Joint Route and Power Assignment in Asynchronous Multi-hop Wireless Networks

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***Abstract*— We consider constructive techniques for joint route and transmit power assignment in asynchronous multi-hop wireless networks. A constrained optimization problem is formulated to maximize power efficiency of the network while enforcing a minimum signal to interference ratio at each link to ensure desired end-to-end QoS. Numerical comparisons suggest that allowing a controlled level of interference may lead to better utilization of available spectrum than prohibiting interference via CSMA/CA.**

I. INTRODUCTION

Wireless ad-hoc networks are envisioned to eliminate the need for a predetermined communication infrastructure, but realizing potential advantages of these networks entails significant technical challenges. Current state of the art in cellular wireless networks sheds limited light on ad-hoc architectures wherein data may be relayed over multiple wireless stations. It is now widely recognized that multi-hop wireless networks entail joint consideration of several layers of the protocol stack, but exact nature of the interplay between different layers is yet to be fully understood. This paper aims to develop a cross-layered framework that accounts for operational constraints which are likely to arise in envisioned applications.

Wireless networking principles are separated from conventional guidelines due to the possibility of destructive radio interference, which refers to the degradation in communication quality in the vicinity of a radio transmission. While power control is the primary means of interference reduction in cellular architectures, ad-hoc architectures support connections over multiple wireless links, and thereby admit several additional parameters that impact interference. In particular, efficient operation of these networks require simultaneous consideration of the following functions:

a) Power control: Power control broadly refers to parsimonious usage of transmission power. On the one hand, potential applications of ad-hoc wireless networks typically envision battery-powered stations; in turn reducing power consumption will continue to be a central objective. On the other hand, a myopic approach to power control is likely to be immature, as routing a connection over a few short links may lead to a situation where downstream links are long and thereby need to use excessive powers. While asymptotic results [9] indicate that taking many short links is more advantageous for dense networks, constructive methodologies are needed for specific topologies with finite number of stations.

b) Routing: Routing determines the distribution of traffic load over a network, and thereby it may reduce the interference experienced by an active receiver by reducing the traffic carried by potential interferers. The apparent simplicity of this observation may be deceptive, as active receivers are also determined by routing. Interference-aware routing for multi-hop wireless networks is rather nontrivial, and it is closely coupled with the selection of transmit powers that determine the possibility of reliable communication between wireless stations.

c) Medium access: Currently IEEE 802.11 is the de-facto MAC standard for wireless networking. IEEE 802.11 is based on collision avoidance, which aims to eliminate interference by enforcing potential interferers to be inactive at the time of a transmission. Although this approach seems well-matched to cellular architectures with modest traffic, its performance is known to scale poorly with increasing traffic volume [19]. Furthermore, from the perspective of fairness and network capacity, optimal implementation of the ”no-interference” paradigm entails network-wide synchronization and time-slot provisioning [6], which do not lend themselves to distributed implementation. It is arguable that ALOHA-based MAC schemes may provide a distributed and scalable alternative. Such schemes have received scant attention in literature so far, but there is increasing awareness in their potential merits, especially in conjunction with CDMA at the physical layer [2], [15], [18], [20].

There is considerable recent work on integrated views of several layers in wireless networking. Power controlled MAC protocols have been considered by [7], [8], [14], [15], [12], [13], [21] in settings that are based on collision avoidance [14], [12], [13], [21], transmission scheduling [7], [8], and limited interference CDMA systems [15], [18]. Routing and power control was considered by [3] with IEEE802.11 at the MAC layer, and by [6], [18] in networks that admit global transmission scheduling. A centralized and randomized policy for dynamic power allocation and routing was studied by [16] under MAC schemes that are of interest in the present paper.

The main theme of the paper is to develop constructive techniques to establish and maintain end-to-end connections subject to quality of service (QoS) requirements and practical limitations of wireless networking. Two design decisions are made at the outset:

i. **QoS criterion.** The QoS objective is defined here as enforcing a predetermined minimum signal-to-interference ratio (SIR) at each station that is actively receiving data. Implicit here is quality of service considerations for error sensitive payload traffic such as TCP, whose throughput degrades significantly with increasing frequency of link errors [5]. Clearly, the present set-up serves to limit the bit error rate on each hop of a multi-hop connection whereas end-to-end error rates will be critical in determining the TCP goodput. We have chosen to work with per-hop performance measures not only due to the attendant analytical convenience, but also because they lead to conservative estimates on the end-to-end performance that are reasonably tight especially for small error rates, which is the regime of interest for practical purposes.

ii. **MAC functionality.** In this paper we consider asynchronous network operation that excludes transmission scheduling. Rather than CSMA/CA based protocols such as IEEE802.11, we consider MAC layer protocols that allow a limited degree of interference between simultaneous transmissions. Namely, it is assumed that medium access is essentially unregulated except that an individual station does not transmit while it is receiving. The primary motivation here is to increase the spatial utilization of the available wireless spectrum. On the one hand one may gain in spatial reuse of available spectrum by allowing a controlled level of interference, on the other hand forward error correction that compensates for resulting errors lead to throughput loss. We quantify this tradeoff in several numerical examples which suggest that the former effect is more dominant. In agreement with other recent results in literature, our results indicate that such MAC schemes, especially with error correction at the link layer to account for interference, may lead to significant capacity gains with respect to the IEEE802.11 standard.

