# Forwarding Interfering Signals in Wireless Ad Hoc Networks under MRC Receiver Processing

Antonios Argyriou
Department of Electrical and Computer Engineering, University of Thessaly, Volos, 38221, Greece.

***Abstract*—Cooperation in wireless networks is embraced today both from cellular and device-to-device (D2D) communication standards. The reason is that this communication paradigm offers much-needed improvements in the spectral efficiency of wireless communication. Its foundation is the cooperation between nodes that are physically in close proximity. This means that it can fit very well in modern networks that are characterized by increased densities of both infrastructure and users. However, higher node density and higher number of opportunities for cooperation means also more interference. In this paper we investigate the potential throughput gain in a densely deployed interference-limited wireless network when the nodes cooperate. We consider a simple cooperative protocol that allows the relays to overhear the interfering signals and then they amplify and forward (AF) the received composite signal. We consider that the final destination employs maximum ratio combining (MRC) of the directly received signal and the forwarded interference. Given the previous protocol and decoding algorithm, we formulate the problem of link scheduling and cooperative interference forwarding (LSCIF) as a mixed integer non-linear program (MINLP) that is solved numerically. In the proposed problem formulation the aggregate signal-to-interference ratio (SIR) expression is decomposed into two separate SIR constraints. In practice this means that the signal that is received at a relay is allowed to be forwarded (the relay link is scheduled) even if the SIR of this particular signal is below the level that the final receiver can decode. Results are presented for the optimal solution and a polynomial time approximation algorithm for different traffic loads, number of relays, and demonstrate significant performance gains.**

## I. Introduction

In wireless networks today there is a shift towards changing the point-to-point paradigm with the aid of helping nodes, otherwise known as relays [1]. Relays offer a cooperative diversity gain [2], higher spectral efficiency [3], while they can also extend the transmission range of other nodes. Hence, they can lead to more efficient use of the scarce wireless resources. These benefits have recently resulted in the adoption of the cooperative paradigm both in the cellular infrastructure standards like LTE-A [4], or even more recently in cellular device-to-device (D2D) wireless networks [4].

However, the presence of multiple nodes that may help as relays can be the source of significant problems, and more specifically interference. The two aspects of the fundamental problem that arises in this case can be explained with the network topology depicted in Fig. 1. When source node $S_1$ uses node $R_1$ to be the cooperative relay that executes the simplest operation like amplify and forward (AF) of the signal destined to $D_1$, the interference generated by this "composite" transmission consists of the interference generated from both $S_1$ and $R_1$ (although in different time slots). The second problem is that this cooperative transmission that originates from $S_1$ is affected by the aggregate interference that is

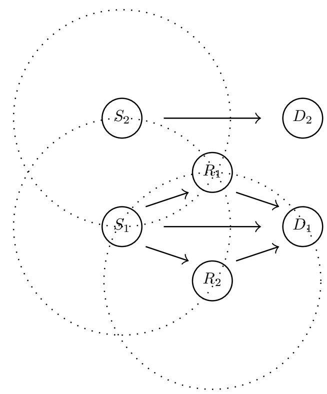



Fig. 1. Sources nodes $S_1$ and $S_2$ transmit simultaneously. Node $R_1$ receives the interfering signal from the two sources and forward it to $D_1, D_2$. The dashed lines depict the transmission range of the respective nodes.

accumulated at node $D_1$ and also at relay $R_1$ (another node $S_2$ interferes in this case). Consequently, there is an inherent tradeoff between the help that the relays can offer and the interference they generate.

To combat interference even in a simple network setting without relays, there is a need for some form of coordination like link scheduling (LS). LS in a wireless network consists of the activation of point-to-point links between source-destination pairs at specific time slots [5], [6]. A schedule that is optimized will allow more network nodes to transmit concurrently by minimizing interference to each other. The same principle applies to cellular standards like LTE-A that employ inter cell-interference coordination (ICIC) while this technique may be combined with channel orthogonalization when appropriate. Now in the context of relay-based cooperative systems the first works on the topic, investigated the LS problem with the same approach for the point-to-point links we discussed a few sentences above [5], [6], but without considering interference. More specifically, the authors in [7] studied the problem for a single source-destination pair and multiple slow moving relays. A scheduling problem that seeks the optimal role for each node (source, relay, or destination) in a three-node network was investigated in [8]. The authors in [9], studied the use of relays as a mechanism to aid in multi-hop communication when the relays applied a decode-and-forward (DF) protocol. The problem was casted as a minimization of the total interference across multiple hops. The same authors considered a simpler form of the same problem but with the joint objective of routing and scheduling in [9]. Recent works started considering the positive implications of interference and proposed another way to attack

