Capacity region of wireless ad hoc networks using opportunistic collaborative communications

O. Simeone[1,2] and U. Spagnolini[1]
(1) Dipartimento di Elettronica e Informazione, Politecnico di Milano, I-20133 Milano, Italy
(2) CWCSPR, ECE Dept., NJIT, Newark, NJ 07102, USA

Abstract— **In this paper, we evaluate the capacity region of wireless ad hoc networks under a recently proposed space-time collaborative scheme. This protocol allows idle nodes to cooperate with the source opportunistically, i.e., whenever their wireless channel from the source is advantageous. The scheme is intrinsically distributed and well suited for an ad hoc scenario.**

It is shown analytically and through simulation that the capacity region of opportunistic collaboration is equal to or larger than (centralized) optimal multi-hop in case spatial reuse is not allowed by the transmission protocol. On the other hand, in case spatial reuse is possible, the relation between the two capacity regions has to be studied case by case. Simulation results prove that opportunistic collaborative communication is a promising paradigm for ad hoc networks that deserves further investigation.

I. Introduction

An increasing number of applications for wireless LAN's and sensor networks is shifting the attention of the communications community from infrastructure-based to ad hoc wireless networks. The first paradigm relates to scenarios, such as cellular systems, where multiple nodes communicates to, or receive from, a single node (the base station or access point). With the recent advances in the information theoretic analysis of the broadcast (point-to-multipoint) channel, the ultimate performance of infrastructure-based wireless networks is quite well understood. On the other hand, complete information theoretic characterization of ad hoc wireless networks, even in the simple cases of relay channels or interference channels, is far from being realized [1].

In [1], the scaling law of a novel quantity defined as transport capacity, measured in bit per second per meter, was derived under the assumption of a static network with multi-hop (MH) and point-to-point coding. A different approach was pursued in [2], where a general framework for the computation of the capacity region of wireless networks was proposed. The framework prescribes the definition of the basic transmission schemes allowed by the selected transmission protocol. The considered protocols in [2] included single/multi-hop transmission with or without spatial reuse, power control and successive interference cancellation. More sophisticated form of coding, such as cooperation [3] or more generally network coding, were not considered. An attempt in this direction was made in [4] were the capacity region of an ad hoc network with single-relay Amplify and Forward (AF) transmission was allowed. The conclusion was therein that, if combined with optimal MH transmission, cooperative transmission through AF yields negligible gains.

A major observation in interpreting the capacity region of [2] is that, in order to achieve the points on the boundary of the region, optimal time-division scheduling among the basic transmission schemes has to be employed. This requires coordination among the nodes on a global level, which is not realistic in an ad hoc network, that intrinsically requires distributed medium-access and routing protocols [5].

In this work, we consider the capacity of a wireless network under the collaborative space-time coding scheme proposed in [6]. Therein, through random coding arguments, an achievable rate is derived under the assumption that idle nodes cooperate opportunistically with the ongoing transmissions, whenever they are able to decode a transmitted signal before the intended destination. This is different from the MH scenario, where optimal routing requires global coordination. We will refer to this random coding scheme as Opportunistic Space-Time collaboration (OST). Notice that we are using the term *opportunistic* in the same sense of [7], where a scheme that can be considered as a practical (uncoded) implementation of OST is investigated. The paradigm is different from standard Decode and Forward (DF) collaborative techniques where the source node must be informed in advance of the presence of collaborative nodes or the length of cooperation intervals is fixed [3].

We show analytically that the (distributed) OST scheme is able to outperform (centralized) optimal MH transmission in a scenario where no spatial reuse is allowed (i.e., multiple concurrent transmissions are not allowed). In other words, in this case the capacity region achievable by OST is larger than that obtained by MH. On the other hand, if spatial reuse is employed, the increased interference caused by the opportunistic transmission of idle nodes of OST can be deleterious to concurrent transmissions, and optimized MH transmission may be advantageous in some cases. Simulation results show that the relation between the capacity region of OST and MH for spatial reuse should be studied case by case and it is not straightforward (i.e., it is not a simple inclusion).

Notation: Lowercase (uppercase) bold denotes column vector (matrix); v_i denotes the ith element of the $N \times 1$ vector $\mathbf{v}$ ($i = 1, ..., N$); A_{nm} is the (n, m)th element of the $N \times M$ matrix $\mathbf{A}$ ($n = 1, ..., N$, $m = 1, ..., M$).

