Parallel Opportunistic Routing in Wireless Networks

Won-Yong Shin, Member, IEEE, Sae-Young Chung, Senior Member, IEEE, and Yong H. Lee, Senior Member, IEEE

Abstract—We study benefits of opportunistic routing in a large wireless ad hoc network by examining how the power, delay, and total throughput scale as the number of source–destination pairs increases up to the operating maximum. Our opportunistic routing is novel in a sense that it is massively parallel, i.e., it is performed by many nodes simultaneously to maximize the opportunistic gain while controlling the interuser interference. The scaling behavior of conventional multihop transmission that does not employ opportunistic routing is also examined for comparison. Our main results indicate that our opportunistic routing can exhibit a net improvement in overall power–delay tradeoff over the conventional routing by providing up to a logarithmic boost in the scaling law. Such a gain is possible since the receivers can tolerate more interference due to the increased received signal power provided by the multiuser diversity gain, which means that having more simultaneous transmissions is possible.

Index Terms—Multihop, multiuser diversity, opportunistic routing, source–destination pair, wireless ad hoc network.

I. INTRODUCTION

In [1], Gupta and Kumar introduced and studied the throughput scaling in large wireless ad hoc networks. They showed that a total throughput scaling of $\Theta(\sqrt{n}/\log n)$ [bps/Hz] can be obtained by using a multihop strategy when $n$ source–destination (S–D) pairs are randomly distributed in a unit area. Multihop schemes were then further developed and analyzed in the literature [3]–[10], while their throughput per S–D pair scales far less than $\Theta(1)$. Recent studies [11], [12] have shown that we can actually achieve $\Theta(n^{1-\epsilon})$ scaling for an arbitrarily small $\epsilon > 0$, i.e., an almost linear scaling of the total throughput, by using a hierarchical cooperation strategy, thereby achieving the best result we can hope for.

Besides the studies to improve the throughput up to the linear scaling, an important factor that we need to consider in practical wireless networks is the presence of multipath fading. The effect of fading on the scaling laws was studied in [3], [6], [7], [13], and [14], where it was shown that achievable throughput scaling laws do not fundamentally change if all nodes are assumed to have their own traffic demands (i.e., there are $n$ S–D pairs) [6], [7], [13] or the effect of fading is averaged out [3], [6], [13], while it was found in [14] that the presence of fading can reduce the achievable throughput up to $\log n$. However, fading can be beneficial by utilizing the multiuser diversity gain provided by the randomness of fading in multiuser environments, e.g., opportunistic scheduling [15], opportunistic beamforming [16], and random beamforming [17] in broadcast channels. Scenarios exploiting the opportunistic gain were also studied in cooperative networks by applying an opportunistic two-hop relaying protocol [18] and in cognitive radio networks with opportunistic scheduling [19]. In [20] and [21], strategies for improving the throughput scaling over nonfaded environments were shown in wireless network models that do not incorporate geometric path loss. In [22], it was shown how fading improves the throughput using opportunistic routing when a single active S–D pair exists in a wireless ad hoc network.

In this paper, we analyze the benefits of fading by utilizing opportunistic routing in multihop transmissions when there are multiple randomly located S–D pairs in a large wireless ad hoc network. Our routing protocol describes how multiple nodes perform opportunistic routing simultaneously (or equivalently, in parallel) in a massive scale. To our knowledge, such an attempt for the network model has never been conducted in the literature. Since the throughput scaling of a multihop protocol is far less than linear, it is natural to assume that only a subset of S–D pairs are active at a time and active S–D pairs are chosen in a round robin fashion. In this paper, we consider a general scenario where the number of active S–D pairs scales as a function of $n$. We are interested in improving the number of simultaneously supportable S–D pairs, while maintaining a constant throughput per S–D pair by using opportunistic routing.

In most network applications, power and delay are also key performance measures along with the throughput. The tradeoff among these measures has been examined in terms of scaling laws in some papers [8]–[10], [23]. In this paper, we analyze a power–delay–throughput tradeoff of both opportunistic routing and regular multihop routing as the number of S–D pairs increases up to the operating maximum, while per-node transmission rate is set to be constant. We first show the existence of a fundamental tradeoff between the total transmission power consumed by all hops per S–D pair, the average number of hops...
Our model for successful reception of a transmission over one hop basically follows the physical model in [1]. The detailed argument is described as follows. Since there is no CSI at the transmitter, we assume that each source node transmits data to its destination at a fixed target rate $R > 0$ independent of $n$. A similar assumption was also made in some earlier work [1], [3]–[14]. As in the earlier studies [15]–[19] dealing with opportunism under the block fading model, we suppose that a packet is decoded successfully if the received signal-to-interference-and-noise ratio (SINR) exceeds a predetermined threshold $\eta > 0$, which is independent of $n$, i.e., $\log(1 + \text{SINR}) \geq R = \log(1 + \eta)$. Then, the total throughput $T(n)$ of the network would be given by $\Omega(M(n))$ if no transmission fails i.e., there is no outage.

III. ROUTING PROTOCOLS

In this section, we describe our routing protocols with and without opportunistic routing. We simply use a multihop strategy in both cases using the nodes other than $S$–$D$ pairs as relays. Hence, we do not assume the use of any sophisticated multiuser detection schemes at the receiver.

Next let us introduce the scaling parameters $P(n)$ and $D(n)$. The average number of hops per $S$–$D$ pair is interpreted as the average delay and is denoted as $D(n)$. The parameter $P(n)$ denotes the average total transmit power used by all hops for an $S$–$D$ pair. Assuming that the transmit power is the same for each hop, we see that $P(n)$ is equal to $D(n)$ times the transmit power per hop. In addition, for both routing schemes, let us suppose that

$$P(n) - \Theta(M(n))^{-1}D(n)^{-\alpha+2}. \quad (2)$$

As a consequence of this choice of power $P(n)$, all the transmit power is scaled in such a way that the average total interference power from the set $I \subset \{1, \ldots, n\}$, consisting of simultaneously transmitting nodes, is given by $\Theta(1)$, which will be analyzed in a later section. Note that this power scaling strategy does not affect the tradeoff among the orders of power $P(n)$, delay $D(n)$, and total throughput $T(n)$ (see Section IV-A for more detailed description).