We provide a mathematical programming formulation for joint routing and power assignment of a given set of end-to-end, multi-hop connections. The routes and transmit powers are determined to ensure that the network delivers acceptable performance. Namely, it is provisioned that the signal to interference ratio at each active receiver is above a certain level for a prescribed fraction of time, given the liberal medium access strategies of active transmitters. The present approach furthermore allows optimizing other performance measures related to power efficiency. The formulation of the paper hinges on a convenient expression of the underlying traffic statistics, and reduces route-power assignment to an optimization problem with linear cost and quadratic constraints. The methods developed here are centralized and they lead to static route and transmit power assignments. While these methods are suitable for applications with fixed wireless topologies and constant bit rate traffic, their numerical study offers insight on the performance that should be anticipated from distributed and dynamic schemes in ad-hoc structures.

The outline of the rest of the paper is as follows. Section II introduces the considered model, and Section III casts joint route and power assignment as a constrained optimization problem. In the general case this problem has nonlinear constraints due to interference bounds, but certain special cases reduce to binary linear programs. Such special cases are numerically studied in Section IV and the performance of the resulting designs are compared to that of IEEE 802.11.

II. MODEL

We consider packet-data communication among a collection R of wireless stations with arbitrary, yet fixed, geographical locations. The stations operate asynchronously in that packets transmissions are not synchronized. The traffic demand on the network is comprised of sessions, each of which refers to a unidirectional end-to-end connection between a source and a destination station. The set of sessions is denoted by $S \subseteq R^2$ so that each session $(s, d) \in S$ is identified by its source s and destination d. Each station is equipped with a receiver and a transmitter, and the network traffic is carried via a communication infrastructure provided by wireless links established between various transmitter-receiver pairs. Sessions may be routed over multiple relay stations.

In transmitting a packet, a station can employ one of L fixed transmit power levels denoted by $\{p_1, p_2, \cdots, p_L\}$. It is assumed that the transmitters share a common spectrum; so when multiple stations transmit simultaneously their intended receivers may experience destructive interference. For each pair of stations $i, j \in R$ let $g(i, j)$ denote the link gain between these stations, so that a transmission of power p_i at station i is received by station j at power $p_i g(i, j)$. In addition to station locations, link gains consolidate the effects of physical layer parameters such as propagation loss and antenna selectivity. We shall disregard self-interference by implicitly assuming that stations locally synchronize their transmissions with their own reception so that no station actually receives and transmits at the same instant.

A wireless link $(i, j) \in R^2$ is *admissible* only if it provides a certain communication quality, in the sense that the signal to interference ratio (SIR) at the receiver of station j is above a prescribed value for at least a prescribed fraction of time. Specifically, for two design parameters $q, \theta > 0$ we require that

$$P(\text{SIR} \geq \theta) \geq q \qquad (1)$$

for all active receivers. It is envisioned that these parameters are selected in accordance with the underlying physical layer technology to limit the bit error rate at each link. Implicit in such a requirement is quality of service guarantees for error sensitive payload traffic such as TCP, whose throughput is known to degrade significantly with increasing frequency of link errors [5].

It is assumed that the capacity of an admissible link, measured in payload bits per second, is a fixed value regardless of the actual value of the average or instantaneous SIR. In particular the present model excludes adaptation of channel coding with respect to the channel conditions. We suitably normalize data rates and take admissible link capacity as 1 unit. In turn each session $(s, d) \in S$ is assumed to generate traffic whose rate $\rho(s, d) \in [0, 1]$ is a fraction.

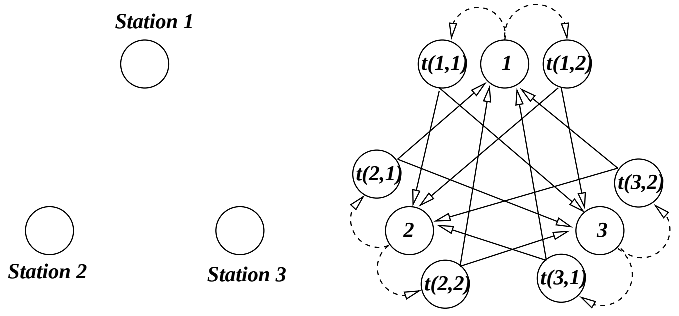
The network employs datagram routing so that packets of a given session may reach their destination after following different routes. In fact packets may be transmitted at a relay node at different power levels so as to limit interference elsewhere in the network. The question of interest is to determine the packet routes and transmission powers in such a way that all utilized links are admissible. It is clear that not all traffic demands can be satisfied subject to this constraint. See for example [9] for related fundamental limits on the capacity of wireless networks. The following section gives a mathematical programming formulation to find a valid route-power configuration provided that one exists. This formulation also allows optimizing relevant measures of performance such as power efficiency and end-to-end bit error rate.