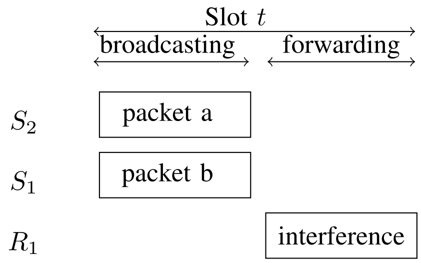



Fig. 2. Cooperative protocol for one slot. Each slot is separated in two phases.

the problem instead of using LS. The solution is based on embracing interference and decoding the interfering signals not only at a single node [10], [11], but also at several network nodes that either select the optimal composite signal of two interfering transmissions for forwarding [**?**], or employ a more advanced distributed protocol [**?**]. The performance results are very promising since the solutions in [10], [11] lead to the so called "multiple-access gain", while the approaches in [**?**], [**?**] lead to diversity and multiplexing gains. However, the cost of these solutions is the more complex processing at the receiver of a relay due to the decoding operation.

Simpler schemes at the relay like AF that take into account the interfering signals have not been considered in the literature. This simpler relay operation is more generic since it is applicable in network scenarios where the relay does not require the reception of the decoded packet, or has power/complexity limitations. Fundamentally, if the relay does not decode but simply forwards the signal, this essentially alters the point-to-point communication link between two nodes since it involves a third node. In this case the forwarding of a signal from the relay is an integral part of the primary transmission of the initial source since the destination node jointly decodes the two signals under an optimal scheme like maximum ratio combining (MRC) [2]. In this paper we want to investigate if it is beneficial for the network throughput to forward the interfering signals that are received by nodes that would not normally cooperate because of interference. Thus, these helping nodes do not act as simple relays but as *relays of interference*. To address the problem for generic network topologies, in this paper we define first an extended physical interference model for such a cooperative wireless network. Then, we show that we can decouple the signal-to-interference ratio (SIR) expression of the AF cooperative transmission in the interference-limited regime of dense networks. Next, we proceed with the formulation of the LS throughput maximization problem in the cooperative wireless network as a mixed integer linear program (MILP). Our problem formulation is generic enough to fit different network topologies like wireless ad hoc networks, D2D networks, and cellular relay-based networks (e.g. LTE).

## II. System Model

**Network Model.** The network model consists of a set $\mathcal{S}$ of $N$ source nodes that communicate with the set of destination nodes $\mathcal{D}$. Communication can be accomplished with the assistance of $R_{max}$ relays that belong in the set $\mathcal{R}$. Each destination may also have multiple incoming sources. Thus, the network model is generic and can reflect either distributed or centralized network topologies. We use the notation $l_{ij}$ to indicate the link from a source $i$ to a destination $j$, while all the links are contained in the set $\mathcal{L}$. Finally there are $T$ slots available that belong in the set $\mathcal{T}$.

**Forwarding Protocol.** The basic forwarding protocol we present adopts two distinct phases (Fig. 2). During the broadcasting phase the sources transmit if they are scheduled. These signals are received by all nodes that do not transmit. During the forwarding phase these nodes forward the interfering signals if they are scheduled by our algorithm. The sources and the relaying nodes that are active in slot $t$ are denoted as $\mathcal{S}_t$, and $\mathcal{R}_t$ respectively.

**Interference Model.** Let us now define the interference model for the proposed system. We present the calculations for the particular link $l_{ij}$. During the broadcasting phase all the sources that transmit will interfere with link $l_{ij}$. Thus, the power of the aggregate interference is expressed as (the first subscript denotes the link and the second the phase)

$$I_{ij,b} = \sum_{l_{mk} \in \mathcal{S}_t \setminus \{l_{ij}\}} \gamma_{mj} P_m^t, \tag{1}$$

where $l_{mk}$ is an auxiliary variable for counting all the links that are active in slot $t$. $P_m^t$ is the transmission power of a source $m$ during slot $t$. We assume a path loss channel and so $\gamma_{mj}$=$1/d_{mj}^a$, where $d_{mj}$ is the distance between source $m$ and destination $j$ while $a$ is the path loss exponent. During the same broadcasting phase, interference will also be present at the relays. Thus, the aggregate interference power that in this case is denoted as $I_{ir,b}$ and is calculated with the same formula given in (2):

$$I_{ir,b} = \sum_{l_{mk} \in \mathcal{S}_t \setminus \{l_{ij}\}} \gamma_{mr} P_m^t \tag{2}$$

