Capacity of Wireless Networks with Heterogeneous Traffic

Mingyue Ji†, Zheng Wang†, Hamid R. Sadjadpour†, J.J. Garcia-Luna-Aceves‡

Department of Electrical Engineering† and Computer Engineering‡
University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
‡ Palo Alto Research Center (PARC), 3333 Coyote Hill Road, Palo Alto, CA 94304, USA
Email:{davidjmy, wzgold, hamid, jj}@soe.ucsc.edu

***Abstract*—We study the scaling laws for wireless ad hoc network in which the distribution of nodes in the network is homogeneous but the traffic is heterogeneous. More specifically, we consider the case in which a node is the sink to k sources sending different information, while the rest of the nodes are part of unicast communications with a uniform assignment of source-destination pairs. We prove that the capacity of these heterogeneous networks is $\Theta(\frac{n}{T_{\max}})$, where $T_{\max}$ and n denote the maximum traffic for a cell and the number of nodes in the network, respectively. Equivalently, our derivations reveal that, when $n-k \neq$ constant, the network capacity is equal to $\Theta\left(\sqrt{\frac{n}{\log n}}\right)$ for $k = O(\sqrt{n \log n})$ and equal to $\Theta\left(\frac{n}{k}\right)$ for $k = \Omega(\sqrt{n \log n})$. Furthermore, the network capacity is $\Theta(1)$ when $n-k =$ constant. These results demonstrate that the capacity of a heterogeneous network is dominated by the maximum congestion in any area of the network.**

I. Introduction

The scaling laws of wireless ad hoc networks with homogeneous traffic and uniform distribution have been extensively studies in the literature. The seminal paper by Gupta and Kumar [1] evaluated the capacity of wireless ad hoc network with uniform traffic and showed that the capacity scales as $\Theta(\frac{n}{\sqrt{\log n}})$ under the protocol model. The information theoretic capacity of wireless ad hoc networks with cooperation among nodes was investigated by Xie and Kumar [2], [3]. Zemlianov and de Veciana [4] investigated the throughput capacity with homogeneous traffic when some nodes are connected to the infrastructure.

Few prior works investigate heterogeneous traffic in the network. Keshavarz-Haddad et al. [5] introduced the concept of transmission arena. Based on that definition, they introduced a method to compute the upper bound of the capacity for different traffic patterns and different topologies of the network. However, the paper did not introduce any closed-form scaling laws for the network capacity. Krishnamurthy et al. [6] discussed different heterogeneous traffic requirements, which depend on the type of data such as audio and video. Liu et al. [7] assumed a heterogeneous traffic for low-priority and high-priority data with different traffic models for them. Rodoplu et al. [8], [9] consider a network with many sources selecting a single node as destination. They introduce the concept of "core capacity" and derived some analytical results for capacity of this type of network and compared it with uniform unicast core capacity. However, their derivations did not lead to a closed form scaling laws; instead, they showed simulation results for the case in which there is a limited number of nodes in the network.

To the best of our knowledge, this is the first paper that provides the scaling laws of such network with heterogeneous traffic as a function of n and other network parameters. Interestingly, we find out that the capacity is dominated by the area in which the majority of traffic in the network passes. This result is intuitive when we assume that all the traffic requirement for each node should be satisfied. Clearly, the node with the highest traffic will dominate the capacity.

The paper is organized as follows. Section II presents the assumptions and definitions needed in our analysis. Section III provides the routing scheme and the lower bound throughput capacity for our network model. Section IV provides the upper bound. Some discussions are presented in Section V and the paper is concluded in Section VI.

II. Wireless Network Model

We consider a network with nodes uniformly distributed in a dense network, where the area of the network is a constant unit square. We assume heterogeneous traffic for the network, such that a single node (called the access point) is the destination for k sources in the network. For the rest of the $n-k$ nodes in the network we assume random and uniformly distributed source-destination pairs. Therefore, the source-destination pair selection for unicast communications is similar to that used by Gupta and Kumar [1] for the rest of $n-k$ nodes in the network. This network model is shown in Figure 1.

The transmission range is assumed to be the same for all the nodes and the communication between nodes is point-to-point. A successful communication between two nodes is modeled according to the protocol model, which is defined below.

