Capacity of Hybrid Wireless Networks with Directional Antenna and Delay Constraint

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Abstract—We study the throughput capacity of hybrid wireless networks with a directional antenna. The hybrid wireless network consists of n randomly distributed nodes equipped with a directional antenna, and m regularly placed base stations connected by optical links. We investigate the ad hoc mode throughput capacity when each node is equipped with a directional antenna under an L-maximum-hop resource allocation. That is, a source node transmits to its destination only with the help of normal nodes within L hops. Otherwise, the transmission will be carried out in the infrastructure mode, i.e., with the help of base stations. We find that the throughput capacity of a hybrid wireless network greatly depends on the maximum hop L, the number of base stations m, and the beamwidth of directional antenna \( \theta \). Assuming the total bandwidth \( W \) bits/sec of the network is split into three parts, i.e., \( W_1 \) for ad hoc mode, \( W_2 \) for uplink in the infrastructure mode, and \( W_3 \) for downlink in the infrastructure mode. We show that the throughput capacity of the hybrid directional wireless network is \( \Theta\left(\frac{n}{W_n\log n}\right) + \Theta(mW_2) \), if \( L = \Omega\left(\frac{\sqrt{n}}{\theta^3/2 + \log^2 n}\right) \); and \( \Theta\left(\theta^2L^2 \log n \right)W_1 + \Theta(mW_2) \), if \( L = o\left(\frac{\sqrt{n}}{\theta^3/2 + \log^2 n}\right) \), respectively. Finally, we analyze the impact of \( L, m \) and \( \theta \) on the throughput capacity of the hybrid networks.

Index Terms—Capacity, Delay, Hybrid, Maximum-L-Hop, Directional Antenna.

I. INTRODUCTION

In the seminal work [1], Gupta and Kumar initiate the study of scaling laws in large ad hoc wireless networks. They assume that nodes are deployed randomly and uniformly over the surface of a sphere of unit area. Each node sends packets to its random choosing node by using multi-hop communication. All the nodes use a common transmit power level. They show that the per-node throughput capacity in random ad hoc network is \( \Theta\left(\frac{n}{\sqrt{\log n}}\right)^2 \text{bits/sec}(\text{W is the total bandwidth of the network}) \), which decreases to zero as \( n \) tends to infinity. They also provide a scheduling and routing strategy that achieves this throughput.

Following this work, researchers have studied capacity scaling laws under different assumptions or applications [2], [3], [4], [5], [6], [7], [8]. Recently, few researchers have studied the capacity of hybrid wireless networks which is composed of ad hoc mode transmission and base stations. Kozat et. al. [9] study the throughput capacity of ad hoc networks with a random flat topology under the presence of an infinite capacity infrastructure networks. They consider the case that both nodes and base stations are randomly deployed, and the number of base stations is on the same order of the number of nodes. They show that the per-node throughput capacity is \( \Theta(W/\log n) \) in random networks. Zemlianov et. al. [10] investigate the throughput capacity of hybrid wireless networks where ad hoc nodes are randomly distributed and base stations are arbitrarily placed. They show that the per-node throughput capacity depends on the number of base stations. Liu et. al. [11] study the throughput capacity of hybrid wireless networks under different network models in one-dimensional and two-dimensional with stip area. Furthermore, Pei et. al. study the throughput capacity using an L-maximum-hop routing strategy [12]. Li et. al. [13] perfect their work by giving an L-maximum-hop resource allocation strategy. Along the same lines, Gupta and Kumar gave an upper bound to the throughput capacity and constructed a matched lower bound [1]. They show that hybrid wireless networks composed of \( n \) normal nodes and \( m \) base stations have higher throughput than pure ad hoc networks under some constructions.

All the above studies investigated the throughput capacity under Omni-directional antennas. Yi et al. study the improvement of capacity in ad hoc wireless networks when a directional antenna is used [14]. They show that the capacity can increase if the directional antenna beamwidth \( \theta \) decreases, and wireless network behaves like wired network if \( \theta \) becomes small enough. Zhang et. al. also investigate the scaling law of throughput capacity of wireless ad hoc networks with phased array antenna [15]. Based on a general interference model for a directional antenna of generic antenna patterns, they show that \( \Theta(\theta) \) scalability in a throughput capacity is achievable. The main reason that it improves the throughput capacity is that using a directional antenna will mitigate the interference of source-destination pairs, which is also used in [16] to study the throughput capacity of multi-channel wireless networks with a directional antenna. There are also other research
groups that studied the throughput capacity when a directional antenna is used under different assumptions as well as different situations [17], [18].

Delay is also an important parameter in wireless ad hoc networks. There are many studies that considered the throughput capacity under some delay constraints. Toumpis et. al. [19] studied the throughput capacity under delay constraints following the same line of investigation initiated in [1] and continued in [3]. Lin et. al. [20] present a systematic methodology for studying the maximum achievable throughput capacity under given delay constraints for large mobile wireless networks. They show that the per-node throughput capacity with constant delay for the i.i.d mobility model can achieve $\Theta(n^{-1/3}/\log^{3/2} n)$. There are also others that studied the tradeoffs between throughput and delay [21], [22], [23].

In this paper, by equipping each node with a directional antenna, we study the throughput capacity of a hybrid wireless network under the $L$-maximum-hop resource allocation strategy. In our network model, a source node will transmit to its destination in ad hoc mode if the destination is at most $L$ hops away from the source. Here, the $L$-maximum-hop resource allocation strategy represents the delay constraint. They can transmit successfully if and only if each source destination node covers each other by their directional antenna beams. Otherwise, if the distance between source and destination is larger than $L$ hops, the transmission will be carried out by the infrastructure mode.

Based on the network model and the assumptions, we first study the throughput capacity of pure ad hoc mode component of the hybrid network. By using the framework of Gupta and Kumar [1], and giving a new transmission schedule and routing construction, we derive the result of pure ad hoc mode throughput capacity. Then, combining with the infrastructure mode throughput capacity, the throughput capacity of the whole hybrid network is obtained. Also, we analyze the impact of $L$, $m$ and $\theta$ on the throughput capacity of the hybrid networks and give some interesting results which could then serve as further directions to the network design.

