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Throughput Capacity of Multi-Channel Hybrid Wireless Network with Antenna Support

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Abstract: Capacity is one fundamental problem in wireless networks. Directional antennas to wireless networks can decrease interference and increase spatial reuse. Thus, it is a great technology to improve throughput capacity of wireless networks. In the paper, the upper and lower bounds of multi-channel hybrid wireless network with antenna supported are investigated. Both simplified antenna model and hybrid antenna model are addressed. Moreover, two scaling regimes are identified, based on the growth of the number of channels relative to that of interfaces.

Keywords: Capacity, directional antenna, multi-channel, hybrid

1 Introduction

Capacity is one of the most important problems in wireless ad hoc networks, which provides the theoretical guideline to its improvement [1]. Moreover, it depends on many aspects of networks such as network architecture, network topology, traffic pattern, network node density, number of channels used for each node, transmission power level, and node mobility[2,3].

In the landmark paper [4], Gupta and Kumar showed that the throughput capacity obtainable by each node for a randomly chosen destination is bits/s assuming that number of mobile nodes are placed randomly, a somewhat disappointing results. Inspired by this work, many researchers have investigated the capacity issue for wireless networks under various constraints and tried to find out the method to improve the throughput capacity [5].

Exploiting mobility is one way to improve throughput capacity [6,7]. Base station is another method. In [8], it was shown that to achieve better investment in the infrastructure is needed. Kozat and Tassiulat [9]showed that for random ad hoc networks with infrastructure support where the ratio of wireless nodes to base station is bounded above by some constant, a throughput capacity of cannot be obtained. Another method to improve the throughput capacity of wireless networks is to use multiple channels. Kyasanur and Vaidya [10] studied the impact of the number of channels and interfaces per node on the capacity of multi-channel ad hoc networks as the number of ad hoc nodes, increases. Moreover, Bhandari and Vaidya [11] studied connectivity and asymptotic transport capacity of the multi-channel pure ad hoc networks with channel switching constraints.

Recently, directional antennas have emerged as a promising technology due to the higher spatial reuse ratio [5,12]. The capacity of single channel ad hoc networks using directional antennas was investigated in [12]. [5] explored the throughput capacity of random single channel directional networks with one-hop relay schemes. Base station and directional antennas are combined considered in [13]. The capacity of multi-channel wireless networks with multiple directional antennas is studied in [14].

However, few studies considered the directional antenna radiation pattern impact on multi-channel hybrid wireless networks which we call as MC-HDA networks, and multi-channel hybrid wireless networks with omnidirectional antennas called as MC-HOA networks. Furthermore, the real directional antenna impact on MC-HDA networks has not been investigated. To the best of our knowledge, there is no theoretical analysis on the throughput capacity of such networks. The paper concentrates on finding the capacity bounds for an MC-HDA network and exploring the benefits of this

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network. Our contributions can be summarized as follows:

*We formally identify MC-HDA networks that characterize the features of multi-channel hybrid networks with multiple directional antennas at each node. The capacity of MC-HDA networks has not been studied before. In [2], only MC-HOA networks are investigated.
*We drive the upper and lower bounds on the capacity of MC-HDA networks under simplified directional antennas model and practical directional antennas which consider the side lobe and back lobe effect of directional antennas.
*Our theoretical results show that integrating directional antennas with multi-channel hybrid networks can increase network connectivity and reduce interference, resulting in improved network capacity. Implications from analytical results are also given.

The remainder of the paper is organized as follows: Definition and notation used in the paper are summarized in Section 2, antenna and other models are described in Section 3, then the upper and lower bounds are presented in Section 4 and 5. We summarize our work in Section 6.

2 Definition and Notation

We use the following notation to represent asymptotic bounds:

$f(n) = O(g(n))$ means there exists some constant α and integer N such that $f(n) \leq \alpha g(n)$ for $n > N$.