II. SYSTEM MODEL

Consider an ad hoc network with n single-antenna nodes, collected in the set $\mathcal{N} = [1, ..., n]$. Each node may want to communicate (an infinite backlog of) data to a single other node (no multicast is allowed), possibly through MH or collaborative transmission. A node that generates a data stream is referred to as the *source* node for the given data stream, whereas the node which the data stream is finally intended to is called the *destination*. In each time-instant there may be multiple active (transmitting) nodes, that may be: *i*) sources of the information stream; *ii*) relays within a MH route on the behalf of a source node; *iii*) relays cooperatively transmitting with a source node according to the OST scheme. When active, each node transmits with power P $[W]$ and is not able to receive simultaneously (half duplex constraint).

A pair of nodes i and $j \in \mathcal{N}$ is separated by a distance d_{ij} $[m]$; moreover, the wireless link between the ith and jth node is characterized by a (Rayleigh) fading coefficient $h_{ij} \sim \mathcal{CN}(0, 1)$. The overall channel gain between the two nodes reads

$$G_{ij} = \rho_0 \left(\frac{d_0}{d_{ij}}\right)^{\alpha} |h_{ij}|^2, \tag{1}$$

where d_0 is a reference distance, α the path loss exponent and ρ_0 an appropriate constant setting the signal-to-noise ratio (SNR) at the reference distance.

Let us denote by $\mathcal{A}^{(t)} \subset \mathcal{N}$ the set of active (transmitting) nodes at a given instant t. We first consider a *non-collaborative* scenario. In this case, for every node $i \in \mathcal{A}^{(t)}$, there is a distinct node j in a set $\mathcal{R}^{(t)} \subset \mathcal{N}$ of receiving nodes ($\mathcal{R}^{(t)} \cap \mathcal{A}^{(t)} = \oslash$) that is intended to receive the signal. Node $j \in \mathcal{R}^{(t)}$ receives the signal from a transmitting node $i \in \mathcal{A}^{(t)}$, where the transmission of the other nodes in $\mathcal{A}^{(t)} \backslash \{i\}$ causes interference on the reception. The resulting SINR reads

$$SINR_j(i, \mathcal{A}^{(t)}) = \frac{G_{ij} P}{N_o B + \sum\limits_{k \in \mathcal{A}^{(t)} \backslash \{i\}} G_{kj} P}, \tag{2}$$

where N_o is the power spectral density of thermal noise $[W/Hz]$ and B is the signal bandwidth.

In a *collaborative* scenario, possibly more than one active node in $\mathcal{A}^{(t)}$ is collaborating for the transmission to $j \in \mathcal{R}^{(t)}$ (i.e., map from $\mathcal{A}^{(t)}$ to $\mathcal{R}^{(t)}$ is many-to-one). Therefore, the set $\mathcal{A}^{(t)}$ can be partitioned into non-overlapping subsets $\mathcal{A}_j^{(t)}$, where $\mathcal{A}_j^{(t)}$ denotes the set of nodes cooperating for transmission to j. The nodes in $\mathcal{A}_j^{(t)}$ are assumed to have decoded the signal by time instant t; moreover, assuming no channel state information at the transmitter, the signal from different cooperating nodes add incoherently and the resulting SINR reads

$$SINR_j(\mathcal{A}_j^{(t)}, \mathcal{A}^{(t)}) = \frac{\sum\limits_{k \in \mathcal{A}_j^{(t)}} G_{kj} P}{N_o B + \sum\limits_{k \in \mathcal{A}^{(t)} \backslash \mathcal{A}_j^{(t)}} G_{kj} P}. \tag{3}$$

Notice that the SNR for collaborative transmission (3) reduces to the SINR with no collaboration (2) for the case where only one active node is active for transmission to node j, i.e., $\mathcal{A}_j^{(t)} = \{i\}$.

III. CAPACITY REGIONS OF WIRELESS AD HOC NETWORKS

In this Section, we briefly review the framework proposed in [2] for the characterization of the capacity of ad hoc wireless networks. A transmission protocol specifies the basic transmission schemes that an ad hoc network can employ at a given time instant. Among the protocols considered in [2], here we focus on MH transmission with or without spatial reuse and do not consider power allocation and successive interference cancellation. Moreover, collaborative transmission through OST will be introduced in Sec. V. For a treatment of the case where single-relay AF cooperation is considered, the reader is referred to [4]. Furthermore, related numerical results are presented in Sec. VI.

