Cooperative Diversity in Interference Limited Wireless Networks

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***Abstract*— Using relays in wireless networks can potentially lead to significant capacity increases. However, within an asynchronous multi-user communication setting, relaying might cause more interference in the network, and significant sum-rate deterioration may be observed. In this work the effect of cooperation in an interference limited, narrow-band wireless network is investigated. It is crucial to determine the optimal trade-off between the amount of throughput gain obtained via cooperation and the amount of interference introduced to the network. We quantify the amount of cooperation using the notion of a *cooperative region* for each active node. The nodes which lie in such a region are allowed to cooperate with the source. We adopt the *decode-and-forward* scheme at the relays and use the physical interference model to determine the probability that a relay node correctly decodes its corresponding source. Through numerical analysis and simulation, we study the optimal cooperative region size to maximize the network sum-rate and energy efficiency, based on network size, relay availability, node decoding threshold, and destination reception capability. It is shown that optimized system performance in terms of the network sum-rate and the power efficiency is significantly improved compared with cases where relay nodes are not exploited or where the cooperative region size is suboptimal.**

***Index Terms*— Cooperative diversity, sum-rate, interference, cooperation gain, cooperative region.**

I. Introduction

Spatial multiplexing gain as a means to increase the capacity has been extensively studied in the context of multiple-input-multiple-output (MIMO) systems [1]. Although the use of multiple-antennas is appealing in theory, in some applications such as wireless sensor networks, it might not be feasible to benefit from this degree of freedom in system design due to the limited size and computing capability of an individual node. However, in such dense environments, using the resources of other peer nodes can help improve the network performance.

In this context, relay nodes can be exploited as a means to increase the capacity in a wireless network. The relay channel first introduced by van der Meulen leads to a communication scheme where instead of point-to-point communication between the source and destination, relays are exploited in a two-hop communication. The key capacity results for the case of a single relay were introduced by Cover and El Gamal in [2]. The capacity region for the relay channel with M relays is not known to date. However, Gastpar and Vetterli [3] have obtained upper and lower bounds on the capacity scaling under Gaussian noise and show that these bounds meet in the limit of large number of nodes.

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A counterpart of MIMO systems has been recently proposed in which the capacity and diversity gain of MIMO systems are obtained via distributed antennas. This scheme, called cooperative diversity, is proposed as a means to combat fading. It is an interesting concept in multi-user communication introduced mainly by Laneman *et al* [4][5] and Sendonaris *et al* [6]. This problem has its roots in the two-hop relay problem which has been an open problem in information theory. Under this setting, the relay channel is used to forward the data causing an increase in the capacity specifically for the cases where the source-destination channel experiences deep fades. Nabar *et al* [7] further evaluate the performance of cooperative schemes in the case of single source, single relay, and single destination and prove that full diversity can be obtained. In [8] Sankaranarayanan, Kramer and Mandayam further consider the case where multiple sources send their message to a relay, and the relay either simply forwards the data or first decodes and then forwards.

Although relay problem remains unsolved in terms of the optimal communication scheme, the studies above have taken significant steps in quantifying the performance gains obtained from cooperation. However, research in this subject has been mainly concentrated on information theoretic considerations, and only a few studies have focused on the system level performance of cooperation such as [9], in which Mergen *et al* study the problem of cooperative broadcast under a single-source single-destination setup with multiple levels of cooperation, where the broadcast performance is quantified by finding a signal decoding threshold above which a message is propagated in the network.

The few prior works which consider multiple sources do not quantify the interference within the network and usually assume there are a set of rules (such as TDM or FDM scheduling), which lead to interference removal. However, for the general non-orthogonal case where multiple sources and relay nodes use the same channel, their transmissions will interfere with each other. In a narrow-band wireless network with multiple sources, interference greatly affects the network capacity and has to be considered. In this work, we study the effect of relaying strategies and cooperation in such a multiple-source network, where the nodes employ un-synchronized transmission. We ask the basic question "How should the nodes optimally balance cooperation and interference to maximize the network capacity?" Extending our preliminary work in [10], we address this question more thoroughly and consider a wider range of important metrics for node communication performance including sum-rate and power savings.

To the best of our knowledge, there is no other work quantifying the trade-off between cooperation and interference in the literature. The closest work to ours is perhaps [11], where Quek et al study a dense wireless sensor network, in which the nodes send one information bit about the existence of a Phenomenon of Interest (PoI) to a fusion center. The authors compare the performance metrics such as the network energy consumption and correct decoding probability at the fusion center of a *parallel fusion architecture* with the *cooperative fusion architecture* (CFA). The authors show trade-offs exist between spatial diversity gain, average energy consumption, delivery ratio of the consensus flooding protocol, network connectivity, node density, and PoI intensity in CFA. Specifically, CFA is advantageous in cases with weak PoI intensity. In our work, although we study the potential energy gain resulting from cooperation, our focus is on a network with multiple sources and relays. By quantifying the added interference in the network resulting from cooperation, we address the question of "Whether or not to cooperate?" from a different view point. Dardari *et al* consider a wireless sensor network in [12] and study the interdependent aspects of WSN communication protocol and signal processing. They study the trade-off between energy conservation and the amount of error in the estimation of a scalar field by using appropriate distributed signal processing methods, which is different from our focus on the added interference as a result of cooperation and its effect on the network energy gain.

The main contributions of this work are three fold. *First*, we present a general network architecture for localized region-based cooperation in a large wireless network with multiple sources. *Second*, we propose an analytical framework to investigate the relation between the cooperative region radius, the interference level, and the relay decoding probability, and we derive the network sum-rate given multiple antennas at the destination as a main metric for cooperative region optimization, in a MIMO multiple access setting. *Third*, we demonstrate the power savings obtained via cooperation under a wide range of activity levels at the nodes, and we evaluate the effect of different decoding thresholds on the network performance. Our numerical and simulation studies provide general design guidelines for optimal relaying in an interference limited network.

The rest of this paper is organized as follows. Section II explains the network model and presents a practical relaying algorithm. Section III explains the details of our analytical framework to study the interaction between relaying and interference, which is reflected in the derivation of the decoding probability for each node. In Section IV we compute the network sum-rate with relaying, based on the results of Sections III, on deriving an estimate for the number of successful relays, which cooperate with each source node. Section V presents the numerical and experimental results. Finally, concluding remarks are given in Section VI.

II. Wireless Network Model and Relaying Scheme

In this section, we explain the network model under consideration and present a generic relaying architecture.

A. Network Model and Data Dissemination

We consider a collection of N nodes placed randomly, uniformly and independently in a disk $\mathbb{A}$. For illustration, we assume a communication setting similar to SENMA [13], in which the nodes on the disk need to communication with a *mobile access point*, which may be the data sink if the network model represents a sensor network. We call it the *Access Point* (AP) throughout this paper. The AP is a powerful unit both in its processing capability and its ability to traverse the network and is located at a variable height h, $0 < h < \infty$ above the center of the disk.