$f(n) = o(g(n))$ means that $\lim_{n\to\infty} f(n)/g(n) = 0$.

$f(n) = \Omega(g(n))$ means that $g(n) = O(f(n))$.

$f(n) = \omega(g(n))$ means that $g(n) = o(f(n))$.

$f(n) = \Theta(g(n))$ means that $f(n) = O(g(n))$ and $g(n) = O(f(n))$.

The traffic between a source-destination pair is referred to as a ”flow”. As in [2], we say that per flow capacity is λ if each flow in the network can be guaranteed a throughput of at least λ , and the network capacity is defined to the aggregate throughput over all the flows in the network, $n\lambda$.

3 Model

MC-HDA networks consist of base stations and ad hoc nodes. All these nodes and stations are uniformly distributed on the surface of a unit torus. Ad hoc nodes alone form a connected topology graph with high probability. In other words, any pair of ad hoc nodes can communicate with each other along the paths that cross only the ad hoc nodes with probability close to one. Base stations are connected through wired and alternative wireless links with relatively high bandwidth. Moreover, base stations only relay traffic, and do not generate their own data. Ad hoc nodes are also allowed to utilize the infrastructure network composed by base stations.

These ad hoc nodes are capable of transmitting and receiving W bits/s via all c channels, and the base stations can also communicate with ad hoc nodes by these common channels. Any node is equipped with m interfaces, and each interface is assumed to be capable of transmitting or receiving data on any channel. For simplicity, the permutation traffic model is adopted where implies that each node is the source of exactly one flow, and each node is the destination of exactly one flow [10, 11]. As [9] Each ad hoc node generates a flow with rate λ for a random destination. n and k are the number of ad hoc nodes and base stations, respectively. We assume that the number of ad hoc nodes per base station is bounded and $lim_{n\to\infty}(n/k) = \beta$ where $\beta \in (0,\infty)$.

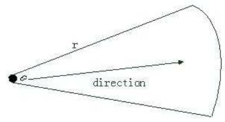

Fig. 1: Simplified antenna model

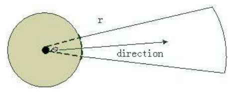

Fig. 2: Hybrid antenna model

3.1 Antenna model

In this paper, two kinds of directional antenna model are used. One is the simplified model, where the directional antenna gain is assumed to be within a specific angle θ ,θ is the beamwidth of the antenna. The gain outside the beamwidth is assumed to be zero which is shown in Fig.1. At any time, the antenna beam can only be pointed to a certain direction [12, 14]. We call such MC-HDA networks using simplified antenna model as MC-HDAS networks.

Another is the practical directional antenna so that we use a hybrid antenna model [12]. In the model, the effect of side lobes and back lobes are considered which is shown in Fig 2. The main lobe of beamwidth θ is characterized as a sector. Side lobes and back lobes form a circle. We define parameter s as the ratio of the radius of the circle and the sector, which is generally less than 1. We call such MC-HDA networks with hybrid antenna model as MC-HDAH networks.

3.2 Interference model

The protocol model proposed by Gupta and Kumar [4] is extended to include directional antennas in the paper. It is the receiver-based interference model proposed in [14]. Our model also only considers both directional transmission and directional reception.

Suppose node X_i transmits over the mth channel to a node X_j . Then this transmission is successfully received by node X_j , for every other node X_k simultaneously transmitting over the same channel, and the guard zone $\delta > 0$, the following condition holds.

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

X_i also denotes the location of a node.

3.3 Channel model

The total data rate is divided equally among the channels, and then the data rate supported by any one of the c channels is W/c bits$/s$.

4 Upper bound

The capacity of MC-HDA networks (both MC-HDAS and MC-HDAH) is limited by two constraints, and each of them is used to obtain a bound on the network capacity. The minimum of the two bounds (the bounds depend on ratio of the number of channels c to the number of interfaces m) is an upper bound on the network capacity.