During the forwarding phase, a set of nodes will act as relays and help a specific subset of the point-to-point links. These relays will also generate interference to each other. The destination processes the directly received and forwarded signals with MRC [2]. The SINR of the cooperative transmission that occurs in two orthogonal time slots is:[1]

$$SINR_{i,j} = \frac{P_i^t \gamma_{ij}}{I_{ij,b} + \sigma^2} + \frac{\sum_{\mathcal{R}_t} P_i^t \gamma_{ir} \gamma_{rj} P_r}{\sigma^2 + \sum_{\mathcal{R}_t} (\sigma^2 + I_{ir,b}) \gamma_{rj} P_r} \tag{3}$$

In the above $\sigma^2$ is the AWGN variance and $P_r$ is a constant power scaling. This expression is important for highlighting the need for optimization. In the numerator of the second fraction we have the power of the useful signal that is forwarded from relay $r$ for a specific link $l_{ij}$. Since in the forwarding phase of slot $t$ several relays transmit (recall that this set is $\mathcal{R}_t$) they also forward part of the useful signal and that is why there is this summation term. In the denominator we have the signal that is received at $r$ and it is forwarded but it is destructive interference for link $l_{ij}$. Thus, the nodes that are

[1]SINR is derived from the received signals at the destination during the broadcasting and forwarding phases. The expressions for single relay are: $y_{j,i} = \sqrt{P_i^t \gamma_{ij}} x + w_j$, and $y_{j,r} = \sqrt{P_r \gamma_{rj}} (\sqrt{P_i^t \gamma_{ir}} x + w_r) + w_j$ respectively. The transmitted symbol is $x$, and the noise sample $w$. MRC results in additive expression for the SINR at the receiver [3].

activated and forward the interfering signals must be selected optimally. Furthermore, for an interference-limited system that we consider in this paper, the previous SINR expression can be approximated as:

$$SINR_{i,j} \approx \frac{P_i^t \gamma_{ij}}{I_{ij,b}} + \frac{\sum_{\mathcal{R}_t} P_i^t \gamma_{ir} \gamma_{rj} P_r}{\sum_{\mathcal{R}_t} (I_{ir,b}) \gamma_{rj} P_r} \tag{4}$$

## III. Problem Formulation

To proceed with the description of the link scheduling and cooperative interference forwarding (LSCIF) problem we introduce first the three vectors of our optimization variables. First, we define the binary vector $\boldsymbol{x} = (x_{ij}^t \in [0,1] : l_{ij} \in \mathcal{L}, t \in \mathcal{T})$ that denotes whether source $i$ transmits to its destination $j$ during slot $t$. Binary vector $\boldsymbol{y} = (y_r^t \in [0,1] : r \in \mathcal{R}, t \in \mathcal{T})$ indicates whether relay $r$ transmits in the forwarding phase of slot $t$. Finally, vector $\boldsymbol{P} = (P_i^t \in \mathcal{P} : i \in \mathcal{S}, t \in \mathcal{T})$ that indicates the transmission power of source $i$ and can take valid values from the set $\mathcal{P}$. $T$ is the maximum number of slots for which the problem is solved, and finally $\beta$ is the SINR packet decoding threshold at the destination [5].

A very important feature of the problem formulation is that it separates the SINR expression, given the interference-limited system approximation in (4) in such a way that the resulting interference constraints maintain a linear form. The key observation that allows the above is that the precise SIR values of the broadcasting and forwarding transmissions for a specific packet and a specific destination do not matter as long as their sum is higher or equal to $\beta$, i.e., if the packet is decodable at the final destination after forwarding. To implement the previous insight in practice, we separate the SIR expression in (4) into the sum of several SIR components by introducing the auxiliary thresholds $z_{0,ij}$ and also $z_{r,ij}$ for each relay $r$ and link $l_{ij}$. These are continuous optimization variables that are contained in the vector $\boldsymbol{z} = (z_{r,ij}^t > 0 : l_{ij} \in \mathcal{L}, r \in \mathcal{R}, t \in \mathcal{T})$. The previous discussion leads to the following two constraints:

$$\frac{P_i^t \gamma_{ij} x_{ij}^t}{\sum_{k \in \mathcal{S}_t \setminus \{i\}} P_k^t \gamma_{kj}} = z_{0,ij}, \forall l_{ij} \in \mathcal{L}, \forall t \in \mathcal{T} \tag{5}$$

$$\frac{P_i^t \gamma_{ir} \gamma_{rj} P_r y_r^t}{(\sum_{k \in \mathcal{S}_t \setminus \{i\}} P_k^t \gamma_{kr}) \gamma_{rj} P_r} = z_{r,ij}, \forall l_{ij} \in \mathcal{L}, \forall r \in \mathcal{R}_t, \forall t \in \mathcal{T} \tag{6}$$

