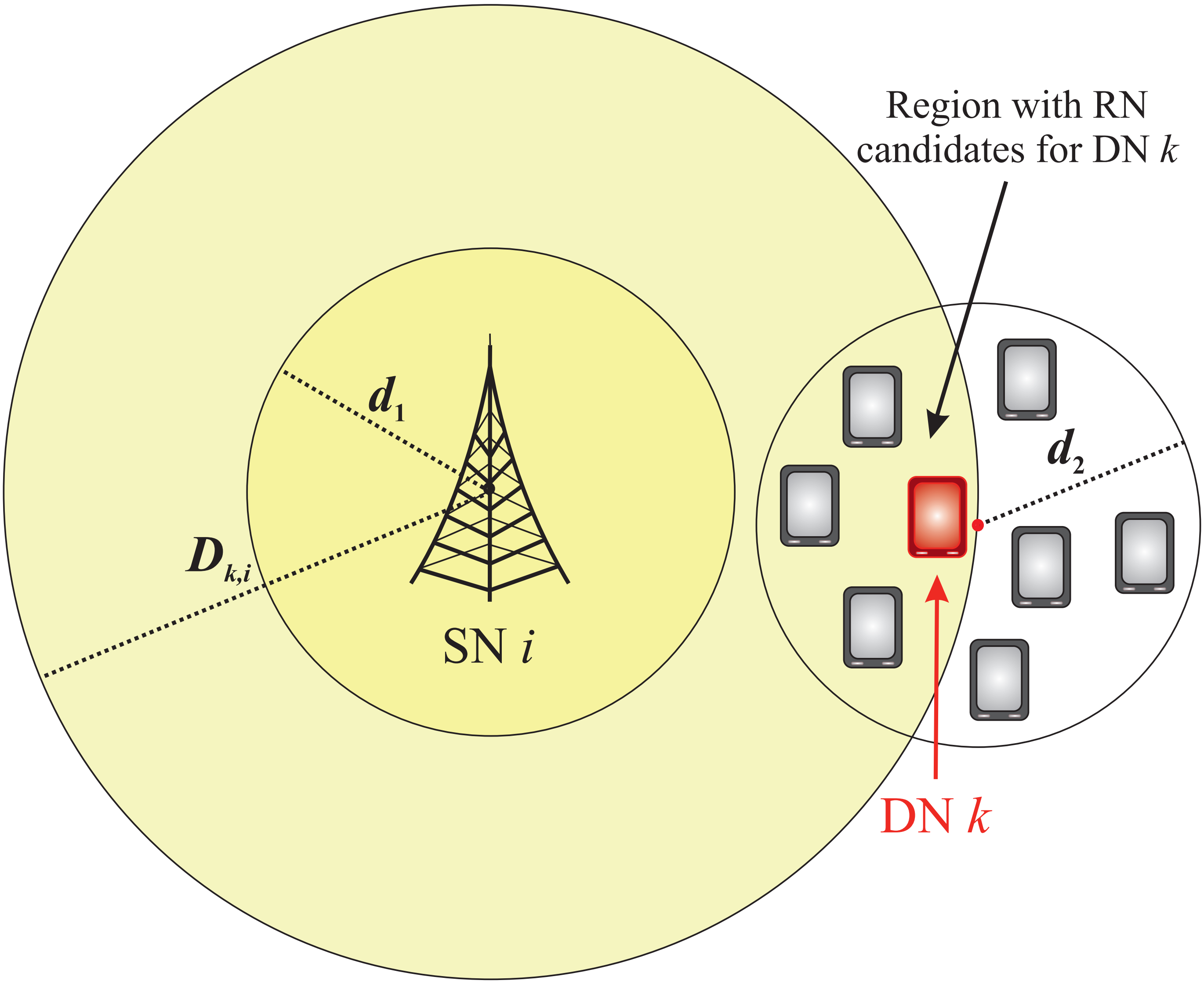

Fig. 3. Illustration of the inter-node distance thresholds considered in the proposed three-step algorithm for determining a limited number of RN candidates for a DN.