Time is assumed to be slotted to intervals of length L equal to the length of a data packet. Each node in the disk incurs an activity event at each slot. In a sensors network, this could mean that the node measures a physical phenomenon in case it senses activity. The activity event of a node at any slot is modeled by an independent Bernoulli random variable u_i for node i,

$$p(u_i) = \begin{cases} p_s, & \text{if} \quad u_i = 1 \\ 1 - p_s, & \text{if} \quad u_i = 0 \end{cases}. \tag{1}$$

We denote by $X_i[k]$ the data packet sent by node i in case of activity at time k. The random process X_i is assumed to be i.i.d among the source nodes. This assumption is motivated by the use of cooperative regions to be explained later, which allows separation between the source nodes so that their activities may be independent.

The AP is assumed to have n_r receive antennas, while the regular nodes each has only one antenna. Since the AP has the capability of interference mitigation using multiple antennas, our focus of interference analysis is on nodes in the disk. Figure 1 gives a simple illustration for a possible direct uplink communication scheme and our proposed cooperative counterpart, which will be discussed in the next section. Path-loss and channel variations are both considered in the channel model. When node i transmits with power $P_i[n]$, node j receives the transmission with power $P_i[n]\gamma_{ij}[n]$. The channel gain can be represented as

$$\gamma_{ij} = \frac{|h_{ij}|^2}{r_{ij}^{\alpha}}, \tag{2}$$

where r_{ij} is the distance between nodes i and j and h_{ij} models the fading channel from node i to j and α is the path loss rolling factor. Throughout the paper a block Rayleigh fading channel is considered for which the channel gain is constant over a block of length L. In our simulation results, we also consider the effect of increasing the line of sight component by using a Rician fading model between the nodes and the AP.

B. Cooperative Scheme

Under the proposed scheme, the nodes are divided to three groups in terms of their operation. The first group are the *active source nodes*, which are the nodes that have a packet to send at the beginning of a slot. The actual set of permissible sources will be chosen among these nodes by the scheduling algorithm, which is explained in detail in the next section. The second group, chosen among the remaining nodes, comprise the set of *potential relays*, which try to cooperate with the sources. These potential relays try to implement a *decode and forward* scheme. The main goal of our work is to find the optimal set of the potential relays and permissible sources, which result in the maximum network sum-rate from the source nodes towards the AP. We further quantify the *relay nodes*, a sub-set of the potential relays, which are indeed successful in the decoding of their intended message. The last set of the nodes comprise the ones not chosen among the active sources and potential relays. These nodes should not attempt to relay and must remain silent during the communication.

We define the ith *cooperative region*, $\mathbb{C}_i$, as the area in which node i acts as a source and its potential relays are contained. We denote its radius by r_C (Fig. 1). The optimal value for this radius will be determined by the value which maximizes the network sum-rate. Relay nodes in each such region usually do not have the capability of simultaneous transmission and reception. Therefore, their transmissions are assumed to be half-duplex.

The communication of a message from the source node is divided into two steps. The source i, after sensing the environment, first broadcasts the message $X_i[k]$ to the AP and the potential relays in its *cooperative region*. A potential relay node can estimate its membership in the cooperative region of active source nodes in its vicinity by estimating its relative distance to the source, possibly by using the received signal power. In the second phase, the potential relays which have successfully decoded the message will forward it to the destination. As we will show later, to maximize the sum-rate, the optimal cooperative region will not cover the whole network but is limited to a small area around each permitted source. Since the successful decoding relays deliver the same message $X_i[k]$, they act as a multi-antenna system sending a common message towards the AP. [1]

The two-phase communication is depicted in Fig. 1. During each slot a different set of sources are activated. Therefore, their corresponding relays are different. For instance, as shown in Fig. 1, suppose the relays from node j's cooperative region were in their reception phase during the last time slot and are now in the cooperative phase. Then they are the first cause of interference to the potential relays in node i's cooperative region. The source nodes which have started their transmission synchronously with source i are the second cause of interference. Source l in Fig.1 represents such an example. Using the same physical model as the one introduced in [14], a relay m is assumed to successfully decode the message sent from the source i if the SINR at m is above a required threshold. The physical model requirement for the decoding at relay m can be written as

[1]One of the key challenges to implementing relay-based cooperation protocols is block and symbol synchronization of the cooperating terminals. Such synchronization might be obtained through periodic transmission of known synchronization prefixes [4]. A detailed study involving the synchronization issue is beyond the scope of this work.

$$\mathrm{SINR}_m = \frac{P_i[k]\gamma_{im}[k]}{N_0 + \sum_{l\in\mathbb{S}[k],l\neq i} P_l[k]\gamma_{lm}[k] + \sum_{j\in\mathbb{C}[k-1]} P_j[k]\gamma_{jm}[k]} > \beta, \tag{3}$$

where the interference at the potential relay nodes during the relay reception phase is either due to other permitted source nodes comprising the set of the active sources, $\mathbb{S}[k]$, at time k, or the relays which have completed their reception in slot $k-1$ and are forwarding their corresponding message to AP in slot k comprising the set $\mathbb{C}[k-1] = \bigcup_{i=1}^{N_p[k-1]} \mathbb{C}_i[k-1]$, where $N_p[k]$ represents the number of permitted sources (cooperative regions) at time k. The noise is assumed to be a complex Gaussian random variable with variance N_0. Due to operation in the high interference regime resulting from multiple simultaneous communications, we neglect the noise effect and base our analysis on SIR at the relays. The parameter β is a design parameter and depends on the level of tolerated interference by the nodes. Since we consider fading in our model, the relays within each region are still probable to go under deep fades. Therefore, some of the relays may not be capable of decoding successfully. However, the closer a relay node is to its corresponding source the higher the decoding probability is.

We define two states for each potential relay, *receive* and *transmit*. During the receive state the signal received at a potential relay is decoded correctly if (3) holds. If a potential relay is in the cooperative region of a source, and it has successfully decoded the message from the source, it transmits the message to the AP in the transmit state. During the relay transmission state we have the following expression

$$Y_m[k] = 0, \quad \mathbf{Y}_d[k] = \sum_{i=1}^{N_p[k]} \mathbf{H}_i\mathbf{X}_i[k] + \mathbf{Z}, \tag{4}$$

where $Y_m[k]$ is the received message at a relay when it is in the transmit state, $\mathbf{Y}_d[k]$ is the received vector of dimension $n_r \times 1$ at the destination, which is a superposition of the messages sent by all zones, $\mathbf{H}_i$ is the channel vector from the set of relays in region i which have successfully decoded the message to the AP in addition to source i itself, $\mathbf{X}_i[k]$ represents the message vector sent out synchronously by the relays of region i and source i, and $\mathbf{Z}$ is zero-mean complex Gaussian noise with independent, equal-variance real and imaginary parts.