A. Opportunistic Routing

Opportunistic routing was originally introduced in [24] and [25] and was further developed in various network scenarios [26]–[29]. When a packet is sent by a transmitting node, it may be possible that there are multiple receivers successfully decoding the packet. Among the relay nodes that successfully decode the transmitted packet for the current hop, the one that is closest to the destination becomes the transmitter for the next hop. Since the packet can travel farther at each hop using this opportunistic routing, the average number of hops can be reduced. Note that the existing protocol in [24]–[29] was designed simply for the case where there exists a single $S$–$D$ pair, and thus, it did not consider the possibility of multiple simultaneously transmitting nodes. The channel gain $h_{ik}$ is given by

$$h_{ki} = \frac{|g_{ki}|}{\sqrt{r_{ki}}}, \quad (1)$$

where $g_{ki}$ is the complex fading process between nodes $i$ and $k$, which is assumed to be Rayleigh with $E[|g_{ki}|^2] = 1$ and independent for different $i$’s and $k$’s. Moreover, we assume the block fading model, where $g_{ki}$ is constant during one packet transmission and changes to a new independent value for the next transmission. $r_{ki}$ and $\alpha > 2$ denote the distance between nodes $i$ and $k$ and the path-loss exponent, respectively. We assume that channel state information (CSI) is available at all the receivers, but not at the transmitters.
not incorporate interference between links, which is a critical problem in wireless networks.

We modify this routing to apply it to our network, composed of multiple nodes performing opportunistic routing simultaneously in a massive scale. Then, we need to carefully design a routing protocol while solving the interference problem caused by simultaneously transmitting nodes. The per-hop distance of this opportunistic transmission is random. However, we can make sure that there are multiple successfully receiving nodes in a given square cell with high probability (w.h.p.) if we control the size of the cell and the distance between the transmitter and the cell. Then, one of the successfully receiving nodes can be the transmitter for the next hop. Short signaling messages [24], [25] need to be exchanged between some candidate relay nodes and the corresponding transmitting node in order to decide who will be the transmitter for the next hop. These messages are transmitted using a different time slot from that for data packets to avoid any interference. More specifically, it is assumed that the two different messages are transmitted at even and odd time slots, respectively, which causes only a factor 2 loss in performance, thus resulting in no degradation in terms of scaling laws.4

As shown in Fig. 1, we divide the whole area into \( \sqrt{A_s(n)} \) square cells with per-cell area \( A_s(n) \). Note that \( A_s(n) = \Theta(1/D(n)^2) \) holds since the average distance between an S–D pair is given by \( \Theta(1) \). We assume XY routing, i.e., the route for an S–D pair consists of a horizontal and a vertical path. Suppose that routing is performed first horizontally and then vertically for each S–D pair, as illustrated in Fig. 1 (\( S_i \) and \( D_i \) denote a source and the corresponding destination node, respectively, for \( i = 1, 2 \)). Then, for each hop in the S–D path, some relay nodes that successfully decode their packets are selected opportunistically for transmission in the next hop (the relaying node selection strategy will be described later in detail). That is, the route for each S–D pair is not predetermined. Nodes operate according to the 25-time division multiple access (TDMA) scheme. This means that the total time is divided into 25 time slots and nodes in each cell transmit 1/25th of the time, while all transmitters in a cell transmit simultaneously.5

Fig. 1. S–D paths passing through the shaded cell.

Fig. 2. Grouping of interfering cells in the 25-TDMA scheme. The first layer represents the outer eight shaded cells.

Our routing protocol consists of two transmission modes, i.e., Modes 1 and 2, where Mode 2 is used for the last two hops to the destination and Mode 1 is used for all other hops (refer to Fig. 1 for the brief operation of two modes).6

Mode 1: We use an example in Fig. 3 to describe this mode. Transmitting nodes in Cell A send packets simultaneously, where one of those can be either source \( S_1 \) or relay node \( R_2 \). A relay node that successfully decodes the packet and is two (Cell B) or three (Cell C) cells apart from the transmitter horizontally (or vertically), for example \( R_1 \) or \( R_3 \) in Fig. 3, is arbitrarily chosen for the next hop. If there is no such node, then an outage occurs, i.e., none of the nodes satisfies \( \text{SINR} \geq \eta \) in the cells. We do not assume any retransmission scheme in our case since we will make the outage probability negligibly small. If there are more than one candidate relay, then we choose one among them arbitrarily. Note that the multiuser diversity gain is roughly equal to the logarithm of the number of nodes in Cells B and C, which will be rigorously analyzed in the next section. We perform Mode 1 until the last two hops to the destination, and then switch to Mode 2. The reason why we hop either two or three cells at a time is because 1) hopping to an immediate neighbor cell can create huge interference to a receiving node near the boundary of the two adjacent cells and 2) always hopping by two cells is not good since it partitions the cells into two groups, even and odd, and a packet can never be exchanged between the two groups.

Mode 2: For the last two hops to the destination, Mode 2 is used. If we use Mode 1 for the last hop, we cannot get any opportunistic gain since the destination is predetermined. Hence, 3Alternatively, a timer-based strategy can be used for selecting the transmitter for the next hop [30].

4Since our aim is to study the performance in the limit of infinite packet length under the block fading model, if the packet length scales fast enough in \( n_t \), then we may conclude that these signaling messages have a negligible overhead.

5Under our opportunistic routing protocol, 25-TDMA scheme is used 1) to guarantee that there are no transmitting and receiving nodes near the boundary of two adjacent cells and 2) to avoid a partitioning problem, which will be discussed later in this section.

6Even for the case where only one hop is needed between an S–D pair, we can artificially introduce an additional hop so that there are at least two hops for every S–D pair.

7By hopping by one cell, the distance between a receiving node and an interfering node can be arbitrarily small.
we use the following two-step procedure for Mode 2. We use
the example in Fig. 4 to explain this mode.

• **Step 1:** In this step, a node in Cell D or E (e.g., $R_4$ or $R_5$
in Fig. 4) transmits its packet, whose signal reaches Cell F.
This is similar to what happens in Mode 1 except that we
are seeing this from Cell F’s perspective. Assuming that
there exist $m$ nodes in Cell F, we arbitrarily partition Cell F
into $\sqrt{m}$ subcells of equal size, i.e., there are roughly $\sqrt{m}$
nodes in each subcell. One node is then opportunistically
chosen among the nodes that received the packet correctly
in each subcell. Therefore, $\sqrt{m}$ nodes are chosen in Cell F
as potential relays for the packet.

• **Step 2:** In Step 2, which corresponds to the last hop, the
final destination in Cell G or H (e.g., $D_1$ or $D_2$ in Fig. 4)
sends a probing packet, i.e., short signaling message, to
see which one of the $\sqrt{m}$ selected relay nodes in each cell
will be the transmitter for the next hop whose channel link
guarantees a successful packet transmission. Finally, the
packet from the selected relay node in cell F is transmitted
to the final destination.

Although there are only $\sqrt{m}$ candidate nodes in each cell in
Mode 2, whereas there were $m$ nodes in Mode 1, this does not
affect the scaling law since the multiuser diversity gain is loga-
rithmic in $m$ and $\log(\sqrt{m}) = \frac{1}{2}\log m$.