III. JOINT ROUTE-POWER ASSIGNMENT

We start the formulation of the joint route and power assignment problem with the definition of an *auxiliary graph* $G = (V, E)$. For each station $i \in R$ and $l = 1, 2, \cdots, L$ let $t(i, l)$ denote the lth transmit power level (whose value is p_l) at station i. Let $T(i) = \{t(i, l) : l = 1, 2, \cdots, L\}$ denote the collection of transmit power levels at station i, and set $T = \cup_{i \in R} T(i)$. The node set V of the auxiliary graph is given by $V = R \cup T$, and the edge set E includes ordered pairs $(i, j) \in V^2$ that satisfies either one of the following two conditions:

(C1) $i \in R$ and $j \in T(i)$,
(C2) $i \in T$ and $j \in R$.

The auxiliary graph should be interpreted as follows. The subset $R \subset V$ of nodes represent the receivers in the wireless topology. In particular one receiver is associated with each station. For each $i \in R$ the subset $T(i) \subset V$ represents a set of transmitters at the same station on which receiver i resides. Hence each of the L the power levels is interpreted as a separate transmitter operating at a fixed power. The edge set E represents possible data flow directions. The edges that comply with condition (C1) above provide flow paths for relayed data, whereas edges that comply with condition (C2) indicate that a given transmission can be received by all receivers, though at different strengths as will be discussed next. Refer to Figure 1 for an example of the auxiliary graph for $|R| = 3$ stations and $L = 2$ power levels. Links



(a) (b)

Fig. 1

(A) Three arbitrarily located stations each with two transmit power levels, and (B) the auxiliary graph. $R = \{1, 2, 3\}$ and $T(j) = \{t(j, 1), t(j, 2)\}$ for $j \in R$. Solid links indicate potential wireless links or interference paths. Dashed links connect receivers with the power-specific transmitters at the same node. These links should be considered as wireline links so that they are neither subject to nor a source of interference.

that comply with condition (C1) above are dashed, the remaining links are solid in the figure.

Joint route and power assignment is formulated as a mathematical program on the auxiliary graph. The formulation is similar to the multi-commodity flow problem [1] with respect to the flow conservation constraints, however imposing the SIR constraints entails a nontrivial departure from standard formulations. A *flow* on the auxiliary graph G is a nonnegative vector $f = (f_{i,j}^{s,d} : (s,d) \in S,\ (i,j) \in E)$ such that $f_{i,j}^{s,d}$ denotes the rate of flow on edge (i,j) due to session (s,d). To formally specify a flow, define

$$\rho_j^{s,d} = \begin{cases} \rho_{s,d} & \text{if } j = d \\ -\rho_{s,d} & \text{if } j = s \\ 0 & \text{otherwise.} \end{cases}$$

Also for $l \in T$ let

$$R(l) = \{j \in R : (j,l) \in E\}.$$

Note that $R(l)$ is the station associated with the transmitter l. A flow then satisfies

$$\sum_{i \in T} f_{i,j}^{s,d} - \sum_{i \in T(j)} f_{j,i}^{s,d} = \rho_j^{s,d} \tag{2}$$

$$\sum_{i \in R(l)} f_{i,l}^{s,d} - \sum_{i \in R} f_{l,i}^{s,d} = 0 \tag{3}$$

for all $j \in R,\ l \in T,\ (s,d) \in S$. The first equality above is a conservation equation for receivers and indicates that a session flows start and end at associated receivers. The second equality is a conservation equation for transmitters and indicates that the net flow through a transmitter in the auxiliary graph is zero. A flow thereby specifies a route-power configuration, which dictates that at each node $j \in R$ a fraction $f_{j,l}^{s,d} / \sum_{l' \in T(j)} f_{j,l'}^{s,d}$ of packets from session (s,d) are transmitted at power level $l \in T(j)$, and a further fraction $f_{l,i}^{s,d} / \sum_{r \in R} f_{l,r}^{s,d}$ of these packets are addressed to station $i \in R$.

The utilization of the receiver at station $j \in R$ is the fraction of time that the receiver is busy receiving packets for which it is the intended destination. These packets are either relayed or terminated at the station. A flow should not prescribe receiver utilizations that exceed unity; in particular

$$\sum_{i \in T} \sum_{(s,d) \in S} f_{i,j}^{s,d} \leq 1 \qquad \text{for all } j \in R. \tag{4}$$

Similarly, the transmitter utilizations should not exceed unity either:

$$\sum_{l \in T(j)} \sum_{(s,d) \in S} f_{j,l}^{s,d} \leq 1 \qquad \text{for all } j \in R. \tag{5}$$

Note that conditions (2)–(5) are standard in capacitated multi-commodity flow problems.

