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

Murat Alanyali\(^1\), Onur Savas\(^1\), and Bülent Yener\(^2\)

Abstract

We consider asynchronous multi-hop wireless networks with a relaxed medium access strategy that only excludes simultaneous transmission and reception at individual stations. A constrained optimization problem is formulated to jointly determine routes and transmit powers for a given set of end-to-end sessions. Solutions of this problem enforce a prescribed signal to interference ratio at the receiver of each link. Numerical comparisons with IEEE 802.11 based scenarios suggest that allowing a controlled level of interference in this manner may lead to better utilization of available spectrum than prohibiting interference via CSMA/CA.

\(^1\)Department of Electrical and Computer Engineering and The Center for Information and Systems Engineering, Boston University.
\(^2\)Department of Computer Science, Rensselaer Polytechnic Institute.
1 Introduction

Well-understood and effectively applied in cellular wireless networks, power control is now under intense investigation in the context of ad-hoc wireless architectures. As ad-hoc wireless networks are envisioned to allow connections to span multiple hops, routing arises as an additional factor in interference reduction. Some fundamental asymptotic results [5] notwithstanding, the interplay between routing and transmit power allocation is yet to be fully understood. Most recent work on this subject concentrate on network-wide transmission scheduling [3, 4] or collision avoidance [7, 8] for medium access control, and statically [3] or dynamically [8] determined transmit powers to limit interference. See also [3] for an optimization scheme to determine the routes in a synchronized network, and [9] for a dynamic scheme for joint routing and power control.

In this paper we consider networks of asynchronous wireless stations in which network-wide transmission scheduling is not possible. Instead, it is assumed that medium access is essentially unregulated except that an individual station does not transmit while it is receiving. The routes and transmit powers are determined to ensure that the network delivers acceptable performance under this liberal access strategy. 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. This approach stands in contrast with collision avoidance based MAC schemes such as that of IEEE 802.11 standard which eliminates interference via CSMA/CA and RTS-CTS handshakes. 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 needed to compensate resulting errors lead to throughput loss. We quantify this tradeoff in several numerical examples which suggest that the former effect is more dominant. The present approach furthermore allows optimizing other performance measures related to power efficiency. The methods developed here are centralized and they lead to static route and transmit power assignments. While these methods are applicable to wireless distribution networks, 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 2 introduces the considered model, and Section 3 casts joint route and power assignment as a constrained optimization problem. In the general case this problem has quadratic constraints due to interference bounds, but certain special cases reduce to binary linear programs. Such special cases are numerically studied in Section 4 and the performance of the resulting designs are compared to that of IEEE 802.11. Some concluding remarks are collected in Section 5.

2 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 their 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 $S \subseteq \mathbb{R}^2$ 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 $\{p_1, p_2, \ldots, p_L\}$. 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 $i, j \in \mathbb{R}$ let $g(i, j)$ denote the link gain between these stations, so that a transmission of power $p_i$ at station $i$ is heard 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 receives and transmits at the same instant.

A wireless link $(i, j) \in \mathbb{R}^2$ 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. More specifically, for two design parameters $q, \theta > 0$ we require that

$$P(\text{SIR} \geq \theta) \geq q \quad (2.1)$$

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 [2].

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 [5] 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.
3 Problem Formulation

Formulation of the joint route and power assignment problem given in this section has the flavor of a multicommodity flow problem on an auxiliary graph that will be defined next. For each station $i \in R$ let $t(i, l)$ denote the $l$th transmit power level (whose value is $p_l$) at station $i$. Let $T(i) = \{t(i, l) : l = 1, 2, \cdots, L\}$ denote the set of transmit power levels at station $i$, and let $T = \bigcup_{i \in R} T(i)$. Define the auxiliary graph $G = (V, E)$ with nodes $V$ and edges $E$ by setting $V = R \cup T$ and by including the ordered pair $(i, j) \in V^2$ in the edge set $E$ if and only if either one of the following two conditions holds:

(i) $i \in R$ and $j \in T(i)$,

(ii) $i \in T$ and $j \in R$.

