

High Transmission Power Increases the Capacity of Ad Hoc Wireless Networks

Arash Behzad and Izhak Rubin, *Fellow, IEEE*

Abstract—In this paper, the effect of transmission power on the throughput capacity of finite ad hoc wireless networks, considering a scheduling-based medium access control (MAC) protocol such as time division multiple access (TDMA) and an interference model that is based on the received signal-to-interference-plus-noise ratio (SINR) levels, is analyzed and investigated. The authors prove that independent of nodal distribution and traffic pattern, the capacity of an ad hoc wireless network is maximized by properly increasing the nodal transmission power. Under the special case of their analysis that the maximum transmission power can be arbitrarily large, the authors prove that the fully connected topology (i.e., the topology under which every node can directly communicate with every other node in the network) is always an optimum topology, independent of nodal distribution and traffic pattern. The present result stands in sharp contrast with previous results that appeared in the literature for networks with random nodal distribution and traffic pattern, which suggest that the use of minimal common transmission power that maintains connectivity in the network maximizes the throughput capacity. A linear programming (LP) formulation for obtaining the exact solution to the optimization problem, which yields the throughput capacity of finite ad hoc wireless networks given a nodal transmit power vector, is also derived. The authors' LP-based performance evaluation results confirm the distinct capacity improvement that can be attained under their recommended approach, as well as identify the magnitude of capacity upgrade that can be realized for networks with random and uniform topologies and traffic patterns.

Index Terms—Ad hoc wireless networks, power control, routing, scheduling, throughput capacity.

I. INTRODUCTION

AD HOC wireless networks are infrastructure-free wireless networks consisting of nodes that communicate with each other across wireless links directly or through possibly intermediate nodes. Capacity (throughput capacity) of an ad hoc wireless network is defined in the usual manner as the maximum data rate that is achievable by all source–destination pairs of nodes [3]–[5], [7], [9], [11], [12]. This value is one of the fundamental characteristics of the network, which is a function of various factors, including nodal density and distribution, mobility, traffic pattern, size of the network, transmission

power and bandwidth constraints, and antenna directionality. In a recent landmark paper [5], Gupta and Kumar studied the capacity of ad hoc wireless networks in the limit as the number of nodes grows to an arbitrarily large level. Under this model, stationary nodes are randomly and uniformly located (over a disk area), and each node sends data to a randomly and uniformly selected destination. Their main result indicates that as the number of nodes per unit area (n) increases, the throughput capacity decreases approximately as $1/\sqrt{n}$.

Grossglauser and Tse [12] exploit nodal mobility to attain multiuser diversity. Allowing for unbounded delay and using only one-hop relaying, they show that mobility increases the capacity asymptotically (as the number of nodes becomes arbitrary large). In turn, in studying an ad hoc wireless network that consists of a finite number of nodes, Jain *et al.* [13] present methods for computing upper and lower bounds on the capacity of finite ad hoc wireless networks with no power control. Using conflict graphs to model constraints on simultaneous transmissions, they formulate a multicommodity flow problem to calculate the latter bounds. Toumpis and Goldsmith [7] investigate the capacity regions for finite ad hoc wireless networks. A capacity region characterizes the set of achievable rate combinations involving all source–destination pairs in the network. Comments are made as to the impact of some simple power level variations on the capacity region. Note that to achieve the highest throughput capacity, all of the above-mentioned papers assume that a fixed communications resource assignment, such as time division multiple access (TDMA), is employed as a medium access control (MAC) mechanism, as also assumed in this paper.

Consider an ad hoc wireless network with n nodes. Given a selected set of nodal transmit power levels $P = (P_1, \dots, P_n)$ (that we assume can be different from node to node but are fixed in time), the throughput capacity $\lambda(P)$ is achieved (in finite time or asymptotically in time) as the system designer selects an optimal temporal (based on the channel sharing MAC protocol) and spatial (based on the routing mechanism) joint scheduling–routing scheme (or simply, optimal joint scheduling and routing scheme) over the underlying (finite or infinite) time period T . The class of admissible joint scheduling and routing schemes under consideration (for a given power vector) is defined as follows: Every joint scheduling and routing scheme induces, in each time slot, successful transmissions of packets across designated links. In this way, packets are transported across the network (possibly in a multihop fashion) from their sources to their associated destinations: Packets routed across a multihop path are buffered at intermediate nodes when awaiting transmission.

Manuscript received February 3, 2004; revised August 10, 2004; accepted October 8, 2004. The editor coordinating the review of this paper and approving it for publication is W. Liao. This work was supported by the Office of Naval Research (ONR) under Contract N00014-01-C-0016, as part of the Autonomous Intelligent Networked Systems (AINS) project, and by the National Science Foundation (NSF) under Grant ANI-0087148.

The authors are with the Electrical Engineering Department, University of California, Los Angeles, CA 90095-1594 USA (e-mail: abehzad@ee.ucla.edu; rubin@ee.ucla.edu).

Digital Object Identifier 10.1109/TWC.2005.858364

Our aim in this paper is to characterize the key features of a power vector solution that achieves the supreme throughput capacity level λ^* over the set of power vectors $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$, where P_i is the transmit power of the i th node and P_{\max} denotes the maximum allowable transmission power, assuming this power limit to be the same for all nodes. That is,

$$\lambda^* = \text{Sup}_P \{ \lambda(P) : P = (P_1, \dots, P_n), \\ 0 \leq P_i \leq P_{\max}, \quad i = 1, \dots, n \}. \quad (1)$$

We call such a power vector an *optimum power vector*, identify an associated *optimal joint scheduling and routing scheme* as an optimum joint scheduling and routing scheme, and denote the resulting throughput capacity level as the *optimum (or maximum) throughput capacity*. We note that the definition of the network topology (i.e., the connectivity graph layout of the network) for a given nodal transmit power vector is as usual based on a link connecting two nodes if they can directly communicate with each other successfully [under a specified minimum required signal-to-noise ratio (SNR) level] when no other transmissions are invoked in the network. We refer to the topology associated with an optimum power vector as an *optimum topology*.

In this paper, we analyze and investigate the effect of transmission power on the throughput capacity of finite ad hoc wireless networks, considering an interference model that is based on the received signal-to-interference-plus-noise ratio (SINR) levels. We prove that, independent of nodal distribution and traffic pattern, the capacity of an ad hoc wireless network is maximized by properly increasing the nodal transmission power. In particular, we prove that, independent of nodal distribution and traffic pattern, there exists an optimum power vector that at least one of its components is equal to P_{\max} . Under the assumption that P_{\max} can be arbitrarily large, we prove that the fully connected topology (i.e., the topology under which every node can directly communicate with every other node in the network in the absence of interference) is always an optimum topology, independent of nodal distribution and traffic pattern. Our result is valid for any interference model that uses the received SINR as the measure of successful reception.