Constraint (5) refers to the SIR of the direct transmission that must be equal to the threshold $z_{0,ij}$. In the denominator we have the power of all the interfering signals from other sources that transmit simultaneously. Also (6) is produced from the second fraction of (4), and it corresponds to the SIR of the forwarded transmission from relay $r$ that must be equal to the threshold $z_{r,ij}$. The interference summation in the denominator is the interference generated from the sources that were activated when source $i$ was transmitting. This signal is also amplified by the relay. *Note that with our formulation the scheduling condition for link $l_{ij}$ can be less restrictive than setting it equal to $\beta$ since $z_{0,ij}$ is an optimization variable. A lower value for $z_{0,ij}$ can be compensated by activating a certain relay.*

For the packet to be decoded, the value of the aggregate SINR must be higher than $\beta$ and so we must set:

$$\sum_{r \in \mathcal{R}_t} z_{r,ij} + z_{0,ij} \geq \beta, \forall l_{ij} \in \mathcal{L}, t \in \mathcal{T} \tag{7}$$

Next, we must ensure that the total power expenditure for a source node during the $T$ slots is within a certain budget. The source must comply with this power budget regardless of how many times it was scheduled:

$$\sum_{t=1}^{T} P_i^t \leq P_i^{max}, \forall i \in \mathcal{S} \tag{8}$$

We also have the per-slot transmitter power constraint. Note that when a source is not scheduled this constraint ensures that the transmission power is set to 0:

$$x_{ij}^t P_i^{t,min} \leq P_i^t \leq x_{ij}^t P_i^{t,max}, \forall l_{ij} \in \mathcal{L}, t \in \mathcal{T} \tag{9}$$

Only one relay is allowed to be used during a specific slot:

$$\sum_{r=1}^{R_{max}} y_r^t \leq 1, \forall t \in \mathcal{T} \tag{10}$$

Each link $l_{ij}$ is scheduled at least $B_{ij}$ slots (which may be an optional constraint):

$$\sum_{t=1}^{T} x_{ij}^t \geq B_{ij}, \forall l_{ij} \in \mathcal{L} \tag{11}$$

The last constraints refer to the discrete and continuous nature of the optimization variables

$$x_{ij}^t, y_r^t \in \{0,1\}, z_{1,j}, z_{2,j} \geq 0, P_i^t \in \mathcal{P}. \tag{12}$$

Finally, the objective is to maximize the number of transmitting sources in the wireless network by scheduling the links that originate from the sources and the links from the relays, under the previous constraints:

$$\max_{\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},\boldsymbol{P}} \quad \frac{1}{T} \sum_{t=1}^{T} \sum_{l_{ij} \in \mathcal{L}} x_{ij}^t \text{ subject to } (5) - (12)$$

This is a mixed integer non-linear program (MINLP).

## IV. Solution Approach

**Linearization of Constraints.** We notice the formulation that there are several terms that are the product of the optimization variables. This can generally be a significant problem due to the non-linear form of these terms. However, the correct classification of these product terms allows us in certain cases to simplify them in linear terms at the cost of more constraints. In our problem, the product of the discrete variable $P_i^t$ and binary variable $y_r^t$ create a non-linear term in (6) while we also notice that a similar product term $P_i^t x_{ij}^t$ exists in (5).