In the case of a protocol that allows MH transmission with no spatial reuse, each transmission scheme is characterized by a transmitter i and a receiver j communicating on behalf of a source node s. The number of available transmission schemes is thus $\breve{M} = n \cdot n(n-1) + 1$, where n is the number of possible source nodes and $n(n-1)$ the number of transmitting-receiving pairs. More generally, if MH and spatial reuse are allowed, every basic transmitting scheme is characterized by a set of active nodes $\mathcal{A}$ and the corresponding set of receiving nodes $\mathcal{R}$, where mapping between $\mathcal{A}$ and $\mathcal{R}$ is one-to-one. Therefore, the number of basic transmission schemes reads $\breve{M} = \sum_{i=1}^{\lfloor n/2 \rfloor} n^i \cdot \frac{n!}{i!(n-2i)!} + 1$ [2].

Each basic transmission scheme, say the mth, is mathematically characterized by a $n \times n$ basic rate matrix $\mathbf{R}_m$, defined as ($s, k = 1, ..., n$ and $m = 1, ..., \breve{M}$):

$$R_{m,sk} = \begin{cases} C_k(i, \mathcal{A}) & \text{if node } k \in \mathcal{R} \text{ receives from any } i \in \mathcal{A}, \text{ with } s \text{ as the source node} \\ -C_j(k, \mathcal{A}) & \text{if node } k \in \mathcal{A} \text{ transmits to any } j \in \mathcal{R}, \text{ with } s \text{ as the source node} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where

$$C_j(i, \mathcal{A}) = B \cdot \log_2(1 + SINR_j(i, \mathcal{A})) \tag{5}$$

is the channel capacity on the wireless link between the ith and the jth node when the set of active nodes is $\mathcal{A}$. It is $R_{m,kk} = 0$ for $k = 1, ..., n$. For the sake of completeness, notice that in the case of cooperative transmission, we will write the capacity of the wireless link between the set of collaborating nodes $\mathcal{A}_j$ and j as

$$C_j(\mathcal{A}_j, \mathcal{A}) = B \cdot \log_2(1 + SINR_j(\mathcal{A}_j, \mathcal{A})), \tag{6}$$

that, as explained in Sec. II reduces to (5) for $\mathcal{A}_j = \{i\}$.

Let us define a $n \times n$ non-negative matrix $\mathbf{R}$, with R_{sd} being the rate between a source s and a destination d ($s, d = 1, ..., n$). The rates in $\mathbf{R}$ are achievable (i.e., $\mathbf{R}$ belongs to the capacity region) if there exist a $\breve{M} \times 1$ vector $\breve{\mathbf{f}} = [\breve{f}_1 \cdots \breve{f}_{\breve{M}}]^T$ such that

$$\mathbf{R} = \sum_{m=1}^{\breve{M}} \breve{f}_m \mathbf{R}_m \text{ with } \sum_{m=1}^{\breve{M}} \breve{f}_m = 1. \tag{7}$$

The elements in $\breve{\mathbf{f}}$ define the fraction of time that the corresponding basic transmission scheme is employed in the time-division schedule that realizes the rates in $\mathbf{R}$. Notice that, as stated in the Introduction, achieving the points on the boundary of the capacity region requires a (centralized) optimization of the time-schedule vector $\breve{\mathbf{f}}$.

In Sec. V, the framework presented above is extended in order to include OST collaboration. In the next Section, we will review the OST scheme and present a performance comparison with MH transmission.

IV. Collaborative communications in ad hoc networks

In this Section, we review the OST scheme proposed in [6]. Our presentation will use a different (but equivalent) mathematical notation in order to make more convenient the analysis in an ad hoc context and to facilitate comparison with (centralized) optimal MH.