The rest of the paper is organized as follows. In Section II, we introduce some definitions and notations. In Section III, we give the hybrid wireless network’s model. In Section IV, we analyze the lower bound and upper bound of the ad hoc mode throughput capacity and give the capacity of the hybrid networks. Finally, we conclude the paper in Section V.

### II. DEFINITIONS AND NOTATIONS

#### A. Definitions

**Throughput:** The average of the number of bits per second that can be transmitted by each node to its destination is defined as the per-node throughput. The sum of per-node throughput over all the nodes in a network is called the throughput of the network.

**Feasible Throughput:** We say that the throughput of a network, denoted by $\lambda(n)$, is feasible if there exists a spatial and temporal scheduling scheme$^3$ that yields an aggregate network throughput of $\lambda(n)$ bits/sec.

**Throughput Capacity of a Network:** Throughput capacity is the guaranteed rate that can be supported uniformly for all source destination pairs. The throughput capacity of random wireless networks is said to be of order $O(f(n))$ bits per second if there is a deterministic constant $c_1 < +\infty$ such that

$$\liminf_{n \to +\infty} P(\lambda(n) = c_1 f(n) \text{ is feasible}) < 1,$$

and is of order $\Theta(f(n))$ bits per second if there are deterministic constants $0 < c_2 < c_3 < +\infty$ such that

$$\liminf_{n \to +\infty} P(\lambda(n) = c_2 f(n) \text{ is feasible}) = 1,$$

$$\liminf_{n \to +\infty} P(\lambda(n) = c_3 f(n) \text{ is feasible}) < 1.$$  

**Delay:** The number of hops that a packet transmitted from a source to its destination.

**With High Probability:** An event $A$ happened with high probability, if $\lim_{n \to +\infty} P(A) = 1$.

#### B. Notations

To facilitate the reading, we list the major notations used in our model and analysis in Table I.

### III. HYBRID WIRELESS NETWORKS-MODEL

#### A. Network Architecture

We consider a two-dimensional hybrid wireless network on the surface of a torus with unit area [22], [23]. The method of

$^3$It means that there exists a choice of a common range $r(n)$, and a scheme to schedule transmissions and choice of routes between sources and destinations, so that the overall data transfer from source nodes to their destinations can achieve such a rate.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>NOTATIONS</th>
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<tbody>
<tr>
<td>$W$</td>
<td>The total bandwidth of the network, which means the rate of data transfer in the network, measured in bits per second</td>
</tr>
<tr>
<td>$W_1$</td>
<td>The ad hoc mode bandwidth of the network</td>
</tr>
<tr>
<td>$W_2$</td>
<td>The uplink bandwidth of infrastructure mode of the network</td>
</tr>
<tr>
<td>$W_3$</td>
<td>The downlink bandwidth of infrastructure mode of the network</td>
</tr>
<tr>
<td>$n$</td>
<td>The number of ad hoc nodes in the network</td>
</tr>
<tr>
<td>$m$</td>
<td>The number of base stations in the network</td>
</tr>
<tr>
<td>$L$</td>
<td>The maximum number of hops of the ad hoc mode transmission</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The beamwidth of a directional antenna</td>
</tr>
<tr>
<td>$r(n)$</td>
<td>The transmission range of the ad hoc node, also the radius of the directional antenna</td>
</tr>
<tr>
<td>$X_i$</td>
<td>Ad hoc node $i$ and its allocation</td>
</tr>
<tr>
<td>$\lambda(n, m)$</td>
<td>Throughput of the whole hybrid network with $n$ ad hoc nodes and $m$ base stations</td>
</tr>
<tr>
<td>$\lambda_0(n, m)$</td>
<td>Throughput of the ad hoc mode transmission</td>
</tr>
<tr>
<td>$\lambda_i(n, m)$</td>
<td>Throughput of the infrastructure mode transmission</td>
</tr>
<tr>
<td>$\lambda_0^i(n, m)$</td>
<td>Per-node throughput of the whole hybrid network with $n$ ad hoc nodes and $m$ base stations</td>
</tr>
<tr>
<td>$\lambda_i^i(n, m)$</td>
<td>Per-node throughput of the ad hoc mode transmission</td>
</tr>
<tr>
<td>$\lambda_i^i(n, m)$</td>
<td>Per-node throughput of the infrastructure mode transmission</td>
</tr>
<tr>
<td>$P$</td>
<td>The probability of an event</td>
</tr>
<tr>
<td>$E$</td>
<td>The expectation of a random variable</td>
</tr>
<tr>
<td>$L_i$</td>
<td>The line that connects two ad hoc nodes</td>
</tr>
<tr>
<td>$\cdot$</td>
<td>The Euclidean distance or just the normal distance in dimension one</td>
</tr>
</tbody>
</table>
modeling the virtual geographic area into mathematical model is widely used in the literature [24]. The architecture of the torus is constructed as following: The unit torus is divided into \((1/\sqrt{a(n)}) \times (1/\sqrt{a(n)})\) equal-sized grids \((a(n))\) is the area of the Voronoi cell defined in section IV), and label them as \(\{(i, j) : i, j = 0, 1, ..., 1/\sqrt{a(n)} - 1\}\). The adjacent cells (defined in section IV, part A) of cell \((i, j)\) are the cells \(\{(i + 1, j), (i - 1, j), (i, j + 1), (i, j - 1), (i - 1, j + 1), (i - 1, j - 1), (i + 1, j + 1), (i + 1, j - 1)\}\), where the addition and subtraction operations are performed modulo \(1/\sqrt{a(n)}\).

We can see that in the unit torus, every cell has eight adjacent cells. The assumption of torus can avoid edge effects, which otherwise complicates the analysis. However, the results derived in the paper are applicable for nodes located on an unit square as well. We also assume that the hybrid network consists of two components: an ad hoc component and an infrastructure component.

In an ad hoc component, with the same transmission range \(r(n)\), the \(n\) nodes are uniformly and independently distributed on the unit torus. The \(n\) nodes are assumed to be static i.e., non-mobile. Each node is equipped with a radio transceiver that enables the node to transmit and receive signals. At any given time, a node can either be in transmit or receive mode, but not both, i.e., half-duplex. As in [13], we choose random sender-receiver pairs so that each node is a source node for one flow and a destination node for at most \(O(1)\) flows.