The graph $(V, E)$ 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 (i) above provide flow paths for relayed data, whereas edges that comply with condition (ii) 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.
Figure 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.

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

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

\[
\sum_{i \in T} f_{i,j}^{s,d} - \sum_{i \in T(j)} f_{j,i}^{s,d} = \rho_j^{s,d} \tag{3.1}
\]

\[
\sum_{i \in R(l)} f_{i,l}^{s,d} - \sum_{i \in R} f_{i,j}^{s,d} = 0 \tag{3.2}
\]

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 \( f_{j,i}^{s,d} / \sum_{l' \in T(j)} f_{j,l'}^{s,d} \) of packets from session \((s,d)\) are transmitted at power level \( l \in T(j) \), and a further fraction \( f_{i,j}^{s,d} / \sum_{r \in R} f_{i,r}^{s,d} \) of these packets are addressed to station \( i \in R \).

The utilization \( u^R(j) \) of a 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; therefore

\[
u^R(j) = \sum_{i \in T} \sum_{(s,d) \in S} f_{i,j}^{s,d} \leq 1 \quad \text{for all } j \in R. \tag{3.3}
\]

Similarly, the transmitter utilizations should not exceed unity either:

\[
u^T(j) = \sum_{i \in T(j)} \sum_{(s,d) \in S} f_{j,i}^{s,d} \leq 1 \quad \text{for all } j \in R. \tag{3.4}
\]
While conditions (3.1)–(3.4) are standard in capacitated multi-commodity flow problems, enforcing the SIR bound (2.1) on admissible links entails a major departure from conventional formulation. We next incorporate these bounds, but first give some definitions. Given a flow $f$, let

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

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. 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,

$$E[X_t(l)] = u_t(R(l)) \quad \text{and} \quad \text{var}[X_t(l)] = u_t(R(l))(1 - u_t(R(l))), \quad l \in T,$$

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 $\lambda$ 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

\[ P \left( \frac{G(l, j)}{I_t(l, j) + \eta} > \theta \right) \geq q \tag{3.5} \]

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 \( \eta \) represents the receiver noise power.

We next express the condition (3.5) in a suitable form via an approximate representation. See Mitra and Morrison [6] 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 [1] to approximate the interference \( I_t(l, j) \) as

\[ I_t(l, j) \approx \sum_{m \in T-\tau(l)} \lambda^{-1} G(m, j) u_m(R(m)) \]

\[ + \left( \sum_{m \in T-\tau(l)} \lambda^{-2} G(m, j)^2 u_m(R(m))(1 - u_m(R(m))) \right)^{1/2} \times N(0, 1), \]

where \( N(0, 1) \) denotes the standard Gaussian random variable. When taken as an exact equality, this expression implies that condition (3.5) is satisfied if and only if

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

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

\[ q = (2\pi)^{-1/2} \int_{-\infty}^{\gamma} \exp(-y^2/2) \, dy. \]
Equivalently
\[
a(l, j) \left( \sum_{m \in T - \tau(l)} G(m, j)u_m(R(m)) - \lambda \frac{G(l, j)}{\theta} + \lambda \eta + \gamma z(l, j) \right) \leq 0, \quad l \in T, \ j \in R, \ (3.6)
\]
where \( z(l, j) \) satisfies
\[
z(l, j)^2 = \sum_{m \in T - \tau(l)} G(m, j)^2u_m(R(m))(1 - u_m(R(m))), \quad z(l, j) \geq 0, \quad l \in T, \ j \in R. \ (3.7)
\]
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:**

   \[
   \text{Minimize} \ Q \ \text{subject to} \ \sum_{l \in T(j)} p(l)u_l(j) \leq Q, \quad j \in R,
   \]

subject to the further constraints (3.1), (3.2), (3.3), (3.4), (3.6), (3.7).