C. Source Scheduling

In the proposed scheme, within each cooperative region only one source is allowed to transmit during each communication cycle. We focus on a snapshot of the network at time k. At time $k-1$, the potential relays have tried to decode their intended message, and among them, the set of the successful decoding relays, $D[k-1]$, forward their messages towards the AP during the slot k. The timing of these two slots has been depicted in Fig. 2. Clearly, in slot k, the sources allowed to transmit should be chosen among the nodes which were not

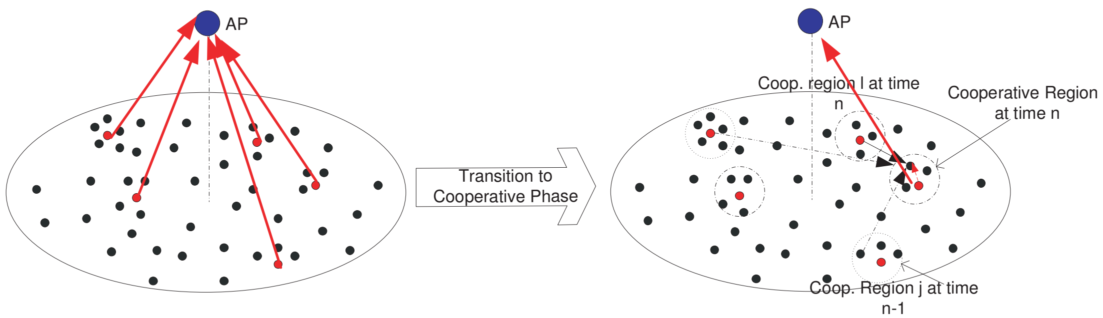

Fig. 1. Network layout. Transition from direct transmission phase to cooperative communication: the relays that have decoded their message in time slot $n-1$ are interfering with the relays which are in their receive state in time n.

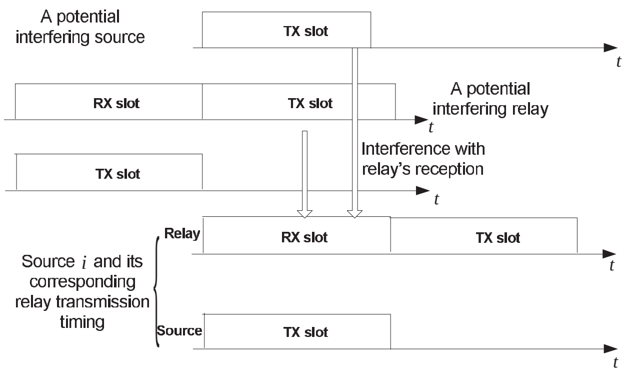

Fig. 2. Timing for a source and its corresponding relay in $\mathbb{C}_i$ as well as possible interferer source and relays.

chosen in the prior slot among the sources, $\mathbb{S}[k-1]$, or relays, $D[k-1]$.

Assuming that we know the optimal cooperative region area $a = \pi r_c^2$, to be determined as a result of our optimization, we can characterize the ultimate number of sources that are permitted to simultaneously transmit as $\lfloor \frac{|\mathbb{A}|}{a} \rfloor$, where $|\mathbb{A}|$ is the coverage area. In practice this number strongly depends on the network topology. Two sources i and j can simultaneously send their messages if they do not lie in the same cooperative region. The problem of finding the set of simultaneous sources can therefore be translated into the maximal independent set (MIS) problem by considering a graph where the vertex set represents the active source nodes and there is an edge between two vertices i and j if and only if their distance $d_{i,j} < 2r_C$. In our experiments, we have implemented the parallel algorithm presented in [15] to solve the MIS problem and found the maximal packing number. During each iteration of this algorithm, the active source nodes can communicate locally to determine if their distance from the source nodes already chosen in the previous iteration is smaller than $2r_C$. Under this setting the communication scheme within each cooperative region can be modeled as a single source and multiple relays.

III. Characterization of the Interference and Decoding Relays in Cooperative Regions

In this section we quantify the interference and the correct decoding probability at a relay as a function of the signal to interference ratio at the relay, for a given size of the cooperative region. Clearly, the amount of interference at a relay is a function of the number of interferers and their relative location to the relay. These interferers either belong to the set $\mathbb{C}[k-1]$ or the set $\mathbb{S}[k]$ as we explained in Section II-C. During the source transmission phase, a relay $m \in \mathbb{C}_i[k]$ decodes the corresponding source if and only if (3) holds. The overall interference at m can then be expressed as

$$\begin{aligned} I_m[k] &= \sum_{l \in \mathbb{S}[k], l \neq i} P\gamma_{lm}[k] + \sum_{j \in \mathbb{C}[k-1]} P\gamma_{jm}[k] \\ &= \sum_{l=1}^{N_p} P\gamma_{lm}[k] + \sum_{j=1}^{D} P\gamma_{jm}[k], \end{aligned} \tag{5}$$

where D_i is the number of nodes which have been successful in decoding within $\mathbb{C}_i[k]$ and $D = \sum_{i=1}^{Np} D_i$ represents the total number of interfering relays, and we have simplified the problem of relay selection by assuming that the nodes transmit with the same power $P_k = P$. We next formulate the cooperative region maximization problem and analytically find the expected number of successful decoding relays within each region.

A. Expected Number of Successful Decoding Relays

We denote the number of relays in region i by the random variable N_C^i. Nodes are uniformly distributed over the disk area. Therefore, the event $m \in \mathbb{C}_i$ has a Bernoulli distribution with $\Pr[m \in \mathbb{C}_i] = \frac{a_i}{|\mathbb{A}|}$, where $a_i = \pi {r_C}^2$. N_C^i follows a binomial distribution as $\Pr[N_C^i = l] = \binom{N}{l}(\frac{a_i}{|\mathbb{A}|})^l(1-\frac{a_i}{|\mathbb{A}|})^{N-l}$ with mean $E[N_C^i] = N\frac{a_i}{|\mathbb{A}|} = N\pi\frac{r_C^2}{|\mathbb{A}|}$. In the following we quantify the expected number of successful decoding relays.

Proposition 1: In the given wireless network within region i, $E[D_i] = \int_0^{r_C} \frac{N}{|\mathbb{A}|}\Pr[SIR(r) > \beta]2\pi r dr$, where $\Pr[SIR(r) > \beta]$ represents the successful decoding probability for a relay located at distance r relative to its source.

Proof: The proof is similar to the proof of Theorem I in [10] (with the slight difference that we have to replace $E[N_r^i]$ by $E[N_C^i] = N\pi\frac{r_C^2}{|\mathbb{A}|}$ in (9) of [10]). ■

We can further compute the expected number of total successful decoding relays within the network.

Proposition 2: In the given wireless network the expected number of total successful decoding nodes during each time slot satisfies $E[D] = E[N_p]E[D_i]$.