**B. Nonopportunistic Routing**

In this case, a plain multihop transmission [1], [8] is performed with a predetermined path for each S–D pair consisting
of a source, a destination, and a set of relaying nodes.
Therefore, there is no opportunistic gain. The whole area is also di-
vided into $1/A_s(n)$ cells with per-cell area $A_s(n)$ and one trans-
mitter in a cell is arbitrarily chosen while transmitting at a fixed
data rate $R > 0$ independent of $n$. We assume the shortest path
routing and the 9-TDMA scheme as in [1] and [8]. However,
even if interference is carefully controlled, a transmission may fail due to fading, causing outages. In this paper, we simply
assume that for the event that an outage occurs (i.e., $\log(1 +\sinr) < R$) for a certain hop, such an event is not counted as
outage, which will give an upper bound on the performance.

**IV. POWER–DELAY–THROUGHPUT TRADEOFF**

Our goal in this section is to analyze the power–
delay–throughput tradeoffs with and without opportunistic
routing. Provided that per-node transmission rate $R > 0$ is
given by a constant independent of $n$, we will show later that
there exists a tradeoff among scaling parameters $M(n)$, $P(n)$,
and $D(n)$ for the two routing protocols that we take into ac-
count. By assuming the per-node rate of $R$, the tradeoff among
the four parameters $T(n)$, $M(n)$, $P(n)$, and $D(n)$ is thus
essentially reduced to the tradeoff among the three parameters
$M(n)$, $P(n)$, and $D(n)$ such that any one of them can be
changed freely, which in turn determines the other two. Note
that with a constant rate $R$, the parameter $M(n)$ is proportional
to the total throughput $T(n)$ since $T(n) = \Theta(M(n))$ if there
is no outage. Note that different protocols will lead to different
power–delay–throughput tradeoffs.

If more power is available, then per-hop distance can be ex-
tended. Since the path-loss exponent $\alpha$ is greater than 2, the
required power increases at least quadratically in the per-hop
distance. On the other hand, the total power consumption of
multihop transmission is linear in the number of hops per S–D
pair. Therefore, it seems advantageous to transmit to the nearest
neighbor nodes if we want to minimize the total power. How-
ever, this comes at the cost of increased delay due to more hops.
In the following sections, we first show that there exists a funda-
mental tradeoff between the total transmission power consump-
tion per S–D pair, the average delay per S–D pair, and the total
throughput, and then show that there is a net improvement in the
overall power–delay tradeoff when our opportunistic routing is
utilized in the network.

**A. Opportunistic Routing**

The relationship among the three parameters $M(n)$, $P(n)$,
and $D(n)$ is derived under the opportunistic routing protocol
described above. More specifically, we are interested in how
many S–D pairs, denoted by $M(n)$, can be active simulta-
neously while maintaining a constant transmission rate $R$ per S–D
pair. In the following, we mainly focus on Mode 1 since Mode
2 can be similarly analyzed with a slight modification. First,
let $\text{SINR}_k^{(m, l)}$ denote the SINR value seen by receiver $k(m, l)$ for the $l$th hop of the $m$th S–D pair, where $l \in \mathcal{H}_m$ and $m \in \{1, \ldots, M(n)\}$. Here, $\mathcal{H}_m = \{1, 2, \ldots, d_m D(n)\}$ denotes the set of hops for the $m$th S–D path, where $d_m$ is a positive parameter that scales as $O(1)$. Then, we have

$$\text{SINR}_k^{(m, l)} = \frac{P_r^{(m, l)}}{N_0 + P_I^{(m, l)}};$$

where $P_r^{(m, l)}$ and $P_I^{(m, l)}$ denote the received signal power at node $k(m, l)$ from the desired transmitter $i(m, l)$ for the $l$th hop of the $m$th S–D pair and the total interference power at node $k(m, l)$ from all interfering nodes, respectively. Specifically, they are given by

$$P_r^{(m, l)} = \left|h_{k(m, l)i(m, l)}\right|^2 \frac{P(n)}{D(n)}$$

and

$$P_I^{(m, l)} = \sum_{i' \in I \setminus \{i(m, l)\}} \left|h_{k(m, l)i'}\right|^2 \frac{P(n)}{D(n)},$$

respectively. Here, $I \subset \{1, \ldots, n\}$ is the set of simultaneously transmitting nodes. Before establishing our tradeoff results, we start from the following lemma, which shows lower and upper bounds on the number of nodes in each cell available as potential relays.

**Lemma 1:** Let $N_\beta(n)$ denote the number of nodes in cell $\beta \in \{1, \ldots, 1/A_\beta(n)\}$. If $A_\beta(n) = \omega(\log n/n)$, then $N_\beta(n)$ is between $\left((1 - \delta_0) A_\beta(n), (1 + \delta_0) A_\beta(n)\right)$, i.e., $\Theta(A_\beta(n))$, w.h.p. for a constant $0 < \delta_0 < 1$ independent of $n$.

The proof of this lemma is given in [11]. In a similar fashion, the number of nodes inside each subcell defined in Mode 2 is between $\left((1 - \delta_0) \sqrt{A_\beta(n)}, (1 + \delta_0) \sqrt{A_\beta(n)}\right)$ w.h.p. Note that the upper and lower bounds on $N_\beta(n)$ are relative to the cell index $\beta$. We now turn our attention to quantifying the amount of interference in our schemes in the following two lemmas.

**Lemma 2:** If $D(n) = o(\sqrt{n/\log n})$ and $D(n) = o(\delta_1^{M(n)}/D(n))$ for a sufficiently small $\delta_1 > 1$, then the number of S–D paths simultaneously passing through each cell is given by $\Theta(M(n)/D(n))$ w.h.p.

**Proof:** This proof technique is similar to that of [8], but a more general result is provided for the case where the size of each cell (or equivalently, the average delay $D(n)$) can be controlled systematically and $M(n)$ scales as a function of $n$. Let $C_m^\beta$ denote an indicator function whose value is one if the path of the $m$th S–D pair passes through a fixed cell $\beta$ and is zero otherwise, where $m \in \{1, \ldots, M(n)\}$ and $\beta \in \{1, \ldots, 1/A_\beta(n)\}$. The total number of paths passing through the cell $\beta$ is given by $C_m^\beta = \sum_{m=1}^{M(n)} C_m^\beta$, which is the sum of $M(n)$ independent and identically distributed (i.i.d.) Bernoulli random variables with probability

$$Pr\left\{C_m^\beta \neq 1\right\} = \Theta(D(n)A_\beta(n)),$$

where the expectation is taken over the matching of S–D pairs as well as the node placement. This is because $M(n)$ S–D pairs are randomly located with uniform distribution on the unit square. Hence, for any constant $0 < \delta_2 \leq 2e - 1$, we get the following:

$$P\{C^\beta > (1 + \delta_2)\Theta(D(n)A_\beta(n))\} \leq \exp\left(\frac{E[C^\beta]}{4}\right)$$

from the Chernoff bound [31]. By computing the following expectation

$$E[C^\beta] = c_0 M(n)/D(n)A_\beta(n) = c_1 \frac{M(n)}{D(n)},$$

where $c_0$ and $c_1$ are some positive constants independent of $n$, we have

$$P\{C^\beta \leq (1 + \delta_2)\Theta(D(n)A_\beta(n))\} \geq 1 - \exp\left(-\frac{c_1 \delta_2^2 M(n)}{4D(n)}\right).$$