A. Optimal multi-hop transmission

Consider fig. 1. Source node s generates a data stream intended for node d. We assume for now that no spatial reuse is allowed. Node s could communicate to d through MH, collaboration or a combination thereof. Let us first consider MH. In this case, according to (7), maximizing the rate R_{sd} entails centralized optimization of the scheduling vector $\breve{\mathbf{f}}$ among the $\breve{M} = n(n-1)+1$ basic transmission modes. Here, for convenience of analysis, we restate the problem of maximizing R_{sd} in the following equivalent way: find *i*) the sequence of $M+1$ hops ($M \leq \breve{M}$), that we denote by the $(M+2)\times 1$ vector $\mathbf{a}$, with $a_1 = s$ and $a_{M+2} = d$; *ii*) the $(M+1)\times 1$ optimal scheduling vector $\mathbf{f}$, where f_m refers to the fraction of time devoted for the hop from node a_m to a_{m+1}, such that

$$R_{sd}^{MH} = \max_{\{\mathbf{a},\mathbf{f}\}} \left(\min_{m=1,\ldots,M+1} f_m C_{a_{m+1}}(a_m) \right) \tag{8}$$

under the constraint $\sum_{m=1}^{M+1} f_m = 1$, where we have defined for simplicity of notation $C_j(i) = C_j(i,i)$ (recall (5)). See fig. 1 for a pictorial view of the problem. From (8), it is clear that the optimal MH route maximizes the bottleneck of the weakest link along the route.

B. Opportunistic Space-Time cooperation

Consider again the situation in fig. 1. According to OST, the source node starts the transmission at a given rate R_{sd}. It is not informed of whether or not the signal will arrive to the destination directly or by collaborative transmission. As soon as a node $a_2 \in \mathcal{N}\backslash\mathcal{A}_d^{(1)}$ ($\mathcal{A}_d^{(1)} = \{s\}$) is able to decode the signal from s, it starts transmitting a cooperating signal (see fig. 2). We denote the (normalized) time instant when successful decoding of the first cooperating node takes place as $0 < f_1 \leq 1$:

$$f_1 = \min_{a_2 \in \mathcal{N}\backslash\mathcal{A}_d^{(1)}} \frac{R_{sd}}{C_{a_2}(\mathcal{A}_d^{(1)})}. \tag{9}$$

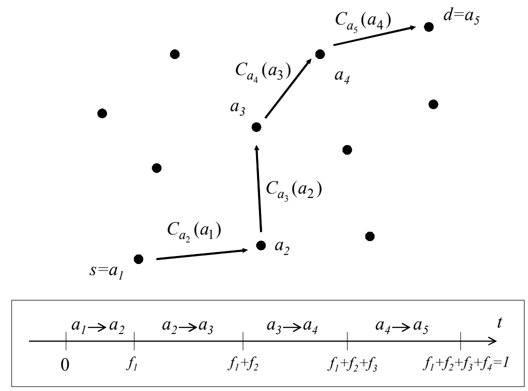

Fig. 1. Illustration of a MH route ($M = 3$).

Node a_2 is able to calculate f_1 since it is assumed to know the channel gain G_{sa_2}, and therefore the capacity $C_{a_2}(s)$. Notice that if there is no node a_2 that has a channel capacity from the source such that $C_{a_2}(\mathcal{A}_d^{(1)}) > R_{sd}$, then we set $a_2 = d$, and no collaboration occurs. Otherwise, the signal transmitted by nodes s and a_2, can be successfully decoded by a third node $a_3 \in \mathcal{N}\backslash\mathcal{A}_d^{(2)}$ ($\mathcal{A}_d^{(2)} = \{s, a_2\}$), as shown in fig. 2. Node a_3 may or not be equal to d and the time of successful decoding is $0 < f_1 + f_2 \leq 1$ with

$$f_2 = \min_{a_3 \in \mathcal{N}\backslash\mathcal{A}_d^{(2)}} \frac{R_{sd} - f_1 C_{a_3}(\mathcal{A}_d^{(1)})}{C_{a_3}(\mathcal{A}_d^{(2)})}. \tag{10}$$

Intuitively, in (10), the numerator is proportional to the number of bits that node a_3 still needs to decode at time f_1; thus, dividing by the capacity $C_{a_3}(\mathcal{A}_d^{(2)})$, we get the additional time that a_3 needs in order to decode the message. At $f_1 + f_2$ the third node starts collaborating and the procedure repeats with $(m = 1, \ldots, M)$

$$f_m = \min_{a_{m+1} \in \mathcal{N}\backslash\mathcal{A}_d^{(m)}} \frac{R_{sd} - \sum_{k=1}^{m-1} f_k C_{a_{m+1}}(\mathcal{A}_d^{(k)})}{C_{a_3}(\mathcal{A}_d^{(m)})}, \tag{11}$$

and $\sum_{m=1}^{M} f_m < 1$.