To resolve the problem above, we do two things. First, we relax the binary variables so that the become continuous. Thus, we allow the binary variables $x_{ij}^t, y_r^t$ to take any value between 0 and 1. Second, with the relaxation we have the product of a continuous and a discrete variable. This precise situation also occurs for the continuous variables $z_{r,ij}$ that are multiplied with the discrete variables $P_i^t$ in (6) and it was not subjected to relaxation. Luckily this type of product terms can be linearized. To do that, let us write $P_i^t = \sum_k q_{i,k}^t p_k$ where each $p_k$ represents a power level from the set $\mathcal{P}$, and $q_{i,k}^t$ are rr_constr_check()

1: Assign $\hat{x}_{ij}^t, \hat{y}_r^t$ according to (13)
2: Set $\hat{y}_r^t \leftarrow 1$ for $r$ with the maximum $\tilde{y}_r^t$. Others 0
3: **for** $l_{ij} \in \mathcal{L}$ **do**
4: $\quad z_{0,ij} \leftarrow \frac{P_i^t \gamma_{ij} \hat{x}_{ij}^t}{\sum_{k \in \mathcal{S}_t \setminus \{i\}} P_k^t \gamma_{kj}}$
5: $\quad z_{r,ij} \leftarrow \frac{P_i^t \gamma_{ir} \gamma_{rj} P_r \hat{y}_r^t}{(\sum_{k \in \mathcal{S}_t \setminus \{i\}} P_k^t \gamma_{kr}) \gamma_{rj} P_r}$
6: **end for**
7: **if** $\sum_{r \in \mathcal{R}} z_{r,ij} + z_{0,ij} \geq \beta$ **then**
8: $\quad$ //schedule is valid
9: **else**
10: $\quad$ //do not schedule the link
11: $\quad \hat{x}_{ij}^t \leftarrow 0$, $\hat{P}_i^t \leftarrow 0$
12: **end if**

Fig. 3. Pseudo-code for checking the constraints of the relaxed LP solution.

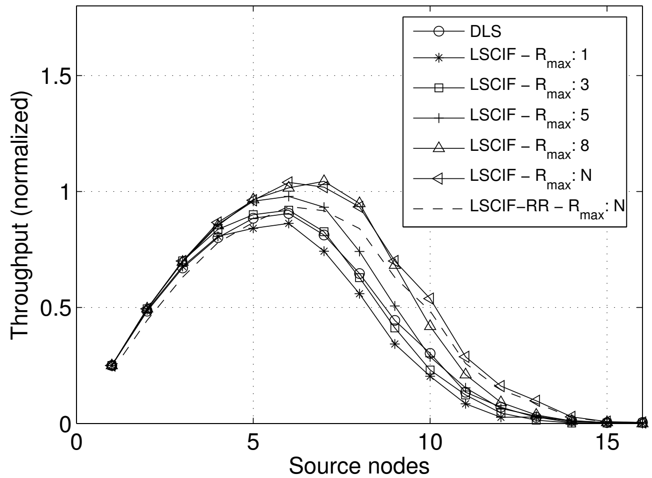
binary variables for which $\sum_k q_{i,k}^t = 1$. The desired product term then takes the form $zP_i^t = \sum_k zq_{i,k}^t p_k$, and then we can define a new continuous variable of the form $w_{i,k}^t = zq_{i,k}^t$ (product of binary and continuous variables that is trivial to linearize by adding four linear constraints [12]). Hence, the result of this discussion is a LP that comes from the relaxation and linearization of the original MINLP.

**MILP Relaxation and Approximation Algorithm.** LPs can be solved in polynomial time with interior point methods. After the LP is solved, the result of the relaxed LP consists of a set of continuous values between 0 and 1 that must be converted to a binary value. We adopt the randomized rounding approach that assigns the final binary values with a certain probability [13] for creating our heuristic. If $\tilde{x}_{ij}^t, \tilde{y}_r^t, \tilde{w}_{i,k}^t, \tilde{z}_{0,j}, \tilde{z}_{r,ij}$ denote the solutions of the LP, the binary values are approximated as:

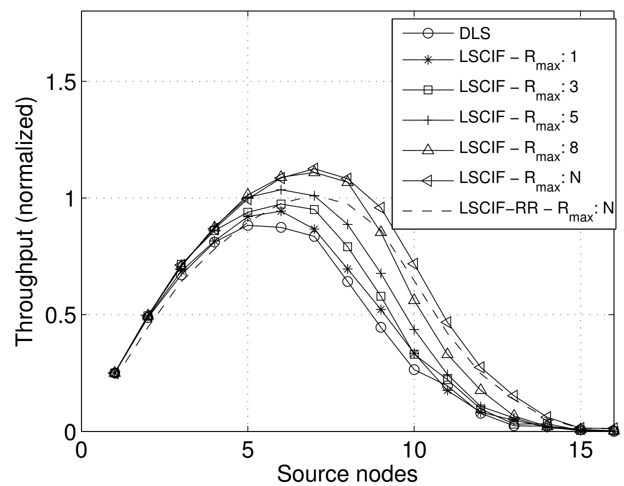
$$\hat{x}_{ij}^t = \begin{cases} \Pr[1] = \tilde{x}_{ij}^t \\ \Pr[0] = 1 - \tilde{x}_{ij}^t \end{cases} \quad \hat{y}_r^t = \begin{cases} \Pr[1] = \tilde{y}_r^t \\ \Pr[0] = 1 - \tilde{y}_r^t \end{cases} \tag{13}$$