Similarly, by the Chernoff bound [31], it follows that

$$P\{C^\beta \geq (1 - \delta_2)\Theta(D(n)A_\beta(n))\} \geq 1 - \exp\left(-\frac{c_1 \delta_2^2 M(n)}{2D(n)}\right),$$

thereby yielding

$$P\{1 - \delta_2\Theta(D(n)A_\beta(n)) \geq C^\beta \geq (1 + \delta_2)\Theta(D(n)A_\beta(n))\} \leq 1 - c_2 D(n)^2 \exp\left(-\frac{c_1 \delta_2^2 M(n)}{4D(n)}\right).$$

Due to the fact that there are $1/A_\beta(n)$ cells in the network, by applying the union bound over $1/A_\beta(n)$ cells, it follows that the number of S–D paths passing through each cell is between $(c_3(1 - \delta_2) M(n)/D(n), c_1(1 + \delta_2) M(n)/D(n))$ with probability of at least

$$1 - c_2 D(n)^2 \exp\left(-\frac{c_1 \delta_2^2 M(n)}{4D(n)}\right)$$

for constant $c_2 > 0$ independent of $n$. This tends to one as $\delta_1^{M(n)/D(n)}$ goes to infinity, i.e., $D(n)\delta_1^{M(n)/D(n)} = o(1)$, where $\delta_1$ is a constant satisfying $1 < \delta_1 < e^{c_3 \delta_2^2/8}$. This completes the proof of this lemma.

**Lemma 3:** Suppose $D(n) = o(\sqrt{n/\log n})$, $D(n) = o(n^{-1} \delta_3^{M(n)/D(n)})$, and $e > 2$, where $\delta_3 > 1$ is a sufficiently small constant. When the 25-TDMA scheme is used, the total interference power $P_r^* k$ at receiving node $k$ from simultaneously transmitting nodes is given by

$$O(P(n)M(n)/D(n)^{n-2})$$

with probability of at least

$$1 - n D(n)\delta_3^{M(n)/D(n)} \exp\left(-c_3 M(n)/D(n)\right)$$

for constant $c_3 > 0$ independent of $n$. Equation (6) tends to one as $n$ increases and the expectation $E[P_r^* k]$ of $P_r^* k$ is given by

$$E[P_r^* k] = \Theta(P(n)M(n)/D(n)^{n-2}).$$
The proof of this lemma is presented in Appendix A. Note that $P^*_{I}$ depends on the path loss exponent $\alpha$.

Now to simply find a lower bound on the throughput, suppose that the threshold value $\eta$ is set to 1.8 Let us focus on the $m$th S–D pair, where $m \in \{1, \ldots, M(n)\}$. Note that a packet from the $m$th source passes through the $m$th S–D pair’s routing path that consists of the set $\mathcal{H}_m = \{1, 2, \ldots, d_m, D(n)\}$ of hops. Accordingly, if the condition $\text{SINR} \geq 1 = \eta$ is not guaranteed for at least one among $d_m, D(n)$ hops of the path, then the data transmission for the $m$th S–D pair will fail, causing outages. To analyze the achievable throughput, it is thus important to examine the probability that the source’s packet is successfully delivered to the final destination node while satisfying $\text{SINR} \geq 1$ for all hops $l \in \mathcal{H}_m$. To be concrete, let $A_m$ denote the event that there is no outage for the $m$th S–D pair, i.e., the event that the condition $\text{SINR}_k^{(m)} \geq 1$ holds for at least one receiver $k(m, l)$ for hop all hops $l \in \mathcal{H}_m$ of the $m$th S–D pair. Here, it follows that $k(m, l) \in \{1, \ldots, N_{\beta_1}(n) + N_{\beta_2}(n)\}$, where $\beta_1$ and $\beta_2$ represent the cell indices that are both two and three cells apart from the desired transmitter along the routing path, respectively. This comes from the fact that two cells are taken into account for selecting one receiving node. Since the Gaussian is the worst additive noise [32], [33], treating all the interference as Gaussian noise lower-bounds the capacity. Hence, by assuming full CSI at the receiver side, the total throughput $T(n)$ is given by

$$
T(n) \geq \sum_{m=1}^{M(n)} \Pr \{ A_m \} \\
\geq \sum_{m=1}^{M(n)} \left\{ 1 - \sum_{l=1}^{d_m, D(n)-2} \left( \Pr \{ \text{SINR}_k^{(m)} < 1 \} \right)^{1-\delta_2} \right\} \Pr \{ \text{SINR}_k^{(m)} < 1 \} \right\}^{1-\delta_2} \sqrt{A_i(n)n} \right) \\
= \Pr \{ \text{SINR}_k^{(m)} < 1 \} \right\}^{1-\delta_2} \sqrt{A_i(n)n} \right)
$$

$$
\geq \sum_{m=1}^{M(n)} \left( 1 - \sum_{l=1}^{d_m, D(n)-2} \Pr \{ \text{SINR}_k^{(m)} < 1 \} \right)^{1-\delta_2} \sqrt{A_i(n)n} \right)
$$

Here, the first inequality comes from the fact that per-node transmission rate is given by $R = \log(1 + \eta) = 1$. The second inequality holds by applying the union bound over all hops for each S–D pair, where the set $\mathcal{H}_m$ of hops is specified by $l \in \{1, \ldots, d_m, D(n)\}$ for Mode 1 and the last two hops to the destination (i.e., $l \in \{d_m, D(n)-1, d_m, D(n)\}$) for Mode 2. Note that Lemma 1 is used to compute the minimum number of nodes in each cell (or in each subcell). In order to further compute the right-hand side of (8), we need to know the distribution of the SINR, which is difficult to obtain for a general class of channel models consisting of both geometric and fading effects. Instead, in [34], asymptotic upper and lower bounds on the cumulative distribution function (CDF) of SINR were characterized.