We next incorporate the SIR bounds (1) on active receivers, starting with some definitions. Given flow f, let

$$u_l(j) = \sum_{(s,d) \in S} f_{j,l}^{s,d}, \qquad j \in R,\ l \in T(j)$$

denote the utilization of power level l at station j. For each transmitter $l \in T$ in the auxiliary graph, let $p(l)$ be the power level of that transmitter. Hence $p(l)$ takes values in the set $\{p_1, p_2, \cdots, p_L\}$, and each power level in this set appears R times within the collection $(p(l) : l \in T)$. Let $X(l) = (X_t(l) : t \geq 0)$ be a binary random process where $X_t(l) = 1$ if and only if station $R(l)$ transmits a packet at power level $p(l)$ at time t. In particular, under steady state operation,

$$\begin{aligned} E[X_t(l)] &= u_l(R(l)) \\ var[X_t(l)] &= u_l(R(l))(1 - u_l(R(l))), \qquad l \in T, \end{aligned}$$

whereas the joint statistics of $(X(l) : l \in T)$ depend on a variety factors including transmission scheduling policies adopted at individual stations. Given transmitter $l \in T$ and receiver $j \in R$, let $G(l,j) = p(l)g(R(l),j)$ be the power coupled to receiver j due to a transmission by transmitter l. The instantaneous interference experienced by receiver j while communicating with transmitter l at time t, denoted by $I_t(l,j)$, is then given by

$$I_t(l,j) = \lambda^{-1} \sum_{m \in T - \tau(l)} G(m,j) X_t(m),$$

where λ denotes a processing gain, and $\tau(l) = \{m \in T : R(m) = R(l)\}$ is the set of transmitters that are co-located with l. Note that the contribution of $\tau(l)$ is excluded since station $R(l)$ can transmit with one power level at a time. An admissible flow assignment therefore satisfies

$$P\left(\frac{G(l,j)}{I_t(l,j)+\eta} > \theta\right) \geq q \qquad (6)$$

in equilibrium for each $l \in T,\ j \in R$ such that $a(l,j) > 0$ where

$$a(l,j) = \sum_{(s,d) \in S} f_{l,j}^{s,d}$$

is the total flow from transmitter l to receiver j, and η is a background receiver noise.

We next express the condition (6) in a suitable form via an approximate representation. See Mitra and Morrison [11] for an example of this approach in power control for cellular data networks. Namely, we shall assume that for each time t the random variables $(X_t(m) : m \in T)$ are correlated sufficiently weakly so that one can appeal to Lindberg's theorem [4] to approximate the interference $I_t(l,j)$ as

$$\begin{aligned} I_t(l,j) \approx & \sum_{m \in T-\tau(l)} \lambda^{-1} G(m,j) u_m(R(m)) \\ & + \left(\sum_{m \in T-\tau(l)} \lambda^{-2} G(m,j)^2 u_m(R(m))(1-u_m(R(m))) \right)^{1/2} \\ & \times N(0,1), \end{aligned}$$

where $N(0,1)$ denotes the standard Gaussian random variable. When taken as an exact equality, this expression implies that condition (6) is satisfied if and only if

$$\begin{aligned} \sum_{m \in T-\tau(l)} G(m,j) u_m(R(m)) \ \leq \ & \lambda \frac{G(l,j)}{\theta} - \lambda\eta \\ & -\gamma \left(\sum_{m \in T-\tau(l)} G(m,j)^2 u_m(R(m))(1-u_m(R(m))) \right)^{1/2} \end{aligned}$$

for each $l \in T$ and $j \in R$ such that $a(l,j) > 0$, where the number γ solves

$$q = (2\pi)^{-1/2} \int_{-\infty}^{\gamma} \exp(-y^2/2) dy.$$

Equivalently for each $l \in T$ and $j \in R$

$$\begin{aligned} a(l,j) \Bigg(& \sum_{m \in T-\tau(l)} G(m,j) u_m(R(m)) \\ & -\lambda \frac{G(l,j)}{\theta} + \lambda\eta + \gamma z(l,j) \Bigg) \ \leq \ 0, \quad (7) \end{aligned}$$

where $z(l,j)$ satisfies

$$\begin{aligned} z(l,j)^2 \ &= \sum_{m \in T-\tau(l)} G(m,j)^2 u_m(R(m))(1-u_m(R(m))) \\ z(l,j) \ &\geq \ 0. \qquad (8) \end{aligned}$$

This completes the specification of a valid flow on the auxiliary graph.

We can now cast joint route and power assignment as a mathematical program. We first consider choosing a flow vector f to minimize either of the following two measures:

1. *Total power consumption:*

$$\text{Minimize} \sum_{j \in R} \sum_{l \in T(j)} p(l) u_l(j),$$

2. *Maximum power consumption:*

$$\begin{aligned} & \text{Minimize } Q \\ & \text{subject to} \sum_{l \in T(j)} p(l) u_l(j) \leq Q, \quad \text{for all} \quad j \in R, \end{aligned}$$

subject to the further constraints (2), (3), (4), (5), (7), (8).