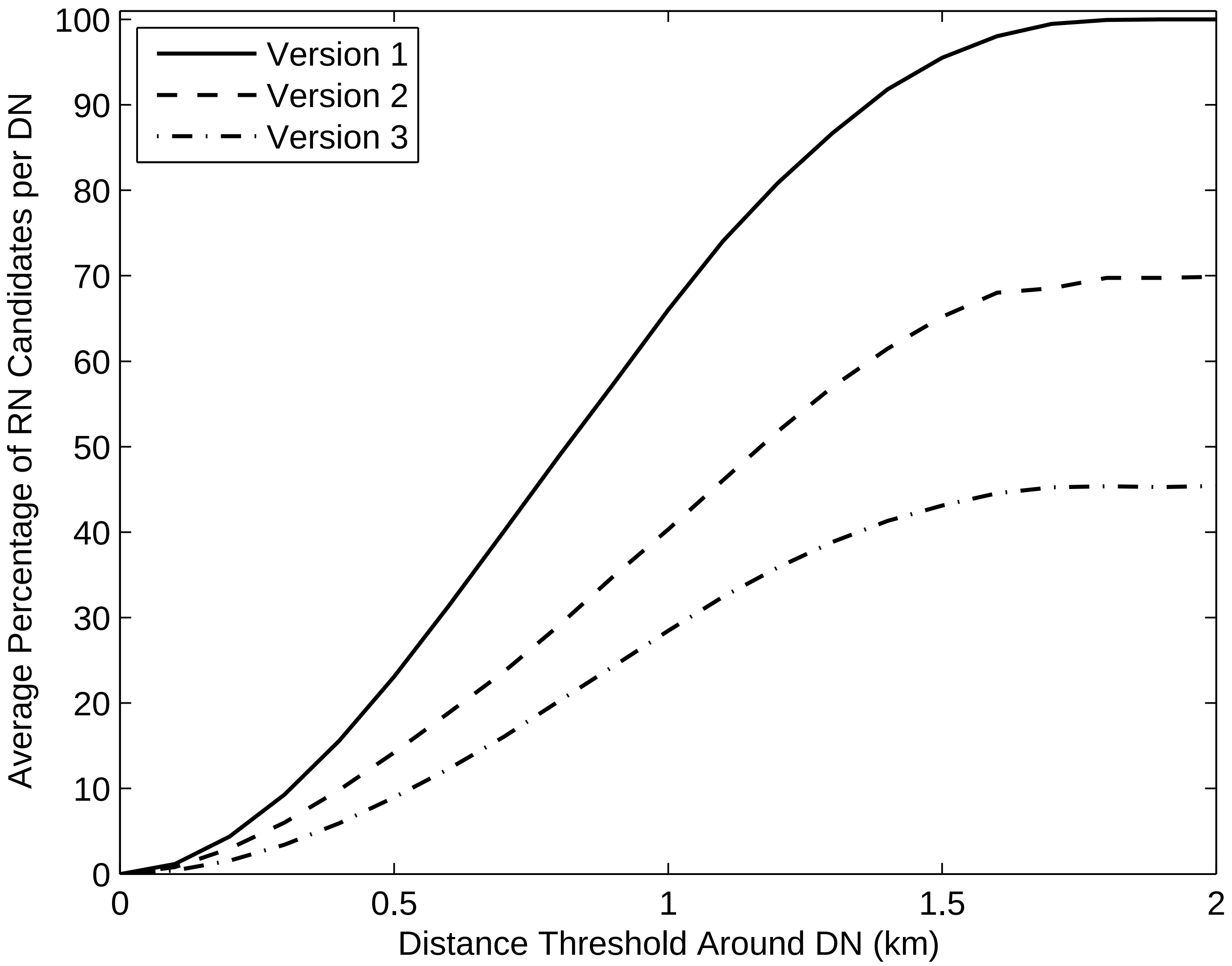

Fig. 4. Average percentage $\overline{P}$ of RN candidates per DN versus distance threshold d_2 for different versions of the three-step algorithm, Rayleigh multipath fading, $\rho_c = 1$ km and for 30 nodes/cell.