This rule means that the final binary solution $\hat{x}_{ij}^t$ is equal to 1 with probability (w.p.) $\tilde{x}_{ij}^t$ and equal to 0 w.p. $1 - \tilde{x}_{ij}^t$. A value for $\tilde{x}_{ij}^t$ closer to 1 increases the probability that a binary 1 is assigned. This process ensures that the cost of the MINLP and LP solutions are the same [13]. Since some constraints might be invalid after the assignment in (13), they must be verified before we obtain the final result. This is accomplished with the algorithm depicted in Fig 3. This algorithm is of polynomial complexity, i.e. $O(NM)$, since the conditions have to be checked for all the source/relay pairs. With this algorithm first we check (10) for all the slots, i.e., to ensure that one relay is activated during a slot $t$. The relay that is selected is the one that has the highest value for $\tilde{y}_r^t$. All the other $\hat{y}_r^t$ are set to zero. Next, we set the SIR thresholds as lines 4-5 indicate. Now after this is done for all the links, the next step of the algorithm is to check if (7) is satisfied. In case (7) is true then the scheduling of the link is finished. If this is not the case, this link is not scheduled by setting $\hat{x}_{ij}^t \leftarrow 0$ and the power $\hat{P}_i^t \leftarrow 0$ (the last is accomplished through the variable $\hat{w}_{i,k}^t \leftarrow 0$). Similar reasoning follows for the every case of binary variable assignments.

**Impact of Packet Buffers and Schedule Length.** The proposed approach can take into account the number of buffered packets at each node. In this case the network throughput should be maximized for multiple periods each of duration $T$. A different priority could be assigned to nodes depending on the buffered packets. This could be accomplished by changing $B_{ij}$ for a specific node every time the problem is solved. One potential metric would be to assign $B_{ij} = \lfloor \frac{\text{Buffered packets at } i}{\text{Buffer size at } i} T \rfloor$, where sources with higher buffer occupancy are prioritized. This approach could also be used for implementing different fairness policies and for adapting to dynamic traffic conditions. Regarding the length of the schedule $T$, there are several works that propose heuristics that can alternate between solving the LSCIF problem, and minimizing $T$ by starting from a high value [6]. They could be combined with our approach.