Constraint 1. Interface Constraints: It can be shown that the protocol model for interference requires that each transmission consumes a certain area, and two simultaneous transmissions occur on the same channel and are successfully received, the area must be disjoint. Therefore we can bound the number of areas.

Lemma 1. The capacity of MC-HDAS networks is $n\lambda = O\left(\frac{nW}{\theta^2 logn}\right)$bits/sec, and that of MC-HDAH networks is $n\lambda = O\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)logn}\right)$bits/sec.

Proof.for MC-HDAS networks, the condition interference zone is $\frac{\theta^2}{(2\pi)^2}$ portion of that when ominidirectional antennas are used at both ends [4,14]. Since for ominidirectional antennas, Therefore, the interference zone is $\frac{\theta^2}{(2\pi)^2}\pi\frac{r_i^2}{4}$ (r_i is the transmission radius)for each transmission on channel i ($1 \leq i \leq c$). Hence, number of simultaneous transmissions on channel i must be smaller than $\frac{16\pi}{\theta^2 r_i^2}$. As a result, given the average number of hops $\overline{h_i}$ for transmissions on channel i , per node flow capacity λ_i on channel i , following inequality holds.

$$n_i\lambda_i\overline{h_i} \leq \frac{16\pi}{\theta^2 r_i^2}\frac{W}{c} \tag{1}$$

It is proved in [4,9] that the transmission radius r_i must at least satisfy the following bound for having a connected graph with probability one.

$$r_i \geq \sqrt{\frac{log(n_i)}{\pi n_i}} \tag{2}$$

Using the inequality and the fact $\overline{h_i}$, and there are c channels in networks, with probability of one, the upper bound holds under any routing and scheduling scheme. For per flow capacity,

$$\lambda \leq \frac{16\pi^2 W}{\theta^2 logn} \tag{3}$$

So the network capacity of MC-HDAS networks is proved $n\lambda = O\left(\frac{nW}{\theta^2 logn}\right)$ bits/s. Next, the MC-HDAH network is considered. Since for each transmission, the conditional interference area is $\pi r^2\left(s^2 + \left(1-s^2\right)\frac{\theta^2}{4\pi^2}\right)$, through the same proof technique, the network capacity of MC-HDAH networks is $n\lambda = O\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)logn}\right)$ bits/sec.

Constraint 2. Interference constraints: The capacity of MC-HDA networks is also limited by the number of simultaneous transmissions supported by interferences in the network.

Lemma 2. The capacity of MC-HDA networks is $O\left(\frac{nWm}{c}\right)$bits/s.

Proof. According to the channel model, each interface can transmit at a rate of $\frac{W}{c}$ bits/s, and each node has m interfaces, so the total network capacity is bounded by $O\left(\frac{nWm}{c}\right)$bits/s.

Combining with the two bounds, the network capacity is bounded by $O\left(min\left(\frac{nW}{\theta^2 logn}, \frac{nWm}{c}\right)\right)$ bits/s for MC-HDAS networks, and $O\left(min\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)logn}, \frac{nWm}{c}\right)\right)$bits/s for MC-HDAH networks.

Theorem 1. The upper bound of the capacity of MC-HDA networks are as follows:

(1)When $\frac{c}{m}$ is $O\left(\left(\frac{\theta}{2\pi}\right)^2 logn\right)$, the network capcity is $O\left(\frac{nW}{\theta^2 logn}\right)$bits/s over a MC-HDAS network; when $\frac{c}{m}$ is $O\left(\left(\theta^2 + \left(4\pi^2 - \theta^2\right)s^2\right) logn\right)$bits/s, the network capacity is $O\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)logn}\right)$bits/s over a MC-HDAH network.