Both optimization problems above are nonlinear due to the quadratic terms in the constraints (7)-(8), but certain special cases lead to linear problems. Namely, consider the case when each session rate $\rho(s,d)$ is either 0 or 1, and no traffic splitting is allowed at relay nodes. Hence each active station employs the same power and same destination address at all times. These integrality constraints thereby imply that valid flows are binary vectors. In turn for $m \in T$ the utilization $u_m(R(m))$ is also binary; and therefore the nonlinear constraint (8) is satisfied if and only if $z(l,j) = 0$. The remaining nonlinear constraint (7) is equivalent to the linear condition

$$\begin{aligned} \sum_{m \in T-\tau(l)} & G(m,j) u_m(R(m)) - \lambda \frac{G(l,j)}{\theta} \\ & + \lambda\eta - (1-a(l,j))\beta \ \leq \ 0 \quad (9) \end{aligned}$$

for all $l \in T$ and $j \in R$, provided that the constant β is chosen large enough such that

$$\beta > \max_{l \in T, j \in R} \left\{ \sum_{m \in T-\tau(l)} G(m,j) - \lambda \frac{G(l,j)}{\theta} + \lambda\eta \right\}.$$

Note that $a(l,j)$ is also binary; hence, by choice of β, constraint (9) is binding only if $a(l,j) > 0$. The resulting optimization is then an integer (in fact binary) linear problem.

The binary formulation allows conveniently addressing the end-to-end bit error rates (BER) in the following fashion. By the union bound, the end-to-end BER along a session that spans H wireless hops is upper bounded by H times the per-link BER. Furthermore this bound is fairly tight if the per-link BER is small, which is typically the regime of practical interest. Since forbidding traffic splitting at relay nodes ensures that all packets of a session follow the same route, and since the interference bounds (6) limit the per-link BER, one can focus on the end-to-end BER by minimizing the maximum number wireless hops taken by the packets:

3. *Maximum number of hops:*

$$\text{Minimize } H \text{ subject to } \sum_{(i,j)\in E} f_{i,j}^{s,d} \le H, \quad (s,d) \in S,$$

subject to the further constraints (2), (3), (4), (5), (9) and $f_{i,j}^{s,d} \in \{0,1\}$ for all $(s,d) \in S,\ (i,j) \in E$.

IV. NUMERICAL RESULTS

This section reports numerical results due to the linear formulation that arises in the special case of full channel utilization in Section III. Although the methodology of the paper is illustrated on specific topologies, qualitative observations obtained here well-represent features of other topologies that we have studied. System parameters that are adopted in this section are given in Table I. Namely, the set of transmit powers is 1 mW, 5 mW, and 10 mW. The propagation model is free space propagation, modulation is BPSK, receiver noise is taken as -105 dBm, and a processing gain of 10 dB is assumed. Each wireless link provides 1 Mbps raw data rate, but is subject to random errors due to interference. It is assumed that each link employs the Reed-Solomon code RS(255, 223) to compensate for such errors. The parameter q in condition (1) is 1 due to the deterministic nature of session traffic.

SIR bound θ	-4.5 dB
Transmit powers p_l	{1,5,10}mW
Modulation	BPSK
Link data rate	1 Mbps
Noise floor η	-105 dBm
Propagation model	Free space
Processing gain λ	10 dB
FEC	RS (255,223)

TABLE I

SYSTEM PARAMETERS ADOPTED IN THE NUMERICAL STUDY.

We first consider the topology of Figure 2 that involves 15 stations scattered in a region of size 120m×120m. There are three unidirectional sessions (0,1), (8,10) and (2,13), each of which has data to send at all times. Figure 2 illustrates the route and power assignments obtained by solving the integer linear problem of Section III via the CPLEX optimization package. Optimizing the power efficiency leads to a total power consumption of 7 mW, whereas minimizing the maximum path length results in at most 2-hop routes at the expense of increasing the total power consumption to 13 mW.

We next examine the end-to-end throughput resulting from the obtained assignments. In this respect note that the parameter $\theta = -4.5$ dB, in conjunction with 10 dB processing gain, amounts to an effective SIR of 5.5 dB. The bit error rate under BPSK modulation is therefore approximately 0.0035. The error correcting code RS(255,223) can correct up to 16 symbol errors where symbol length is 8 bits; in turn the codeword error rate at this SIR level is approximately 0.001. If lost codewords are retransmitted until successful, then codewords are transmitted on the average 1.001 times on each link; therefore the end-to-end throughput is roughly $(223/255) \times (1.001)^{-1}$ Mbps. In order to compare this throughput to that of CSMA/CA based MAC protocols, we simulated the IEEE 802.11 via the OPNET simulation package on the same topology and with identical physical parameters. Since the stations are closely packed in the current topology, all station pairs can communicate with one hop even with the lowest power level; in turn multi-hop routing is not required and each packet is delivered to its destination in one hop. Due to close proximity of stations, spatial reuse is not possible via CSMA/CA, consequently the available capacity (minus protocol overheads) is divided roughly equally among the sessions. In particular capacity savings via power controlled CSMA/CA as observed in [12] do not arise here. The numeric values for the two studied cases are listed in Table II(a).