Both optimization problems above are nonlinear due to the quadratic terms in the constraints (3.6)-(3.7), but certain special cases admit linear formulations. 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 (3.7) is satisfied if and only if \( z(l, j) = 0 \). Note that the parameter \( q \) in condition (2.1) is 1 due to the deterministic nature of session traffic. The remaining nonlinear constraint (3.6) is equivalent to the linear condition

\[
\sum_{m \in T - \tau(l)} G(m, j) u_m(R(m)) - \lambda \frac{G(l, j)}{\theta} + \lambda \eta - (1 - a(l, j)) \beta \leq 0, \quad l \in T, \; j \in R, \quad (3.8)
\]

provided that the constant \( \beta \) is chosen large enough such that

\[
\beta > \max \left\{ \sum_{m \in T - \tau(l)} G(m, j) - \lambda \frac{G(l, j)}{\theta} + \lambda \eta : l \in T, \; j \in R \right\}.
\]

Note that \( a(l, j) \) is also binary, and by choice of \( \beta \) constraint (3.8) is binding only if \( a(l, j) > 0 \). The resulting optimization is then an integer (in fact binary) linear problem.

The above linear formulation prescribes that all packets of a session follow the same route. Since the interference bound (3.5) aims to limit per-link bit error rate, one can now focus on the end-to-end bit error rate by minimizing

3. Maximum number of hops: Find flow \( f \) to

Minimize \( Q \) subject to

\[
\sum_{(i,j) \in E} f_{i,j}^{s,d} \leq Q, \quad (s, d) \in S,
\]

subject to the further constraints (3.1), (3.2), (3.3), (3.4), (3.8) and \( f_{i,j}^{s,d} \in \{0, 1\} \) for all \( (s, d) \in S, \; (i, j) \in E \).
4 Numerical Results

This section reports a numerical evaluation of route and transmit power assignments obtained via the linear integer program formulation of Section 3. Although the methodology is illustrated on specific topologies, the qualitative observations obtained here well-represent features of several other topologies that we have studied. The system parameters that are employed in this section are given in Table 1. 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 error correcting code RS(255,223) to compensate such errors.

We first consider the topology of Figure 2 that involves 15 stations scattered in a region of size $120 \times 120$ m. 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 three integer linear problems of Section 3 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 $\theta = -4.4$ dB, in conjunction with 10 dB processing
Figure 2: Solutions of (a) total power and maximum power minimization, and (b) maximum hop count minimization on a 15 station network.
SIR bound $\theta$ & $-4.4$ dB  \\
Transmit powers $p_l$ & $\{1,5,10\}$ mW  \\
Modulation & BPSK  \\
Link data rate & 1 Mbps  \\
Noise floor $\eta$ & $-105$ dBm  \\
Propagation model & Free space  \\
Processing gain $\lambda$ & 10 dB  \\
FEC & RS(255,223)  \\

Table 1: System parameters adopted in the numerical study.

gain, amounts to an effective SIR of 5.6 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 same situation when each station adopts the IEEE 802.11 MAC protocol. The simulations were performed 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 of spectrum 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 [7] do not arise here. The numerical
values for the two studied cases are listed in Table 2(a).

The impact of random errors is often remarkably more pronounced when the payload
traffic is flow-controlled [2], and it is interesting to see if the methods of the present paper
lead to gains in throughput at higher layers of the protocol stack. 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 throughput under the route/power assignment of Figure 2(b) and under the
IEEE 802.11 MAC protocol are listed in Table 2(b). Here the numerical values pertaining to
the present 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 taken as 7 codewords (1561 bytes); so each TCP packet is lost
with probability less than 0.007 on each link. It is assumed that the reverse traffic due to
ACK packets induces negligible interference, but ACK packets are subject to error rates
dictated by the SIR values at their respective receivers. Table 2(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.
Table 2: End-to-end throughput of individual sessions: (a) no flow control, (b) TCP payload.