Under the special case that the transmission power levels of all nodes are assumed to be identical (yet programmable), we prove that the power vector $P = (P_1 = P_{\max}, \dots, P_n = P_{\max})$ always (i.e., independent of nodal distribution and traffic pattern) maximizes the capacity of the ad hoc wireless network. This result is in sharp contrast to the results in [1] and [5], which are based on the *Protocol Interference Model*¹ and are valid for any number of nodes. The latter results state that the upper

¹Based on the Protocol Interference Model, a transmission from node i to node j is successfully received if 1) the distance between node i and node j is less than or equal to a common transmission range r [which is proportional to the common transmission power level $P(r)$] [i.e., $d(i, j) \leq r$] and 2) for every other node k simultaneously transmitting with node i , $d(k, j) \geq (1 + \Delta)r$, where $d(u, v)$ represents the distance between node u and node v , and Δ is a real nonnegative number [5]. In many references, $(1 + \Delta)r$ is referred to as the *interference range*.

bound for the throughput capacity is inversely proportional to the common transmission range r . The authors then conclude that the common nodal transmit power level should be reduced to the lowest value at which the network is connected. We note that the Protocol Interference Model does not generally provide a comprehensive scrutiny of reality for scheduling-based MAC schemes due to the relativity of transmission power and the aggregate effect of interference in wireless networks, among other reasons [6], [8], [10].

As another special case of our analysis, we assume the following: 1) transmission power of all nodes are identical; 2) nodes are randomly and uniformly located; 3) every node is a source of a transmission whose destination is uniformly and independently distributed; and 4) the *Physical Interference Model*² is used as the measure for successful reception of transmissions. Under such a model, our result regarding the optimality of $P = (P_1 = P_{\max}, \dots, P_n = P_{\max})$ stands in sharp contrast with the interpretation of the asymptotic behavior result presented in [5]. The latter result, which is proven to hold for the Protocol Interference Model as well as for the Physical Interference Model, suggests the use of minimal common transmission power that maintains connectivity in the network (P_{\min}), showing it to asymptotically achieve a (per source–destination) throughput level that is in the order of the throughput capacity. This result has been interpreted to indicate that the minimum common transmission power that maintains connectivity in the network maximizes the throughput capacity [1], [5]. We note that, based on the aforementioned four assumptions, the above result regarding the order of throughput under P_{\min} is asymptotically correct. However, when considering an ad hoc wireless networks with a finite number of nodes, one must also examine the magnitude of the constant factors used in the asymptotic analysis. Specifically, our numerical results clearly illustrate that the throughput capacity under P_{\min} does not achieve the maximum throughput capacity (over the set of all nodal power vectors) for finite ad hoc wireless networks.

We also derive a linear programming (LP) formulation for obtaining the exact solution to the optimization problem that yields the throughput capacity of finite ad hoc wireless networks given a nodal transmit power vector. We use this LP formulation to compare our results versus previous results that appeared in the literature by solving about 2000 LP problems (corresponding to distinct randomly and uniformly generated networks) using the ILOG CPLEX 7.0 software. Our LP-based performance evaluation results confirm the distinct capacity improvement that can be attained under our recommended approach, as well as identify the magnitude of capacity upgrade that can be realized for networks with random and uniform topologies and traffic patterns.

The rest of this paper is organized as follows. In Section II, the system model is presented. Mathematical analysis and numerical results are discussed in Sections III and IV, respectively. Conclusions are presented in Section V.

²Based on the Physical Interference Model, a transmission is successful if the observed SINR at the intended receiver is not less than a threshold [5]. The Physical Interference Model is explained in detail in Section II.

II. SYSTEM MODEL

We consider an ad hoc wireless network that consists of n nodes, which are located based upon any arbitrary distribution in a given area. During the period of operation under consideration in this paper (T), we assume network nodes to be immobile. Every node, when scheduled to access the communications channel, transmits at a fixed data rate of W bits per second, and variations in transmission power merely affect the transmission range. Every transmission is intended for a single receiver. All nodes are equipped with identical half-duplex radios (in that they are limited by the same maximum power level) and with omnidirectional antennas. A node can receive from at most one other node in the same time instant. We assume node i to transmit at a fixed (yet programmable) transmission power P_i , $0 \leq P_i \leq P_{\max}$, $i = 1, 2, \dots, n$; assume a transmission to occupy the entire bandwidth of the system under consideration. Channel time is slotted into identical synchronized time slots. Slot duration τ is assumed to be equal to the transmission time of a packet plus some overhead duration that includes the maximum propagation delay. Nodes are continuously active so that source nodes have infinite reservoirs of packets to send to their destinations. Without loss of generality and for the sake of presentation simplicity, we assume every source node to be associated with a single destination. The source–destination association can be selected based on an arbitrary traffic pattern. Consequently, some nodes may not necessarily function as source or destination nodes.

There is a communication link from node i to node j if node i can directly communicate with node j under power level P_i in the absence of interference. Let us represent a direct transmission from node i to node j (where there is a communication link from node i to node j) whose source is node s by $i \xrightarrow{s} j$. A transmission scenario $S_{(M)} = \{i_1 \xrightarrow{s_1} j_1, \dots, i_M \xrightarrow{s_M} j_M\}$ is defined as a candidate set of direct transmissions that are considered to all take place at the same time slot, where all transmitting and receiving nodes are distinct. For such a transmission scenario $S_{(M)}$ under nodal transmit power vector $P_{(M)} = (P_{i_1}, \dots, P_{i_M})$, $0 \leq P_{i_k} \leq P_{\max}$, $k = 1, 2, \dots, M$, we say that the transmission from i_k is *successful* if the received SINR at the intended receiver j_k is not less than the minimum required threshold γ [2], i.e.,

$$\frac{G_{i_k j_k} P_{i_k}}{\left(N_{j_k} + \sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} P_{i_r} \right)} \geq \gamma, \quad k = 1, 2, \dots, M \quad (2)$$

in which G_{ij} is the propagation gain (incorporating the effects of link loss phenomena such as fading and shadowing) for direct transmission from node i to node j (where G_{ij} is assumed to be independent of power levels) and N_{j_k} ($N_{j_k} > 0$) is the thermal noise power at receiver j_k . We refer to such a generic model for successful reception of a packet as the *SINR-Based Interference Model*.

Consider the following special case of the general interference model used in this paper. Let α and $d(i, j)$ denote the path loss exponent (when it is identical for all links in

the network) and the distance between node i and node j , respectively. Let $N_{j_k} = N$ denote the noise power (assumed for this special case to be identical for all nodes in the network) and $G_{ij} = 1/d^{\alpha}(i, j)$, $i, j = 1, \dots, n, i \neq j$. Then, the SINR-Based Interference Model reduces to the special distance-based scheme used in [5], known as the Physical Interference Model.

Based on the definition of transmission scenario, for an ad hoc wireless network with n half-duplex nodes, there can be at most

$$N_S = \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} \binom{n}{2i} \binom{2i}{i} (i!)(n-1)^i \quad (3)$$

distinct transmission scenarios, noting that the maximum number of simultaneous transmissions in a time slot is equal to $\lfloor n/2 \rfloor$ [7] and the maximum number of transmitter–receiver pairs is given by $\binom{n}{2i} \binom{2i}{i} (i!)$ when there are i simultaneous transmissions, $i = 1, \dots, \lfloor n/2 \rfloor$.

