Title
A NewCommunication Scheme for MANETs

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A New Communication Scheme for MANETs

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***Abstract*— The communication protocols used in wireless ad hoc networks today have been designed to support reliable communication between senders and receivers that compete with other sender-receiver sets for the use of the shared bandwidth. This competition-driven approach prevents wireless ad hoc networks from scaling with the number of nodes. We introduce a collaboration-driven approach to the sharing of the available bandwidth in wireless ad hoc networks, which we call *opportunistic cooperation*. This scheme is based on the integration of multiuser detection and position-location information with frequency and code division in mobile ad hoc networks (MANETs). Transmissions are divided in frequency and codes according to nodal locations, and successive interference cancellation (SIC) is used at receivers to allow them to decode and use all transmissions from strong interfering sources. We show that both the link's Shannon capacity and the per source-destination throughput scale like $O(n^{\frac{\alpha}{2}})$ (upper-bound) and $\Omega[f(n)]$ (lower-bound), for n nodes in the network, a path loss parameter $\alpha > 2$, and $1 \le f(n) < n^{\frac{\alpha}{2}}$.**

I. Introduction

The protocol stacks of wireless ad-hoc networks implemented or proposed to date have been designed to try to *avoid* interference. Hence, communication protocols used in wireless ad-hoc networks today are meant to support reliable communication among senders and receivers that are *competing* with one another for the use of the shared bandwidth. This "competition-driven" view of bandwidth sharing has had profound implications on network architectures and methods used to access the channel and disseminate information. Gupta and Kumar [1] showed that, in a wireless connected network with static nodes, the throughput for each node degrades as the number of nodes increases under the competition-driven view of networking. That is, it scales as $\Theta(1/\sqrt{n\log(n)})$, [1] where n is the number of nodes in the network.

Grossglauser and Tse [2] analyzed a two-hop, single-relay forwarding scheme for MANETs in which a source passes a packet to a relay that in turn delivers it to the destination when the two nodes are close to each other. This and many subsequent studies on how to make MANETs scale by using mobility [2], [3], [4], consider each transmission as competing with all the other concurrent transmissions in the network. However, because a relay cooperates with a source by storing the source's packet until it is close enough to the intended destination, the throughput of MANETs can be increased.[2]

Recently, Toumpis and Goldsmith [5] have shown that the capacity regions for ad hoc networks are significantly increased when multiple access schemes are combined with spatial reuse (i.e., multiple simultaneous transmissions), multihop routing (i.e., packet relaying), and SIC, even without performing power control. Also, SIC circuits with simple implementation and low complexity have been introduced recently [6], and code division multiple access (CDMA) [7] and global positioning system (GPS) [8] technologies have been already integrated into a single IC chip [9]. Although CDMA and SIC for ad hoc networks have been studied in the past [10], [11], [12], prior approaches have assumed that each transmission competes with others.

From the above results, it appears that a cooperative approach to bandwidth sharing is not only desirable for attaining more scalable MANETs, but feasible in practice. In this paper, we present an integrated approach to cooperative bandwidth sharing in MANETs and propose what we call *opportunistic cooperation*.[3] With opportunistic cooperation, nodes access the available channel(s) and forward information across a MANET in such a way that concurrent transmissions become useful at destinations or relays. Hence, sender-receiver pairs collaborate, rather than compete, with others. We show that, by utilizing mobility [2], multiuser diversity [4] [13], SIC, and cognition,[5] the link's Shannon capacity and the per source-destination throughput attain an upper-bound of $O(n^{\frac{\alpha}{2}})$ and a lower-bound of $\Omega[f(n)]$, for n total nodes in the network, a path loss parameter $\alpha > 2$, and $1 \le f(n) < n^{\frac{\alpha}{2}}$.

Section II summarizes the basic network model that has been used recently to analyze the capacity of wireless networks [1], [2], [3], [4], [10]. Section III describes the *opportunistic cooperation* implementation. Section IV presents the the link's Shannon capacity, the per source-destination throughput, and the bandwidth requirement. Section V compares our approach with previous schemes. Section VI concludes the paper.

II. Network Model

The term *cell* denotes the set of nodes located inside a defined area of the network. The *receiver range* of a node is defined as the radius, measured from the node, which contains all other

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[1] Ω, Θ and O are the standard order bounds. $\log(\cdot)$ is the natural logarithm.

[2] In [2], the per source-destination throughput scales as $\Theta(1)$.

[3] The term "opportunistic" is used here to indicate that the number of nodes cooperating with one another in a cell during a communication session is a random variable.

[4] i.e., a node transmits a packet to all its nearest neighbors, and those relays deliver the packets to the destinations when each destination becomes a close neighbor of each relay.