In an infrastructure component, \(m\) base stations are regularly placed in the network, as shown in Fig. 1. Similar to the frequency reuse pattern in the traditional cellular networks, a 9-square-cell reuse model is formed by dividing the unit torus into small squares. Each small square is called a square-cell\(^4\) and is covered by one base station in the center. Base stations do not generate any traffic themselves. They serve purely as infrastructure, i.e., neither sources nor destinations. Furthermore, we assume each base station is connected to its adjacent base stations by optical links so that the base station to base station links have infinite capacity.

For the convenience of capacity analysis in different traffic

\(^4\)We assume \(1/\sqrt{a(n)}\) is integer for simplicity of analysis.

\(^3\)For example, if \((i,j)=(0,0)\), \(1/\sqrt{a(n)} = 8\), the adjacent cells of \((0,0)\) are \((1,0)\), \((7,0)\), \((0,1)\), \((0,7)\), \((7,1)\), \((7,7)\), \((1,1)\), \((1,7)\).

\(^2\)Note that we call it square-cell distinguish from the Voronoi cell stated in section IV.

mode (ad hoc mode and infrastructure mode), and also in order that the adopted model here is closely related to practical systems, we employ bandwidth partitioning and consider the ad hoc mode traffic and infrastructure mode traffic separately. This is because bandwidth partitioning can be implemented with the multi-channel capability provided by current radio devices, and different traffic types have different scaling behaviors.

B. Directional Antenna Model

In the study of wireless networks, there are many types of directional antenna models. In this paper, we consider the directional antenna model as shown in Fig. 2. We approximate the directional antenna as a circular sector with angle \(\theta\) and radius equal to the transmission/reception range \(r(n)\). The angle of the sector approximates the beamwidth of the antenna [14]. In reality, the directional antenna pattern consists of a mainlobe which is the direction of maximum radiation or reception and several smaller backlobes arising due to inefficiencies in antenna design. For simplicity, we ignore discussing backlobes in this paper.

In our directional model, the directional antenna gain is within the specific angle \(\theta\), which is the beamwidth of the antenna. The gain outside the beamwidth is assumed to be zero. We assume that each antenna is steerable, i.e., each node can point its antenna in any desired direction. Nodes can use their antennas for directional transmission and/or directional reception. That is, at any time, the antenna beam can only be placed to a certain direction. Thus, the probability that the beam covers a direction is \(\theta/2\pi\). We also assume each node is equipped with only one directional antenna.

It is generally well known that modeling a real directional antenna is complex, this is the main reason for using a simple directional antenna in our model. In this paper, as we will show in the following sections, the interference area of the nodes in the unit torus is the only characteristic that decided the results. Simplifying the shape of the antenna pattern will not change this property and using a complex model will not result in a fundamental change in this work, in particular on the throughput capacity analysis.

C. Receiver-based Interference Model

Based on the protocol model in [1], we propose a receiver based interference model with extensions of directional anten-
If node $X_i$ transmits to node $X_j$, the transmission is successful if the antenna beam of the two nodes $X_i$, $X_j$ will cover each other and no nodes within the region covered by $X_j$’s antenna beam will interfere with $X_j$’s reception as shown in Fig. 2. Therefore, for every other node $X_k$ simultaneously transmitting, and the guard zone $\Delta > 0$, the following condition holds.

$$
\begin{align*}
|X_k - X_j| & \geq (1 + \Delta)|X_i - X_j| \\
\text{or } X_k's \text{ beam does not cover node } X_j
\end{align*}
$$

where $X_i$ not only denotes the location of a node but refers to the node itself. Fig. 2 also shows that a transmission from node $X_k$ will not cause interference to $X_i$’s transmission since the antenna beam of $X_k$ does not cover receiver $X_j$.

**D. Resource Allocation Strategy**

There are two transmission modes in hybrid wireless networks: ad hoc mode and infrastructure mode. In an ad hoc mode, packets are forwarded from the source node to the destination node and can only be relayed by the normal nodes, i.e., without the help of base stations. While in an infrastructure mode, packets are transmitted from the source to the base station, and then forwarded to the destination.

In this paper, we consider a directional $L$-maximum-hop ($L \geq 1$) resource allocation strategy. If a destination can be reached within $L$ hops from a source under the directional transmission, then the packets can be transmitted from this source to the destination in an ad hoc mode. Otherwise, packets are transmitted in the infrastructure mode. Fig. 1 shows that packets transmit from node $X_i$ to node $X_j$ in an ad hoc mode or an infrastructure mode.

Moreover, we assume a total available bandwidth of $W$ bits/sec, which can be carried over multiple sub-channels with different frequency bands (for example multiple orthogonal channels). We divide the wireless channel so that ad hoc mode transmissions and infrastructure mode transmissions go through different sub-channels. We further divide the sub-channel for infrastructure mode transmissions into uplink and downlink parts, according to the direction of the transmissions relative to the base station.

The bandwidth assigned to intra-cell, uplink, and downlink sub-channels are $W_1$, $W_2$, and $W_3$, respectively. The transmission rates should sum to $W$, i.e., $W_1 + W_2 + W_3 = W$\textsuperscript{7}. Since the uplink has the same amount of traffic as the downlink, we have $W_2 = W_3$. Thus, $W = W_1 + 2W_2$.

**IV. CAPACITY OF HYBRID WIRELESS NETWORKS UNDER DIRECTIONAL L-MAXIMUM-HOP RESOURCE ALLOCATION STRATEGY**

In this section, under the conditions of directional antennas and $L$-maximum-hop resource allocation strategy, we derive the capacity of hybrid wireless networks. We assume all nodes are equipped with directional antennas. Based on the assumption that the transmission in the ad hoc mode, and the transmission of uplink and downlink in the infrastructure mode use different frequency bands, i.e., $W_1$, $W_2$, and $W_3$, respectively. We assume there is no interference between these three types of traffic. Since there is no interference between ad hoc mode and infrastructure mode transmissions, we can look at throughput capacity contributed by transmissions at these two modes separately (denoted ad hoc mode throughput capacity and infrastructure mode throughput capacity, respectively).