We define the cardinality of the set of successful transmissions in a transmission scenario $S_{(M)} = \{i_1 \xrightarrow{s_1} j_1, \dots, i_M \xrightarrow{s_M} j_M\}$ employing power vector $P_{(M)} = (P_{i_1}, \dots, P_{i_M})$, $0 \leq P_{i_k} \leq P_{\max}$, $k = 1, 2, \dots, M$, as the *spatial reuse factor of the transmission scenario* $S_{(M)}$ with respect to $P_{(M)}$. We define a transmission scenario $S_{(M)}$ to be *feasible* under power vector $P_{(M)}$ [or, equivalently, under power vector $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$] if all its transmissions are successful. Consequently, the spatial reuse factor of a feasible transmission scenario $S_{(M)}$ under power vector $P_{(M)}$ is equal to M . Clearly, every admissible joint scheduling and routing scheme under power vector $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$, over the underlying (finite or infinite) time period can be represented by a sequence of feasible transmission scenarios under power vector P allocated to (finite or infinite) consecutive time slots. We refer to such a sequence as a *scenario sequence* with respect to power vector P . The i th scenario sequence with respect to power vector P and the associated (per source–destination) throughput are denoted as $\text{SQ}_i(P)$ and $\lambda_{\text{SQ}_i(P)}$, respectively. Furthermore, the set of all possible distinct scenario sequences, each operating under the same power vector P , is denoted as $X(P)$. Then, based on the definition of the scenario sequence, we can express the throughput capacity under power vector P also as

$$\lambda(P) = \sup_i \{ \lambda_{\text{SQ}_i(P)} : \text{SQ}_i(P) \in X(P) \}. \quad (4)$$

III. MATHEMATICAL ANALYSIS

A. Some Theoretical Results

Definition: Relative Maximality: Let $P_{(M)} = (P_{i_1}, \dots, P_{i_M})$ be an arbitrary power vector, whereby $0 < P_{i_k} \leq P_{\max}$, $k = 1, \dots, M$. Power vector $P'_{(M)} = (P'_{i_1}, \dots, P'_{i_M})$ is said to be *relatively maximized* with respect to power vector $P_{(M)}$ if

$$P'_{(M)} = \alpha (P_{(M)}) P_{(M)} \quad (5)$$

where $\alpha(P_{(M)})$ is a real positive scalar defined as

$$\alpha(P_{(M)}) = \min_{k=1, \dots, M} \left\{ \frac{P_{\max}}{P_{i_k}} \right\}. \quad (6)$$

Furthermore, a power vector is said to be *relatively maximum* if at least one of its components is equal to P_{\max} .

Lemma 1: Let $S_{(M)} = \{i_1 \xrightarrow{s_1} j_1, \dots, i_M \xrightarrow{s_M} j_M\}$ be an arbitrary transmission scenario under power vector $P_{(M)} = (\beta P_{i_1}, \dots, \beta P_{i_M})$, $0 < \beta P_{i_k} \leq P_{\max}$, $k = 1, \dots, M$, where β is a real positive number. The spatial reuse factor of transmission scenario $S_{(M)}$ with respect to this power vector $P_{(M)}$ is a monotonically nondecreasing function of β in interval $(0, \alpha(\beta^{-1} P_{(M)})]$, independent of nodal distribution and traffic pattern.

Proof: Let us consider an arbitrary transmission $i_k \xrightarrow{s_k} j_k$, $k = 1, \dots, M$ in $S_{(M)}$. Based on relation (2), transmission $i_k \xrightarrow{s_k} j_k$ is successfully received at node j_k if

$$\frac{G_{i_k j_k} \beta P_{i_k}}{\left(N_{j_k} + \sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} \beta P_{i_r} \right)} \geq \gamma. \quad (7)$$

The derivative of the left-hand side of (7) with respect to β can be calculated as

$$\frac{\partial}{\partial \beta} \left(\frac{G_{i_k j_k} \beta P_{i_k}}{\left(N_{j_k} + \sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} \beta P_{i_r} \right)} \right) = \frac{G_{i_k j_k} P_{i_k} N_{j_k}}{\left(N_{j_k} + \sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} \beta P_{i_r} \right)^2} \quad (8)$$

and is noted to be always nonnegative. Therefore, by increasing the value of β , the SINR at j_k remains constant or increases. In fact, in the limit as $\beta \rightarrow \infty$, the SINR at j_k converges to a constant, i.e.,

$$\lim_{\beta \rightarrow \infty} \left(\frac{G_{i_k j_k} \beta P_{i_k}}{\left(N_{j_k} + \sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} \beta P_{i_r} \right)} \right) = \frac{G_{i_k j_k} P_{i_k}}{\left(\sum_{\substack{r=1 \\ r \neq k}}^M G_{i_r j_k} P_{i_r} \right)}. \quad (9)$$

Similarly, the SINR at all other intended receivers increase as β increases. Therefore, the spatial reuse factor of transmission scenario $S_{(M)}$ under $P_{(M)}$ is a monotonically nondecreasing function of β , $\beta \in (0, \alpha(\beta^{-1} P_{(M)})]$. ■

We note that the result described by Lemma 1 contrasts similar results that have been derived by assuming the Protocol Interference Model, in which the “interference range” $(1 + \Delta)r$ of every transmission increases with the increase in nodal transmit power. Specifically, based on the Protocol Interference Model, the spatial reuse factor of any transmission scenario

$S_{(M)}$ (with more than one transmission) under $P_{(M)}$ converges to zero as β becomes sufficiently large.

Theorem 2: If $P' = (P'_1, \dots, P'_n)$ is relatively maximized with respect to $P = (P_1, \dots, P_n)$, then $\lambda(P) \leq \lambda(P')$, independent of nodal distribution and traffic pattern.

Proof: Let P' be relatively maximized with respect to P . Based on Lemma 1, every feasible transmission scenario $S_{(M)} = \{i_1 \xrightarrow{s_1} j_1, \dots, i_M \xrightarrow{s_M} j_M\}$ under power vector $P_{(M)} = (P_{i_1}, \dots, P_{i_M})$ is also a feasible transmission scenario under $P'_{(M)} = (P'_{i_1}, \dots, P'_{i_M})$. Therefore, based on the definition of scenario sequence, every scenario sequence under P is also a scenario sequence under P' .

Now, let N_{i, p_i} represent the set of all nodes j in which there is a communication link from node i to node j under power level P_i , $i = 1, \dots, n$. Since $P'_i \geq P_i$, node i may be able to directly communicate with some additional nodes under P'_i , i.e., $N_{i, p_i} \subseteq N_{i, p'_i}$, $i = 1, \dots, n$. As a result, under power vector P' , additional routes may be explored, which translate into supplementary scenario sequences. Therefore, $X(P) \subseteq X(P')$.

Assume that the i th scenario sequence with respect to a power vector P is the same as the j th scenario sequence with respect to a power vector P' , i.e., $\text{SQ}_i(P) \equiv \text{SQ}_j(P')$. Since every scenario sequence with respect to a power vector P consists of a sequence of transmission scenarios that are feasible under the power vector P , all of the transmissions involved in each of the transmission scenarios in $\text{SQ}_i(P)$ are successful. Similarly, all of the transmissions involved in each of the transmission scenarios in $\text{SQ}_j(P')$ are successful. Therefore, based on the fact that $\text{SQ}_i(P) \equiv \text{SQ}_j(P')$, we have $\lambda_{\text{SQ}_i(P)} = \lambda_{\text{SQ}_j(P')}$. Consequently, since $X(P) \subseteq X(P')$ and based on (4), we conclude that $\lambda(P) \leq \lambda(P')$, independent of nodal distribution and traffic pattern. ■

Lemma 3: An optimum power vector always exists.

Please see Appendix A for the proof.

Theorem 4: Independent of nodal distribution and traffic pattern, there exists a relatively maximum power vector that maximizes the throughput capacity of an ad hoc wireless network.