In this paper, as mentioned earlier, we assume the transmit power in (2), which makes the analysis of scaling laws much simpler. Then, using (7) in Lemma 3 and (2), it follows that the average total interference power $\mathbb{E} \left[ P^k_{I}^{(m, l)} \right]$ at receiving node $k(m, l)$ ($l \in \mathcal{H}_m$ and $m \in \{1, \ldots, M(n)\}$) becomes $\Theta(1)$, which is the best situation we can hope for to maintain the fixed transmission rate $R > 0$ for each hop. This is because if $\mathbb{E} \left[ P^k_{I}^{(m, l)} \right]$ is not $O(1)$, then we can scale down all transmit powers proportionally such that $\mathbb{E} \left[ P^k_{I}^{(m, l)} \right] = \Theta(1)$ without loss of optimality in scaling. This is because the received signal power $R^k_{I}^{(m, l)}$ from the desired transmitter should be $\Theta \left( \mathbb{E} \left[ P^k_{I}^{(m, l)} \right] \right)$ to maintain a fixed rate $R$ per S–D pair and having such higher power from both the signal and the interference is unnecessary. On the other hand, if $\mathbb{E} \left[ P^k_{I}^{(m, l)} \right] = o(1)$, then it follows that $\text{SINR}_k^{(m, l)} = \Theta \left( \mathbb{E} \left[ P^k_{I}^{(m, l)} \right] \right)$. We can thus scale up all transmit powers proportionally such that $\mathbb{E} \left[ P^k_{I}^{(m, l)} \right] = \Theta(1)$ in order to increase the SINR value, resulting in an improved per-node transmission rate. As a consequence, it is possible to find the CDF of the SINR in (8) when our opportunistic routing is utilized. Let $\mathcal{A}_I$ denote the event that $P^k_{I} = O(1)$ holds for receiving node $k$ in the network. By using (1), (3), (4), and the condition $D(n) = o(n^{-1}M(n)^{\alpha}D(n))$ in Lemma 3, we then have

$$
\Pr \{ \text{SINR}_k^{(m, l)} < 1 \} = \Pr \left\{ \frac{h_k(m, l)}{P^k_{I}} \frac{P(n)}{D(n)} < N_0 + \frac{P^k_{I}}{D(n)} \right\} < 1
$$

$$
\leq 1 - \Pr \left\{ h_k(m, l)P^k_{I} \frac{P(n)}{D(n)} \geq c_4 \right\} \Pr \{ A_I \}
$$

$$
= 1 - \exp \left( -\frac{c_5}{P(n)D(n)^{\alpha}} \right) \Pr \{ A_I \}
$$

$$
\leq 1 - \exp \left( -\frac{c_5}{P(n)D(n)^{\alpha}} \right)
$$

$$
\exp \left( -\frac{h_k(m, l)}{P^k_{I}} \frac{P(n)}{D(n)} \right) \Pr \{ A_I \}
$$

$$
= 1 - c_6 \exp \left( -\frac{c_6}{P(n)D(n)^{\alpha}} \right)
$$

Here, the second equality comes from the fact that per-hop distance is given by $\Theta(1/D(n))$. The third equality holds since the squared channel gain $g_k(m, l) = \frac{M(n)}{D(n)}$ follows the chi-square distribution

8If $\eta$ is optimized, then the achievable rates can be slightly improved. However, for analytical convenience, we just assume $\eta = 1$. 

with two degrees of freedom. The third inequality comes from (2) and (6). The last equality holds since it follows that
\[
1 - nD(n)\frac{M(n)}{D(n)} \exp \left( -c_3 \frac{M(n)}{D(n)} \right) = \Theta(1)
\]
under the condition \( D(n) = o(n^{-1/3}M(n)/D(n)) \). Note that the upper bound on the probability \( \Pr \{ \text{SINR}_k^m < 1 \} \) is identical for all hops \( l \in \mathcal{H}_n \), since it does not depend on \( l \). Now we are ready to derive the scaling laws for \( P(n) \), \( D(n) \), and \( T(n) \) in terms of \( M(n) \) by using (2), (8), and (9).

**Theorem 1:** Suppose that \( P(n) = \Theta(M(n)) \), transmission rate \( R \) per S–D pair is a positive constant, and \( D(n) = o(n^{-\delta}M(n)/D(n)) \), where \( \delta > 1 \) is a sufficiently small constant. If \( M(n) = O(n^{1/2-\epsilon}) \) and \( M(n) = \Omega(\log n) \), then the opportunistic routing achieves the power
\[
P(n) = \Theta \left( \frac{M(n)^{\alpha+1}}{(\log n)^{\alpha+5}} \right),
\]
the delay
\[
D(n) = \Theta \left( \frac{M(n)}{\log n} \right),
\]
and the total throughput \( T(n) = \Omega(M(n)) \) w.h.p., where \( \epsilon > 0 \) is an arbitrarily small constant.

**Proof:** By substituting (9) into (8), the total throughput \( T(n) \) can be lower-bounded by
\[
T(n) \geq \sum_{m=1}^{M(n)} \left\{ 1 - \left( d_m D(n) + (1 + \delta_0) \sqrt{A_x(n)n} \right) \right. \\
\cdot \left. \left( 1 - c_6 \exp \left( -c_5 \frac{e_0}{P(n)D(n)^{\alpha-1}} \right) \right) \right\}^{1-\delta_2} \sqrt{A_x(n)n}
\]
\[
\geq M(n) \left\{ 1 - \left( \hat{D}(n) + 2 \sqrt{A_x(n)n} \right) \right. \\
\cdot \left. \left( 1 - c_6 \exp \left( -c_5 \frac{e_0}{P(n)D(n)^{\alpha-1}} \right) \right) \right\}^{1-\delta_2} \sqrt{A_x(n)n}
\]
where \( \hat{D}(n) = \max\{d_1, \ldots, d_M\}D(n) \). To guarantee \( T(n) = \Omega(M(n)) \) w.h.p. with no outage for transmissions, we thus need the following equality:
\[
\left( \hat{D}(n) + 2 \sqrt{A_x(n)n} \right) \\
\cdot \left( 1 - c_6 \exp \left( -c_5 \frac{e_0}{P(n)D(n)^{\alpha-1}} \right) \right) = \epsilon_0
\]
for an arbitrarily small \( \epsilon_0 > 0 \). Then, it follows that
\[
\max \left\{ \frac{n}{D(n)^{\gamma}}, \sqrt{\frac{n}{D(n)^{\gamma}}} \right\} \left( 1 - \delta_0, \sqrt{n^{\gamma}} \right) = \Theta(1)
\]
which yields
\[
\begin{align*}
P(n)D(n)^{\alpha-1} & \log \left( \frac{\sqrt{n}}{D(n)\log n} \right) = \Theta(1), \quad \text{if } D(n) = o(n^{1/4}) \\
P(n)D(n)^{\alpha-1} & \log \left( \frac{\sqrt{n}}{D(n)\log D(n)} \right) = \Theta(1), \quad \text{if } D(n) = \Omega(n^{1/4}).
\end{align*}
\]
After some calculation, using (2) and (12), we obtain
\[
M(n) = \Theta \left( (P(n)M(n))^{\frac{1}{\alpha+2}} \log \left( \frac{\sqrt{n}(P(n)M(n))^{\frac{1}{\alpha+2}}}{\log n} \right) \right)
\]
and
\[
M(n) = \Theta \left( D(n) \log \left( \frac{\sqrt{n}}{D(n)\log D(n)} \right) \right).
\]
From (13) and the condition \( D(n) = o(n^{-1}M(n)/D(n)) \), it follows that
\[
D(n) = O \left( \frac{n^{1/2-\epsilon}}{\log n} \right)
\]
and
\[
M(n) = O \left( n^{1/2-\epsilon} \right)
\]
for an arbitrarily small \( \epsilon > 0 \), and hence, we have
\[
M(n) = \Theta \left( (P(n)M(n))^{\frac{1}{\alpha+2}} \log n \right)
\]
and
\[
M(n) = \Theta \left( D(n) \log n \right)
\]
under the constraints (14) and (15), finally resulting in (10) and (11). Let \( \delta = \min\{\delta_1, \delta_3\} \), where \( \delta_1 \) and \( \delta_3 \) are shown in Lemmas 2 and 3, respectively. If we choose a constant \( \delta_4 \geq 3/(2 \log \delta) \), independent of \( n \), satisfying
\[
M(n) = \delta_4 \log n,
\]
then it is seen that the condition \( D(n) = o(n^{-1}M(n)/D(n)) \) always holds from (11). We also have \( M(n) = \Omega(\log n) \) due to (11). This completes the proof of this theorem.