Definition 2.1: Protocol Model:
Assume that there is a single common communication range $r(n)$ for all nodes. Node i at location X_i can successfully transmit to node $i(R)$ at location $X_{i(R)}$ if $|X_i - X_{i(R)}| \leq r(n)$ and for every node k located at X_k, $k \neq i$ that transmits at the same time, $|X_k - X_{i(R)}| \geq (1+\Delta) r(n)$. The quantity Δ guarantees a guard zone around the receiver.

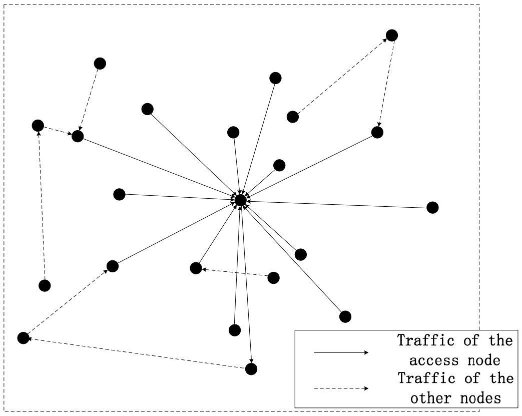

Fig. 1. The Network Model

Definition 2.2: Feasible Throughput:
A throughput of $\lambda_i(n)$ bits per second is said to be feasible for the i^{th} source-destination pair if there is a common transmission range $r(n)$, and a scheme to schedule transmissions and there are routes between source and destination, such that source i can transmit to its destination at such rate successfully. For heterogeneous traffic, the feasible throughput is defined for each source-destination pair.

Definition 2.3: Order of Throughput Capacity: The total throughput capacity is said to be of order $\Theta(f(n))$ bits per second if there exist a constant c and c' such that

$$\lim_{n\to\infty} \Pr(\lambda(n) = \sum_{i=1}^{n} \lambda_i(n) = cf(n) \text{ is feasible}) = 1; \text{ and}$$
$$\liminf_{n\to\infty} \Pr(\lambda(n) = \sum_{i=1}^{n} \lambda_i(n) = c'f(n) \text{ is feasible}) < 1. \tag{1}$$

III. The Lower Bound of the Capacity

We need to emphasize that there are two types of traffic in our model. One traffic is associated to the k sources transmitting packets to the access node and the other traffic stems from the rest of $n-k$ nodes in the network with unicast communications. Therefore, we need to define the routing protocol and scheduling under this traffic model.

A. The Routing Scheme and the Scheduling Protocol

The selection of sources for the access node i is based on the technique described in [10]. We randomly and uniformly select k locations in the network and choose the closest nodes to these k locations as sources for the access node. The routing trajectory is a straight line L_i from access node to these k locations. Then the packets traverse from each source to destination in a multi-hop fashion passing through all the cells that cross L_i. For the rest of j nodes with unicast traffic where $1 \le j \le n-k$, both selections of source-destination pairs and routing is similar to the above technique.

For the scheduling scheme, we utilize a TDMA scheme similar to [10] with some modifications to take into account the heterogeneity of the traffic.

B. The traffic caused by access node

Let us define a traffic from node i to node j as commodity [9]. Clearly, the number of commodities for access node is k which is also equivalent to the number of lines (paths) passing through the cell that contains the access node. For simplicity of the analysis, we assume that the access node is located at the center of the network. Now we compute the number of commodities for a cell that has a distance of x from the access node. From Fig. 2 and by choosing $X_iC = \sqrt{2}$, the area of triangle is

$$S_{X_iAB} = \sqrt{2}\frac{\sqrt{2}d_n}{\sqrt{(x+d_n)^2 - d_n^2}} < \frac{2d_n}{x}, \tag{2}$$

$d_n = C_1\sqrt{\frac{\log n}{n}}$ is selected to guarantee the connectivity between adjacent cells in the network [1] and C_1 is a constant factor.

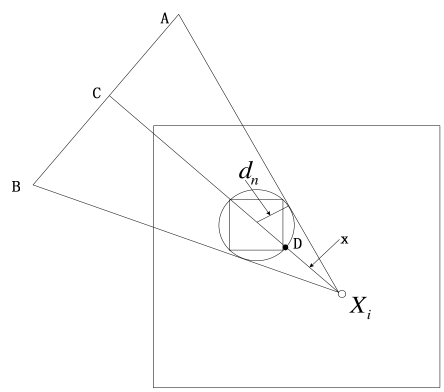

Fig. 2. A geometric description of traffic by the access node in the network

Theorem 3.1: For any cell with a distance of x_j from the access node, the upper bound for the number of commodities caused by the traffic from the access node is

$$N_j < 2\frac{d_n}{x_j}k \tag{3}$$

when $k = \Omega(\sqrt{\frac{n}{\log n}})$.