(a) $z_{0,ij}$=$z_{r,ij}$=5dB

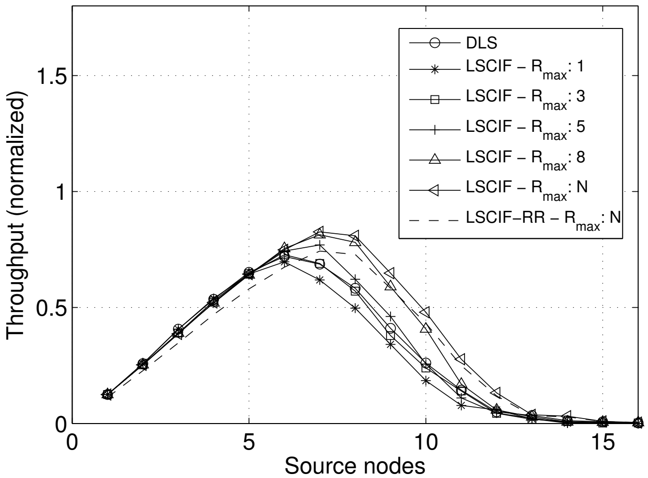



(b) $z_{0,ij}$=4dB,$z_{r,ij}$=6dB

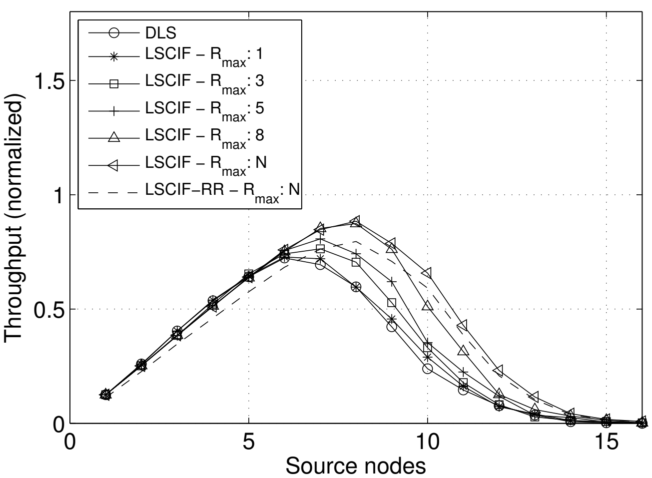
Fig. 4. Results with constant auxiliary thresholds. $B$=$T$=8 slots.

## V. Performance Evaluation

In this section we compare the performance of LSCIF with that of direct LS (DLS) [5], [6]. The purpose of the comparison is to help identify the potential performance benefits of

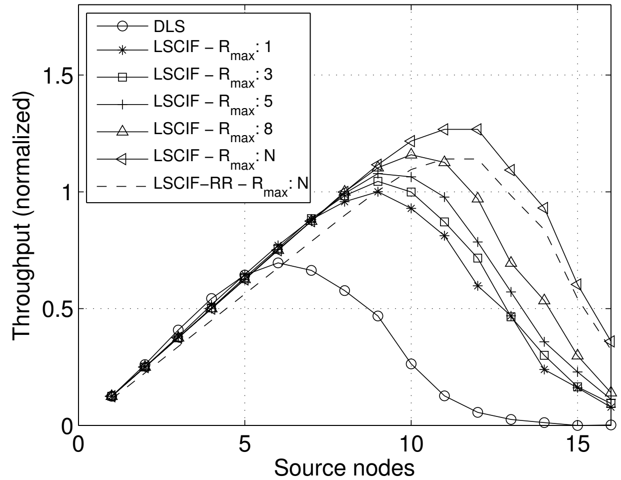



(a) $z_{0,ij}$=$z_{r,ij}$=5dB

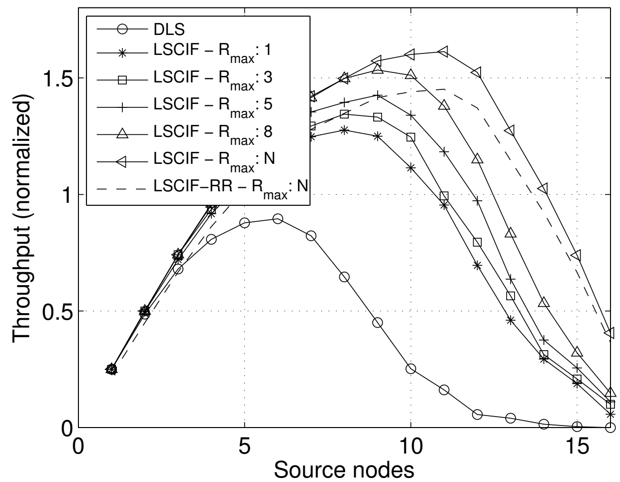



(b) $z_{0,ij}$=4dB,$z_{r,ij}$=6dB

Fig. 5. Results with constant auxiliary thresholds. $B$=4,$T$=8 slots.




(a) $B$=4,$T$=8 slots




(b) $B$=8,$T$=8 slots

Fig. 6. Results with optimized auxiliary thresholds.

forwarding interference. Most of the results correspond to the optimal solution calculated with CPLEX Optimization Studio V12.5.0 while we also have results for the approximation algorithm. For LSCIF we test different number of maximum available relays. Also we consider that each source has one destination and also $B_{ij}$=$B$ for all the links. In other words, we experimented with different traffic loads in terms of the required slots that must be active $B$, but in each experiment all the nodes were configured with the same load. The system parameters are: $\beta$=10dB, $P_i^{t,max}$=300mW, $P_r$=300mW, $P_i^{t,min}$=0.01$P_i^{t,max}$. Node distances are randomly and uniformly selected in the range $[0, 100]$ with $a$=3. In the figures the horizontal axis depicts the number of nodes $N$ and the vertical axis the normalized throughput.