We also assume that the three transmission traffic can be carried out simultaneously and then we get the throughput capacity of the network, denoted by $\lambda(n, m)$, represented as $\lambda(n, m) = \lambda_a(n, m) + \lambda_i(n, m)$, where $\lambda_a(n, m)$ and $\lambda_i(n, m)$ denote the throughput capacity contributed by the ad hoc mode transmissions and the infrastructure mode transmissions, respectively. Also, as defined earlier, we use $\lambda^0_a(n, m)$, $\lambda^0_1(n, m)$ and $\lambda^0_i(n, m)$ to denote the corresponding per-node throughput capacity, respectively.

**A. Ad Hoc Mode Throughput Capacity**

For the ad hoc mode component, $n$ nodes are uniformly and independently distributed on a unit planar torus. We first divide the unit square into small cells with area $a(n)$ that satisfies each of them and can hold at least one node. Then, we divide the cells into different non-interfering groups using the definition of interfering neighbors (defined below). Finally, the proposed routing strategy forwards packets from cell to cell. This connects the originating cell to the destination cell carrying the nodes’ information as well as its randomly chosen end point. Based on this, we can get the achievable lower bound by following the steps described in [1], omitting the proof for some lemmas.

**Voronoi Tessellation:** Given a set of $n$ points in a plane, Voronoi tessellation divides the domain into a set of polygonal regions, the boundaries of which are the perpendicular bisectors of the lines joining the points. The Voronoi tessellation is denoted as $V_n$.

**Lemma 1:** We choose the cells to be squares as an example mainly to simplify presentation and can achieve the same result.

Then for the $n$ nodes, we can construct a Voronoi tessellation $V_n$ satisfying the following property:

- (V1) Every Voronoi cell contains a disk with radius $k_1\sqrt{\log n/n}$ for some $k_1 > 1$.
- (V2) Every Voronoi cell is contained in a disk with radius $\rho(n) = k_2\sqrt{\log n/n} = \sqrt{2a(n)}/2$ for some $k_2 > k_1$.
- (V3) Each Voronoi cell contains at least one node.
- (V4) We choose the range $r(n)$ of each transmission so that $r(n) = 2\sqrt{2a(n)}$, which allows direct communication within a Voronoi cell and between adjacent Voronoi cells.

**Adjacent Voronoi Cells:** We say that two Voronoi cells are adjacent if they share a common point (every Voronoi cell is a closed set).

**Interfering Neighbors:** we say two cells are interfering neighbors if there is a point in one cell which is within a distance $(2 + \Delta)r(n)$ of some point in the other cell.

\footnote{Notice that here the bandwidth means the maximum rate of data transfer that a transmission can support, measured in bits per second. And $W_1$, $W_2$, $W_3$ are constant which have no relation with the number of nodes $n$ and base stations $m$.}
Lemma 2: When the directional antennas are used by the nodes in the network, every cell in \( V_i \) has no more than \( c_1 \) interfering neighbors. \( c_1 \) depends only on \( \Delta \) and grows no faster than linearly in \((1 + \Delta)^2\).

Proof: We set the transmission range \( r(n) \) to be 
\[ 2\sqrt{2a(n)}, \]
then we know that a node in one cell can communicate with any node in its eight neighboring cells.

Based on the interference mode, the transmission is successful only when other transmitting nodes are \((1 + \Delta)r(n)\) away from the receiver or the receiver is not covered by the antenna beam of other transmitting nodes. Let us consider that a transmitter \( X_j \) within cell \( B \) is transmitting a data packet to a receiver \( X_j \) within cell \( A \) as shown in Fig. 3. Since the transmission range between \( X_i \) and \( X_j \) is \( r(n) \), the distance between two transmitter \( X_k \) and \( X_i \) must be less than \((2 + \Delta)r(n)\), if \( X_k \) causes the interference with \( X_j \). Thus, an interfering area is a square with an edge length less than \( 2(2 + \Delta)r(n) + \frac{3}{2}r(n) \), which is loosely bounded by \( 3(2 + \Delta)r(n) \).

Consider the directional antenna, in order to guarantee a successful transmission, the antenna beam of a transmitter and its corresponding receiver must point at each other. That is, the nodes within the beam of the receiver can interfere with its reception, and also the transmitter’s beam which covers the receiver can interfere with the receiver. Therefore, the probability that nodes interfere with each others is \((\frac{\pi}{2\pi})^2\).

Combining the two points, we can derive that there are at most \( c_2 = \frac{(3(2 + \Delta)r(n))^2}{a(n)} \cdot \left(\frac{\pi}{2\pi}\right)^2 = 72(2 + \Delta)^2 \cdot \frac{\theta^2}{4\pi^2} \sim O(\theta^2(1 + \Delta)^2) \) interfering cells in the square network. Hence, \( c_1 = c_2 - 1 \) is an upper bound on the number of interfering neighbors of the cell, which is a constant and independent of \( a(n) \) and \( n \).

Transmission Schedule: In the Protocol Model, there is a schedule for transmitting packets such that in every \((1 + c_1)\) slots, each cell in the tessellation \( V_n \) gets one slot for packet transmission, and all transmissions are successfully received within a distance \( r(n) \) from their transmitters.

Routing Construction: For each source node \( X_i \), \( 1 \leq i \leq n \), it will choose the destination for packets to transmit as follows. First, \( X_i \) will randomly choose a location \( Y_i \), then the destination according to \( X_i \) is chosen as \( X_{\text{dest}(i)} = \{ X_j | \min_{1 \leq j \leq n} || X_j - Y_i || \} \). Let \( L_i \) denotes the straight segment connecting \( X_i \) and \( Y_i \), the packets will transmit from \( X_i \) to \( X_{\text{dest}(i)} \) along \( L_i \) from cell to cell that are intersected by \( L_i \). In each hop, the packet is transmitted from one cell to the next cell intersecting \( L_i \). Because of directional antenna, any node in the cell can be chosen as a receiver with probability \( \frac{\theta^2}{4\pi^2} \). Finally, after reaching the cell containing \( Y_i \), the packet will be forwarded to \( X_{\text{dest}(i)} \) in the next active slot for that cell.

Under the \( L \)-maximum-hop resource allocation strategy using directional antenna, we now find the bound probability that \( L_i \) intersects a given Voronoi cell \( V \) and has been used for forwarding packets.