Proof: Refer to Appendix I for the proof. ■

B. Expected Number of Interfering Nodes

Since the nodes are randomly distributed on the disk, the number of interferer nodes is a random variable. In time slot k the relays which have been successful in their reception phase in slot $k-1$ interfere with the relays receiving in the current slot. The total number of interfering relays can therefore be formulated as

$$N_{I_{\text{relay}}}[k] = \sum_{j=1}^{N_p[k]-1} N^j_{I_{\text{relay}}}[k], \quad (6)$$

where $N^j_{I_{\text{relay}}}[k]$ represents the number of successful decoding relays within cooperative region j (which have been successful in receive mode during slot $k-1$). Due to the symmetry of the communication structure in different slots, the number of interferers is stationary and we remove the time dependence in the expectation. An upper bound for the number of circular cooperative regions that can be packed in the disk area equals $\lfloor \frac{|\mathbb{A}|}{\pi r_C^2} \rfloor$ as explained in Section II-C. Furthermore, the event of being an active source is Bernoulli with probability p_s and the expected number of active sources equals $p_s N$. Since this number can not exceed the above limit, we conclude $E[N_p] = \min(p_s N, \lfloor \frac{|\mathbb{A}|}{\pi r_C^2} \rfloor)$. Using the conditional expected value law, we can write

$$E[N_{I_{\text{relay}}}] = E_{N_p}\left[E[N_{I_{\text{relay}}}|N_p = n_p]\right] = E_{N_p}\Big[\sum_{j=1}^{N_p-1} E[N^j_{I_{\text{relay}}}]\Big].$$

Based on our interference analysis in Section III-C it will be shown that the geographic location of the cooperative region only slightly affects the amount of interference at each relay. However, the relative location of the relay to its corresponding source is the main factor which affects the amount of interference. Using this symmetry and the fact that the interferer relays are the relays that are transmitting a message which has been successfully decoded during the previous time slot, we can conclude that the expected number of interferer relays in any region i equals to that of another region j. We therefore can write

$$E[N_{I_{\text{relay}}}] = E_{N_p}\left[(N_p-1)E[N^j_{I_{\text{relay}}}]\right] = (E[N_p]-1)E[N^j_{I_{\text{relay}}}]. \quad (7)$$

Finally, the total number $N_I[k]$ of interfering nodes is the sum of $N_{I_{\text{relay}}}$ and the number of sources in the current slot which are interfering with relay m's reception. Since the source corresponding to the relay has to be removed from the set of interfering sources, we have $E[N_I] = E[N_{I_{\text{relay}}}] + E[N_p] - 1$.

C. Interference Analysis: A Continuum Approach

In this section we explain the details for deriving an approximation to the amount of interference at each relay. The channel from each interfering node l to the relay m is assumed to undergo Rayleigh fading. We further assume that the magnitude of fading is constant for each packet (quasi-static fading). To find a closed from expression for the amount of interference, we use a continuum type approach similar to the one used in [16] in crux.

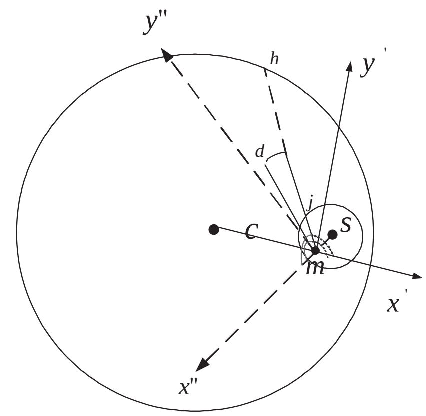

Fig. 3. Snapshot of a disk and a cooperative region. A source and its relay m is shown. Differential elements of the disk area have been considered to find the overall interference at m by integrating over this area.

Figure 3 demonstrates a possible cooperative region (the small circle). The area outside this circle is the potential interference region. For each interfering node l, the amount of interference to node m equals $I_{lm} = \frac{P}{r_{lm}^\alpha}|h_{lm}|^2$. We consider Rayleigh fading. Therefore $|h_{lm}|^2$ has exponential distribution with parameter 1, and hence $E[I_{lm}] = \mu_l = \frac{P}{r_{lm}^\alpha}$. We consider a wireless network with high node density ρ. In such a *continuum* model we can use a differential approach to evaluate the expected value of interference at m. Since there are a total of $N_I[k]$ interfering nodes, in the limit of a large number of nodes, in each differential element we have $\frac{N_I}{|\mathbb{A}|} r dr d\theta$ nodes. Therefore, an element $d\theta$ as depicted in Fig. 3 on average causes the following amount of interference

$$dI = \frac{P}{r^\alpha}\frac{N_I r dr d\theta}{|\mathbb{A}|} = \frac{P}{r^{\alpha-1}}\frac{N_I}{|\mathbb{A}|} dr d\theta = \rho \frac{P}{r^{\alpha-1}} dr d\theta. \quad (8)$$

The overall expected interference at node m is, therefore, $E[I_m] = \int_{\mathfrak{S}} dI$, where the integration is performed over $\mathfrak{S}$, the potential interferer region.

For a differential element located at angle θ with respect to x' in Fig. 3, the segment mh represents the distance of the maximum interferer, $d_{\max}(\theta)$. Here, x' is the axis in the direction cm. The segment mj is the distance of m from the minimum possible interferer, and it is represented as $d_{\min}(\omega)$, where ω is the angle of mj with x'' defined in the direction of sm (these coordinates are used to find the equations for the two circles). The derivation of $d_{\min}(\omega)$ and $d_{\max}(\theta)$ is explained in Section III-C [10] for the interested reader. The overall expected interference at m can be formulated as

$$\begin{aligned} E[I_m] &= \int_0^{2\pi}\int_{d_{\min}(-\theta+\angle x' m x'')}^{d_{\max}(\theta)} \rho \frac{P}{r^{\alpha-1}} dr d\theta \\ &= \frac{\rho P}{\alpha-2}\int_0^{2\pi}\Big[\frac{1}{d_{\min}(-\theta+\angle x' m x'')^{\alpha-2}} - \frac{1}{d_{\max}(\theta)^{\alpha-2}}\Big] d\theta. \end{aligned} \quad (9)$$

In general, numerical integration is needed to solve the above integral. However, in our analysis we have considered

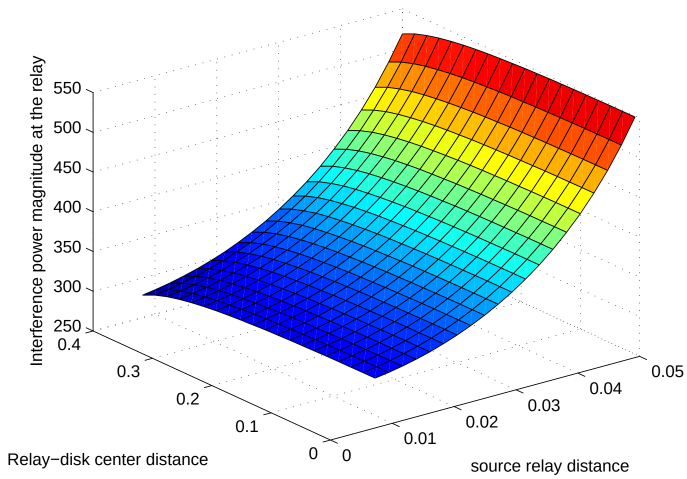

Fig. 4. The amount of interference (normalized by the number of interferers) at a relay versus relay's location in disk and its location relative to its source. $r_c = 0.05$ and $|\mathbb{A}| = 1$.