**Backlogged Traffic and Constant Auxiliary Thresholds.** In Fig. 4 the performance is presented both for LSCIF and DLS. In Fig. 4 $B$=$T$=8 which means that all the nodes are backlogged and desire to transmit a data packet in every slot. LSCIF always outperforms DLS even with a single relay. Also the performance of LSCIF reaches a peak for a higher number of seven sources. Also note that as the number of sources is increased, the performance of DLS deteriorates faster than the performance of LSCIF and this is only because the increased node density increases the interference. Furthermore, when the number of relays is equal to the number of sources, then the maximum performance can be reached. In general a higher number of maximum available relays increases performance since more options exist for the scheduling algorithm. However, the increased number of available relays cannot help when the node density is increased beyond a certain point (even when the number of relays is equal to the number of sources). For different $z_{0,ij}$=4dB,$z_{r,ij}$=6dB in Fig. 4(b) the results present a similar trend while the peak performance has a minor increase. This result is very important and it actually means that small variations for $z_{0,ij}$ and $z_{r,ij}$ lead to minor throughput differences.

**Reduced Traffic and Constant Auxiliary Thresholds.** For a lighter traffic load of $B$=4 slots with $T$=8 in Fig. 5(a,b), we see that the performance trend is similar. The throughput increase is now lower for a smaller number of sources due to the decreased traffic load. Also the peak performance does not reach the same level as before. Nevertheless, LSCIF still offers performance benefits in this case of lower traffic demand. The performance of our heuristic is also very good when compared with the optimal solution.

**Optimized Auxiliary Thresholds.** Now we consider the case that $z_{0,ij}$, $z_{r,ij}$ are independently optimized for each specific node $j$ according to our complete optimization scheme. The results for different traffic loads can be seen in Fig. 6. In this case we observe significant performance gains over the static assignment that was used previously since now more nodes can be scheduled. Thus, there is not very strong justification for jointly optimizing these auxiliary thresholds. Note that all these results were obtained under a path loss channel model which means that the problem does not require instantaneous channel knowledge to be solved. This makes our approach very promising for real networks regardless of the specific topology.

## VI. Conclusions

In this paper we presented a MINLP formulation for the problem of cooperative interference forwarding in densely deployed interference-limited wireless networks. A low complexity AF scheme is adopted at the cooperative relays for forwarding the composite signal from multiple interfering sources. The MINLP formulation is enabled by the separation of the SIR of the forwarding transmission into linear constraints and the introduction of auxiliary packet decoding thresholds for the SIR. We also presented an approximation algorithm for solving the problem in polynomial time. The throughput improvement was significant for different traffic scenarios and settings of the auxiliary thresholds. Our future steps will be focused on the development of a solution algorithm suitable for a distributed implementation, and also the application of our idea in LTE relay networks.

## References


[1] E. C. van der Meulen, "Transmission of information in a t-terminal discrete memoryless channel," Ph.D. dissertation, Department of Statistics, University of California, Berkeley, CA, 1968.

[2] J. N. Laneman, G. Wornell, and D. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *ISIT*, 2001.

[3] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[4] 3GPP, "LTE-Advanced," http://www.3gpp.org/specifications/releases/68-release-12, 2013.

[5] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Trans. on Information Theory*, vol. 46, no. 2, pp. 288–304, March 2000.

[6] G. Brar, D. M. Blough, and P. Santi, "Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks," in *MOBICOM*, 2006.

[7] A. Wittneben, I. Hammerstrom, and M. Kuhn, "Joint cooperative diversity and scheduling in low mobility wireless networks," in *IEEE Globecom*, 2004.

[8] I. Krikidis and J. Belfiore, "Scheduling for amplify-and-forward cooperative networks," *Vehicular Technology, IEEE Transactions on*, vol. 56, no. 6, pp. 3780–3790, 2007.

[9] C.-Y. Hong and A.-C. Pang, "3-approximation algorithm for joint routing and link scheduling in wireless relay networks," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 2, pp. 856 –861, feb. 2009.

[10] A. Argyriou and A. Pandharipande, "Cooperative protocol for analog network coding in distributed wireless networks," *IEEE Trans. on Wireless Communications*, vol. 8, no. 10, pp. 2014–2023, October 2010.

[11] S. Katti, S. Gollakota, and D. Katabi, "Embracing Wireless Interference: Analog Network Coding," in *SIGCOMM*, 2007.

[12] D. Bertsekas, A. Nedic, and A. Ozdaglar, *Convex Analysis and Optimization*. Athena Scientific Press, 2003.

[13] C. D. Raghavan, Prabhakar; Tompson, "Randomized rounding: A technique for provably good algorithms and algorithmic proofs," *Combinatorica*, vol. 7, no. 4, p. 365374, 1987.