(2)When $\frac{c}{m}$ is $\Omega\left(\left(\frac{\theta}{2\pi}\right)^2 logn\right)$, the network capacity is $O\left(\frac{nWm}{c}\right)$bits/s over a MC-HDAS network; when $\frac{c}{m}$is $\Omega\left(\left(\theta^2 + \left(4\pi^2 - \theta^2\right)s^2\right) logn\right)$bits/s, the network capacity is $\varnothing\left(\frac{nWm}{c}\right)$bits/s over a MC-HDAH network.

While there may be other constraints on capacity as well, the constraints we consider is sufficient to provide a tight bound.

5 Lower bound

In the section, we provide a construction of the routing scheme and scheduling strategy to establish a lower bound of the network capacity. We first deal with MC-HDAS networks, and provide a construction of a routing scheme and a transmission schedule for $(1,c)$network, and then extend the result to a (m,c) network by using Lemma 2 in [10].

5.1 Cell construction

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The surface of the unit torus is divided into square cells using a square grid, and we denote each of area by $\alpha(n)$, similar to that used in [2,10]. In particular, we set $\alpha(n) = max\left(\frac{100log(n)}{n}, \frac{c}{n}\frac{\theta^2}{4\pi^2}\right)$. The transmission radii of each node are set to $\sqrt{8\alpha(n)}$, thereby satisfying the requirement that any node in one cell can communicate with any other node in its neighboring cells, and also to guarantee that ad hoc nodes form a connected graph with probability one. We need to bound the number of ad hoc nodes and base stations that are present in each cell.

Lemma 3. Both the number of base stations and ad hoc nodes belonging to any cell are asymptotical in the same order, i.e.$\Theta(n\alpha(n))$[2]. **Proof.**We provide a proof based on Vapnik-Chervonenkis (VC-theory).Because base stations are randomly located on the unit torus, the probability that any base station belongs to a specific cell is $\Theta(n\alpha(n))$. The set of axis-parallel square D' are known to have VC-dimension 3. Similar to the proof in [2,4], We set $\varepsilon = \sigma = 50log(n+k)/(n+k)$ to satisfy the VC-theory, and then we have

$$Prob\left(\sup_{d\in D}\left|\frac{N_d}{k} - \alpha(n)\right| \le \frac{50log(n+k)}{n+k}\right) > 1 - \frac{50log(n+k)}{n+k}$$

Where N_d is the number of base stations in Cell d. Therefore, with high probability, the following result holds:

$$k\left(a(n) - \frac{50log(n+k)}{n+k}\right) \le N_d \le k\left(a(n) - \frac{50log(n+k)}{n+k}\right)$$

because $lim_{n\to\infty}(n/k) = \beta$ where $\beta \in (0,\infty)$, so

$$\frac{na(n)}{\beta} - \frac{50log(1+1/\beta)n}{1+\beta} \le N_d \le \frac{na(n)}{\beta} + \frac{50log(1+1/\beta)n}{1+\beta},$$

provided $\alpha(n) > 50log(n+k)/(n+k)$.

Since $\alpha(n) = max\left(\frac{100log(n)}{n}, \frac{c}{n}\frac{\theta^2}{4\pi^2}\right)$, so the condition is always satisfied, and we obtain that the number of base stations belongs to any cell is i.e.$\Theta(n\alpha(n))$.

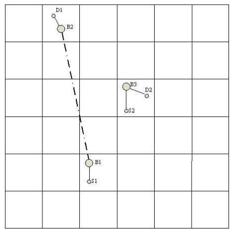

Fig. 3: Routing scheme

Following the same proof procedure, we can also obtain the same result for ad hoc nodes. Hence, we can conclude that both the number of base stations and ad hoc nodes belonging to any cell are asymptotical in the same order, i.e.$\Theta(n\alpha(n))$.

If a node in Cell A interferes with another transmission in Cell B, this cell is called as interfering cell. Then we prove that the number of interfering cells around a cell is a constant, which is independent of $a(n)$ and n .