At the end of the transmission, $0 \leq M \leq N-2$ nodes cooperate with the source s and thus belong to the set of active nodes $\mathcal{A}_d^{(M+1)}$. The activating order is defined by the $(M+2)\times 1$ vector $\mathbf{a} = [a_1 = s, a_2, \ldots, a_{M+2} = d]^T$ and the corresponding activating times are in the $(M+1)\times 1$ vector $\mathbf{f}$ ($f_{M+1} = 1 - \sum_{m=1}^{M} f_m$). See fig. 2 for an illustration of the procedure. It is shown in [6] that the rate achievable by this distributed greedy procedure maximizes the following quantity

$$R_{sd}^{OST} = \max_{\{\mathbf{a},\mathbf{f}\}} \left(\min_{m=1,\ldots,M+1} \sum_{k=1}^{m} f_k C_{a_{m+1}}(\mathcal{A}_d^{(k)}) \right) \tag{12}$$

under the constraint $\sum_{m=1}^{M+1} f_m = 1$. Moreover, it is proved through random coding arguments that the rate (12) is achievable under the assumption that channel state information is available only at the receiving end of each wireless link.

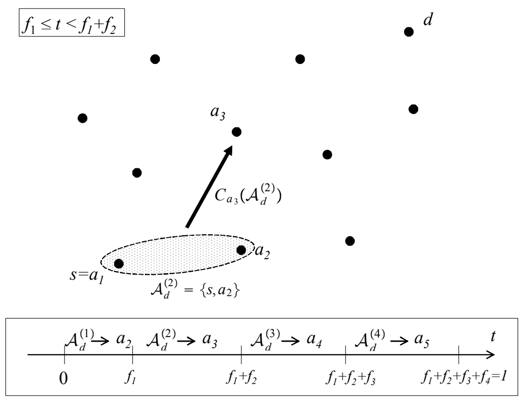

Fig. 2. Illustration of the OST scheme ($M = 3$).

Comparing the rate (12) with (8), it easy to see that, since the collaborative capacity $C_{a_{m+1}}(\mathcal{A}_d^{(m)})$ is larger or equal than $C_{a_{m+1}}(a_m)$ for any m, then (distributed) OST performs equal to or outperforms MH, in the sense that OST provides a larger (or equal) achievable rate.

C. MH vs. OST with spatial reuse

So far we have considered that no spatial reuse is allowed by the transmission protocol, that is, no concurrent transmission of another stream of data can take place at the same time. In general, there may be a number of sources that want to communicate at the same time with their corresponding destinations. The OST still works as explained above. The sources transmit simultaneously, ignoring whether or not some node will collaborate with their transmission. All idle nodes listen to the transmissions. As soon as a node manages to decode one of the signals from any of the sources, treating the others as interference, it starts transmitting. A detailed description of the procedure is easily derived from the discussion above.

By allowing MH and spatial reuse, multiple transmitter-receiving pairs can transmit at the same time. Contrary to OST, where distributed interference is generated by concurrent transmissions of collaborative nodes, interference from MH only impacts on a local area around the transmitting-receiving pair (the size of which depends on average on the path loss exponent α). Therefore, MH may provide a larger capacity region for a transmission protocol that allows spatial reuse. As we show in Sec. VI through numerical results, the relationship between the capacity region of MH and OST with spatial reuse may be involved (it is not in general a simple inclusion) and should be considered case by case. Next Section discusses the computation of the basic rate matrices and thus the capacity regions (from (7)) of ad hoc networks using OST with or without spatial reuse.