[5] To allow a node to know where it is and who the nodes in the same cell are.

nodes of the same cell. The *cluster* associated with a given node is the set of cells reached by the receiver range of this node.

Our assumptions are consistent with prior work [1], [2], [10]. Also, in this paper, nodes are considered to have SIC capability.

The modeling problem we address is that of a MANET in which n mobile nodes move in a unit square area. To simplify our analysis, we assume that cells have square shapes, each with area equal to $a(n) = \frac{1}{\phi n}$, in which $\phi \in (0,1)$ is the cell area parameter of the network. We consider that the communication occurs only among those nodes that are close enough (i.e., in same cell), so that interference caused by farther nodes is low, allowing reliable communication. In other words, the receiver chooses the closest nodes because they present the best channel, in a respective order, due to the assumption of the simple path propagation model, i.e., the receiver takes advantage of multiuser diversity [13]. Our model resembles the one introduced by Grossglauser and Tse [2], who consider a packet to be delivered from source to destination via one-time relaying.

The position of node i at time t is indicated by $X_i(t)$. Nodes move according to the *uniform mobility model* [3], in which the steady-state distribution of the mobile nodes is uniform.

Each node simultaneously transmits and receives data during a communication time period, through different frequency bands, since each data link is assumed half-duplex. This period of communication is called a *communication session*. Furthermore, each session is divided into two parts. A neighbor discovery protocol is used by nodes during the first part to obtain their neighbors information (e.g., node identification (ID)), and the transmission of data is performed during the second part. Each node has a unique ID that does not change with time, and each node can simultaneously be a source (or relay) while transmitting and a destination (or relay) while receiving, during a session. Each source node picks a single arbitrary destination to whom it sends packets.

III. Opportunistic Cooperation

In *opportunistic cooperation*, many nodes transmit concurrently to many other neighbor nodes, and all such transmissions are decoded. Thus, a node may concurrently send to and receive from many nodes. Since full-duplex data communication in the same frequency band is not practical, we present an example of how *opportunistic cooperation* can be implemented with a scheme based on frequency division multiple access (FDMA) and CDMA that supports many-to-many communication.

A. Bandwidth Allocation

In our specific implementation of opportunistic cooperation, we use two types of channels. Control channels are used by nodes to obtain such information as the identities of strong interference sources, the data packets expected by destinations, and the state of data channels (by virtue of training sequences). Nodes employ conventional digital transceivers for the control channels. Data channels are used to transmit data taking advantage of SIC at the receivers. Thus, there are two separate transmitter (receiver) circuits in each node. One circuit is intended to transmit (receive) control packets, and the other is used to transmit (receive) data packets. Both circuits operate in different time and frequency with respect to each other.

Control (or Signaling) Channels: Each cell is allocated a control frequency band from twelve non-overlapping control frequency bands required (and available), ω_1 to ω_{12}, to enable frequency reuse while avoiding interference in the control channels from nearby cells. Each control frequency band ω_i has a size of $|\omega_i| = \Delta\omega$ for $i = 1, ..., 12$. Hence, the total bandwidth required for the control channels is $\Delta\omega_C = 12\Delta\omega$.

The maximum number of cells in a cluster associated to a given node is twelve. The number of cells and the cluster shape are chosen such that if the receiver range has maximum value, i.e., almost $\sqrt{2a(n)}$, then the receiver range reaches all these cells. Also, two cells employing the same control frequency band are kept at least $\sqrt{5a(n)}$ units away from each other, i.e., a safe guard-zone separation, thus guaranteeing asymptotic constant non-zero signal-to-noise and interference ratio (SNIR) as $n \to \infty$ [4] in the control channel, making signaling feasible and allowing control frequency reuse.

To simplify the control signaling required among nodes to determine which control channel a given node should use, each node is assumed to know its own position (but not the position of any other node) by utilizing a GPS circuit [8], and to store a geographical map of the cells in the network with its associated control frequencies. The GPS is also used to provide an accurate common time reference to keep all nodes synchronized.

Each node uses the control channel receiver to listen to the control channel of the cell as well as to the other 11 control channels, in order to obtain the IDs and training sequences of the other nodes in its cell and in the cluster it perceives, while not transmitting during the neighbor discovery phase.

Data Channels: To allow code reuse in the data channels while reducing the negative effects of interference, each cell is allocated a set of PN sequences (or codes) from the twelve different code sets available, ξ_1 to ξ_{12}, for communication in each data channel. Accordingly, each non-overlapping data channel is a half-duplex link of bandwidth ΔW. If A is the maximum number of nodes allowed to communicate in any cell, then $\Delta W_D = A\Delta W$ is the data bandwidth required for the entire network and $M = 12A$ distinct PN sequences are needed for local data communication. M is also called the spreading factor (or processing gain). Also, $\Delta W = BM$, where B is the original data bandwidth before spreading [7].