Lemma 4. The number of cells that interfere with the transmissions of a specific cell is bounded above by a constant k_1 (when $k_1 = 81(2+\delta)^2\frac{\theta^2}{4\pi^2}$) [14].

5.2 Routing strategy

. There are two routing strategy [2] which is shown in Fig.3: one, if destination node is located in the same cell as source node, then packets are transmitted to its destination node directly; otherwise, packets are firstly transmitted to the base station in its own cell that is with the least number of flows load. Next, the base station forwards the data to that base station that is located at the same cell with the destination node and with the least number of flows. Lastly, the base station transmits the data to the destination node directly. In the routing scheme, the flows through base stations are balanced; otherwise some base station may become the traffic bottleneck. Thus, when a flow needs to pass through a cell, from amongst all base stations in the cell, it is assigned to the one which has the least number of flows assigned on it so far.

The following lemma is to bound the number of flows assigned to any base station in any cell.

Lemma 5. The number of flows that are assigned to any one base station in any cell is $O(1)$ with high probability [2].

5.3 Transmission scheduling

.From lemma 4, the number of cells that interfere with the transmissions of a specific cell is bounded above by a constant k_1 that only depends on δ . Thus, we have a scheduling of length (k_1+1) slots that can allocate a cell-slot for each cell in a round robin fashion. In each cell-slot, the corresponding cells are active. We divide one second into $O(k_1+1)$ cell-color slots and each cell-slot has a length of $\Omega\left(\frac{1}{(k_1+1)}\right)$ seconds.

Next, the transmission scheduling is responsible for generating a within-cell scheduling to ensure that at any instant, there is no more than one transmission on any given channel, and no node expected to transmit or receive more than one packet in the cell.

We first assign a channel for every node in the cell that is ready to transmit packets from c available channels. There are $\Theta(n\alpha(n))$ nodes in any cell with high probability from Lemma.3,i.e. at most $k_3 n\alpha(n)$ nodes for some constant k_3 that can be numbered from 1 to $k_3 n\alpha(n)$. A node numbered q is allowed to transmit on channel $(q \bmod c)+1$.

We further divide each cell-color slot into mini-slots. Then, we build a schedule for each transmission over a channel in the active cell. We construct a conflict graph in two steps. Firstly, create a separate vertex for each transmission in the cell, and each vertex for each transmission has two properties: the assigned channel and two endpoints of the transmission. Secondly, connect two vertices by an edge if they satisfy two requirements: the same channel or at least one same endpoint. The scheduling problem thus reduces to obtaining a vertex-coloring of this graph. It can be easily seen that the degree of the conflict graph is $O\left(\frac{n\alpha(n)}{c}\right)+1=O\left(\frac{n\alpha(n)}{c}\right)$. It is well known that a graph with maximum degree e can be vertex-colored with at most $e+1$ colors. Therefore, the conflict graph can be vertex-colored with at most $\lceil\frac{k_3 n\alpha(n)}{c}\rceil$ colors. Thus, the cell-slot is further divided into $\Omega\left(\frac{1}{\lceil\frac{k_3 n\alpha(n)}{c}\rceil}\right)$ equal length mini-slots, and all flows get a slot for transmission. Each channel can transmit at the rate of $\frac{W}{c}$bits/s. Thus, combined with cell-slot and mini-slot, for each flow,

$$\lambda(n)=\Omega\left(\frac{W}{c(k_1+1)\lceil k_3 n\alpha(n)/c\rceil}\right)$$
$$=\Omega\left(\frac{W}{c\lceil\frac{\theta^2}{4\pi^2}k_3 n\alpha(n)/c\rceil}\right)\ bits/s$$

since, $\lceil\frac{\theta^2}{4\pi^2}k_3 n\alpha(n)/c\rceil \le \frac{\theta^2}{4\pi^2}k_3 na(n)/c+1$,

we have $\lambda(n)=\Omega\left(\frac{W}{\frac{\theta^2}{4\pi^2}k_3 n\alpha(n)+c}\right)$ bits/s.