Proof: Let us assume that there is no optimum relatively maximum power vector. Then, based on Lemma 3, there exists an optimum power vector P^* that is not relatively maximum. Let λ^* and P' denote the optimum throughput capacity of the underlying network and the relatively maximized power vector with respect to P^* , respectively. However, based on Theorem 2, $\lambda^* \leq \lambda(P')$, which contradicts the suboptimality of every relatively maximum power vector and completes the proof. ■

In general, an optimum power vector is a function of nodal distribution and traffic pattern. However, based on Theorem 4, there always exists an optimum power vector that is relatively maximum. Intuitively, this is due to the fact that relative maximality provides a higher *combinatorial diversity* (i.e., higher degree of freedom in terms of the optimization of the joint scheduling and routing scheme). In fact, as we illustrate in our numerical analysis (Section IV), the latter property leads to considerable increase in the capacity of ad hoc networks. The following conclusions follow directly from the latter theorem.

Corollary 4.1: Independent of the underlying nodal distribution and traffic pattern, there exists a power vector that maximizes the capacity of an ad hoc wireless network for which at least one of the components is equal to P_{\max} .

Corollary 4.2: Under the special case that the maximum transmission power is sufficiently high, the fully connected topology is an optimum topology of an ad hoc wireless network, independent of nodal distribution and traffic pattern.

Corollary 4.3: Under the special case that the transmission power of all nodes is assumed to be identical, the power vector $P = (P_1 = P_{\max}, \dots, P_n = P_{\max})$ maximizes the capacity of an ad hoc wireless network, independent of nodal distribution and traffic pattern.

B. LP Formulation

We provide in this section an LP formulation for analysis of the throughput capacity of ad hoc wireless networks over the operational period T that can represent an unlimited duration, for an infinite horizon operation, or it can denote a finite sufficiently long operational period. We assume the nodes to operate under a given nodal transmit power vector.

For a given ad hoc wireless network and nodal transmit power vector P , we define $s_{ij}^{(k)}$, $k = 1, \dots, N'_S$, $i = 1, \dots, n$, $j = 1, \dots, n$, as in (10), shown at the bottom of the page, where N'_S denotes the total number of feasible transmission scenarios for the underlying ad hoc wireless network under power vector P .³ Let $\bar{a} = (a_1, \dots, a_{N'_S})$, where a_k , $k = 1, \dots, N'_S$, represent the fraction of time over an arbitrary finite positive period T' allocated to the k th feasible transmission scenario $\sum_{k=1}^{N'_S} a_k = 1$, $a_k \geq 0$. Assuming $A = \{(a_1, \dots, a_{N'_S}) : \sum_{k=1}^{N'_S} a_k = 1, a_k \geq 0\}$ and $\{(i_1, j_1), \dots, (i_\Phi, j_\Phi)\}$ represent the set of all given source–destination pairs, we first define the nonlinear optimization problem given as

$$\text{Max}_{\bar{a} \in A} \text{Min}_{l \in \{1, \dots, \Phi\}} \left(\sum_{k=1}^{N'_S} s_{i_l j_l}^{(k)} a_k \right) \quad (11)$$

$$\text{s.t.} \quad \sum_{k=1}^{N'_S} s_{ij}^{(k)} a_k \geq 0, \quad i = 1, \dots, n, \quad j = 1, \dots, n \quad (12)$$

$$\sum_{k=1}^{N'_S} a_k = 1 \quad (13)$$

$$a_k = 0, \quad k \in K \quad (14)$$

$$a_k \geq 0, \quad k = 1, \dots, N'_S \quad (15)$$

³Note that we keep all the feasible transmission scenarios in the same order, over all time slots.

where $K = \{k : s_{i_l j_l}^{(k)} = -1 \text{ for at least one } l, l = 1, \dots, \Phi, k = 1, \dots, N'_S\}$ and a_k 's are the only decision variables. Constraint (12) describes the flow conservation requirement at every node (i.e., the amount of outgoing flow cannot be larger than the amount of incoming flow), and constraint (14) prohibits a packet after its arrival at destination from further retransmission.

We next show that the optimal value attained by the objective function of the above nonlinear optimization problem represents an upper bound on the throughput capacity of the network (under the given transmit power vector) over the period T' . But first, we introduce the following two requirements (i.e., the *realizability requirements*) that are not incorporated into the definition of the optimization problem.

- 1) *Integrity requirement:* In the definition of the optimization problem, we allow the decision variables (a_k 's) to be arbitrary real values between zero and one. As a result, $a_k T'$ is not necessarily equal to the duration of an integral number of time slots, $k = 1, \dots, N'_S$. Therefore, a feasible solution of the optimization problem is not necessarily realizable over the period T' . We refer to the requirement that confines a_k 's to the values for which $a_k T'$ is equal to the duration of an integral number of time slots as the *integrality requirement*, $k = 1, \dots, N'_S$.
- 2) *Causality requirement:* Assuming that a feasible solution of the optimization problem satisfies the integrality requirement, yet, such a solution does not determine the order of the resulting transmission scenarios to be performed over time slots. In fact, every sequencing of the resulting transmission scenarios (associated with the feasible solution of the optimization problem) might yield a noncausal routing (i.e., an intermediary node relays a packet from another node before that packet actually arrives) over the period T' . Hence, a feasible solution of the optimization problem is not necessarily realizable over the period T' . We refer to the requirement limiting a_k 's to values that are associated with at least one causal routing scheme over the period T' as the *causality requirement*.

For every feasible solution of the above nonlinear optimization problem [i.e., $(a_1, \dots, a_{N'_S})$] that also satisfies the realizability requirements, $\sum_{k=1}^{N'_S} s_{ij}^{(k)} a_k$ represents the achievable data rate (in packets per slot) associated with the source–destination pair (i_l, j_l) , averaged over period T' . Therefore, if all of the feasible solutions of the optimization problem had satisfied the realizability requirements, the optimum value of the objective function would have represented the throughput capacity of the network over the period T' . However, a feasible solution of the optimization problem does not

$$s_{ij}^{(k)} = \begin{cases} 1, & \text{if in the } k\text{th feasible transmission scenario under } P, \\ & j \text{ is the receiver of a packet whose (original) source is } i, \quad i \neq j \\ -1, & \text{if in the } k\text{th feasible transmission scenario under } P, \\ & j \text{ is the transmitter of a packet whose (original) source is } i, \quad i \neq j \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

necessarily satisfy the integrality and causality requirements over the period T' . Therefore, only a subset of the feasible space of the optimization problem [i.e., the values of $\bar{a} = (a_1, \dots, a_{N'_S})$ that concurrently satisfy all the constraints of the optimization problem] simultaneously satisfies the integrality and causality requirements. Let S represent the above subset of the feasible space. Since S is a subset of the feasible space of the optimization problem, then the maximum value of the objective function over the set S (which is equal to the throughput capacity over the period T') cannot be larger than the optimum value of the objective function (over the original feasible space). Consequently, we conclude that the optimal value attained by the objective function by solving the above-mentioned optimization problem, $\text{Max}_{\bar{a} \in A} \text{Min}_{l \in \{1, \dots, \Phi\}} (\sum_{k=1}^{N'_S} s_{i_l j_l}^{(k)} a_k)$, represents an upper bound on the throughput capacity of the network (under a given transmit power vector) over the period T' .