Because a PN sequence can be associated to a sequence of bits [7], they can be ordered and grouped as follows. $\xi_1 = \{C_1, ..., C_A\}$, $\xi_2 = \{C_{A+1}, ..., C_{2A}\}$, ..., $\xi_{12} = \{C_{11A+1}, ..., C_{12A}\}$, in which C_i stands for the i^{th} PN sequence (or code). In this way, any set of twelve cells, numbered from 1 to 12, has a different set of codes. Therefore, by construction, the cluster seen by any node is composed of cells having distinct numbers, and consequently, different codes.

As we discuss in Section III-B, the signaling in the control channel provides each node in a cell i knowledge of who the other nodes in this same cell are, and the node uses this information to choose a data channel to receive data, as well as to select a code for transmission from the available PN sequences in ξ_i based on its own and neighbor IDs, in the following order[6]: (i) The node with the highest ID in cell i is associated with the

[6] For simplicity, we indicate W_j as the data channel associated to node j.

data channel ΔW centered at W_1, as well as it is assigned the first PN sequence in ξ_i. (ii) The node with the second highest ID in cell i is associated with the data channel ΔW centered at W_2, as well as it is assigned the second PN sequence in ξ_i, and this continues for all nodes in cell i. (iii) The data channels not utilized become idle in cell i. It happens in those cells where the number of nodes is less than A.

Note that, in a communication session, each node only needs to know the nodes in its cell (obtained during the neighbor discovery phase) and the signal strengths received from them (by virtue of CDMA-SIC), in order to set its receiver range.

At time t, each cell has Z nodes such that the data communication is Z-to-Z, i.e., many-to-many communications (see Fig. 1), where Z is a random variable. Each node employs a multi-user transmitter DS-CDMA [7] (i.e., it transmits up to $Z-1$ simultaneous data packets per session in which, due to FDMA, each packet is sent through a different data channel, as illustrated in Fig. 1(downlink)), spreading the data using the PN sequence associated to its ID. The node can transmit a different data packet in each channel or choose to send the same data packet in all (non-idle) channels, or a combination of both, depending on the fact that the node has packet for any destination in the same cell it is located. Thus, multi-copies of the same packet can be simultaneously relayed to reduce delay [4].

Given that each node is endowed with a multi-user detector (the SIC circuit) for its associated receiving data channel, it is able to decode the $Z-1$ simultaneous transmissions from all nodes in its cell (see Fig. 1(uplink)).

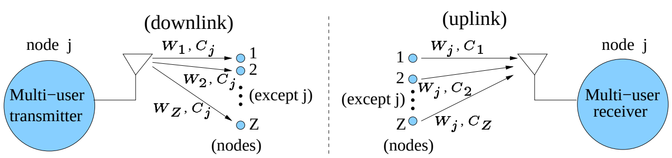

Fig. 1. Downlink and uplink description for data channels in a cell. Communication is Z-to-Z (i.e., many-to-many).

B. Channel Access and Data Packet Forwarding

Access to the channel is controlled by the signaling that takes place over the control channels. Such signaling occurs simultaneously in all cells, without suffering high interference from each other because of the different frequency assignment and consequent safe guard-zone separation (see Section III-A).

The signaling among the nodes in the same cell must be one-to-many and cannot assume knowledge of who the nodes in a cell are, because nodes are mobile. Each node needs to inform the other nodes in its present cell about its own presence in the cell, plus other control information. From Fig. 2, access to the channel is divided in time into a discovery phase and a data-transmission phase. The period of "neighbor discovery" t_{disc} and the period for transmission of data t_{data} are constant and independent of the number of nodes in the network (n). Together, they compose a "communication session." The common time reference for communication sessions is obtained through the GPS circuit. The values of t_{disc} and t_{data} are system design parameters. t_{disc} is subdivided into multiple slots, each of length T. Hence, $T = \frac{t_{disc}}{N}$, where N is a positive integer to calculate according to some given criterion as explained later.

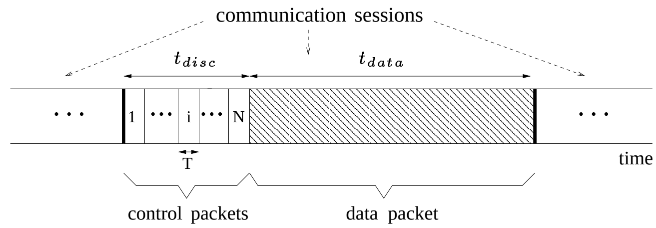

Fig. 2. Time series representation of control and data packets. t_{disc} is the neighbor discovery phase. t_{data} is the time period for transmission of data. t_{disc} plus t_{data} form a communication session.