Lemma 3: Using directional antenna, For segment \( L_i \) and Voronoi cell \( V \), under the \( L \)-maximum-hop routing strategy,
\[
P(L_i \text{ intersects } V \text{ using } W_1 \text{ forwards packets successfully}) \leq c_3\theta^2L_i(\log \frac{n}{n})^2
\]

Proof: By Lemma 1, Voronoi cell \( V \) is contained in a disk of radius \( k_2\sqrt{\log n}/n \). Suppose \( X_i \) lies at a distance \( x \) from the center of this disk as shown in Fig. 4, then the angle \( \alpha \) subtended at \( X_i \) by the disk is no more than \( \frac{c_4 \sqrt{\log n}}{2\pi} \cdot \frac{c_5L_i^2(n)^2}{2\pi} \). If \( Y_i \) does not lie in the sector, then line \( L_i \) cannot intersect the disk containing the cell \( V \), and we know that \( L_i \) is formed from connecting \( X_i \) to \( Y_i \) with probability \( \left(\frac{\pi}{2\pi}\right)^2 \). Thus, the probability that \( L_i \) intersects the disk is and is used for forwarding packets is no more than \( \frac{c_6L_i^2}{x} \cdot \left(\frac{\log n}{n}\right)^2 \cdot \frac{\theta^2}{4\pi^2} \).

Since \( X_i \) is uniformly distributed on the plane of unit disk, the probability density that it is at a distance \( x \) from the center of the disk is bounded above by \( 2c_7\pi x \). Besides, in order for \( L_i \) to intersect \( V \), we need \( 2\rho(n) \leq x \leq Lr(n) \). As a result,
we can obtain
\[ P(L_i \text{ intersects } V \text{ using } W_1 \text{ forwards packets successfully}) \leq \int_{k_2 \sqrt{\frac{\Delta}{\pi n}}}^{2\sqrt{2k_1L\sqrt{\frac{\Delta}{\pi n}}}} \frac{c_6 L^2}{x} \left( \frac{\log n}{n} \right)^2 \frac{\theta^2}{4\pi^2} \cdot 2c_7 \pi x dx \]
\[ \leq c_3 \theta^2 L^3 \left( \frac{\log n}{n} \right)^2 \]

Since there are \( n \) lines \( \{L_i\}_{i=1}^n \), connecting \( X_i \) and \( Y_i \), the average number of lines passing through a Voronoi cell that uses frequency band \( W_1 \) is bounded as follows:

\[ E(\text{ Number of lines in } \{L_i\}_{i=1}^n \text{ intersects } V \text{ using } W_1 \text{ forwards packets successfully}) \leq c_3 \theta^2 L^3 \left( \frac{\log n}{n} \right)^2. \]

Based on the above lemma, by using the Chernoff Bound, we have the following two results.

**Lemma 4:** For any constant \( c_4 > c_3 \), there is a \( \delta'(n) \to 0 \) such that
\[ P(\sup_{V \in V_n}(\text{ Number of lines in } \{L_i\}_{i=1}^n \text{ intersects } V \text{ using } W_1 \text{ forward packets successfully})) \leq P(\sup_{V \in V_n}(\text{ Number of lines in } \{L_i\}_{i=1}^n \text{ intersects } V \text{ using } W_1 \text{ forwards packets successfully})) \leq c_3 \theta^2 L^3 \left( \frac{\log n}{n} \right)^2 \]

**Proof:** First, we bound the number of routes served by one particular cell \( V \). Define i.i.d. random variable \( \xi_i \), \( 1 \leq i \leq n \), as follows:
\[ \xi_i = \begin{cases} 1, & \text{if } L_i \text{ intersects } V; \\ 0, & \text{otherwise}. \end{cases} \]

Then \( P(\xi_i = 1) = p \), for all \( i \), where \( p \) is defined in Lemma 3.

Denote by \( Z_n \) the total number of routes served by \( V \). Then \( Z_n = \xi_1 + \xi_2 + \cdots + \xi_n \). Thus, by the Chernoff Bound, for all positive \( m \) and \( a \), \( P(Z_n > m) \leq e^{-c_4 \lambda_1 n} \). Because of \( 1 + x \leq e^x \), we have
\[ Ee^{aZ_n} = (1 + (e^a - 1)p)^n \leq \exp(n(e^a - 1)p) \leq \exp(c_3(e^a - 1)\sqrt{n \log n}). \]

Now choosing \( m = c_4 \sqrt{n \log n} \), we get
\[ P(Z_n > c_4 \sqrt{n \log n}) \leq \exp(\sqrt{n \log n}(c_3(e^a - 1) - ac_4)). \]

Since \( c_4 > c_3 \), one can choose \( a \) small enough such that \( P(Z_n > c_4 \sqrt{n \log n}) < \exp(-\epsilon \sqrt{n \log n}) \), for some constant \( \epsilon > 0 \). Thus, by the union bound, we have
\[ P(\text{Some cell intersects more than } c_4 \sqrt{n \log n \text{ lines})} \leq \sum_{k,j} P(\text{Cell } V \text{ intersects more than } c_4 \sqrt{n \log n \text{ lines})} \]
\[ \leq \frac{1}{a(n)} \exp(-\epsilon \sqrt{n \log n}) = \frac{n}{2k_2^2 \log n} \exp(-\epsilon \sqrt{n \log n}) \]
\[ = \frac{n}{K \log n} \exp(-\epsilon \sqrt{n \log n}), \]

where \( \frac{1}{a(n)} \) is the number of cells in \( V_n \) and \( K \) is a constant which equals to \( 2k_2^2 \). It is trivial that the right hand side goes to zero as \( n \) goes to infinity.

Note that the frequency band \( W_1 \) carries traffic of rate \( \lambda_0(n, m) \) bits per second, we have the following bound.

**Lemma 5:** There is a \( \delta'(n) \to 0 \) such that
\[ P(\sup_{V \in V_n}(\text{ Traffic needing to be carried by cell } V)) \leq c_3 \lambda_0(n, m) \theta^2 L^3 \left( \frac{n}{n} \right) \exp(-\epsilon \sqrt{n \log n}) \]
\[ \leq c_3 \lambda_0(n, m) \theta^2 L^3 \left( \frac{n}{n} \right) \exp(-\epsilon \sqrt{n \log n}) \leq \frac{W_1}{c_2} \quad (1) \]

From now on, we have derived a lower bound on the per-node throughput capacity contributed by ad hoc mode transmissions, which is shown in the following proposition by changing equation (1).