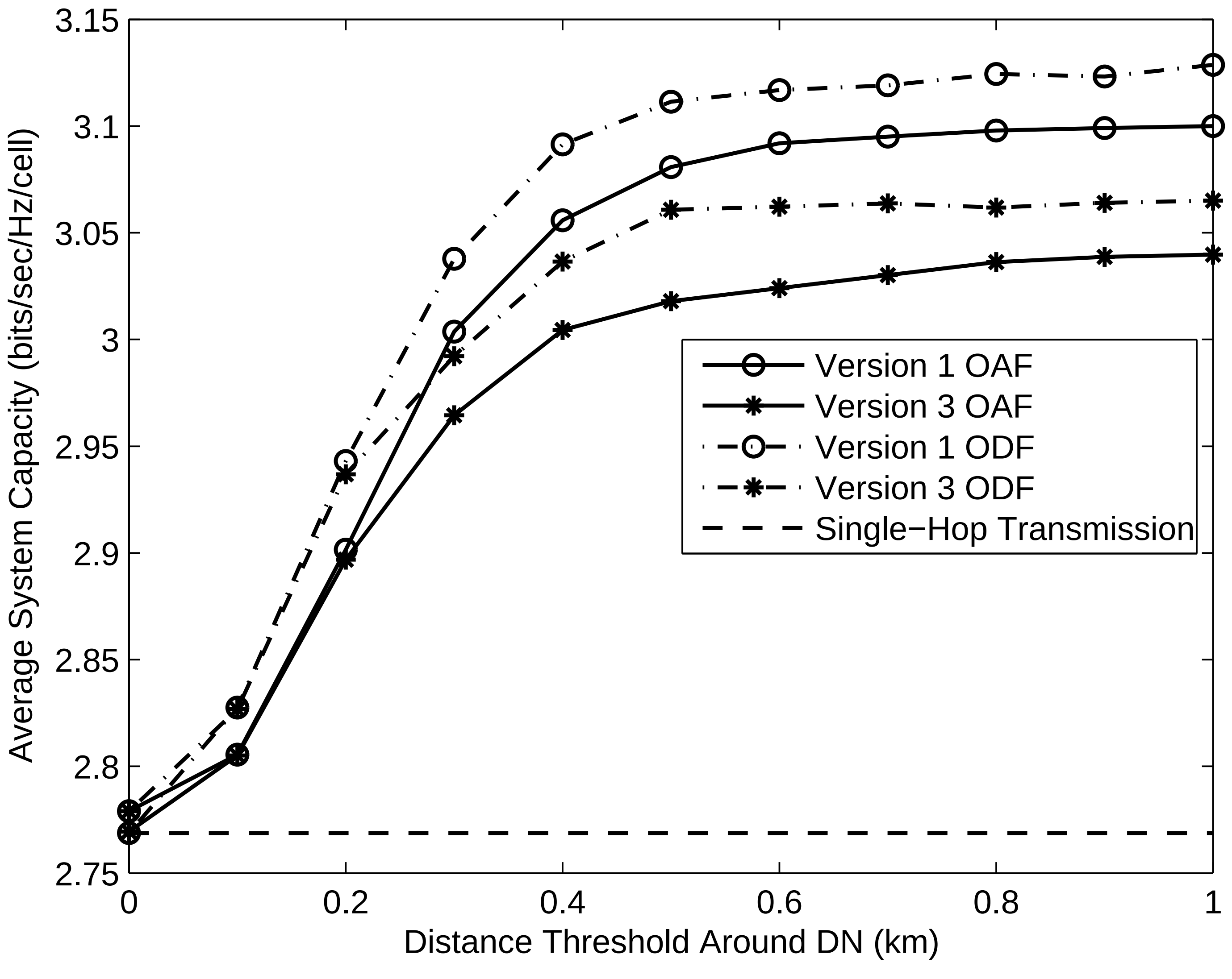

Fig. 5. ASC $\overline{C}$ versus distance threshold d_2 for different versions of the three-step algorithm, Rayleigh multipath fading, $\rho_c = 1$ km, system SNR = 20 dB and for both proactive ODF and OAF relaying.