Each node simultaneously senses the channel to detect collision while transmitting in the control channel, for example, using echo cancelling techniques [14]. Accordingly, the nodes involved in a collision do not participate in that session anymore, i.e., they remain silent until the next session. Also, since only A codes are available per cell, then, only the first A nodes that successfully announced their control packets during t_{disc} are going to transmit (or receive) data during t_{data} for that session. Since this access is random and independent from the node ID, thus, no privilege is given to a node with high ID value. The ID's are used only to order the code assignment in each cell.

Each time the discovery period is about to begin, each node randomly chooses one of the T mini-slots and transmits its control packet. If there is no collision, i.e., if the other nodes in the same cell choose different mini-slots to transmit, then all the other nodes in the cell will receive this packet. A collision happens every time two or more nodes in the same cell choose to transmit in the same mini-slot. Let Z_i be the number of nodes in the same cell choosing the mini-slot i to transmit their control packets. Let Z_{max} be the maximum number of nodes in any cell. The probability of collision $\mathbb{P}_c$ is given by

$$\mathbb{P}_c = \mathbb{P}\{Z_i \geq 2\} = 1 - \left(1 - \tfrac{1}{N}\right)^{Z_{max}} - \tfrac{Z_{max}}{N}\left(1 - \tfrac{1}{N}\right)^{Z_{max}-1}. \quad (1)$$

The criterion used to choose N is as follows. We calculate N such that there is no collision with probability approaching 1 as $n \to \infty$, for example, with probability $\geq 1 - \frac{\log(\log(n))}{\log(n)}$. From (1), $\mathbb{P}_c \leq 1 - \left(1 - \frac{1}{N}\right)^{Z_{max}}$. Accordingly, we choose

$$\mathbb{P}_c \leq 1 - \left(1 - \tfrac{1}{N}\right)^{Z_{max}} \leq \frac{\log(\log(n))}{\log(n)}$$

$$\Longrightarrow N \geq \left\lceil \left[1 - \left(1 - \frac{\log(\log(n))}{\log(n)}\right)^{\frac{1}{Z_{max}}} \right]^{-1} \right\rceil = N_{min}, \quad (2)$$

in which $\lceil x \rceil$ stands for the ceil function (i.e., the smallest integer greater than or equal to x), and N_{min} is the actual value to be implemented for N. Thus, we have

$$T = \frac{t_{disc}}{N_{min}}. \quad (3)$$

The following lemma provides the relationship between Z_{max} and n, which proof is skipped for brevity.

Lemma 1 *For the uniform mobility model, with probability approaching 1 as $n \to \infty$, the maximum number of nodes in any cell, is given by*

$$Z_{max} = \left\lceil \frac{3\log(n)}{\log(\log(n^{\phi}))} \right\rceil. \quad (4)$$

$$SNIR = \frac{P_{ij}(t)g_{ij}(t)}{BN_0 + \underbrace{\frac{1}{M}\sum_{\substack{k\,\in\,range\\ k\neq i}} P_{kj}(t)g_{kj}(t)}_{COI} + \underbrace{\frac{1}{M}\sum_{\substack{k\,\notin\,range\\ C_k\neq C_i}} P_{kj}(t)g_{kj}(t) + \sum_{\substack{k\,\notin\,range\\ C_k=C_i}} P_{kj}(t)g_{kj}(t)}_{DEI}}. \quad (5)$$

Although Z_{max} is the maximum number of nodes in any cell, in practice, the number of codes to be used is limited. Thus, at most A nodes in any cell are allowed to get a code and communicate during t_{data}. However, Z_{max} grows very slowly with n. Thus, by choosing, for example, $A \geq 10$, for practical values of ϕ, the fraction of cells having more than A nodes can be bounded by a small constant, for n large. Accordingly, the total number of cells in the network is (# of cells) $= 1/a(n) = \phi n$. By considering the uniform mobility model, the fraction of cells containing $Z = j$ nodes for $n >> j$ is obtained by

$$\mathbb{P}\{Z=j\} = \binom{n}{j}\left(\frac{1}{\phi n}\right)^j\left(1-\frac{1}{\phi n}\right)^{n-j} \approx \frac{1}{j!}\left(\frac{1}{\phi}\right)^j e^{-1/\phi}. \quad (6)$$

The fraction of cells having more than A nodes for given ϕ can be upper-bounded by

$$\mathbb{P}\{Z > A\} \leq \sum_{j=A+1}^{\infty} \frac{1}{j!}\left(\frac{1}{\phi}\right)^j e^{-1/\phi} \leq \frac{1}{(A+1)!}\left(\frac{1}{\phi}\right)^{A+1}. \quad (7)$$

For example, for $\phi = \frac{1}{3}$ and $A = 10$, $\mathbb{P}\{Z > A\} \leq 0.0044$.