By defining a single nonnegative dummy variable λ and substituting relation (11) with

$$\text{Max}_{\bar{a} \in A} \lambda \quad (16)$$

$$\text{s.t.} \quad \sum_{k=1}^{N'_S} s_{i_l j_l}^{(k)} a_k - \lambda \geq 0, \quad l = 1, \dots, \Phi \quad (17)$$

it can be clearly seen that the nonlinear optimization problem is transformed into an equivalent LP problem. It is apparent that the optimal value of the objective function of the optimization problem as defined by (12)–(17) (and not the throughput capacity over the period T' itself) is independent of the length of the period T' since the decision variables (a_k 's) are allowed to assume arbitrary real values between zero and one. Therefore, the optimal value of the objective function of this optimization problem is also an upper bound on the throughput capacity of the underlying network over the operational period T . While in solving the optimization problem we ignore the realizability requirements, we prove in Appendix B (Lemma 5, Lemma 6, and Theorem 7) that the optimal value of the objective function (which is an upper bound of the throughput capacity over any operational period) is indeed equal to the throughput capacity of the network over a sufficiently long operational period T .

From the computation point of view, when a large number of nodes/flows are involved, we note that the computational limitation of calculating the throughput capacity of ad hoc wireless networks based on the LP formulation is in the verification of the feasibility of all transmission scenarios, the number of which grows factorially fast as the number of nodes increases.

IV. NUMERICAL ANALYSIS

In this section, we use the LP optimization model to evaluate our theoretical results derived in the previous section. Let P_{\min} denote the minimal common transmission power that maintains connectivity in the underlying network [1], [5]. The Physical Interference Model [5] is used as the measure for successful reception of transmissions, and every node is assumed to be the source node of a transmission. In particular, the path loss exponent is set to be 4, the noise power is -90 dBm,

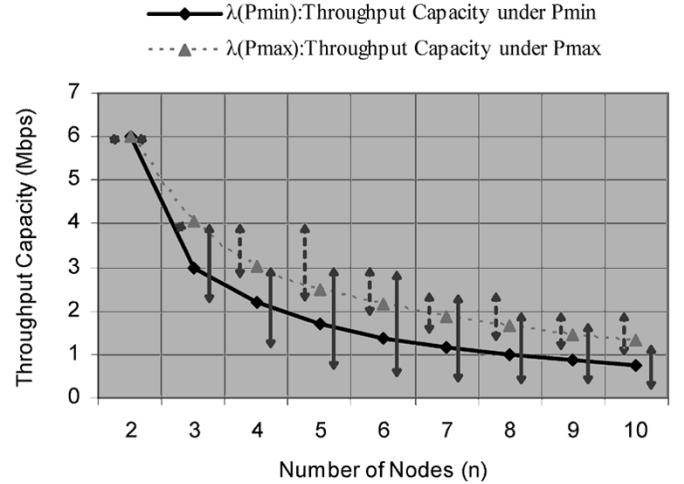


Fig. 1. Illustration of the throughput capacity under low and high transmit power levels.

and the minimum required SINR is 10 dB. All transmissions are performed at $W = 12$ Mb/s and the minimum required SNR is 13 dB. P_{\max} is set to be $5W$ in order to maintain the fully connected topology, independent of the distribution of nodes, while P_{\min} is selected based on the underlying nodal distribution. For each n , $2 < n \leq 10$, we randomly and uniformly generated 100 layout realizations for nodes in a 500×500 m square. For each realization, the destination of each source node was uniformly and independently selected. The throughput capacity for each layout was then calculated by solving the LP optimization model using the ILOG CPLEX 7.0 software for two cases, namely: 1) the transmit power of all nodes was equal to P_{\min} ; and 2) the transmit power of all nodes was equal to P_{\max} . Interestingly, for all 100 instances of each n , $n > 5$, the capacity under P_{\max} was strictly greater than that under P_{\min} . The average capacity for each n was then calculated over the 100 topologies under P_{\min} [$\lambda(P_{\min})$] and under P_{\max} [$\lambda(P_{\max})$].

In Fig. 1, we depict the average throughput capacity (recalling it to be defined as the *guaranteed* data rate per source–destination pair) of an ad hoc wireless network under P_{\min} and P_{\max} as a function of the number of nodes. We observe the monotonic decrease in the throughput capacity under both P_{\min} and P_{\max} , which is consistent with the results in [5] regarding the reduction in capacity with the increase in the number of nodes (under the aforementioned assumptions). As illustrated in Fig. 1, the capacity under P_{\max} is markedly greater than that under P_{\min} . We also illustrate the domain (i.e., the range of values attained) of the throughput capacity for each n , $n = 2, \dots, 10$, over the 100 random instances, under P_{\min} and under P_{\max} with solid arrows and long dashed arrows, respectively. Note that for $n = 2$ under P_{\min} as well as P_{\max} , and for $n = 3$ under P_{\max} , all realizations yield the same throughput capacity level.

In Fig. 2, we show the percentage increase in capacity under P_{\max} with respect to that under P_{\min} , as a function of the number of nodes. Clearly, our numerical results show that $\lambda(P_{\max})/\lambda(P_{\min})$ {or equivalently $[\lambda(P_{\max})/\lambda(P_{\min})] - 1$ } is a monotonically increasing function of n for $n = 2, \dots, 10$.

TABLE I
COMPARISON BETWEEN (MAXIMUM) NUMBER OF TRANSMISSION SCENARIOS (N_S) AND THE AVERAGE NUMBER OF FEASIBLE TRANSMISSION SCENARIOS UNDER P_{\max} [$N'_S(P_{\max})$] AND UNDER P_{\min} [$N'_S(P_{\min})$]

n (Number of nodes)	2	3	4	5	6	7	8	9	10
N_S	2	12	144	1040	19650	196,812	5,227,712	67,189,824	2,300,229,090
$N'_S(P_{\max})$	2	12	30.16	92.97	290.82	1170.46	12,375.54	112,588.90	504,668.96
$N'_S(P_{\min})$	2	6	17.79	58.83	194.65	934.03	7453.29	100,541.71	480,041.33
$N'_S(P_{\max}) - N'_S(P_{\min})$	0	6	12.37	34.14	96.17	236.43	4922.25	12,047.19	24,627.63

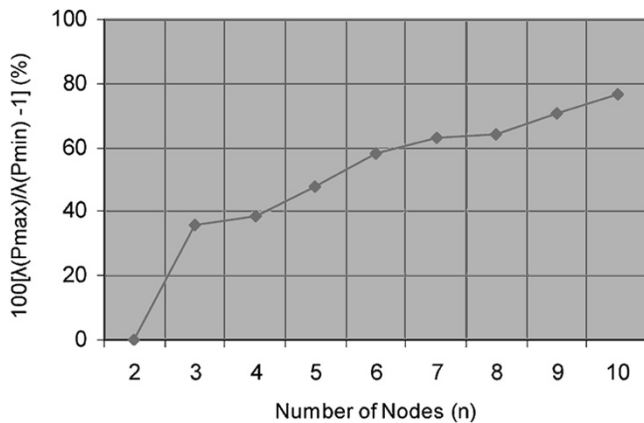


Fig. 2. Capacity gain under high transmission power.

For an ad hoc wireless network with ten nodes (averaging over the 100 randomly generated networks), a 78% capacity gain is observed under high transmission power.