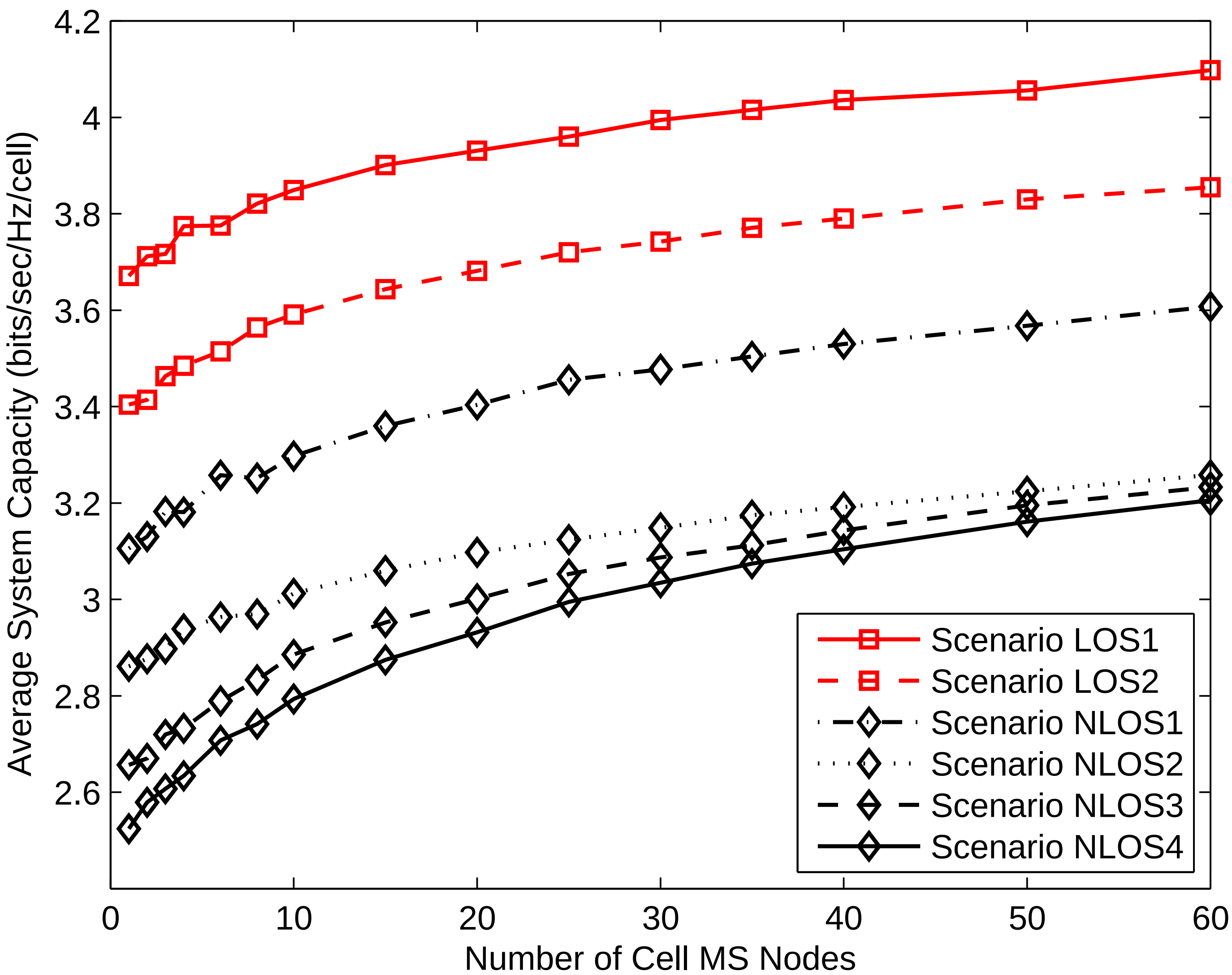

Fig. 6. ASC $\overline{C}$ versus the number of cell MS nodes K for proactive RS with ODF transmission, $\rho_c = 1$ km, system SNR = 20 dB and for different multipath fading conditions.