**Proposition 1 (Lower bound):** For ad hoc mode transmissions using a directional antenna, under the L-maximum-hop resource allocation strategy, there are two cases:
1) when \( L = \Omega(\frac{n^{1/3}}{\theta^2 \log^{2/3} n}) \), there is a deterministic constant \( c > 0 \) not depending on \( n, \Delta, \text{ or } W_1 \), such that
\[ \lambda_0(n, m) = \frac{c n W_1}{\theta^2 (1 + \Delta) L^3 \log^2 n} \]
bits per second is feasible with high probability, i.e.,
\[ \lambda_0(n, m) = \Omega\left(\frac{n W_1}{\theta^2 L^3 \log^2 n}\right) \]
2) when \( L = o(\frac{n^{1/3}}{\theta^2 \log^{2/3} n}) \), there is a deterministic constant \( c > 0 \) not depending on \( n, \Delta, \text{ or } W_1 \), such that
\[ \lambda_0(n, m) = W_1 \]
bits per second is feasible with high probability.

Next, we will get the upper bound of the per-node throughput capacity under the conditions of directional antenna and L-hop-resource allocation strategy.

**Lemma 6:** By using directional antenna for every node, the number of simultaneous transmissions for the whole network is no more than
\[ N_{max} = \frac{4\pi^2}{\theta^2} \frac{4}{c_5 \pi \Delta^2 r^2(n)} \]
in the Protocol Model.

**Proof:** If every node is equipped with an Omni-directional antenna, and that node \( X_i \) transmits successfully to node \( X_j \) and node \( X_k \) transmit successfully to node \( X_i \) at the same time, then from the triangle inequality, as shown in Fig. 5, we have,
\[ |X_j - X_i| \geq |X_j - X_k| - |X_k - X_i| \]
\[ \geq (1 + \Delta)|X_i - X_j| - |X_k - X_i|. \]
Similarly,
\[ |X_i - X_j| \geq |X_i - X_j| - |X_i - X_j| \geq (1 + \Delta)|X_k - X_i| - |X_i - X_j|. \]

Adding the two inequalities, we obtain
\[ |X_i - X_j| \geq \frac{\Delta}{2}(|X_k - X_i| + |X_i - X_j|). \]

Because of \(|X_k - X_i| \leq r(n)\) and \(|X_i - X_j| \leq r(n)\), we have
\[ \frac{\Delta}{2}(|X_k - X_i| + |X_i - X_j|) \leq \Delta r(n). \]

Then, no other node \(X_u\) within a distance \(\Delta r(n)\) of \(X_j\) and no other node \(X_v\) within a distance \(\Delta r(n)\) of \(X_i\) can be simultaneously receiving a separate transmission in the Omnidirectional antenna mode. For the directional antenna mode, the interfering area becomes small because of the beamwidth \(\theta\). Sectors of radius \(\frac{\Delta r(n)}{2\theta}\) with beamwidth \(\theta\) have an area of \(\frac{\theta^2}{2\pi} \cdot \frac{4}{c_5 \Delta r(n)}\). If we consider the directional receiving probability as reducing the area of the sector, we can consider the sector area as \(\frac{\theta^2}{4\pi} \cdot \frac{4}{c_5 \Delta r(n)}\) for simplicity. Then, the network can support no more than \(N_{\max} = \frac{4a^2}{\theta^2} \cdot \frac{4}{c_5 \Delta r(n)}\) simultaneous transmissions.

Under the \(L\)-maximum-hop resource allocation strategy, by using directional antenna in every node, we can calculate the mean number of hops that a packet transmitted from a source to its destination denoted by \(\bar{h}\),
\[ \bar{h} \geq 1 \cdot \frac{(\theta/2\pi)^2 \cdot \pi r^2(n)}{(\theta/2\pi)^2 \cdot \pi L^2 r^2(n)} + 2 \cdot \frac{(\theta/2\pi)^2 \cdot 3\pi r^2(n)}{(\theta/2\pi)^2 \cdot \pi L^2 r^2(n)} + \cdots + L \cdot \frac{(\theta/2\pi)^2 \cdot L^2 - (L - 1)^2 \pi r^2(n)}{(\theta/2\pi)^2 \cdot \pi L^2 r^2(n)} = \frac{4L^3 + 3L^2 - L}{6L^2} \sim L. \]

The right hand side of the formula is calculated by the definition of expectation, i.e., the sum of the product of number of hops that a packet transmitted from a source to its destination and its probability.

Since each source generates \(\lambda^0_a(n, m)\) bits per second, there are \(n\) sources, each of which transmits to its destination in ad hoc mode with a probability of \((\theta/2\pi)^2 \cdot \pi L^2 r^2(n)\), then the total number of bits per second served by the entire network needs to be at least \(n \cdot (\theta/2\pi)^2 \cdot \pi L^2 r^2(n) \cdot \bar{h} \lambda^0_a(n, m)\). To ensure that all the required traffic is carried, we therefore need
\[ n(\theta/2\pi)^2 \pi L^2 r^2(n) \bar{h} \lambda^0_a(n, m) \leq N_{\max} \cdot W_1 \]
thus
\[ \lambda^0_a(n, m) \leq \frac{c_0 W_1}{\theta^4 \Delta^2 L^3 \log^2 (n)} \]

Since \(r(n) > \sqrt{\frac{\log n}{n}}\) is necessary to guarantee connectivity with high probability [25], we obtain
\[ \lambda^0_a(n, m) \leq \frac{c_1 n W_1}{\theta^4 \Delta^2 L^3 \log^2 (n)} \]

Thus, by equation (2) and \(\lambda^0_a(n, m) \leq W_1\), we arrive at the following proposition.

**Proposition 2 (Upper bound):** For ad hoc mode transmissions, under the \(L\)-maximum-hop resource allocation strategy, using directional antenna, we have the following two cases:

1. when \(L = \Omega(\sqrt{n^{1/3} \log^{2/3} n})\), an upper bound on per-node throughput capacity is
\[ \lambda^0_a(n, m) = \frac{c_1 n W_1}{\theta^4 \Delta^2 L^3 \log^2 (n)} \]
bits per second, where \(c_1 \) is not depending on \(n, \Delta, \) or \(W_1\).