Data packet forwarding consists of two phases [2], [4]: The packet is transmitted from the source to possibly several relay nodes during *Phase 1* (i.e., multi-copies can be forwarded), and it is delivered later to its destination by only one of the relay nodes during *Phase 2*. Both phases occur concurrently, but *Phase 2* has priority in all communications. These multiple one-time relays for the same packet provide better delay performance since the copies of the same packet follow different random routes, looking for the destination, reducing delay [4].

C. Interference in a Data Channel

Although the nodes are synchronized, data packets are received at a given node asynchronously due to the different distances from each transmitting node. Besides, fading effects can amplify the asynchronous nature of packet reception. Thus, even if the codes are orthogonal, they exhibit partial cross-correlation at the receiver, which results in multiple access interference (MAI) [7].

The interference in the data channel at a node j, regarding node i transmitting to node j through W_j, is defined as the signals coming from all transmitting nodes in the network, via W_j, except node i. It can be decomposed in the following two types.

Destructive Interference (DEI) for the node j comes from nodes, transmitting in W_j, outside the receiver range of j. DEI constitutes the part of the interference that will not be decoded.

Constructive Interference (COI) comes from nodes, transmitting in W_j, within the receiver range of j. By construction (see Section III-A), the nodes within the receiver range of j, transmitting in W_j, use different codes exhibiting partial cross-correlation due to the asynchronous nature of the uplink channel [7]. COI constitutes the decodable part of the interference.

If node i transmits data to j at time t, via W_j, the SNIR at the receiver j, without SIC, is given by (5) [2], where $range$ [7] is the set of nodes transmitting in W_j and reached by the receiver range of node j, C_i is the PN sequence used by sender node i, $P_{ij}(t) = P\ \forall(i,j)$ is the transmit power chosen by node i to transmit to node j (i.e., $P_{ij}(t)$ is constant for all pair (i,j)), $g_{ij}(t)$ is the channel path gain from node i to j, B is the original bandwidth of the data signal (before spreading), BN_0 is the noise power (where N_0 is the noise power spectral density), M is the spreading factor, COI and DEI are the total interference in W_j at node j. The summation terms in the denominator of (5) containing the factor $1/M$ constitute the multiple access interference (MAI) [7], and the last summation term (without the factor $1/M$) is consequence of code reuse in the network and we call it *same code interference* (SCI). Thus, $SCI = \sum_{\substack{k\,\notin\,range\\ C_k=C_i}} P_{kj}(t)g_{kj}(t)$, such that, $MAI + SCI = COI + DEI$. MAI and SCI presentations are easier for calculating SNIR as explained later.

The channel path gain g_{ij} is assumed to be a function of the distance only (i.e., the simple path propagation model) [1], [2], therefore, $g_{ij}(t) = \frac{1}{|X_i(t)-X_j(t)|^\alpha} = \frac{1}{r_{ij}^\alpha(t)}$, in which α is the path loss parameter, and $r_{ij}(t)$ is the distance between i and j.

D. Hybrid FDMA/CDMA Data Transceiver

From Fig. 1(downlink), the FDMA/CDMA data transmitter in node j selects packets previously relayed to node j which have their destination nodes present in the same cell, spread the data using the code C_j assigned to node j, and transmits each one of them through each different frequencies associated to each distinct destination node. If the node assigned to a data channel is not a destination for a relayed packet, then the transmitter selects a new packet generated locally by node j.

The basic decoding scheme of the CDMA-SIC data receiver scheme is given in [6] (see also Fig. 1(uplink)), in which the decoding is performed successively from the strongest signal to the weakest. The use of training sequences obtained through the control channels allow to obtain a local estimation of the wireless channel. Thus, with the simple path propagation model assumed, the strongest signal decoded first comes from the closest neighbor to node j (not necessarily in the same cell of j but in the cluster it perceives), while the weakest (decoded last) is the farthest node to node j in the cell node j is located. Let MAI' be the remaining multiple access interference at node j after applying SIC up to node i, i.e.,

$$MAI' = \frac{1}{M}\sum_{\substack{\forall k\,:\,g_{kj}<g_{ij}\\ C_k\neq C_i}} P_{kj}(t)g_{kj}(t). \quad (8)$$

Therefore, the resulting SNIR (called $SNIR'$) from node i to node j after applying SIC is given by

$$SNIR' = \frac{P_{ij}(t)g_{ij}(t)}{BN_0 + MAI' + SCI}. \quad (9)$$

Note that, depending on the position of the node j, it may have nodes transmitting from adjacent cells closer than a far

[7] $k \notin range$ means the nodes outside the receiver range of node j transmitting in W_j.

node in the same cell. Therefore, j has to be able to decode the data signals from these adjacent cell nodes before decoding the signal from the far node of the same cell. This explains why each node also needs to obtain the training sequences from the other nodes located outside its cell but still within its receiver range. The receiver uses the information obtained during the neighbor discovery phase to retain the data packets from nodes in the same cell as j, dropping the outside cell packets since node j cannot keep track of all nodes in adjacent cells to see if this packet is for relaying or destination. Besides, from (5), SIC is fundamental to derive (9) and a node have all packets from the same cell successfully decoded.