Due to the asymptotic order c , either $na(n)$ or c will dominate the denominator of $\lambda(n)$. Hence, the network capacity is equal to,

$n\lambda(n)=\Omega\left(Min\left(\frac{W}{\frac{\theta^2}{4\pi^2}\alpha(n)},\frac{nW}{c}\right)\right)$ bits/s. Then we obtain that when $c=O\left(\left(\frac{\theta}{2\pi}\right)^2 logn\right)$,$n\lambda(n)=\Omega\left(\frac{nW}{\theta^2 logn}\right)$ bits/s; and when $c=\Omega\left(\left(\frac{\theta}{2\pi}\right)^2 logn\right)$,$n\lambda(n)=\Omega\left(\frac{nW}{c}\right)$ bits/s.

For MC-MDAH network,the condition interference zone is $\left(s^2+(1-s^2)\frac{\theta^2}{4\pi^2}\right)$ portion of that when omnidirectional antennas are used, compared to $\frac{\theta^2}{4\pi^2}$ portion for MC-HDAS network. The surface of a unit torus then can be divided into square cells using a square grid, and we then set $\alpha(n)=max\left(\frac{100log(n)}{n},\frac{c}{n}\left(s^2+(1-s^2)\frac{\theta^2}{4\pi^2}\right)\right)$ to satisfy the connectivity requirement for MC-MDAH network.

Thus, according to the same construction processes, the throughput capacity of MC-HDAH networks is equal to

$$\Omega\left(Min\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)\alpha(n)},\frac{nW}{c}\right)\right)bits/s$$

Then we obtain that when c is $O\left((\theta^2+(4\pi^2-\theta^2)s^2)logn\right)$ bits/s, the network capacity is $\Omega\left(\frac{nW}{(\theta^2+(4\pi^2-\theta^2)s^2)logn}\right)$ bits/s; When c is $\Omega\left((\theta^2+(4\pi^2-\theta^2)s^2)logn\right)$ bits/s, the network capacity is $\Omega\left(\frac{nWm}{c}\right)$ bits/s over a MC-HDAH network.

Based on Lemma.2 in [10], we have the following theorem for the (m,c) multi-channel hybrid wireless network:

Theorem.2 The network capacity of a (m,c) multi-channel hybrid wireless network with antenna support is as follows:

(1)When $\frac{c}{m}$ is $O\left(\left(\frac{\theta}{2\pi^2}\right)^2 logn\right)$, the network capacity is $\Omega\left(\frac{nW}{\theta^2 logn}\right)$ bits/s over a MC-HDAS networks; When $\frac{c}{m}$ is $O\left((\theta^2+(4\pi^2-\theta^2)s^2)logn\right)$ bits/s, the network capacity is $\Omega\left((\theta^2+(4\pi^2-\theta^2)s^2)logn\right)$ bits/s over a MC-HDAH networks.

(2)When $\frac{c}{m}$ is $\Omega\left(\left(\frac{\theta}{2\pi^2}\right)^2 logn\right)$, the network capacity is $\Omega\left(\frac{nWm}{c}\right)$bits/s over a MC-HDAS networks; When $\frac{c}{m}$ is $\Omega\left((\theta^2+(4\pi^2-\theta^2)s^2)logn\right)$bits/s, the network capacity is $\Omega\left(\frac{nWm}{c}\right)$ bits/s over a MC-HDAH networks. The upper and lower bounds have the same order, so the bounds are tight.

6 Conclusion

In the paper, we address the throughput capacity of multi-channel hybrid wireless network with antenna support. Both MC-HDAS network with simplified antenna model and MC-HDAH network with hybrid antenna model are dealt with. We have found that using directional antennas in multi-channel hybrid networks not only can enhance network connectivity but also reduces interferences. Combining directional antennas with multi-channel hybrid wireless network can achieve significant improvement on the network performance.

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