In Table I, we analyze the reasons behind the significant difference between $\lambda(P_{\min})$ and $\lambda(P_{\max})$. Based on Theorems 2 and 4, this difference is rooted in the higher number of feasible transmission scenarios achievable under P_{\max} . In this table, we compare the (maximum) number of transmission scenarios (N_S) and the average number of feasible transmission scenarios (averaging over 100 layouts) under P_{\min} [$N'_S(P_{\min})$] and under P_{\max} [$N'_S(P_{\max})$] as a function of the number of nodes. In particular, we note the major increase in difference between $N'_S(P_{\min})$ and $N'_S(P_{\max})$ as the number of nodes increases. This is to a large extent due to the fact that as the number of nodes increases, P_{\min} decreases (by definition), while P_{\max} remains constant. The increase in the difference between $N'_S(P_{\min})$ and $N'_S(P_{\max})$ as a function of n results in higher capacity gain under P_{\max} as n grows from 2 to 10, which explains the result depicted in Fig. 2. In particular, we note that for an ad hoc wireless network with ten nodes, there are (on average) more than 24 000 additional feasible transmission scenarios under the high transmission power level, which, in turn, leads to astronomically higher number of supplementary scenario sequences.

In the following, we consider one of the randomly generated nodal layouts and its associated random traffic pattern used in the numerical results presented above. In Table II, we illustrate the underlying traffic pattern and nodal coordinates

TABLE II
RANDOMLY GENERATED TRAFFIC PATTERN AND NODAL LAYOUT FOR AN AD HOC WIRELESS NETWORK

NODE	DESTINATION	X (m)	Y (m)
1	9	151	498
2	6	144	191
3	9	14	407
4	3	97	151
5	4	331	258
6	10	119	54
7	10	485	295
8	1	273	166
9	4	191	451
10	9	362	353

(X, Y). The parameter values are identical to those used in the numerical analysis discussed above. In Fig. 3(a) and (b), we present the topology under P_{\min} and the topology under P_{\max} , respectively. For this particular nodal distribution realization, P_{\min} is equal to 31 mW, for which the throughput capacity is equal to 1/17 packets per slot, or equivalently, 0.706 Mb/s. In turn, the throughput capacity under P_{\max} is equal to 5/38 packets per slot, or equivalently, 1.579 Mb/s. This throughput capacity level is more than twice the throughput capacity value attained under P_{\min} .

In Fig. 4, we illustrate the throughput capacity of the above realization as a function of common transmission power level as well as a function of total transmission power level, in which the latter is defined as the total number of nodes (ten) times the underlying common transmission power level. Interestingly, we observe an exponential increase in the throughput capacity as common power increases from P_{\min} to 200 mW, with the corresponding throughput capacity increased from 0.706 to 1.5 Mb/s. Increasing common transmission power from 200 to 300 mW does not affect the throughput capacity, while increasing the common power from 300 to 400 mW slightly improves the throughput capacity (i.e., the throughput capacity is increased from 1.5 to 1.55 Mb/s). Furthermore, increasing the common power from 400 to 1100 mW does not affect the throughput capacity, while increasing the common power level from 1100 to 1200 mW upgrades the throughput capacity slightly from 1.55 to 1.58 Mb/s. The latter minor improvement is due to the fact that under 1200 mW, the transmission scenario $\{4 \xrightarrow{4} 3, 7 \xrightarrow{7} 10\}$ becomes feasible, whereby it is not a feasible transmission scenario under 1100 mW. We observe that further increase in common transmit power level does not change the value of the throughput capacity for this

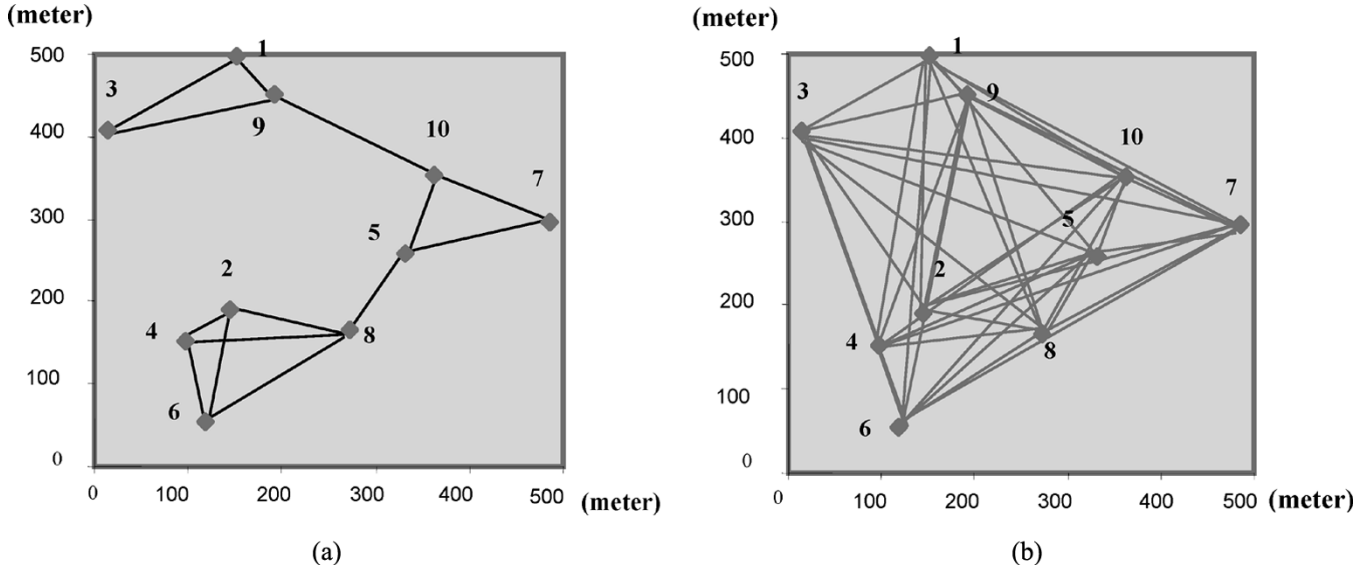


Fig. 3. (a) Illustration of the topology under P_{\min} . (b) Illustration of the topology under P_{\max} .

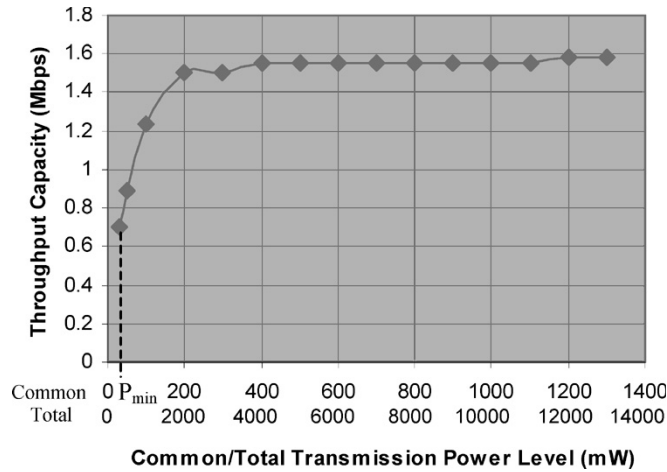


Fig. 4. Throughput capacity as a function of common/total transmission power level.

particular topological and traffic pattern realization. Clearly, as the operational area becomes larger, the smallest common power value that yields the highest (saturated) throughput capacity level tends to assume higher values.

V. CONCLUSION

In this paper, we analyze and investigate the effect of transmission power on the throughput capacity of finite ad hoc wireless networks, considering a scheduling-based MAC protocol such as TDMA and an interference model that is based on the received SINR levels. We prove that, independent of nodal distribution and traffic pattern, the throughput capacity of an ad hoc wireless network is maximized by properly increasing the nodal transmit power level. This is mainly due to the fact that high transmission power provides a higher combinatorial diversity (i.e., higher degree of freedom in terms of the optimization of the joint scheduling and routing scheme).