V. Capacity region with collaborative communications

As explained in Sec. III, according to (7), the capacity region is specified by the basic rate matrices corresponding to the basic transmission schemes of the transmission protocol. In the following, we discuss how to construct the basic rate matrices for a transmission protocol that allows OST with or without spatial reuse. Let us consider no spatial reuse. In this case, there are $\breve{M} = n(n-1)$ basic rate matrices corresponding to all the pairs of source-destination nodes. In particular, each transmission scheme is characterized by a source s and a destination d, and the basic rate matrix reads (recall (12))

$$R_{m,ij} = \begin{cases} R_{sd}^{OST} & \text{for } i = s \text{ and } j = d \\ 0 & \text{otherwise} \end{cases} . \quad (13)$$

On the other hand, if we consider spatial reuse, each transmission scheme is characterized by $Q = 1, ..., \lfloor n/2 \rfloor$ source-destination pairs $\{s_k, d_k\}_{k=1}^{Q}$. Since there are $n!/(Q! \cdot (n-2Q)!)$ distinct choices for the Q source-destination pairs, the number of basic transmission schemes reads $\breve{M} = \sum_{k=1}^{\lfloor n/2 \rfloor} n!/[Q!(n-2Q)!] + 1$. Moreover, the basic rate matrix for the transmission scheme characterized by source-destination pairs $\{s_k, d_k\}_{k=1}^{Q}$ reads (rigorous definition of $R_{s_k d_k}^{OST}$ can be found in [9])

$$R_{m,ij} = \begin{cases} R_{s_k d_k}^{OST} & \text{for } i = s_k \text{ and } j = d_k \text{ for } k = 1, ..., Q \\ 0 & \text{otherwise} \end{cases} . \quad (14)$$

VI. Numerical results

In this Section, we consider the capacity region of the linear and ring networks in fig. 3. The bandwidth is $B = 1MHz$; the noise power spectral density is $N_0 = -100dBm/Hz$; the reference distance is $d_0 = 10m$, that coincides with the distance between nodes in the linear network and with the radius in the ring network; the transmitted power is $P = 20dBm$; the path loss exponent is $\alpha = 4$; the constant ρ_0 is set so that the average SNR at d_0 with no interference is $0dB$ ($\rho_0 P/N_0 = 10dB$).

First, we consider the linear network with $n = 5$ nodes in fig. 3-(a). A slice of the capacity region corresponding to rates R_{21} and R_{35} is shown in fig. 4 for the case where no fading occurs, i.e., $|h_{ij}|^2 = 1$ in (1), in order to get a clear insight into the problem. It is expected that, while node 2 should transmit directly to node 1, node 3 could conveniently use the help of node 4 in conveying information to 5. Therefore, we expect R_{35} to be largely affected by both MH and collaborative transmission. As a reference, fig. 4 shows the capacity region for the case where only direct transmission from the source to the destination with no spatial reuse is allowed. In this case R_{21} is at most $1Mb/s$ (in fact $SNR_2(1) = 0dB$) whereas R_{35} is at most $0.0875Mb/s$ due to the increased distance between source and destination. Let us consider now transmission protocols that do not allow spatial reuse. Introducing MH, the maximum rate R_{21} remains the same (direct transmission is advantageous) whereas R_{35} increases up to $0.5Mb/s$. As expected from the analysis in Sec. IV, the capacity region with OST is even larger than MH since collaboration between 3 and 4 for the transmission to 5 is more effective than simple MH. For further reference, the performance of single-relay AF collaboration [4] is also shown. As stated in Sec. IV, the region

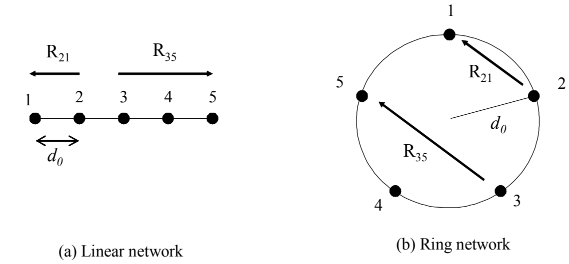

Fig. 3. Linear and ring network topologies. The communication rates R_{21} and R_{35} are shown for reference.

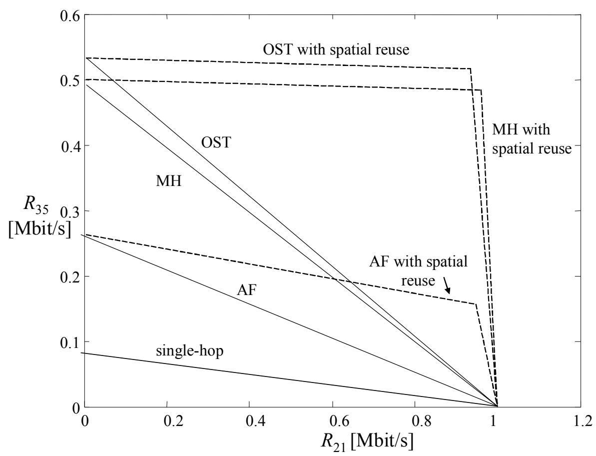

Fig. 4. Capacity regions slices in the plane R_{21} versus R_{35} for different transmission protocols (linear network).