**B. Nonopportunistic Routing**

In this section, the scaling result of nonopportunistic routing is shown for comparison. As addressed before, the total interference power \( P_I^k \) at receiving node \( k \) needs to be \( O(1) \), and it thus follows that \( P(n)M(n)D(n)^{\alpha-2} = \Theta(1) \) due to Lemma
3 and (2). In this case, we investigate how the delay \( D(n) \) and the power \( P(n) \) scale when there are \( M(n) \) simultaneously active S–D pairs, while maintaining a constant \( R > 0 \), as in Section IV-A. The power–delay–throughput tradeoff is derived in the following theorem.

**Theorem 2:** Suppose that \( P(n) = \Theta(M(n)^{-\alpha+2}) \) for \( \alpha > 2 \) and transmission rate \( R \) per S–D pair is a positive constant. If \( M(n) = \Omega(n^{1/2-\epsilon}) \) and \( M(n)^2 = \Omega(|\log n|) \) for an arbitrarily small \( \epsilon > 0 \), then the nonopportunistic routing achieves the power

\[
P(n) = \Theta(M(n)^{-\alpha+1}),
\]

the delay

\[
D(n) = \Theta(M(n)),
\]

and the total throughput \( T(n) = \Theta(M(n)) \).

The proof of this lemma almost follows the same line as that of Theorem 1. Note that there is no logarithmic term in the two equations shown above. We also remark that using (16) and (17) results in the relationship

\[
P(n) = \Theta(D(n)^{-\alpha+1})
\]

between \( P(n) \) and \( D(n) \).

**C. Performance Comparison**

Now we show that the opportunistic routing exhibits a net improvement in overall power–delay tradeoff over the conventional nonopportunistic routing. Figs. 5 and 6 show how the power \( P(n) \) and the delay \( D(n) \) scale with respect to the number \( M(n) \) of simultaneously active S–D pairs, corresponding to the total throughput \( T(n) \). \( R_o \) and \( R_{ao} \) denote the scaling curves with and without opportunistic routing, respectively. We only take into account the range of \( M(n) \) between \( \log n \) and \( n^{1/2-\epsilon} \) for an arbitrarily small \( \epsilon > 0 \), which is the operating regimes in our work, due to various constraints that we assume in the model. Hence, the multiuser diversity gain may not be guaranteed if \( M(n) \) scales faster than \( n^{1/2-\epsilon} \) for a vanishingly small \( \epsilon > 0 \) (e.g., it is shown in [7] that when \( M(n) = \Theta(\sqrt{n}) \), the benefit of fading cannot be exploited in terms of scaling laws). We observe that \( P(n) \) decreases while \( D(n) \) increases as we have more active S–D pairs in both schemes. This is because we assume a fixed transmission rate \( R > 0 \) independent of \( n \), which implies that for receiver \( k \in \{1, \ldots, n\} \), the power \( P_{1,k}^{(m)} \) and \( P_{1,k}^{(m,0)} \) need to be \( \Omega(1) \) and \( O(1) \), respectively, as mentioned earlier. Then, to maintain the interference level \( E_{k}^{(m,0)} \) at \( O(1) \) as \( M(n) \) increases, more hops per S–D pair are needed, i.e., per-hop distance needs to be increased. Hence, from the above argument, we may conclude that the power is reduced at the expense of the increased delay, and therefore, there is a fundamental tradeoff between the two scaling parameters \( P(n) \) and \( D(n) \). Furthermore, it is seen that utilizing the opportunistic routing increases the power compared to the nonopportunistic routing case, but it can reduce the delay significantly. Thus, it is not clear whether our opportunistic routing is beneficial or not from Figs. 5 and 6. However, if we plot the power \( P(n) \) versus the delay \( D(n) \) as in Fig. 7, then it can be clearly seen that opportunistic routing scheme \( (R_o) \) exhibits a better overall power–delay tradeoff than that of nonopportunistic routing scheme \( (R_{ao}) \), while providing a logarithmic boost in the scaling law. For example, if the delay \( D(n) \) is given by \( \log n \), then the power \( P(n) \) is reduced \( \log n \) times by using the opportunistic routing. In this case, it is further seen from Fig. 6 that the number \( M(n) \) of simultaneously supportable S–D pairs is improved by \( \log n \), i.e., logarithmic boost on the total throughput \( T(n) \). This gain comes from the fact that the received signal power increases due to the multiuser diversity gain based on the use of opportunistic routing, which allows more simultaneous transmissions since more interference can be tolerated.

**V. CONCLUSION**

The scaling behavior of large ad hoc networks using opportunistic routing protocol in the presence of fading has been char-
acterized. Specifically, it was shown how the power, delay, and total throughput scale as the number of S–D pairs increases, while maintaining a constant per-node transmission rate. We proved that for the range of simultaneously active S–D pairs between \( \log n \) and \( n^{1/2-\epsilon} \) for an arbitrarily small \( \epsilon > 0 \), our parallel opportunistic routing exhibits a net improvement in overall power–delay tradeoff over the conventional scheme employing nonopportunistic routing, while providing up to a \( \log n \) boost in the scaling law due to the multiuser diversity gain.