$\alpha = 4$. For this case it can be shown that (more detailed explanation is given in [10], p.g. 5)

$$E[I_m] = 2\frac{\rho P}{\alpha - 2}\Big(\frac{|\mathbb{A}|\pi^2}{\pi^2 d^4(c,m) - 2\pi|\mathbb{A}|d^2(c,m) + |\mathbb{A}|^2} - \frac{\pi r_C^2}{d^4(s,m) - 2d^2(s,m)r_C^2 + r_C^4}\Big). \tag{10}$$

Figure 4 represents the normalized value, $\frac{E[I_m]}{N_I}$, of the expected interference within the disk of unit area, as a function of the distance between the disk center c and the relay m. Also, the effect of the relay location relative to its corresponding source, within each cooperative region, has been considered. Note that interestingly the change of the distance relative to the disk center does not cause substantial change in the expected interference value. However, within each region, a possible relay that is closer to the region boundaries undergoes a higher amount of interference as expected.

D. Successful Decoding Probability

In this section we will give an approximation for $\Pr[SIR_m > \beta]$. We consider equal power $P = 1$ for all nodes. The interference at relay m can be formulated as $I_m = \sum_{j=1}^{N_I} I_m^j$, where each interference element has an exponential distribution with mean μ_l as we explained in Section III-C. We replace N_I by its expected value as an approximation, and assume that individual interference elements have equal means $\mu = \frac{E[I_m]}{E[N_I]}$. Then, we have the sum of $E[N_I]$ i.i.d exponential random variables with mean μ, which has Erlang distribution with parameter $E[N_I]$ and mean $\mu E[N_I] = E[I_m]$. Hence,

$$f_{I_m}(x) = \frac{x^{E[N_I]-1}}{(E[N_I]-1)!\mu^{E[N_I]}} e^{-\frac{x}{\mu}}, \quad \text{for} \quad x \geq 0. \tag{11}$$

The distribution of the signal power received at node m located at distance d from the corresponding source s can then be computed and the details are given in Appendix II. The main result of this section therefore can be stated as

Corollary 1: We can formulate the outage probability for each relay as

$$\Pr[SIR_m \leq \beta] = F_Y(\beta) = 1 - \frac{1}{\left(1 + \frac{\mu\beta}{\mu_s}\right)^{E[N_I]}}. \tag{12}$$

Here $\mu_s = \frac{P}{d^\alpha}$ is a function of the node's relative distance d with its corresponding source. The expected number of decoding nodes within each cooperative region can therefore be formulated by the result of Proposition 1 and is a function its radius.

In the next section we use this result to find the optimal area for the cooperative region, in which the relays are allowed to decode and forward. To simplify the analysis we assume that this area is a circle and the radius of this circle is the same for all active nodes. The latter is justified by the fact that the average amount of interference at each relay is not sensitive to the relative location of the cooperative region within the planar disk, while the distance of the relay from its corresponding source is the determining factor. The metric of interest in this case is the network sum-rate.

IV. Network Sum-rate Optimization

In Section III we introduced an analytical framework to quantify the number of successful decoding relays. To derive the overall network sum-rate, we consider the following two-part contribution of data flow toward the AP. In the first part, the set of active sources scheduled to transmit send their message towards the destination. This phase can be modeled as multiple-access communication. In the second part, the set of successful decoding relays forward the decoded message to the AP as depicted in Fig. 1. In this phase, the successful decoding relays constitute a *cooperative MIMO* system. The relay nodes within each cooperative region $\mathbb{C}_i$ serve as the multiple antennas sending a common message synchronously. The network sum-rate during these two phases can be written as

$$R_{\text{Total}} = \frac{1}{2}(R_{\text{Ph1}} + R_{\text{Ph2}}), \tag{13}$$

where R_{Ph1} is the sum rate during the first non-cooperative phase and R_{Ph2} is the sum-rate during the second phase when cooperation is in effect.

The cooperative region radius optimization can be written as

$$\begin{aligned} r_{\text{opt}} &= \arg\max_{r_C} E[R_{\text{Ph2}}] = \arg\max_{r_C} \sum_{i=1}^{N_p} E[R_i(D_i)] \\ &\text{subject to} \quad m \in D_i \Leftrightarrow SIR_m > \beta \quad \text{and} \\ &\forall i,j \quad d(i,j) > 2r_{\text{opt}}, \end{aligned} \tag{14}$$

where we use the notation $R_{\text{Ph2}} = \sum_{i=1}^{N_p} R_i(D_i)$ to clarify that $R_i(D_i)$, the data rate corresponding to region i, is based on having D_i nodes in this region. This optimization is constrained by the fact that any relay m within a region has to satisfy the SIR requirements to correctly decode. Also, the distance requirement imposed by scheduling has to be satisfied.

The above optimization problem is non-convex in r_C, so we use the following approximation

$$r_{\text{opt}} \simeq \arg\max_{r_C} \sum_{i=1}^{N_p} R_i(E[D_i]). \tag{15}$$

This approximation arises since the expected value of a concave function $f(x)$ obeys $E[f(x)] \leq f[E[x]]$ based on Jensen's inequality. The inequality becomes tight as the concavity decreases and the comparison between our results from analysis and simulation suggest that the bound is indeed tight. Therefore, the choice of the cooperative region which results in the maximum expected number of decoding relays, $E[D_i]$, will maximize the network sum-rate. The problem in this case is easier to solve since $E[D_i]$ can be computed using the result of Proposition 1 and (12) in terms of r_C (noting that N_I is a function of r_C). We solve this optimization problem numerically.

The capacity of a MIMO channel has been derived in the landmark work of Telatar [1]. Next, we further clarify the multiuser MIMO model and show that our setting follows the same scheme, assuming that the AP has access to the channel state information. The number of transmit antennas in each region i equals to the number of successful decoding nodes, approximated by $E[D_i]$. Then, the uplink of a MIMO channel with multiple users can be modeled using (4), where $\mathbf{H}_i$ is the $n_r \times E[D_i]$ matrix representing the channel response from the cooperating nodes of region i to the AP, and $\mathbf{x}_i$ represents the $E[D_i] \times 1$ vector of the cooperative message sent from region i. Note that since the nodes are located close to each other and at each instance we only consider the nodes which have successfully decoded the message, we can assume full cooperation and consider them as multiple-antennas sending the same message. Given the channel state information is known at the receiver, the capacity region with multiple receive antennas can be expressed as [17]

$$\sum_{i=1}^{M} R_i(E(D_i)) \leq E_{\mathbf{H}}[\log\det(\mathbb{E}_{n_r} + \frac{P}{Z_0}\sum_{i=1}^{M}\mathbf{H}_i\mathbf{H}_i^H)] \\ \forall M, 1 \leq M \leq N_p, \tag{16}$$

where $\mathbb{E}_{n_r}$ is the $n_r \times n_r$ identity matrix and $\mathbf{Z} = [z_1, \ldots, z_{n_r}]^T$ is the noise vector at the receiver, where we assume z_i to be a Gaussian RV with variance Z_0. Replacing $M = N_p$ results in the expression giving the maximum achievable sum-rate.