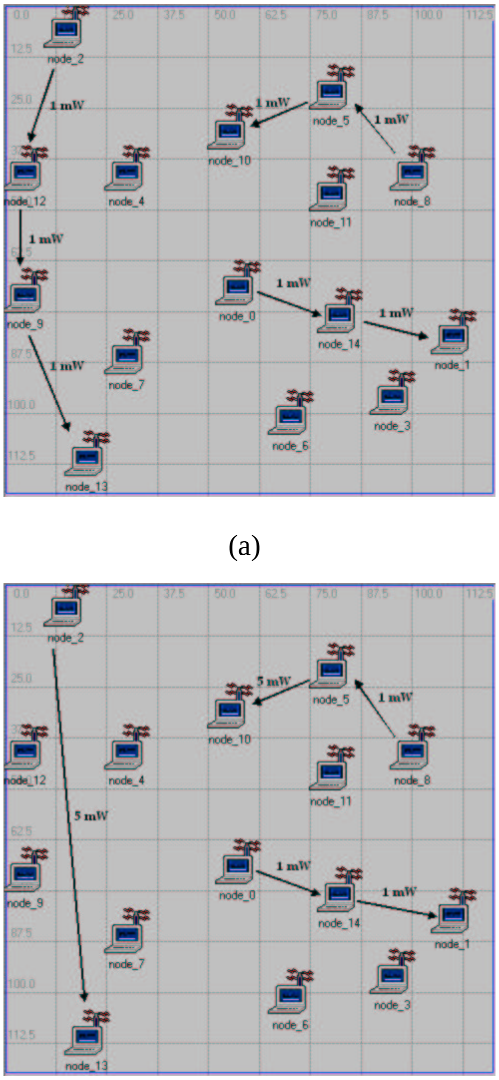
The impact of random errors is often remarkably more pronounced when the payload traffic is flow-controlled, and it is interesting to see if the methods of the present paper lead to capacity gains in that case. To shed some light on this issue, we next consider the scenario of the above paragraph with TCP payload. Namely, each session is a 50Mbyte FTP file download over TCP, and each end-to-end throughput is computed by dividing the size of the file by the time it takes to complete the download. The achieved throughputs for the two cases are listed in Table II(b). Here the numerical values pertaining to the present design method are also computed via OPNET simulations, by using packet discarders that emulate link errors with the same probabilities determined in the above paragraph. Namely, TCP packet size is 6 codewords (roughly 1400 bytes); so each TCP packet is lost with probability roughly 0.006 on each link. It is assumed that the reverse traffic due to ACK packets induces negligible interference, but ACK packets are also subject to error rates as the forward traffic. Table II(b) suggests that the impact of errors is stronger for the presented design method, however there are still significant capacity advantages in allowing limited interference. It should be noted that this observation is conservative, since the link error probabilities are obtained with respect to the SIR lower bound θ and actual SIR values may be higher. In fact in the present case the average SIR over active receivers is -3 dB, in turn the actual throughputs are higher than suggested by Table II(b).

The SIR bound θ is clearly a key parameter that determines feasibility of solutions as well as their resulting performances. Figure 3 indicates that as θ is increased to impose higher wireless link quality, the total throughput of the three sessions increases at the expense of increased total power consumption. There is a limit to that regime, as when θ exceeds a certain threshold finding valid assignments becomes infeasible.

Finally, we consider a larger geographic area to examine the effects of spatial reuse of available spectrum in the IEEE 802.11 scenario. To this end, we study the topology of Figure 4 on a 3.5 km × 2.5 km grid. We assume that stations transmit at a single power level, namely 1 mW, and the circles in the figure indicate communication ranges of active stations in that case. The routing given in the figure is obtained by adopting $\theta = -5$ dB. In the IEEE 802.11 scenario, packets also follow these routes by being switched at intermediate stations if necessary. The numerical values of throughputs with TCP payload are given in Table III. Note that since some spatial reuse is be achieved via CSMA/CA, the resulting throughput is higher compared to the previous topology, however the throughput of the present design method is still noticeably better.

V. DISCUSSION

This paper formulates joint route and power assignment in asynchronous multi-hop wireless networks as a constrained optimization problem. The formulation entails a relaxed MAC strategy whose worst-case performance is guaranteed via the assignment of routes and transmit powers. This philosophy stands in contrast with collision avoidance based MAC protocols, in that it allows a prescribed level of interference so as to increase the spatial utilization of available spectrum. Obtained numerical results suggest that higher network capacity can be thereby obtained.