Proof: The average number of lines passing through the cell ($\mathrm{E}[N_{x_j}]$) whose distance from access node i is x_j is less than $2\frac{d_n}{x_j}k$ since k source nodes are uniformly distributed in the network. Utlizing the Chernoff bound [11], we have

$$\Pr\left(N_{x_j} - \mathrm{E}[N_{x_j}] > \delta\,\mathrm{E}[N_{x_j}]\right)$$
$$< \exp\left[-((1+\delta)\log(1+\delta) - \delta)\,\mathrm{E}(N_{x_j})\right] \tag{4}$$

and

$$\Pr\left(N_{x_j} - \mathrm{E}[N_{x_j}] < -\delta\,\mathrm{E}[N_{x_j}]\right) < \exp\left[-\frac{\delta^2}{2}\,\mathrm{E}[N_{x_j}]\right] \tag{5}$$

where $0 < \delta < 1$. Combining the results and considering $\mathrm{E}[N_{x_j}] < \frac{2d_n}{x_j}k$, we obtain

$$\Pr\left(|N_{x_j} - \mathrm{E}[N_{x_j}]| > \delta\,\mathrm{E}[N_{x_j}]\right) < \exp\left[-((1+\delta)\log(1+\delta)-\delta)\frac{2d_n}{x_j}k\right] + \exp\left[-\frac{\delta^2}{2}\frac{2d_n}{x_j}k\right]. \quad (6)$$

Thus, the probability that the values of the random variables N_{x_j} for all j can simultaneously be arbitrarily close to $\mathrm{E}[N_{x_j}]$ is given by

$$\begin{aligned}
&\Pr\left[\bigcap_j |N_{x_j} - \mathrm{E}[N_{x_j}]| < \delta\,\mathrm{E}[N_{x_j}]\right] \\
&= 1 - \Pr\left[\bigcup_j |N_{x_j} - \mathrm{E}[N_{x_j}]| > \delta\,\mathrm{E}[N_{x_j}]\right] \\
&\geq 1 - \sum_j \Pr\left[|N_{x_j} - \mathrm{E}[N_{x_j}]| > \delta\,\mathrm{E}[N_{x_j}]\right] \\
&> 1 - \sum_j \left(\exp\left[-((1+\delta)\log(1+\delta)-\delta)\frac{2d_n}{x_j}k\right]\right. \\
&\left. + \exp\left[-\frac{\delta^2}{2}\frac{2d_n}{x_j}k\right]\right). \quad (7)
\end{aligned}$$

Denote that if $k = \Omega(\sqrt{\frac{n}{\log n}})$ and $d_n = \Theta(\sqrt{\frac{\log n}{n}})$, then this probability tends to 1 when $n \to \infty$. ■

C. The traffic caused by unicast communications

In this section, we derive the number of lines passing through each cell because of unicast traffic in the network. Since the unicast traffic is distributed uniformly in the network, this value is the same for all the cells in the network.

Lemma 3.2: For any cell S, the maximum number of lines intersecting this cell caused by unicast traffic is given by

$$\Pr(\text{Maximum number of lines } L_i \text{ passing through } S \leq C_2(n-k)\sqrt{\frac{\log n}{n}}) \to 1,$$

when $n - k \neq$ constant.

Proof: Our proof is similar to that of [10] except that we account for $n-k$ unicast pairs in the network. The probability that the destination node j is x away from the source node is $C_3\pi(x+d_n)$ [10] where C_3 is a constant. Thus, the probability p that there is a line passing through the cell S which is with distance x from j is

$$\Pr(L_i \text{ intersects } S) = p < \int_{d_n}^{\sqrt{2}} \left(\frac{2d_n}{x} \bigvee 1\right) k \cdot C_3 \times \pi(x+d_n)dx \leq C_4\sqrt{\frac{\log n}{n}} \quad (8)$$

where C_4 is a constant value. Each of $n-k$ nodes randomly and uniformly selects any other node in the network as destination. Define i.i.d. random variable I_i as

$$I_i = \begin{cases} 1 & \text{If } L_i \text{ intersect } S \\ 0, & \text{Otherwise} \end{cases} \quad (9)$$