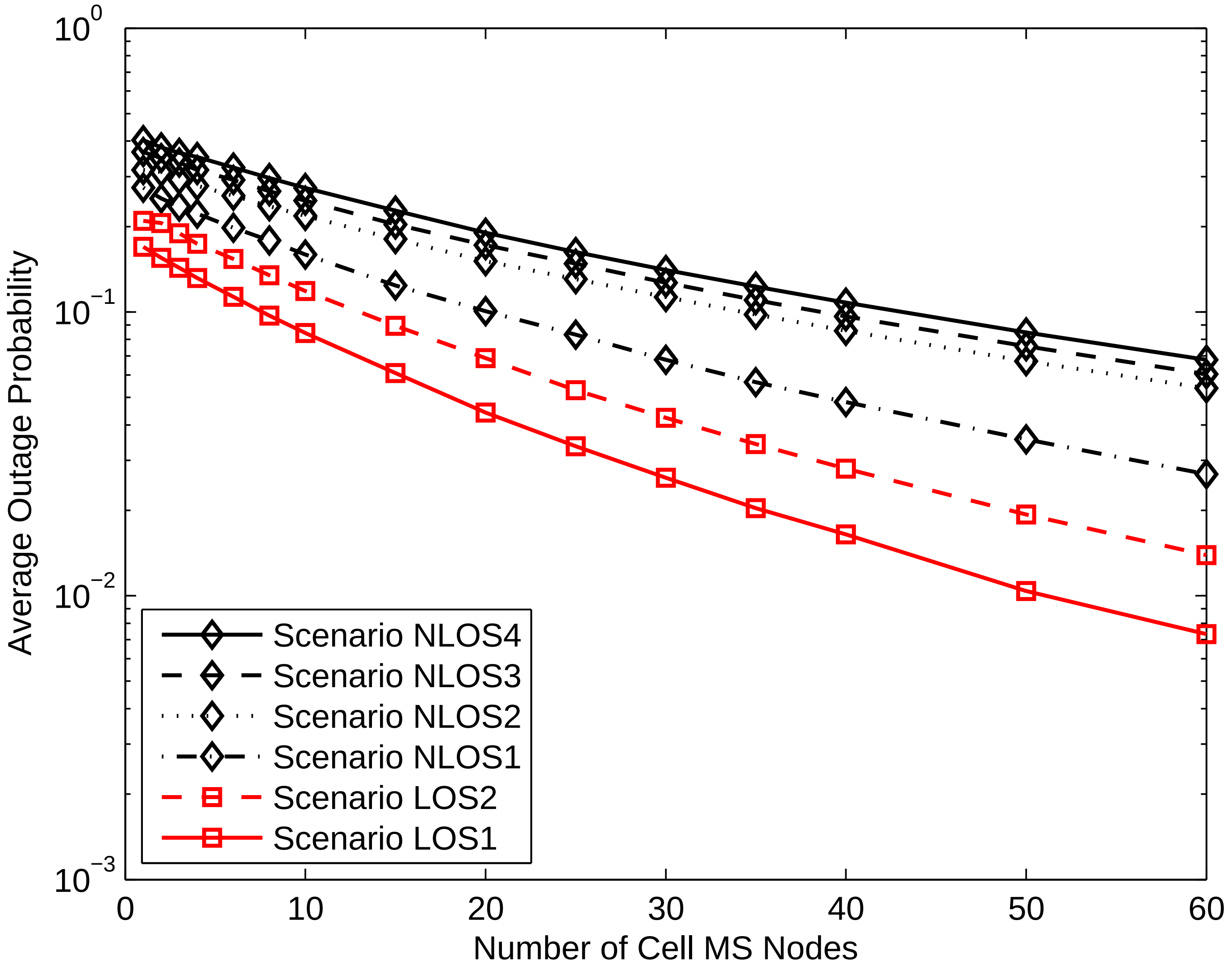

Fig. 7. AOP $\overline{P}_{\mathrm{O}}$ versus the number of cell MS nodes K for reactive RS with ODF transmission, $\rho_c = 1$ km, system SNR = 20 dB, R_s = 1 bits/sec/Hz and for different multipath fading conditions.