IV. Capacity and Bandwidth Analysis

A. Link's Shannon Capacity

The link's Shannon capacity R_{ij} in the data channel W_j, in which node j receives from node i, after j applying SIC up to node i, from (9), is given (in units of nats) by [15]

$$R_{ij} = B\log\left(1+\frac{P_{ij}(t)g_{ij}(t)}{BN_o+MAI'+SCI}\right). \tag{10}$$

MAI' can be computed by using Fig. 3. Assume that the center of the unit square area is the origin O of the (x,y) coordinates, and that, at time t, the receiver node j is located at the point Q with coordinates $(x_Q, y_Q) \in (-\frac{1}{2}, \frac{1}{2})$. The calculation considers the transmitting node i located at a distance $c_2\sqrt{a(n)}$ from j, while due to SIC, all the remaining interfering nodes are at a distance greater than $c_2\sqrt{a(n)}$ from j, where $c_2 \in (0, \sqrt{2})$ depends on the distance between nodes j and i in the cell. We divide the square unit area network in four triangles and compute the interference generated from each of these regions, such that $MAI' = \sum_{l=1}^{4} MAI'_l$. Similar to [4], for a uniform distribution of the nodes, we consider a differential element area $r dr d\gamma$ that is distant r units from node j. Since the nodes are uniformly distributed and n grows to infinity, the node density in the network is $\frac{n}{1}$, and the summation in (8) can be bounded by an integral. Thus, MAI'_l at node j is upper-bounded by

$$MAI'_l(n) \;\le\; \int\int_{region\ MAI'_l} \frac{P}{Mr^{\alpha}}\,\phi\,\epsilon_j\,\frac{n}{1}\,r\,dr\,d\gamma, \tag{11}$$

in which ϵ_j is the fraction of cells using the bandwidth W_j. Accordingly, ϵ_j equals the fraction of cells containing at least j nodes, in which $j \in [2, A]$. From (6), we have

$$\epsilon_j = \mathbb{P}\{Z \ge j\} \approx 1 - \sum_{k=0}^{j-1} \frac{1}{k!}\left(\frac{1}{\phi}\right)^k e^{-1/\phi}. \tag{12}$$

Thus, for $\alpha > 2$, and using that $a(n) = \frac{1}{\phi n}$, from (11) we obtain with some manipulations

$$\begin{aligned} MAI'_l(n) &\le \int_{\gamma_{min_l}}^{\gamma_{max_l}} \int_{c_2\sqrt{a(n)}}^{r_{max_l}(\gamma)} \frac{P\,\phi\,\epsilon_j\,n}{Mr^{\alpha-1}}\,dr\,d\gamma \\ &\le \frac{c_{3_l}\,\epsilon_j\,n^{\frac{\alpha}{2}}}{M}\left(1-\frac{c_{4_l}}{n^{\frac{\alpha}{2}-1}}\right), \end{aligned} \tag{13}$$

in which c_{3_l} and c_{4_l} are positive constants for given l, (x_Q, y_Q), c_2, ϕ, P, and α. Therefore,

$$MAI' = \sum_{l=1}^{4} MAI'_l \le \frac{c_5\,\epsilon_j\,n^{\frac{\alpha}{2}}}{M} \le \frac{c_5 n^{\frac{\alpha}{2}}}{M}, \tag{14}$$

since $\epsilon_j \in [0,1]$, and $(1-\frac{c_{4_l}}{n^{\frac{\alpha}{2}-1}}) \le 1$ for n large. c_5 is a positive constant function of the location (x_Q, y_Q) of node j.

On the other hand, the same code interference (SCI) can be upper-bounded by using the same procedure as done before for MAI'. Consequently, it can be shown that

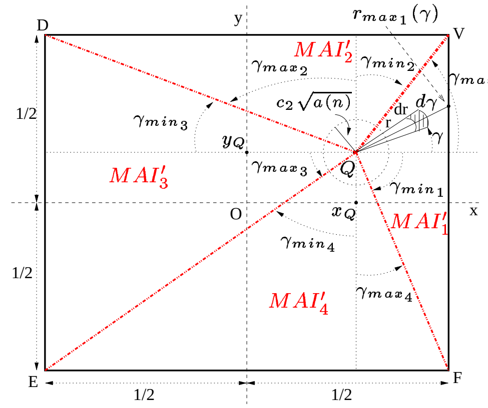

Fig. 3. Interference regions for node i communicating with node j. The angle γ increases in the counterclockwise direction.