**APPENDIX**

A) Proof of Lemma 3: There are \( 8l \) interfering cells in the \( l^{th} \) layer of 25-TDMA (refer to Fig. 2). Let \( P_{I,(l)}^k \) denote the total interference power at a fixed receiving node \( k \) from simultaneously transmitting nodes in the \( l^{th} \) layer, where \( l \in \{1, \ldots, \bar{D}(n)\} \) for some constant \( \bar{D} > 0 \) independent of \( n \). Note that the distance between a receiving node and an interfering node in the \( l^{th} \) layer is between \((5l-4)\sqrt{A_x(n)}\), thereby providing a lower bound on \( P_{I,(l)}^k \). By Lemma 2, the number of simultaneously transmitters in each cell is given by \( \Theta(M(n)/D(n)) \), w.h.p. Thus, from (1) and (5), the expectation \( E[P_{I,(l)}^k] \) is lower-bounded by

\[
E[P_{I,(l)}^k] \geq \frac{c_7(8l)P(n)/D(n)}{(5l-4)\sqrt{A_x(n)}\alpha} \frac{M(n)}{D(n)} E\left[ g_{k,i}^2 \right]
\]

for any nodes \( i \) and \( k \), where \( c_7 \) and \( c_8 \) are some positive constants independent of \( n \). Similarly by taking \((5l-4)\sqrt{A_x(n)}\) for the Euclidean distance between a receiver and simultaneously transmitting nodes in the \( l^{th} \) layer, we obtain

\[
E[P_{I,(l)}^k] \leq \frac{c_8 P(n)M(n)D(n)^{\alpha-2}}{(5l-4)^{\alpha-1}}
\]

for constant \( c_9 \) independent of \( n \), which results in

\[
E[P_{I,(l)}^k] = \Theta\left(\frac{P(n)M(n)D(n)^{\alpha-2}}{(5l-4)^{\alpha-1}}\right)
\]

Moreover, let \( P_{I,(0)}^k \) denote the total interference power from other transmitting nodes in the cell including a desired transmitter (see the shaded cell located in the center in Fig. 2). Then as above, we have \( E[P_{I,(0)}^k] = \Theta(P(n)M(n)D(n)^{\alpha-2}) \), and hence, it follows that \( E[P_{I,(l)}^k] = \Theta(P(n)M(n)D(n)^{\alpha-2}) \) since \( \sum_i 1/(5l-4)^{\alpha-1} \) is bounded by a certain constant for \( \alpha > 2 \).

Now we focus on computing the probability \( \Pr\left\{ P_{I,(l)}^k > (1 + \delta_5)E[P_{I,(l)}^k]\right\} \) by using the Chernoff bound, where \( \delta_5 > 1 \) is a constant independent of \( n \). From the fact that \( r_{k,i} = \Theta(r_{k,i'}) \) for all transmitting nodes \( i \) and \( i' \) in the same layer and receiving node \( k \), we have

\[
\Pr\left\{ P_{I,(l)}^k > (1 + \delta_5)E[P_{I,(l)}^k]\right\}
\]

\[
\leq \Pr\left\{ \sum_{i \in I_l} \frac{|g_{k,i}|^2}{P_{I,(l)}^k} > (1 + \delta_5)E\left[ \sum_{i \in I_l} \frac{g_{k,i}}{r_{k,i}^{\alpha}} \right]^2 \right\}
\]

\[
\leq \Pr\left\{ \sum_{i \in I_l} \frac{|g_{k,i}|^2}{(5l-4)\sqrt{A_x(n)}\alpha} > (1 + \delta_5)E\left[ \sum_{i \in I_l} \frac{g_{k,i}}{r_{k,i}^{\alpha}} \right]^2 \right\}
\]

\[
= \Pr\left\{ \sum_{i \in I_l} |g_{k,i}|^2 > c_{10}(8l)(1 + \delta_5)M(n)/D(n) \right\}
\]

for constant \( c_{10} > 0 \) independent of \( n \). Here, \( I_l \) is the set of simultaneously interfering nodes in the \( l^{th} \) layer. Since the Chernoff bound for the sum of i.i.d. chi-square random variables \( |g_{k,i}|^2 \) with two degrees of freedom is given by [35], for a certain constant \( 0 < \epsilon_1 < \delta_5 - \log(1 + \delta_5) \), (18) can be upper-bounded by

\[
\Pr\left\{ P_{I,(l)}^k > (1 + \delta_5)E[P_{I,(l)}^k]\right\} \leq (1 + \delta_5)^{c_{10}(8l)M(n)/D(n)(\delta_5 - \epsilon_1)}
\]

\[
\leq (1 + \delta_5)^{8c_{10}M(n)/D(n)(\delta_5 - \epsilon_1)}
\]

which tends to zero as \( M(n)/D(n) = \omega(1) \). We remark that the event \( P_{I,(l)}^k > (1 + \delta_5)E[P_{I,(l)}^k] \) for all \( l \in \{0, \ldots, \bar{D}(n)\} \) is a sufficient condition for the event \( P_{I,0}^k \leq (1 + \delta_5)E[P_{I,0}^k] \). Thus, by the union bound over all layers (including the cell with a desired transmitter), we have the following inequality:

\[
\Pr\left\{ P_{I,0}^k \leq (1 + \delta_5)E[P_{I,0}^k] \text{ for all } l \in \{0, \ldots, \bar{D}(n)\} \right\}
\]

\[
\geq 1 - \sum_{l=0}^{\bar{D}(n)} \Pr\left\{ P_{I,(l)}^k > (1 + \delta_5)E[P_{I,(l)}^k]\right\}
\]

\[
= 1 - (1 + \bar{D}(n))(1 + \delta_5)\frac{M(n)}{D(n)} \exp\left( -8c_{10} M(n)/D(n)(\delta_5 - \epsilon_1) \right)
\]

where the first inequality holds since there exist \( \bar{D}(n) \) layers, for some \( \bar{D} > 0 \) independent of \( n \). Finally, using the union bound over \( n \) nodes in the network yields that the total interference power \( P_k^n \) at receiving node \( k \) is given by \( O(E[P_{I,0}^k]) \) (or \( O(P(n)M(n)/D(n)^{\alpha-2}) \)) with probability of at least

\[
1 - 2\bar{D}(n)(1 + \delta_5)\frac{M(n)}{D(n)} \exp\left( -8c_{10} M(n)/D(n)(\delta_5 - \epsilon_1) \right)
\]
which tends to one as $n D(n)\delta_2^{M(n)\frac{M(n)}{D(n)}} = o(1)$ for a certain constant $1 < \delta_2 < \left(\frac{\alpha\delta_1 - 1}{1 + \delta_1}\right)^{\frac{M\alpha}{\delta_2}}$.

This completes the proof of this lemma.

REFERENCES

[1] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[2] D. E. Knuth, “Big Omicron and big Omega and big Theta,” *ACM SIGACT News*, vol. 8, pp. 18–24, Apr.–Jun. 1976.

[3] P. Gupta and P. R. Kumar, “Towards an information theory of large networks: an achievable rate region,” *IEEE Trans. Inf. Theory*, vol. 49, no. 8, pp. 1877–1894, Aug. 2003.

[4] O. Dousse, M. Franceschetti, and P. Thiran, “On the throughput scaling of wireless relay networks,” *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2756–2761, Jun. 2006.