It is shown in [1] that for the case of Gaussian sources with and channel matrices $\mathbf{H}_i$ with i.i.d complex Gaussian entries with mean zero, the above sum can be analytically expressed in terms of Laguerre polynomials. In our system model, since it is assumed that the AP is located at a height h far enough from the nodes, the expected power received at the AP from all sensing nodes approximately equals $\frac{P}{h^\alpha}$. Assuming Rayleigh fading, the elements of each matrix $\mathbf{H}_i$ have a Gaussian distribution and are scaled by the above expected power factor. Hence, for our model, $\mathbf{H}_i$ can be written as a scaled version of a matrix $\mathbf{H}_i^{'}$ with zero mean complex Gaussian elements, $\mathbf{H}_i = \frac{1}{h^\alpha}\mathbf{H}_i^{'}$, with P normalized to 1. We can now apply Theorem 2 in [1] to find an analytical expression for the network sum-rate. This theorem states that the capacity of a single-user MIMO channel with n_t transmit and n_r receive antennas with power constraint P_{total} on the transmit side and under Rayleigh fading equals $C(n_r, n_t, P_{\text{total}}) = \int_0^\infty \log(1 + \frac{P_{\text{total}}}{n_t}\lambda)\sum_{s=0}^{f-1}\frac{s!}{(s+a-f)!}[L_s^{a-f}(\lambda)]^2\lambda^{a-f}e^{-\lambda}d\lambda$, where $f = \min(n_r, n_t)$, $a = \max(n_r, n_t)$, $L_s^{a-f}(x) = \frac{1}{s!}e^x x^{f-a}\frac{d^s}{dx^s}(e^{-x}x^{a-f+s})$ is the associated Laguerre polynomial of order s [1]. The author further generalizes the proof and show that under the multiuser setting with M senders each having power P_{total}, the sum-rate satisfies $\sum_{i=1}^{M} R_i(n_t) \leq C(n_r, Mn_t, MP_{\text{total}})$.

In our setting, the number of transmitter virtual antennas in each region is $n_t = E[D_i]$, the number of receiver antennas is n_r, and the power constraint for the transmitters within each region is $P_{\text{total}} = n_t P$. Thus, the achievable sum-rate satisfies $\sum_{i=1}^{E[N_p]} R_i \leq C(n_r, E[N_p]E[D_i], E[N_p]E[D_i]\frac{P}{h^\alpha})$.

V. Numerical Analysis and Simulation Results

In this section we present numerical results based on the proposed analytical framework and compare them with the simulation results. The capacity maximization problem has been solved numerically by changing the cooperative region radius and finding its optimum value. We have assumed the path loss roll-off factor to be $\alpha = 4$ within the planar disk as justified in [13] for wireless networks with low-lying antennas. The free space path loss factor between the nodes and the AP is however, considered to be $\alpha = 2$.

The two metrics of interest for this setting are the sum-rate and the power efficiency. To avoid the event of very close nodes, which causes the strength of the received signal to be unlimited in our model, a minimum distance ϵ is assumed between the nodes. For the unit disk with N nodes, $N\pi\epsilon^2 < |\mathbb{A}| = 1$ is needed to guarantee that all nodes can be located within the disk. We assumed $\epsilon = \frac{1}{\sqrt{5\pi N}}$. For the simulation, the capacity results have been averaged over 25 different network topologies. In all cases, the AP is assumed to be located at height $h = 1$ above the network and $Z_0 = 1$ has been considered.

A. Effect of Cooperative Region Radius and Number of Receive Antennas

Figure 5 presents log-scaled plots of the sum rate for a network with $N = 1000$ nodes. The effect of different numbers of receive antennas n_r based on the capacity results of the previous section is also shown. As we expect, the total number of successful nodes in decoding determines the capacity. We observe that the curves for different numbers of receive antennas have the same characteristic in terms of the point where the maximum sum-rate occurs. The determining factor for the network sum-rate is the total number of cooperative regions and the number of decoding nodes within each region. Therefore, the optimum region radius is the same for different values of n_r. However, the increase in the number of antennas will result in spatial multiplexing which causes the capacity increase shown in the curves. Furthermore, this figure suggests

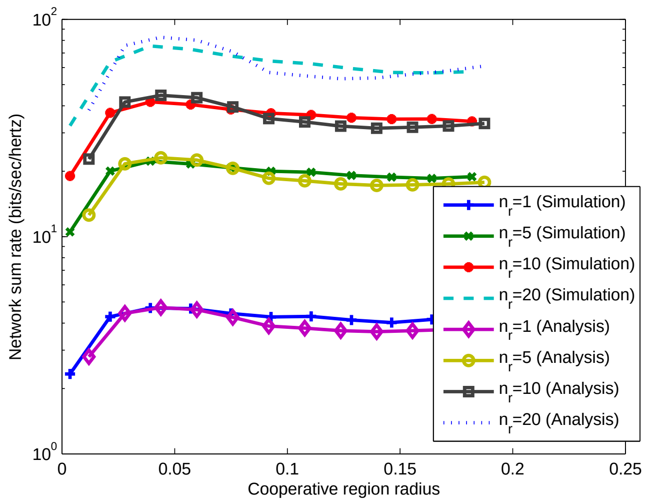

Fig. 5. Network sum rate for different number of antennas at the destination. $p_s = 0.02$.

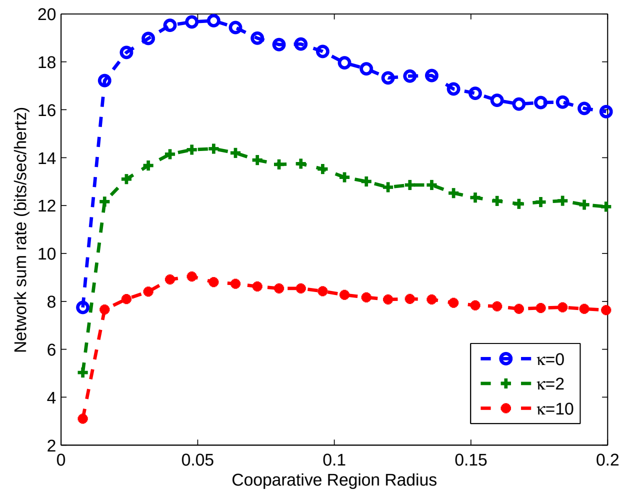

Fig. 6. Network sum rate for $n_r = 5$ and different values of κ. $p_s = 0.02$.

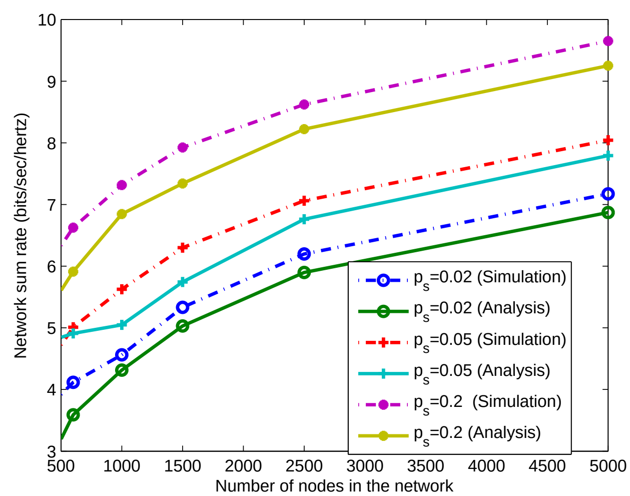

Fig. 7. Maximum Network sum rate for different number of nodes in the network and different activity probabilities

that the choice of the optimal region radius is crucial for all values of n_r.