2. when \(L = o(\sqrt{n^{1/3} \log^{2/3} n})\), an upper bound on per-node throughput capacity is
\[ \lambda^0_a(n, m) = W_1. \]

Notice that the probability that one node will transmit to its destination node in an ad hoc mode is \((\theta/2\pi)^2 \cdot \pi L^2 r^2(n)\). Let \(N_i (1 \leq i \leq n)\) be a random variable defined as follows
\[ N_i = \begin{cases} 1, & \text{source node } i \text{ transmits to its destination node in an ad hoc mode;} \\ 0, & \text{otherwise.} \end{cases} \]

Let \(N_T\) be a random variable defined as the total number of source nodes transmitting in an ad hoc mode, i.e., \(N_T = \sum_{i=1}^n N_i\). Thus, the expected number source nodes in an ad hoc mode is
\[ E(N_T) = E\left(\sum_{i=1}^n N_i\right) = \sum_{i=1}^n E(N_i). \]

Since \(P(N_i = 1) = (\theta/2\pi)^2 \cdot \pi L^2 r^2(n)\), and \(r(n)\) needs to be \(\Theta(\sqrt{\log n})\) to make the network connected [3], we have
\[ E(N_T) = 1 \cdot (\theta/2\pi)^2 \cdot \pi L^2 r^2(n) + 0 \cdot (1 - (\theta/2\pi)^2 \cdot \pi L^2 R^2(n)) = \frac{\theta^2}{4\pi} L^2 \log n. \]

Thus,
\[ E(N_T) = n \cdot \frac{\theta^2}{4\pi} L^2 \log n = \frac{\theta^2}{4\pi} L^2 \log n. \]

Also use the Chernoff bounds, we have
- For any \(\delta > 0\),
\[ P\left[N_T > (1 + \delta) \frac{\theta^2}{4\pi} L^2 \log n\right] < \left[\frac{1 + e^\delta}{(1 + e^\delta)^{1+\delta}}\right]^{\frac{\theta^2}{4\pi} L^2 \log n}. \]
- For any \(0 < \delta < 1\),
\[ P\left[N_T < (1 - \delta) \frac{\theta^2}{4\pi} L^2 \log n\right] < e^{-\frac{1}{2} \delta^2 \frac{\theta^2}{4\pi} L^2 \log n}. \]
From the above, we can obtain for any $0 < \delta < 1$,
\[
P\left[ N_T - \frac{\theta^2}{4\pi} L^2 \log n \right] > \frac{\theta^2}{4\pi} L^2 \log n < e^{-\alpha \frac{\theta^2}{4\pi} L^2 \log n},
\]
where $\alpha > 0$. So, as $n \to \infty$, the total number of source nodes transmitting in an ad hoc mode is equal to $\frac{\theta^2}{4\pi} L^2 \log n$ with probability $1$.

Thus, the total ad hoc mode traffic is $n \frac{\theta^2}{4\pi} L^2 r^2(n) \lambda_0(n, m)$. Combining proposition 1 and proposition 2 leads to the following Theorem.

**Theorem 1:** Under the $L$-maximum-hop routing strategy, by using a directional antenna, the throughput capacity of the network contributed by ad hoc mode transmissions is
\[
\lambda_a(n, m) = \begin{cases} 
\Theta\left(\frac{nW}{\theta^2 L \log n}\right), & L = O\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right); \\
\Theta\left(\frac{\theta^2 L^2 \log n}{W} W_1\right), & L = o\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right). 
\end{cases}
\]

**B. Infrastructure Mode Throughput Capacity**

For the throughput capacity contributed by transmissions in the infrastructure mode, there exists a 9-cell frequency reuse pattern. We know that the bandwidth of uplink and downlink for infrastructure mode transmission is $W_2$. Thus, the throughput capacity per cell is upper bounded by $W_2$ and lower bounded by $\frac{3}{2} W_2$.

**Lemma 9:** Under the $L$-maximum-hop routing strategy, the throughput capacity of the network contributed by infrastructure mode transmissions is
\[
\lambda_i(n, m) = \Theta(m W_2).
\]

**C. Throughput Capacity of the Network**

We can obtain the following theorem based on the results of Theorem 1 and Lemma 9.

**Theorem 2:** Under the $L$-maximum-hop resource allocation strategy, by using directional antenna, the throughput capacity of the network is
\[
\lambda(n, m) = \begin{cases} 
\Theta\left(\frac{nW}{\theta^2 L \log n}\right) + \Theta\left(m W_2\right), & L = O\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right); \\
\Theta\left(\frac{\theta^2 L^2 \log n}{W} W_1\right) + \Theta\left(m W_2\right), & L = o\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right). 
\end{cases}
\]

Case 1: $L = O\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right)$.

We have $\lambda(n, m) = \Theta\left(\frac{nW}{\theta^2 L \log n}\right) + \Theta(m W_2)$.

- If $m = O\left(\frac{nW}{\theta^2 L \log n}\right)$, then we can have higher throughput when $W_1 = 0$, i.e., $W_2 = W/2$, and $\lambda_{\text{max}}(n, m) = \Theta(m W_2)$ and hence,
\[
\lambda_{\text{max}}(n, m) = \begin{cases} 
\Theta(W), & m = O(n); \\
\Theta\left(\frac{nW}{\theta^2 L \log n}\right), & m = o(n). 
\end{cases}
\]

- If $m = \Theta\left(\frac{W^2 L^2 \log n}{W} W_1\right)$, then we can have higher throughput when $W_2 = 0$, i.e., $W_1 = W$, and $\lambda_{\text{max}}(n, m) = \Theta\left(\frac{W^2 L^2 \log n}{W} W_1\right)$ and hence,
\[
\lambda_{\text{max}}(n, m) = \Theta\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right),
\]
which means that in this case, when the antenna beamwidth $\theta$ becomes small enough, the throughput capacity will be large enough until it becomes a constant not exceeding $W/2$.