We note that our selection of the optimal power vector to have the relative maximality feature also provides a high level of robustness under dynamic topologies induced by mobility. Further, we did not include energy consumption as an objective for the networks under consideration in this paper. The analysis of the tradeoffs among capacity, energy consumption, and robustness under the high transmission power is part of our ongoing research. Moreover, the implications of the relative maximality feature on delay and network lifetime under various centralized/distributed MAC schemes are interesting directions for future research.

APPENDIX A

Proof of Lemma 3: Let Ω_k represent the set of all power vectors $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$, which results in the same throughput capacity $\lambda^{(k)}$ over the underlying finite or infinite period. Since every scenario sequence under power vector P is composed of a sequence of feasible transmission scenarios under power vector P , then $X(\hat{P}) = X(\tilde{P})$ if the set of feasible transmission scenarios under $\hat{P} = (\hat{P}_1, \dots, \hat{P}_n)$ and the set of feasible transmission scenarios under $\tilde{P} = (\tilde{P}_1, \dots, \tilde{P}_n)$ are identical. Therefore, based on (4), the use of two power vectors \hat{P} and \tilde{P} results in the same throughput capacities if their associated sets of feasible transmission scenarios are identical. On the other hand, based on (3), the total number of transmission scenarios, and hence, the total number of feasible transmission scenarios, is always less than or equal to N_S . Therefore, the total number of distinct sets of feasible transmission scenarios is bounded from above by $\sum_{i=0}^{N_S} \binom{N_S}{i}$, which is equal to 2^{N_S} . Hence, the total number of distinct Ω_k 's is always finite and bounded by 2^{N_S} . That is, the set of all power vectors $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$ can be partitioned into a finite number of (equicapacity) sets Ω_k , which results in the same throughput capacity $\lambda^{(k)}$. As a result, exactly one of the sets (Ω^*) achieves the supreme throughput capacity level over the

underlying finite or infinite period. Consequently, any power vector in Ω^* is an optimum power vector. ■

APPENDIX B

In the following lemma, we prove that there always exist a finite time period $T' = T'_{\text{rep}}$ for which an optimal solution of the optimization problem satisfies the integrality requirement.

Lemma 5: There always exist a finite positive time period $T' = T'_{\text{rep}}$ and an optimal solution of the LP formulation, $\bar{a}^* = (a_1^*, a_2^*, \dots, a_{N'_S}^*)$, such that

$$a_k^* T'_{\text{rep}} = c_k \tau, \quad k = 1, \dots, N'_S \quad (18)$$

where τ is the duration of a time slot and c_k is a nonnegative integer.

Proof: Let $\bar{a}^* = (a_1^*, a_2^*, \dots, a_{N'_S}^*)$ denote an optimal solution of the LP formulation. Since the input–output coefficients and the right-hand side constants of the LP are rational numbers, a_k^* 's are also rational numbers.⁴ Therefore, a_k^* 's can be represented in their rational format $a_k^* = a_{k,N}^*/a_{k,D}^*$ such that $a_{k,N}^*$ and $a_{k,D}^*$ are relatively prime, $k = 1, \dots, N'_S$. Then, $\text{LCM}\{a_{k,D}^*, k = 1, \dots, N'_S\}\tau$ is the smallest value of T'_{rep} that satisfies (18), where $\text{LCM}\{\cdot\}$ is the least common multiplier function. ■

Assume that time slots in T'_{rep} associated with \bar{a}^* are labeled as $1, 2, \dots, \sum_{k=1}^{N'_S} c_k$, where c_k 's are identical to those in (18) and $\sum_{k=1}^{N'_S} c_k = T'_{\text{rep}}/\tau$ is equal to the number of time slots within the T'_{rep} period. Clearly, there are $(\sum_{k=1}^{N'_S} c_k)! / (c_1! c_2! \dots c_{N'_S}!)$ number of distinct ways to allocate the time slots of period T'_{rep} to the feasible transmission scenarios such that c_k slots are assigned to the k th feasible transmission scenario, $k = 1, \dots, N'_S$. We refer to each of the latter distinct allocations as an implementation of the optimal solution \bar{a}^* over the time period T'_{rep} . Suppose $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$ denotes the maximum number of slots that are allocated to a single transmission ($i \xrightarrow{s} j$) under an implementation of \bar{a}^* over T'_{rep} . Further, assume that $l_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$ represents the maximum route length (in hops) among all the source–destination routes associated with an implementation of \bar{a}^* over T'_{rep} . Clearly, the values of $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$ and $l_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$ are independent of the underlying implementation of the optimal solution \bar{a}^* over the time period T'_{rep} .

Lemma 6: For every finite positive time period (T'_{rep}) and optimal solution of the LP formulation [$\bar{a}^* = (a_1^*, a_2^*, \dots, a_{N'_S}^*)$] that satisfy (18), there always exist a finite ini-

tialization period T'_{trans} of duration $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})[l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1]T'_{\text{rep}}$ for backlogging packets at intermediate nodes such that every implementation of \bar{a}^* over the period T'_{rep} yields a causal routing.

Proof: Suppose the time period T'_{rep} and the optimal solution \bar{a}^* satisfy (18). Now, consider a finite initialization period T'_{trans} that consists of $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1)$ periods of T'_{rep} duration, denoted here by $T'_{\text{trans}}(1), \dots, T'_{\text{trans}}(n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1))$. The allocation of transmission scenarios to each period $T'_{\text{trans}}(m)$, $m = 1, \dots, l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1$, is formed in two consecutive steps, namely: 1) an arbitrary implementation of \bar{a}^* over $T'_{\text{trans}}(m)$; and 2) subsequent removal of transmissions $i \xrightarrow{s} j$ that correspond to the h th hop of the associated source–destination paths, $h = m + 1, m + 2, \dots$ [for instance, in $T'_{\text{trans}}(1)$, only transmissions take place that are transmitted from the source of the packet]. In this manner, at the end of period $T'_{\text{trans}}(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1)$, every intermediate node from a source to a destination has one packet associated with the underlying source–destination pair. The allocation of transmission scenarios to the remaining periods [i.e., $T'_{\text{trans}}(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}})), \dots, T'_{\text{trans}}(n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1))$] are formed by $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1$ cyclic repetition of the allocation over the first $(l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) - 1)$ periods within the T'_{trans} as discussed above. Therefore, at the end of the initialization period T'_{trans} , every intermediate node from a source to a destination has $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$ packet associated with the associated source–destination pair. Consequently, based on the definition of $n_{\text{max}}(\bar{a}^*, T'_{\text{rep}})$, every implementation of \bar{a}^* over the first period T'_{rep} after the initialization period yields a causal routing. ■

As a special case, when every packet is directly routed from its source to its associated destination [i.e., $l_{\text{max}}(\bar{a}^*, T'_{\text{rep}}) = 1$], the duration of initialization period T'_{trans} becomes equal to zero.

Theorem 7: The optimal objective function value of the LP is equal to the throughput capacity of the network under the given nodal power vector for sufficiently long operational period T .