The main reasons for the difference between the analysis and simulation are the edge effect, the approximations used in calculating the average sum-rate, and the fact that it is not possible in general to quantify the number of active sources chosen by the scheduling scheme analytically. Since nodes are randomly located, the actual number of sources chosen by the MIS algorithm is less than the number determined by the theoretical results.

We also consider a Rician fading model between the nodes and the AP. The parameter κ (so-called K-factor) is the ratio of the energy in the specular path to the energy in the scattered paths ([17], Section 2.4.2). The larger κ is the more deterministic the channel is. Figure 6 demonstrates the existence of an optimal cooperative region radius for different values of κ, assuming equal channel power for all values of κ. By increasing the deterministic component of the channel gain, the overall sum-rate decreases since the MIMO channel no longer benefits from a rich scattering environment. The effect of deterministic part of the channel on MIMO capacity is explained in more detail in [18].

In Figure 7, the maximum network sum-rate is depicted for different number of nodes within the network and different activity probabilities at the nodes. It can be seen in the figure that increasing the activity probability leads to sum-rate increase as expected. Also, having more nodes in the network results in more sources and, therefore, more cooperative regions to be scheduled during each transmission. Figure 8 gives more precise intuition of how the scheme works. For each activity probability p_s, increasing the number of nodes results in cooperative regions with smaller radii to be optimal. This is expected since our scheduling algorithm only allows non overlapping cooperative regions. As the number of nodes increases we have to pack more cooperative regions and it makes intuitive sense for the optimal regions to be smaller. Another interesting observation is the decrease in the optimal radius with the increase in activity probability p_s. For the cooperative region of node i, choosing a large value for the radius results in shutting down many sources that lie in the cooperative region. The capacity loss due to this overcomes the gain obtained by cooperation. This fact suggests that in networks with high data arrival rates, choosing direct transmission is the optimal strategy compared to the cooperative strategy.

In Figure 9 the probability of successful decoding at a relay versus the relay's distance from the source is given, for three different values of r_C with $r_{\text{opt}} = 0.05$. As the figure suggests, increasing the region radius above the optimum value does not further improve the system performance.

As an example, consider a relay located at the distance 0.02 from its corresponding source. For the region radius $r_{\text{opt}} = 0.05$, the probability of successful decoding at this relay equals 0.51. This value is almost the same for a region with radius $r_{\text{opt}} = 0.11$ and increases to 0.85 for $r_{\text{opt}} = 0.19$. However,

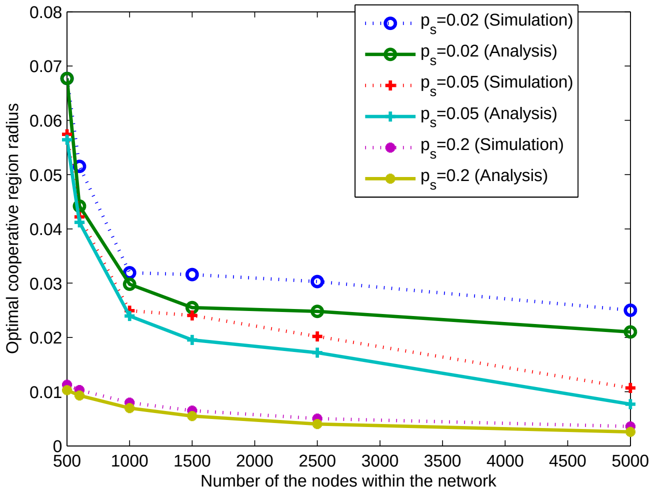

Fig. 8. Optimal cooperative region radius for different number of nodes and different activity probabilities.

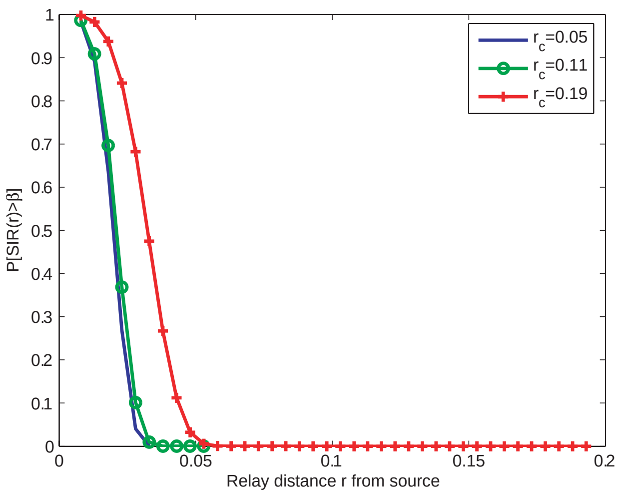

Fig. 9. Probability of successful decoding versus relay distance from source.

for the region with a higher radius of 0.19, as we can see from the figure, there is a very small probability of correctly decoding for the relays located further than $r_{\text{opt}} = 0.05$ from the source. In this case, by allowing a bigger cooperation region we have allowed the amount of interference in the network to increase due to more interfering relays, while there is only little increase in the number of decoding relays which are close to the source. This results in the overall decrease of the sum-rate compared to the case of relaying with optimal cooperative region radius.

B. Effect of Node Decoding Threshold

The decoding threshold, β, of potential relay nodes can lead to noticeable change of the sum-rate and energy savings within the network. In this section we study this effect for a wide range of changes in the decoding threshold. Having a small threshold leads to the idealized scenario where the nodes can tolerate a high level of interference. On the other hand, a big decoding threshold will result in the case where cooperation cannot benefit the network by increasing its capacity or power efficiency, and direct transmission in both slots will be the optimal transmission strategy.

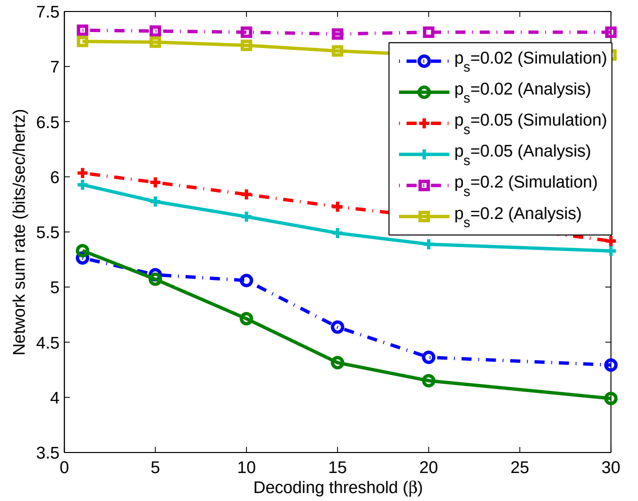

Fig. 10. Optimal network sum-rate versus different values of decoding threshold.