- If $m = O\left(\frac{W^2 L^2 \log n}{W} W_1\right)$, then we can have higher throughput when $W_1 = 0$, i.e., $W_2 = W/2$, and $\lambda_{\text{max}}(n, m) = \Theta(m W_2)$ and hence,
\[
\lambda_{\text{max}}(n, m) = \Theta\left(\frac{nW}{\theta^2 L \log n}\right),
\]
with $\theta \leq 2\pi$, and the maximum-hop $L$ and the number of base stations is smaller which means that the per-node throughput capacity mainly depends on $L$ and $n$ and diminishes as $n$ goes large and the network cannot scale.

Case 2: $L = o\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right)$.

We have $\lambda(n, m) = \Theta\left(\frac{\theta^2 L^2 \log n}{W} W_1\right) + \Theta(m W_2)$.

- If $m = \Theta\left(\frac{W^2 L^2 \log n}{W} W_1\right)$, then we can have higher throughput when $W_2 = 0$, i.e., $W_1 = W$, and $\lambda_{\text{max}}(n, m) = \Theta\left(\frac{W^2 L^2 \log n}{W} W_1\right)$ and hence,
\[
\lambda_{\text{max}}(n, m) = \Theta\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right);
\]

as $\theta \leq 2\pi$, and the maximum-hop $L$ and the number of base stations is smaller which means that the per-node throughput capacity mainly depends on $L$ and $n$ and diminishes to zero as $n$ goes to infinity.

- If $m = o\left(\frac{nW}{\theta^2 L \log n}\right)$, then we can have higher throughput when $W_2 = 0$, i.e., $W_1 = W$, and $\lambda_{\text{max}}(n, m) = \Theta\left(\frac{nW}{\theta^2 L \log n}\right)$ and hence,
\[
\lambda_{\text{max}}(n, m) = \Theta\left(\frac{n^{1/3}}{\theta^{2/3} \log^{1/3} n}\right),
\]
in this condition, $\theta$ is small, but the maximum-hop $L$ and the number of base stations $m$ are also small. Thus, combining them will cause the per-node throughput capacity to diminish to zero as $n$ goes to infinity.

The result in Theorem 2 is described in the following three figures. Fig. 6a shows the relationship between throughput capacity $\lambda(n, m)$ and the maximum hop numbers $L$. It shows that when the number of base stations $m$ and the directional antenna beamwidth $\theta$ are both fixed, the throughput capacity...
first increases with $L$ then decreases with $L$. The reason why $\lambda(n, m)$ decreases with $L$ when $L = \Omega(n^{1/3})$ is that the interference is more when $L$ is large enough.

Fig. 6.b shows the relationship between the throughput capacity $\lambda(n, m)$ and the number of base stations $m$ when $L$ is larger or smaller than $n^{1/3}$. It gives the same information that there is a critical number of $m$ for the throughput capacity. When $m$ is larger than the number, the throughput capacity is linear with $m$ and it keeps constant when $m$ is smaller than the critical number. This is meaningful because the base stations paly a key role in the throughput capacity when its number is large. If $m$ is not large enough, the bandwidth of the wire link between the base stations is limited, which causes limited increase in the throughput capacity.

Fig. 7 gives the relationship between $\lambda(n, m)$ and $\theta$ when other parameters are fixed. It shows that in the case $L = \Omega(n^{1/3})$ and $m = o(n^{1/3})$ (Fig. 7.a), the directional antenna beamwidth $\theta$ can improve the throughput capacity significantly when it decreases to zero. It also shows that when $L = o(n^{1/3})$ and $m = o(n^{1/3})$ (Fig. 7.b), $\theta$ gives little contribution to the throughput capacity.

From the above, we arrive at the following results.

**Corollary 1:** Under the $L$-maximum-hop resource allocation strategy, using a directional antenna,

1) when $L = \Omega(n^{1/3})$, (i) if $m = \Omega(n^{1/3})$, we can have higher throughput when $W_2 = 0$, and the network can scale if $m = \Omega(n)$; (ii) if $m = o(n^{1/3})$, we can have higher throughput when $W_2 = 0$, and the throughput can scale only when the antenna beamwidth $\theta = o(1/\sqrt{L\log n})$.  

2) when $L = o(n^{1/3})$, (i) if $m = \Omega(n^{1/3})$, we can have higher throughput when $W_1 = 0$, and the network can scale only if $m = \Omega(n)$; (ii) if $m = o(n^{1/3})$, whatever value of $\theta$, this will diminish on the per-node throughput and it cannot scale.

In summary, the number of base stations play an important role in the throughput capacity. The cooperation of a directional antenna beamwidth $\theta$ and resource allocation strategy can also improve the throughput capacity if $m$ is small. As shown in Table I, the network throughput capacity can achieve $\Theta(W)$ when $m = \Omega(n)$. We can improve the throughput capacity by increasing the maximum-hops $L$ and decreasing the directional antenna beamwidth $\theta$ if the number of base stations is small. But if the number of base stations and the maximum-hops are both small, the directional antenna can not provide throughput capacity improvement.

### V. Conclusion

In this paper, we studied the throughput capacity in hybrid wireless networks under the condition that each node is equipped with a directional antenna. We proved that under the $L$-hop maximum resource allocation strategy, the per-node throughput capacity in hybrid networks greatly depends on the maximum hop count $L$, the number of base stations $m$ and the beamwidth of directional antenna $\theta$. Moreover, by analyzing the relationship between $L$, $m$ and $\theta$ we find that when $m = \Omega(n)$, the per-node throughput can be $\Theta(1)$ regardless of what value $L$ and $\theta$ can take, and if $m = o(n^{1/3})$, only when $L = \Omega(n^{1/3})$ and $\theta = o(1/\sqrt{L\log n})$ can the per-node throughput scale.

As future research directions, we plan to study the broadcast capacity and/or multicast capacity in the proposed mode. We also plan to investigate the throughput capacity and the delay trade offs.

### Acknowledgment

This work is supported by National Fundamental research grant (2010CB731803, 2009CB302042), NSF China (No. 60702046, 60832005, 60972050, 60632040); China
Ministry of Education (No. 20070248095); Qualcomm Research Grant; China International Science and Technology Cooperation Program (No. 2008DFA11630); PUIJANG Talents (08PJ14067); Shanghai Innovation Key Project (08511500400); National Key Project of China (2009ZX03003-006-03, 2009ZX03002-003, 2009ZX03002-005); National High tech grant of China (2009AA01Z248, 2009AA011802);

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