where $i = 1, 2, \cdots, n-k$. It is clear from Eq. (8) that $\Pr(I_i = 1) = p < C_4\sqrt{\frac{\log n}{n}}$. Denote $Z_n = \sum_{i=1}^{n-k} I_i$ as the number of lines passing through the cell S. Thus for positive values of a and m and using Chernoff Bound, we have

$$\Pr(Z_n > m) \leq \frac{\mathrm{E}\,e^{aZ_n}}{e^{am}}. \quad (10)$$

Furhter,

$$\begin{aligned}
\mathrm{E}\,e^{aZ_n} &= (1 + (e^a - 1)p)^{n-k} \\
&\leq \exp((n-k)(e^a-1)p) \\
&\leq \exp(C_4(n-k)(e^a-1)\sqrt{\frac{\log n}{n}}) \quad (11)
\end{aligned}$$

Let's define $m = C_2(n-k)\sqrt{\frac{\log n}{n}}$, then Eq. (11) becomes

$$\begin{aligned}
&\Pr(Z_n > C_2(n-k)\sqrt{\frac{\log n}{n}}) \\
&\leq \exp((n-k)\sqrt{\frac{\log n}{n}}(C_4(e^a-1) - C_2a)). \quad (12)
\end{aligned}$$

If we select C_2 such that $C_2a - C_4(e^a-1) = \epsilon > 0$, then

$$\Pr(Z_n > C_2(n-k)\sqrt{\frac{\log n}{n}}) \leq \exp(-\epsilon(n-k)\sqrt{\frac{\log n}{n}}). \quad (13)$$

If the area for each cell is defined as $s_n^2 = \Theta(\frac{\log n}{n})$, then by utilizing the union bound we arrive at

$$\begin{aligned}
&\Pr(\text{Some cells have more than } (n-k)\sqrt{\frac{\log n}{n}} \text{ lines}) \\
&\leq \sum_{\text{all the cells}} \Pr(Z_n > (n-k)\sqrt{\frac{\log n}{n}}) \\
&\leq \frac{1}{s_n^2}\exp(-\epsilon(n-k)\sqrt{\frac{\log n}{n}}) \\
&= \frac{n}{2C_1\log n}\exp(-\epsilon(n-k)\sqrt{\frac{\log n}{n}}). \quad (14)
\end{aligned}$$

This probability goes to zero as n tends to infinity as long as $n - k \neq$ constant. ■

D. The Lower Bound of the Capacity

1) Case of $n - k \neq$ constant: From the previous two sections, we deduce that the number of lines passing through a cell with distance x from the access node is upper bounded as $\frac{2d_nk}{x} + C_2(n-k)\sqrt{\frac{\log n}{n}}$ and for the cell that contains the access node is $k + C_2(n-k)\sqrt{\frac{\log n}{n}}$. In the traditional analysis of capacity with homogeneous traffic, the inverse of traffic for a cell using a TDMA scheme provides the throughput capacity. Given that this value varies for different cells in heterogeneous traffic, we assign a bandwidth to the cell that is proportional to the number of lines passing through a cell. This assignment is based on the fact that each link in the network has the same bandwidth (similar to the approach by Gupta and Kumar) but more allocation of bandwidth is given to a cell with higher traffic. Clearly, our results demonstrate that the cell that contains the access node has the highest traffic. If we divide the network into layers of cells starting from the access point as shown in Fig. 3, the traffic for cells in each layer is the same order. Let's assume the traffic for each layer is T_i where $i = 1, ..., \Theta(\sqrt{\frac{n}{\log n}})$. Then our bandwidth requirement for each layer is given by

$$\frac{W_o}{T_o} = \frac{W_1}{T_1} = ... = \frac{W_{\Theta(\sqrt{\frac{n}{\log n}})}}{T_{\Theta}(\sqrt{\frac{n}{\log n}})} = c(n). \tag{15}$$

Note that $W_o = W_{\max}, T_o = T_{\max}$ and $c(n)$ is a pre-determined function of n. This assumption basically means that more bandwidth is provided to a cell with higher traffic.