Figure 10 illustrates the capacity decrease as a result of increases in the decoding threshold β. As we expect, the change in the sum-rate is small in cases where we have a higher activity probability ($p_s = 0.2$), which is due to the fact that the optimal solution either does not involve cooperation or the amount of cooperation is negligible. Therefore, the change in the threshold does not significantly affect the performance. However, the decrease is apparent in the low activity regime ($p_s = 0.02$). We have studied the change of optimal cooperative region in Figure 11. For lower decoding thresholds, the cooperation performance is not significantly affected by the amount of interference. This fact results in large radius in an optimal cooperative region. However, increasing the threshold causes the relays to be more sensitive to interference. This leads to ineffectiveness of the relays that are close to the boundaries of a large cooperative region, which suggests the choice of smaller regions as the optimal solution in cooperative communication.

C. Cooperative Gain

We evaluate the power efficiency by using the notion of cooperation gain. To define this notion more precisely, we assume that there are N_s active sources within the network each transmitting with power P under the direct transmission setting. We call the achievable rate under this setting $\mathbf{R}_{\text{dir}}$. We compute the overall required power under the cooperative setting to achieve the same sum-rate (i.e., we have $\mathbf{R}_{\text{Tot}} = \mathbf{R}_{\text{dir}}$). Under the optimal cooperative setting, a total of $N_p + D$ nodes are active (where N_p represents the number of sources and D represents the number of successful decoding relays), each sending with power P' to achieve an overall throughput of $\mathbf{R}_{\text{Tot}} = \mathbf{R}_{\text{dir}}$. The cooperation gain of the network is defined

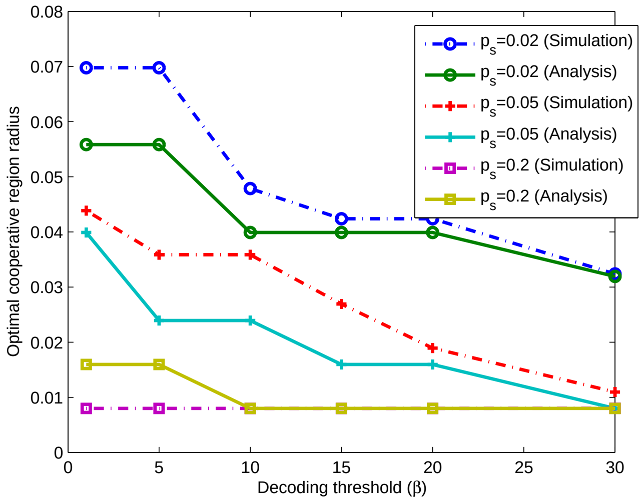

Fig. 11. Optimal cooperation region radius versus the decoding threshold.

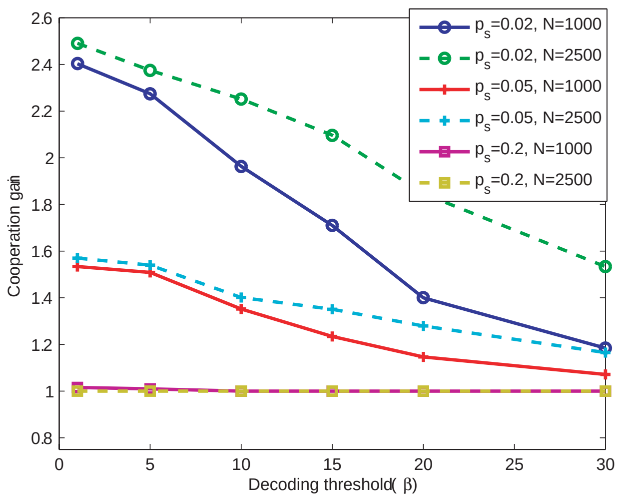

Fig. 12. Cooperative gain versus the decoding threshold.

as

$$\text{Cooperation Gain} = \frac{N_s P}{(N_p + D)P'}. \tag{17}$$

As shown in Figure 12, the simulation results show significant power savings for low arrival networks with low decoding threshold. The power saving effect decreases with the increase in the threshold or activity. In order to compare the power savings as a function of the number of nodes, we consider networks with the same total transmission power. Figure 12 shows that despite increasing the number of nodes when using cooperation, which results in each node having a smaller share of power, the network cooperation gain increases.

VI. Conclusion

This work presents an analytical framework to study the effect of cooperation in large wireless networks with interference mitigation. We have evaluated the potential sum-rate increase and power savings that can be obtained via cooperation. The performance gain obtained via cooperation is limited by the inherent increase in the amount of interference that the relays can cause. We study the optimal amount of cooperation by evaluating the trade-off between exploiting the nodes as relays and the increase of interference caused by asynchronous transmission of the relays in a dense wireless network. We introduce the notion of cooperative regions, whose radius can be optimized to maximize the overall network sum-rate. The power efficiency obtained via the choice of the optimal cooperative regions is evaluated. Numerical results based on the proposed analysis provide design guidelines for optimal relaying in interference limited wireless networks and illustrate the potential performance gains obtained by cooperation.

Appendix I
Proof of Proposition II

Note that D_is are not independent from N_p and the conditional probability results do not apply. Wald's equality [19] states that if $\{D_i | 1 < i < N_p\}$ are i.i.d random variables each with mean $E[D_i]$ and N_p is a stopping rule for D_i and $D = D_1 + \ldots + D_{N_p}$, then $E[D] = E[D_i]E[N_p]$. We first show that N_p is a stopping rule for D_i. For any source $1 < i < N$, if it is allowed to transmit it means that the scheduling algorithm permits region i to be added to the set of cooperative regions. Therefore, for a new source chosen among the network nodes, it has to satisfy this distance criterion. This criterion is only dependent on the location of other sources $1, \ldots, i-1$, which have been selected by the scheduler prior to choosing i. Therefore, N_p is a stopping rule, and by Wald's equality $E[D] = E[N_p]E[D_i]$.

Appendix II
Derivation of the CDF of SIR at the Relays

The received signal from s at m has the average power $\mu_s = \frac{P}{d^\alpha}$, and therefore, the distribution of the received power z in a Rayleigh environment follows $f_Z(z) = \frac{1}{\mu_s} e^{-\frac{z}{\mu_s}}$. In a large network with interference, we assume that the amplitude of noise at each relay is small relative to the interference. Therefore, it suffices to find the distribution of SIR, $Y = \frac{Z}{I_m}$. Since Z and I_m are positive, the distribution of the SIR is computed as

$$\begin{aligned}
F_Y(y) &= \int_{x=0}^{\infty} \int_{z=0}^{z=xy} f_Z(z) f_{I_m}(x) dz dx \\
&= \int_{x=0}^{\infty} \int_{z=0}^{z=xy} \frac{1}{\mu_s} e^{-\frac{z}{\mu_s}} \frac{x^{E[N_I]-1}}{(E[N_I]-1)!\mu^{E[N_I]}} e^{-\frac{x}{\mu}} dz dx \\
&= \int_{x=0}^{\infty} (1 - e^{-\frac{yx}{\mu_s}}) \frac{x^{E[N_I]-1}}{(E[N_I]-1)!\mu^{E[N_I]}} e^{-\frac{x}{\mu}} dx \\
&= 1 - \frac{1}{(1 + \frac{yE[I_m]}{\mu_s})^{E[N_I]}},
\end{aligned} \tag{18}$$

where we have used the table of integrals [20] to obtain the last equality.

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