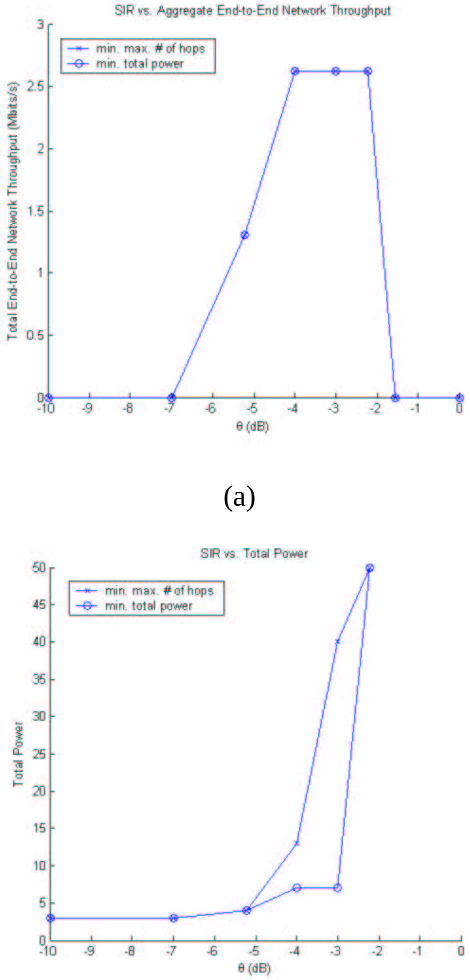
(a)

(b)

Fig. 2

SOLUTIONS OF (A) TOTAL POWER AND MAXIMUM POWER MINIMIZATION, AND (B) MAXIMUM HOP COUNT MINIMIZATION ON A 15 STATION NETWORK IN AN AREA OF 120M×120M.

Although the present paper reduces the network design



(a)

(b)

Fig. 3

THE VARIATION OF (A) TOTAL END-TO-END THROUGHPUT, AND (B) TOTAL POWER CONSUMPTION WITH RESPECT TO SIR BOUND θ.

problem to standard mathematical programs that can be solved by commercial optimization packages, the entailed computational complexity still quickly grows with the network size. Fast heuristic approaches would be required to approximate the exact solutions in situations that involve large numbers of stations and power levels.

The outlined method is centralized, so it is suitable for applications that admit provisioning by a network controller. In light of the resulting capacity gains it is tempting to seek distributed online implementation of the method. Online routing and power control under moderate traffic conditions entails significant challenges.

(s,d) pair	End-to-end throughput	
	Centralized Assignment	IEEE 802.11
(0,1)	836 Kbps	245 Kbps
(2,13)	836 Kbps	245 Kbps
(8,10)	836 Kbps	248 Kbps

(a)

(s,d) pair	End-to-end throughput	
	Centralized Assignment	IEEE 802.11
(0,1)	611 Kbps	243 Kbps
(2,13)	602 Kbps	244 Kbps
(8,10)	602 Kbps	248 Kbps

(b)

TABLE II

END-TO-END THROUGHPUT OF INDIVIDUAL SESSIONS: (A) NO FLOW CONTROL, (B) TCP PAYLOAD. SIR BOUND $\theta = -4.5$ DB IN BOTH CASES. THE PRESENT DESIGN REFERS TO THE ASSIGNMENT OF FIGURE 2(B), AND PACKETS ARE DELIVERED IN A SINGLE HOP UNDER IEEE 802.11.

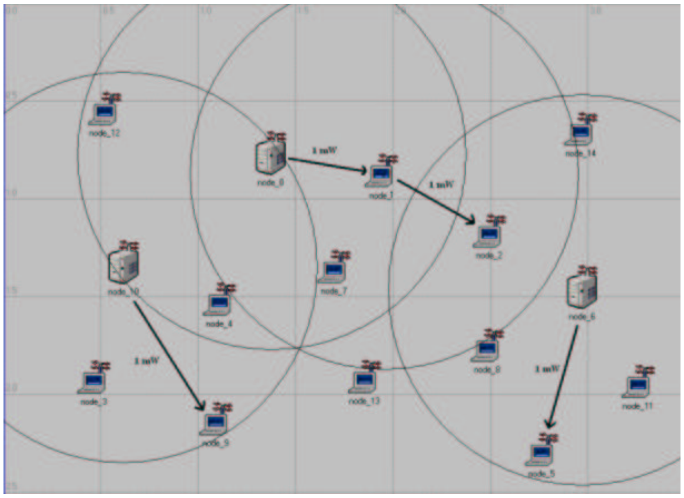


Fig. 4

ROUTE ASSIGNMENT WITH SINGLE TRANSMIT POWER 1 MW.

(s,d) pair	End-to-end throughput	
	Centralized Assignment	IEEE 802.11
(0,2)	602 Kbps	331 Kbps
(6,5)	611 Kbps	352 Kbps
(10,9)	611 Kbps	353 Kbps

TABLE III

END-TO-END THROUGHPUT OF INDIVIDUAL SESSIONS IN THE TOPOLOGY OF FIGURE 4 WITH TCP PAYLOAD. SIR BOUND $\theta = -5$ DB AND SET OF TRANSMIT POWERS IS A SINGLETON.