[5] M. Franceschetti, O. Dousse, D. N. C. Tse, and P. Thiran, “Closing the gap in the capacity of wireless networks via percolation theory,” *IEEE Trans. Inf. Theory*, vol. 53, no. 3, pp. 1009–1018, Mar. 2007.

[6] F. Xue, L.-L. Xie, and P. R. Kumar, “The transport capacity of wireless networks over fading channels,” *IEEE Trans. Inf. Theory*, vol. 51, no. 3, pp. 834–847, Mar. 2005.

[7] Y. Nebat, R. L. Cruz, and S. Bhardwaj, “The capacity of wireless networks in nonergodic random fading,” *IEEE Trans. Inf. Theory*, vol. 55, no. 6, pp. 2478–2493, Jun. 2009.

[8] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, “Optimal throughput-delay scaling in wireless networks—Part I: The fluid model,” *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2568–2592, Jun. 2006.

[9] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, “Optimal throughput-delay scaling in wireless networks—Part II: Constant-size packets,” *IEEE Trans. Inf. Theory*, vol. 52, no. 11, pp. 5111–5116, Nov. 2006.

[10] W. J. Reed, “Transport capacity of wireless networks,” in *Proc. IEEE INFOCOM*, vol. 55, no. 9, pp. 441–450, Jul. 2008.

[11] R. Motwani and P. Raghavan, *Randomized Algorithms*. Cambridge, U.K.: Cambridge Univ. Press, 1995.

[12] D. Shah and D. Tse, “A note on multihop wireless networks,” *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2593–2594, Jun. 2006.

[13] K. Zeng and S. Nelakuditi, “On the efficacy of opportunistic routing,” in *Proc. IEEE Commun. Soc. Conf. Sens., Mesh Ad Hoc Commun. Netw.*, San Diego, CA, USA, Jun. 2007, pp. 441–450.

[14] S. Weber, J. G. Andrews, and N. Jindal, “On the effect of fading, channel inversion, and threshold scheduling on ad hoc networks,” *IEEE Trans. Inf. Theory*, vol. 53, no. 11, pp. 4127–4149, Nov. 2007.

[15] A. El Gamal and J. Mammen, “Optimal hopping in ad hoc wireless networks,” in *Proc. IEEE INFOCOM*, Barcelona, Spain, Apr. 2006, pp. 1–10.

[16] A. Ozturk, O. Lévêque, and D. N. C. Tse, “Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks,” *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3549–3572, Oct. 2007.

[17] U. Niesen, P. Gupta, and D. Shah, “On capacity scaling in arbitrary wireless networks,” *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 3959–3982, Sep. 2009.

[18] A. Jovicic, P. Viswanath, and S. R. Kulkarni, “Upper bounds to transport capacity of wireless networks,” *IEEE Trans. Inf. Theory*, vol. 56, no. 11, pp. 5121–5137, Nov. 2009.

[19] T. Towsley and J. G. Andrews, “A fluid model for wireless networks,” *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 3959–3982, Sep. 2009.

[20] M. Franceschetti, V. W. S. Wong, and H. V. Poor, “Optimistic beamforming using dumb antennas,” *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1277–1294, Jun. 2002.

[21] M. Sharif and B. Hassibi, “On the capacity of MIMO broadcast channels with partial side information,” *IEEE Trans. Inf. Theory*, vol. 51, no. 2, pp. 506–522, Feb. 2005.

[22] S. Cui, A. M. Haimovich, O. Somekh, and H. V. Poor, “Opportunistic relaying in wireless networks,” *IEEE Trans. Inf. Theory*, vol. 55, no. 1, pp. 5121–5137, Nov. 2009.

[23] C. Shen and M. P. Fitz, “Opportunistic spatial orthogonalization and its application in fading cognitive radio networks,” *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 192–199, Feb. 2011.

[24] R. Gowaikar, B. Hochwald, and B. Hassibi, “Communication over a wireless network with random connections,” *IEEE Trans. Inf. Theory*, vol. 52, no. 7, pp. 2857–2871, Jul. 2006.

[25] M. Ebrahimi, M. A. Maddah-Ali, and A. K. Khandani, “Throughput scaling laws for wireless networks with fading channels,” *IEEE Trans. Inf. Theory*, vol. 53, no. 11, pp. 4250–4254, Nov. 2007.

Won-Yong Shin (S’02–M’08) received the B.S. degree in electrical engineering from Yonsei University, Seoul, Korea, in 2002. He received the M.S. and the Ph.D. degrees in electrical engineering and computer science from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2004 and 2008, respectively.

From February 2008 to August 2008, he was a Visiting Scholar in the School of Engineering and Applied Sciences, Harvard University, Cambridge, MA. From September 2008 to August 2009, he was with the Brain Korea Institute and CHiPS at KAIST as a Postdoctoral Fellow. From August 2009 to April 2010, he was with the Lumicomm, Inc., Daejeon, Korea, as a Visiting Researcher. In May 2010, he joined Harvard University as a Postdoctoral Fellow and was promoted to an Assistant Professor. Since March 2012, he has been with the Division of Mobile Systems Engineering, College of International Studies, Dankook University, Yongin, Korea, where he is currently an Assistant Professor. His research interests are in the areas of information theory, communications, signal processing, and their applications to multiuser networking issues.

Sae-Young Chung (S’89–M’00–SM’07) received the B.S. (summa cum laude) and M.S. degrees in electrical engineering from Seoul National University, Seoul, South Korea, in 1990 and 1992, respectively, and the Ph.D. degree in electrical engineering and computer science from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2000.

From September 2000 to December 2004, he was with Airvana, Inc., Chelmsford, MA, USA. Since January 2005, he has been with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, where he is currently a KAIST Chair Professor. He has served as an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS since 2009. He is the Technical Program Co-Chair of the 2014 IEEE International Symposium on Information Theory. His research interests include network information theory, coding theory, and wireless communications.
Yong H. Lee (S’81–M’84–SM’98) was born in Seoul, Korea, on July 12, 1955. He received the B.S. and M.S. degrees in electrical engineering from Seoul National University, Seoul, Korea, in 1978 and 1980, respectively, and the Ph.D. degree in electrical engineering from the University of Pennsylvania, Philadelphia, PA, in 1984.

From 1984 to 1988, he was an Assistant Professor with the Department of Electrical and Computer Engineering, State University of New York, Buffalo, NY. Since 1989, he has been with the Department of Electrical Engineering at Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, where he is currently a Professor and the Provost of KAIST. His research activities are in the area of communication signal processing, which includes interference management, resource allocation, synchronization, estimation, and detection for code-division multiple access (CDMA), time-division multiple access (TDMA), orthogonal frequency division multiplexing (OFDM), and multiple-input multiple-output (MIMO) systems. He is also interested in designing and implementing transceivers.