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<tr>
<th>(s,d) pair</th>
<th>End-to-end throughput</th>
<th>Present design</th>
<th>IEEE 802.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,1)</td>
<td>836 Kbps</td>
<td>245 Kbps</td>
<td></td>
</tr>
<tr>
<td>(2,13)</td>
<td>836 Kbps</td>
<td>245 Kbps</td>
<td></td>
</tr>
<tr>
<td>(8,10)</td>
<td>836 Kbps</td>
<td>248 Kbps</td>
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<th>IEEE 802.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,1)</td>
<td>611 Kbps</td>
<td>243 Kbps</td>
<td></td>
</tr>
<tr>
<td>(2,13)</td>
<td>601 Kbps</td>
<td>244 Kbps</td>
<td></td>
</tr>
<tr>
<td>(8,10)</td>
<td>601 Kbps</td>
<td>248 Kbps</td>
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</tr>
</tbody>
</table>

The SIR bound $\theta = -4.4$ dB in both cases. The present design refers to the route/power assignment of Figure 2(b), and packets are delivered in a single hop under IEEE 802.11.
It should be noted that the SIR lower bound $\theta$ is taken as reference in calculating the packet loss probabilities, and actual SIR values are typically higher. In fact, under the route/power assignment of Figure 2(b), the average SIR over active receivers, provided that all active transmitters are transmitting packets, is $-3 \text{ dB}$ as opposed to $\theta = -4.4 \text{ dB}$. Hence the discussion of the above paragraphs leads to conservative estimates for the throughput achieved via the route/power assignment of the proposed methodology. Note also that this conclusion is valid if each link is active at all times, possibly transmitting blank packets in the absence of payload bits. Clearly, further gains in TCP throughput should be anticipated if stations are allowed to transmit payload packets only.

The SIR bound $\theta$ is clearly a key parameter that determines feasibility of solutions as well as their resulting performances. Figure 3 indicates that as $\theta$ 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 $\theta$ 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 case when each station uses the IEEE 802.11 MAC protocol. To this end, we study the topology of Figure 4 on a $3.5 \text{ km} \times 2.5 \text{ km}$ grid. We assume that stations transmit at a single power level, namely $1 \text{ mW}$, and the circles in Figure 4 indicate communication ranges of active stations in that case. The routing given in the figure is obtained by minimizing the maximum hop-count (criterion 3 in Section 3) subject to the SIR
Figure 3: The variation of (a) total end-to-end throughput, and (b) total power consumption with respect to the SIR bound $\theta$. 
bound $\theta = -4.4$ dB. In the IEEE 802.11 scenario, packets also follow these routes by being relayed at intermediate stations if necessary. The numerical values of throughputs with TCP payload are given in Table 3. Since some stations may simultaneously transmit packets in the CSMA/CA scenario, some level of spatial reuse is achieved; hence the resulting throughput is higher compared to the previous topology. However the throughput of the present design method is still noticeably better.

5 Conclusion

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
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<tr>
<td></td>
<td>Present design</td>
</tr>
<tr>
<td>(0,2)</td>
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<td>(6,5)</td>
<td>611 Kbps</td>
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<td>(10,9)</td>
<td>611 Kbps</td>
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Table 3: End-to-end throughput of individual sessions in the topology of Figure 4 with TCP payload. The SIR bound $\theta = -4.4$ dB and the set of transmit powers is a singleton.

strategy whose performance is guaranteed to exceed prescribed values when the obtained route/power assignment is employed. This philosophy is 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. The numerical results of this paper suggest that higher network capacity can be thereby obtained in the case when sessions fully utilize the available link capacity. The proposed method is centralized, so it is suitable for applications that admit a network controller. On the other hand, potential gains appear to be remarkable and thereby justify seeking distributed online implementation of the method.

References