The literature on adaptive routing in mobile ad-hoc networks is rich, and a variety of routing protocols have been developed to deal with the issue effectively [17], [10]. These protocols predominantly focus on routing in the face of station mobility, in that their operation is a function of the logical connectivity of the network. When the network traffic is light, end-to-end sessions typically do not interfere with each other, as typically a small number of sessions are active at any given instant. In turn admissibility of a route broadly depends on the geographical locations of network nodes. When the light-traffic condition does not hold, whether reliable communication can be achieved between two given stations at a given time depends on the activity patterns of other sessions at that time. Typical applications result in bursty session traffic characteristics; in turn the state of a wireless link changes at the burst time scale. This time scale is much faster than the time scale at which network connectivity changes due to station mobility. Realizing the potential of multi-hop wireless networking will arguably entail adaptive self-organization schemes that are agile at the burst time scale.

REFERENCES

[1] R.K. Ahuja, T.L. Magnanti, and J.B. Orlin, *Network Flows: Theory, Algorithms, and Applications,* Prentice Hall, 1993.

[2] F. Bacelli, B. Blaszcyszyn, and B. Muhlethaler, ”An Aloha protocol for multi-hop mobile wireless networks,” 41st Allerton Conference on Communications, Control and Computing. Champaign, 2003.

[3] P. Bergamo, A. Giovanardi, A. Travasoni, D.Maniezzo, ”Distributed power control for energy efficient routing in adhoc networks,” Wireless Networks, vol. 10, pp. 29–42, 2004.

[4] P. Billingsley, *Probability and Measure,* Wiley, 1986.

[5] H. Chaskar, T. V. Lakshman and U. Madhow, ”TCP Over Wireless with Link Level Error Control: Analysis and Design Methodology,” *IEEE/ACM Transactions on Networking,* vol. 7, no. 5, pp. 605-615, 1999.

[6] R. L. Cruz and A. V. Santhanam, “Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks,” *Proceedings of IEEE Infocom 2003,* 2003.

[7] T. ElBatt, S. Krishnamurthy, D. Connors and S. Dao ”Power Management for Throughput Enhancement in Wireless Ad hoc Networks,” IEEE International Conference on Communications (ICC), June 2000.

[8] T. ElBatt and A. Ephremides ”Joint Scheduling and Power Control for Wireless Ad hoc Networks,” IEEE Computer and Communications Conference (INFOCOM), June 2002.

[9] P. Gupta and P. R. Kumar, ”The capacity of wireless networks,” *IEEE Transactions on Information Theory,* vol. IT-46, pp. 388-404, 2000.

[10] http://www.ietf.org/html.charters/manet-charter.html.

[11] D. Mitra and J. A. Morrison, ”A Distributed Power Control Algorithm for Bursty Transmission on Cellular, Spread Spectrum Wireless,” in *Wireless Information Networks,* J.M. Holtzman Ed., pp. 201-212, Kluwer, 1996.

[12] J. P. Monks, V. Bharghavan and W. W. Hwu, “A Power Controlled Multiple Access Protocol for Wireless Packet Networks,” *Proceedings of IEEE Infocom 2001,* 2001.

[13] J. P. Monks, J. P. Ebert, A. Wolisz and W. W. Hwu, “A Study of the Energy Saving and Capacity Improvement Potential of Power Control in Multi-hop Wireless Networks,” *Proceedings of 26th IEEE Conferenec on Local Computer Networks,* 2001.

[14] A. Muqattash and M. Krunz, ”Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks,” in Proceedings of the IEEE INFOCOM 2003 Conference, San Francisco, April 2003.

[15] A. Muqattash and M. Krunz, ”CDMA-based MAC protocol for wireless ad hoc networks,” in Proceedings of the ACM MobiHoc 2003 Conference, Annapolis, Maryland, June 2003.

[16] M. J. Neely, E. Modiano and C. E. Rohrs, “Dynamic Power Allocation for Time Varying Wireless Networks,” *Proceedings of IEEE Infocom 2003,* 2003.

[17] C. Perkins, ”Ad-hoc Networking,” Addison-Wesley, 2000.

[18] B. Radunovic and J. Le Boudec, ”Joint scheduling, power control, and routing in symmetric one-dimensional multi-hop wireless networks,” WiOpt, INRIA, Nice, France, March 2003.

[19] S. Ray, J. Carruthers, and D. Starobinski, ”RTS/CTS-induced Congestion in Ad-Hoc Wireless LANs,” IEEE WCNC 2003, New Orleans, pp. 1516-1521, March 2003.

[20] Y.E. Sagduyu and A. Ephremides, “Energy-efficient collision resolution in wireless ad-hoc networks,” Infocom 2003.

[21] S.L. Wu, Y.C. Tseng, and J.P. Sheu, “Intelligent medium access for mobile ad-hoc networks with busy tones and power control,” IEEE JSAC, 18(9):1647–1657, 2000.