achievable by MH and spatial reuse does not have a simple relation with the one obtained using OST and spatial reuse. For instance, in this case, OST allows to obtain larger rates for R_{35} for a fixed rate R_{21}, whereas MH yields (slightly) larger rates for R_{21} for a fixed rate R_{35}.

Similarly to the linear network, a slice of the capacity regions in the plane R_{21} versus R_{35} for the ring network is shown in fig. 5. All the arguments discussed above for the linear network can be applied to the ring network as long as no spatial reuse is allowed by the transmission protocol. In particular, the capacity region with OST is larger than with MH and this is even more so than in the case of a linear network since node 3 can collaborate with both nodes 4 and 2 while communicating with 5. However, if spatial reuse is allowed, the capacity region with MH is significantly wider than (but it does not include) that with OST. This is because with MH two concurrent data streams going from node 3 to 5 either through 4 or through the path 2-1 can be transmitted with limited interference. As a final remark on the capacity regions in fig. 4 and 5, we notice that, as warned in [4], adding single-relay AF communications to MH does not increase the capacity regions.

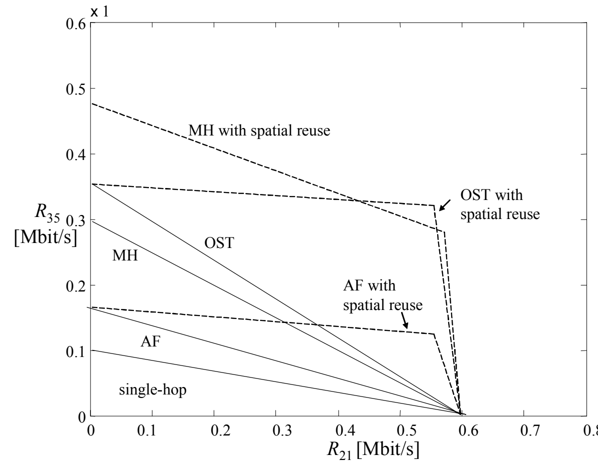

Fig. 5. Capacity regions slices in the plane R_{21} versus R_{35} for different transmission protocols (ring network).

VII. Concluding remarks

IIn this letter, the scheme proposed in [6] for opportunistic collaborative communication (OST) has been investigated for application in wireless ad hoc networks. Performance of OST is studied according to the achievable rates obtained in [6] by assuming random coding. Therefore, the results herein have to be interpreted as a theoretical upper bound on the performance that motivate further research on designing practical coding schemes, such as the overlay coding technique based on convolutional coding presented in [8].

References

[1] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 46, pp. 388-404, Mar. 2000.

[2] S. Toumpis and A. J. Goldsmith, "Capacity regions for wireless ad hoc networks," *IEEE Trans. Inform. Theory,* vol. 2, no. 4, pp. 1877-1894, July 2003.

[3] J. N. Laneman, David N. C. Tse and Gregory W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[4] M. Qin and R. S. Blum, "Capacity of wireless ad hoc networks with cooperative diversity: a warning on the interaction of relaying and multi-hop routing," in *Proc. ICC 2005*.

[5] S. Toumpis and A.J. Goldsmith, "Performance, optimization, and cross-layer design of media access protocols for wireless ad hoc networks," *in Proc. IEEE ICC 2003*, vol. 3, pp. 2234-2240, May 2003.

[6] P. Mitran, H. Ochiai and V. Tarokh, "Space–time diversity enhancements using collaborative communications," *IEEE Trans. Inform. Theory,* vol. 51, no. 6, pp. 2041-2057, June 2005.

[7] A. Scaglione and Y.-W. Hong, "Opportunistic large arrays: cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Processing*, vol. 51, no. 8, pp. 2082-2092, Aug. 2003.

[8] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470-1476, Sept. 2004.

[9] O. Simeone and U. Spagnolini, "Capacity of wireless ad hoc networks using opportunistic collaborative communications," submitted.