Proof: The proof is based on construction, which demonstrates that an optimal solution of the optimization problem can be realized (i.e., it satisfies the realizability requirements) over sufficiently long operational period T . Consider a finite time period T'_{rep} and an optimal solution $\bar{a}^* = (a_1^*, a_2^*, \dots, a_{N'_S}^*)$ of the optimization problem, which satisfy (18) (note that Lemma 5 guarantees the existence of such a time period and optimal solution). Now, consider the implementation of \bar{a}^* over the initialization period T'_{trans} as described in Lemma 6. Following the T'_{trans} period, consider an arbitrary implementation of \bar{a}^* over period T'_{rep} . Subsequent feasible transmission scenarios are formed as cyclic repetitions of the first period T'_{rep} after T'_{trans} . Since the implementation of \bar{a}^* over the first period of T'_{rep} after T'_{trans} yields a causal routing (Lemma 6), due to the flow conservation constraint, the subsequent periods of T'_{rep} will also yield a causal routing. Further, due to the finite duration of the initialization period, using a sufficiently large number of repetitions of the above arbitrary implementation over T'_{rep} reaches within an arbitrary deviation $\varepsilon \geq 0$ from the optimal value of the objective function

⁴We note that an optimal solution of an LP problem is an extreme point whose coordinates are rational numbers for the LP problem presented above. This is based on the fact that the coordinates of every extreme point of the feasible region of an LP problem is attained by performing elementary row operations on the input–output coefficients and the right-hand side constants of the LP formulation. On the other hand, the set of rational numbers (i.e., rationals) forms a field (denoted by Q) [14], hence, elementary row operations on the rational numbers cannot yield an irrational number. Consequently, since the input–output coefficients and the right-hand side constants in the LP presented by (12)–(17) are rational numbers, we conclude that the coordinates of every extreme point of the LP are also rational numbers.

of the optimization problem. (Over the infinite time horizon, the resulting throughput reaches precisely the optimal value of the objective function of the optimization problem in an asymptotic fashion, i.e., $\varepsilon \downarrow 0^+$.) Since we already illustrated that the optimal value of the objective function is an upper bound for the throughput capacity over the operational period T , we conclude that the optimal value of the objective function is indeed equal to the throughput capacity of the network under the given nodal power vector over the operational period T . ■

REFERENCES

- [1] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar, "Power control in ad hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol," in *Proc. Eur. Wireless*, Florence, Italy, Feb. 2002, pp. 156–162.
- [2] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 2002.
- [3] N. Bansal and Z. Liu, "Capacity, delay and mobility in wireless ad hoc networks," in *Proc. IEEE Information Communications (INFOCOM)*, San Francisco, CA, Apr. 2003, vol. 2, pp. 1553–1563.
- [4] S. Yi, Y. Pei, and S. Kalyanaraman, "On the capacity improvement of ad hoc wireless networks using directional antennas," in *Proc. ACM Mobile Ad Hoc Networking and Computing (MOBIHOC)*, Annapolis, MD, Jun. 2003, pp. 108–116.
- [5] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
- [6] J. Gronkvist and A. Hansson, "Comparison between graph-based and interference-based STDMA scheduling," in *Proc. ACM Mobile Ad Hoc Networking and Computing (MOBIHOC)*, Long Beach, CA, Oct. 2001, pp. 255–258.
- [7] S. Toumpis and A. J. Goldsmith, "Capacity regions for wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 2, no. 4, pp. 736–748, Jul. 2003.
- [8] A. Behzad and I. Rubin, "On the performance of graph-based scheduling algorithms for packet radio networks," in *Proc. IEEE Global Telecommunications (GLOBECOM)*, San Francisco, CA, Dec. 2003, vol. 6, pp. 3432–3436.
- [9] E. J. Duarte-Melo and M. Liu, "Data-gathering wireless sensor networks: Organization and capacity," *Comput. Netw. (COMNET): Special Issue on Wireless Sensor Networks*, vol. 43, no. 4, pp. 519–537, Nov. 2003.
- [10] T. Elbatt and A. Ephremides, "Joint scheduling and power control for wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 1, pp. 74–85, Jan. 2004.
- [11] B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks," in *Proc. IEEE Information Communications (INFOCOM)*, San Francisco, CA, Apr. 2003, vol. 2, pp. 1543–1552.
- [12] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Trans. Netw.*, vol. 10, no. 4, pp. 477–486, Aug. 2002.
- [13] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Proc. ACM Mobile Computing and Networking (MOBICOM)*, San Diego, CA, Sep. 2003, pp. 66–80.
- [14] D. C. Lay, *Linear Algebra and Its Applications*. New York: Addison-Wesley, 2002.



Arash Behzad received the B.Sc. degree (with honors) in industrial engineering from Azad University, Tehran, Iran, in 1996, the M.Sc. degree in industrial engineering, with an emphasis on operations research, from Sharif University of Technology, Tehran, Iran, in 1998, and the Ph.D. degree in electrical engineering from the University of California, Los Angeles (UCLA), in 2004.

He served as a Lecturer on operations research at the School of Engineering, Azad University, during the academic year 1999–2000. He is currently a Staff

Scientist at Broadcom Corporation's home and wireless networking business unit and a Staff Research Associate in the Electrical Engineering Department, UCLA. His areas of research include IEEE 802.11 wireless local area network (LAN) integrated systems, communications and telecommunications networked systems, power-controlled medium access control in wireless networks, combinatorial optimization, and various aspects of combinatorics with emphasis on graph theory.

Dr. Behzad is a member of the Institute of Operations Research and Management Sciences (INFORMS) and the American Mathematical Society (AMS). He was the recipient of the Best Paper Award in the area of operations research and the Best Overall Paper Award in industrial engineering at the Third National Conference of Industrial Engineering in 1996. He received the University of California MICRO Fellowship during the academic year 2000–2001 to pursue the Ph.D. degree in microelectronics at UCLA. He was also a recipient of the Outstanding Achievement Award from the Association of Professors and Scholars of Iranian Heritage in May 2004, and was nominated for the Outstanding Ph.D. Award in the Electrical Engineering Department for the academic year 2004–2005.



Izhak Rubin (S'69–M'71–SM'83–F'87) received the B.Sc. and M.Sc. degrees from the Technion–Israel Institute of Technology, Haifa, Israel, in 1964 and 1968, respectively, and the Ph.D. degree from Princeton University, Princeton, NJ, in 1970, all in electrical engineering.

Since 1970, he has been in the faculty of the University of California, Los Angeles (UCLA), School of Engineering and Applied Science, where he is currently a Professor in the Electrical Engineering Department. He has had extensive research, publi-

cations, consulting, and industrial experience in the design and analysis of commercial and military computer communications and telecommunications systems and networks. At UCLA, he leads a large research group. He also serves as President of the IRI Computer Communications Corporation, a leading team of computer communications and telecommunications experts engaged in software development and consulting services. During 1979–1980, he served as Acting Chief Scientist of the Xerox Telecommunications Network. Over the last several years, he has been responsible for developing innovative ad hoc wireless networking architectures, protocols and integrated system, and network management techniques and software for unmanned-vehicle (UV)-aided ad hoc multiter wireless networks and C4ISR systems.

Dr. Rubin has been serving as Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS, the ACM/Baltzer *Journal on Wireless Networks*, the *Optical Networks* magazine, the *Photonic Network Communications* journal, and the *Communications Systems* journal. He served as Co-Chairman of the 1981 IEEE International Symposium on Information Theory, Program Chairman of the 1984 NSF-UCLA Workshop on Personal Communications, Program Chairman of the 1987 IEEE INFOCOM Conference, and Program Co-Chair of the IEEE 1993 Workshop on Local and Metropolitan Area Networks.