$$SCI = \sum_{\substack{k \notin range \\ C_k = C_i}} P_{kj}(t) g_{kj}(t) \;\le\; c_6\,\epsilon_j n^{\frac{\alpha}{2}} \;\le\; c_6 n^{\frac{\alpha}{2}}. \tag{15}$$

Hence, from (14) and (15), it results that the total remaining interference after SIC at node j is upper-bounded by

$$MAI' + SCI \;\le\; \frac{c_5 n^{\frac{\alpha}{2}}}{M} + c_6 n^{\frac{\alpha}{2}}. \tag{16}$$

If we consider the expansion $B = f(n)$ of the original data bandwidth, such that $1 \le f(n) < n^{\frac{\alpha}{2}}$, then, a lower-bound for R_{ij} can be obtained by using the maximum interference. Thus, from (10) and (16), the corresponding link's Shannon capacity lower-bound as $n \to \infty$, for node j receiving from node i, is obtained by

$$R_{ij} \ge f(n)\,\underbrace{\log\left(1+\frac{c_7 n^{\frac{\alpha}{2}}}{f(n)N_o + \frac{c_5 n^{\frac{\alpha}{2}}}{M} + c_6 n^{\frac{\alpha}{2}}}\right)}_{\xrightarrow{n\to\infty} c_8} = c_8\,f(n), \tag{17}$$

in which c_7 and c_8 are positive constants for given α, ϕ, P, M, N_o, c_2, R, and (x_Q, y_Q). *In (17), interference dominates noise for the bandwidth expansion* $1 \le B < n^{\frac{\alpha}{2}}$.

On the other hand, if we consider a scenario such that there is no limitation on available bandwidth, then we can obtain an upper-bound for R_{ij}. Accordingly, from (10),

$$R_{ij} = B\log\left(1+\frac{c_7}{\frac{BN_o}{n^{\frac{\alpha}{2}}} + \frac{1}{n^{\frac{\alpha}{2}}}(MAI'+SCI)}\right). \tag{18}$$

Now, from (16) and (18), and by taking $B \ge c_9 n^{\frac{\alpha}{2}}$, for some positive constant c_9 and n sufficiently large, it results that

$$\frac{1}{n^{\frac{\alpha}{2}}}(MAI' + SCI) \;\le\; \frac{c_5}{M} + c_6 \;\le\; \frac{BN_o}{n^{\frac{\alpha}{2}}}. \tag{19}$$

Thus, the term $\frac{BN_o}{n^{\frac{\alpha}{2}}}$ becomes dominant in the denominator of (18) when $B \ge c_9 n^{\frac{\alpha}{2}}$ and $n \to \infty$. From (18) and (19), for $B \ge c_9 n^{\frac{\alpha}{2}}$, we have the following upper-bound for the link's Shannon capacity as $n \to \infty$

$$R_{ij} = n^{\frac{\alpha}{2}}\,\underbrace{\frac{B}{n^{\frac{\alpha}{2}}}\log\left(1+\frac{c_7}{\frac{BN_o}{n^{\frac{\alpha}{2}}} + \frac{1}{n^{\frac{\alpha}{2}}}(MAI'+SCI)}\right)}_{\xrightarrow{n\to\infty} c_{10}} = c_{10} n^{\frac{\alpha}{2}}, \tag{20}$$

in which c_{10} is a positive constant. *Here, noise dominates interference due to the large bandwidth expansion.*

Thus, (17) and (20) describe two limiting cases. The former is the minimum capacity attained if we use the bandwidth expansion $1 \le B < n^{\frac{\alpha}{2}}$. The latter is the maximum capacity reachable if the available bandwidth is large such that $B \ge c_9 n^{\frac{\alpha}{2}}$. Note that any increase in B beyond $c_9 n^{\frac{\alpha}{2}}$ will not change the order of the upper-bound of the capacity.

B. Per Source-Destination Throughput

From Section III-B, each node accesses the data channel at a constant rate $\delta = \frac{t_{data}}{t_{disc}+t_{data}}$ with probability approaching 1 as $n \to \infty$, such that each source sends one packet per session to its destination. Each node is guaranteed, in each data channel, a communication rate of R_{ij} lower- and upper-bounded by (17) and (20), respectively. Also, this available communication rate has to be divided among all routes the node must serve per session per channel. However, due to the mobility and the routing scheme, each node serves only one route per session per data channel, i.e., the node either relays a new packet or it delivers a packet to a destination. Thus, the number of routes every node has to service per session per data channel is (# of served routes) $= 1$. Moreover, all cells containing at least two nodes are able to execute FDMA/CDMA and SIC successfully. From (6), $\mathbb{P}\{Z \geq 2\} \approx (1 - e^{-1/\phi} - \frac{1}{\phi} e^{-1/\phi})$. Hence, with probability approaching 1 as $n \to \infty$, the per source-destination throughput $\lambda(n)$ is obtained by [4]

$$\lambda(n) = \frac{R_{ij}\, \delta\, \mathbb{P}\{Z \geq 2\}}{\text{\# of served routes}} = c_{11}\, R_{ij}, \tag{21}$$

where c_{11} is a positive constant for given t_{disc}, t_{data}, and ϕ. From (17), (20), and (21), we proved the following Theorem.

Theorem 1 *By employing mobility, CDMA, SIC, and one-time relaying of packets using the opportunistic cooperation strategy, the ad hoc network attains, with probability approaching 1 as $n \to \infty$, the upper- and lower-bound per source-destination throughput given respectively by*

$$\lambda(n) = O\left(n^{\frac{\alpha}{2}}\right) \quad \text{and} \quad \lambda(n) = \Omega\left[f(n)\right], \tag{22}$$

where $1 \leq f(n) < n^{\frac{\alpha}{2}}$.

The Theorem shows that, by using *opportunistic cooperation*, the per source-destination throughput increases with n. Furthermore, the throughput upper-bound is the highest reported in the literature for ad hoc networks.

C. Bandwidth Scalability

The total bandwidth requirement (ΔW_{total}) for the entire network has two components. One from the control channels ($\Delta\omega_C$), and the other from the data channels (ΔW_D).

From (2) and (3), Lemma 1, and noting that $\Delta\omega$ in each control channel equals $2/T$, due to the Nyquist rate, it results that

$$\Delta\omega_C = \frac{24 N_{min}}{t_{disc}} = \Theta\left[1 - \left(1 - \frac{\log(\log(n))}{\log(n)}\right)^{\frac{1}{\left\lceil \frac{3\log(n)}{\log(\log(n^{\phi}))} \right\rceil}}\right]^{-1}. \tag{23}$$

From Section III-A, $\Delta W = BM = 12AB$ [7]. Thus, the bandwidth scalability in each data channel associated to the upper- and lower-bound capacity is given respectively by

$$\Delta W = \Omega\left(n^{\frac{\alpha}{2}}\right) \quad \text{and} \quad \Delta W = \Theta[f(n)], \tag{24}$$

where $1 \leq f(n) < n^{\frac{\alpha}{2}}$.

The total bandwidth for the entire network is obtained by

$$\Delta W_{total} = \Delta W_D + \Delta\omega_C = A\Delta W + \Delta\omega_C, \tag{25}$$

where ΔW and $\Delta\omega_C$ are given above.

V. Comparison with Previous Schemes

(i) Mobile network case: In [2], only the cells containing exactly one sender and at least one receiver are able to forward packets (i.e. $\{senders(L) = 1, receivers(K) \geq 1\}$) [4]. In *opportunistic cooperation*, all cells containing at least two nodes are able to successfully forward packets (i.e., $\{Z \geq 2\}$). Thus, our collaboration-driven strategy provides the following performance gain G over the scheme in [2] based on comparison to the fraction of cells that successfully forward packets,

$$G = \frac{\mathbb{P}\{Z \geq 2\}}{\mathbb{P}\{L=1, K \geq 1\}} = \frac{1 - e^{-1/\phi} - \frac{1}{\phi} e^{-1/\phi}}{\frac{1}{\phi} e^{-1/\phi}\left(1 - e^{-1/\phi}\right)} > 1 \;\forall\, \phi \in (0,1). \tag{26}$$

(ii) Static network case: By applying the principles of *opportunistic cooperation* to static networks we obtain the same throughput lower-bound of $\Omega[n^{\frac{\alpha-1}{2}}/(\log(n))^{\frac{\alpha+1}{2}}]$ as in [10] (which employed bandwidth expansion in [1]), but our scheme requires a smaller bandwidth of $\Omega[n^{\frac{\alpha}{2}}/(\log(n))^{\frac{\alpha}{2}-1}]$ compared to $\Theta[n(n^2\log(n))^{\frac{\alpha}{2}}]$ in [10], since we use SIC.

VI. Conclusions

It was shown that we can obtain Shannon capacity and per source-destination throughput increasing with the total number of nodes n in wireless ad hoc networks, by employing mobility, FDMA/CDMA, SIC, and one-time relaying of packets taking advantage of opportunistic cooperation among nodes. Accordingly, interference from close neighbors is no longer harmful, but rather endowed with valuable data that we can take advantage of. This technique also allows for code reuse and reduces the bandwidth scalability of the network. In addition, because multi-copy relaying of packets is employed, the delay performance is improved and follows the description given in [4].

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