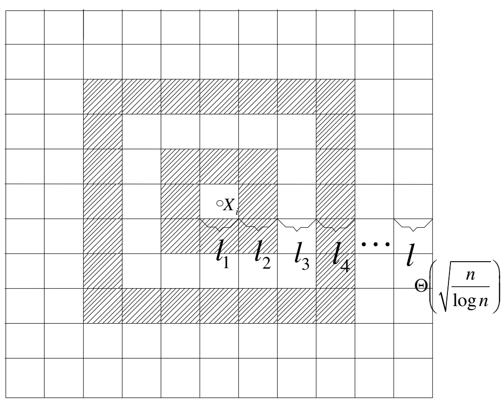

Fig. 3. The layers around X_i

The average number of nodes in each cell is proportional to $\Theta(\log n)$, then the lower bound capacity is

$$\begin{aligned} C_{\text{lower}} &= \frac{1}{MW_{\max}} \left(\sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} \frac{8lW_l}{T_l} + \frac{W_0}{T_0} \right) \cdot \Theta(\log n), \\ &= \frac{1}{MW_{\max}} \left(\sum_{l=0}^{\Theta(\sqrt{\frac{n}{\log n}})} 8lc(n) + c(n) \right) \cdot \Theta(\log n), \\ &= \frac{1}{MW_{\max}} \cdot \Theta(\frac{n}{\log n} + \sqrt{\frac{n}{\log n}}) \cdot \Theta(\log n) \cdot c(n), \\ &= \Omega(\frac{c(n)n}{W_{\max}}) = \Omega(\frac{n}{T_{\max}}), \end{aligned} \tag{16}$$

where M is the TDMA parameter that is required to separate cells in order to satisfy the protocol model.

Note that the capacity defined in this paper is the total capacity since the traffic for each node is different and per node capacity may not be meaningful.

2) Case of $n - k = constant$: Under this condition, clearly all the traffic is contributed by the access node and since each source is sending different packet to the access node, the achivable capacity is $\Omega(1)$ by allowing one source at the time to transmit its packet to the access node.

Combining the above results, we state the following theorem for the achivable lower bound.

Theorem 3.3: The achievable lower bound for a heterogeneous traffic with maximum number of traffic of $T_{\max}$ for a cell can be given as follows.

$$C_{\text{lower}} = \begin{cases} \Omega(\frac{n}{T_{\max}}) & \text{when } n-k \neq C_5 \\ \Omega(1) & \text{when } n-k = C_5 \end{cases} \tag{17}$$

Note that Theorem 3.1 is proved only for $k = \Omega(\sqrt{\frac{n}{\log n}})$. However when $k = O(\sqrt{\frac{n}{\log n}})$, we can still take advantage of the upper bound for $T_{\max}$ because there is less traffic under this condition and the upper bound holds.

IV. The Upper Bound of the Capacity

We first compute the capacity for the case when $n - k \neq$ constant. The capacity can be defined as

$$\begin{aligned} C_{\text{upper}} &= \frac{\text{the sum of capacity for all cells}}{\text{the average number of hops for source-destination pairs}} \\ &\times \frac{1}{\text{maximum bandwidth expansion} \times \text{TDMA parameter}}. \end{aligned}$$

First, we consider the case when $k = \Omega\left(\sqrt{\frac{n}{\log n}}\right)$. It is easy to show that $x \geq (2l-1)\frac{\sqrt{2}d_n}{2}$ where l varies from a constant value up to $\Theta(\sqrt{\frac{n}{\log n}})$ depending on the location of cell from the access node. From this lower bound for x, we can derive the upper bound for T_l.

$$T_l < \begin{cases} \frac{2d_nk}{(2l-1)\frac{\sqrt{2}d_n}{2}} + C_2(n-k)\sqrt{\frac{\log n}{n}} & l \neq 0 \\ k + C_2(n-k)\sqrt{\frac{\log n}{n}} & l = 0 \end{cases} \tag{18}$$

Then the capacity can be derived as

$$
\begin{aligned}
C_{\text{upper}} =& \frac{1}{MW_{\max}} \cdot \left(\sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} \frac{8lW_l}{\frac{L-o(1)}{r(n)}} + \frac{W_0}{\frac{L-o(1)}{r(n)}} \right) \\
\overset{a}{\leq}& \frac{1}{W_{\max}M(L-o(1))} r(n)c(n) \times \\
& \left(\sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} 8l \left(\frac{2d_n k}{(2l-1)\frac{\sqrt{2}d_n}{2}} + C_2(n-k)\sqrt{\frac{\log n}{n}} \right) \right. \\
& \left. + \left(k + C_2(n-k)\sqrt{\frac{\log n}{n}} \right) \right) \\
=& \frac{1}{W_{\max}M(L-o(1))} r(n)c(n) \left(2\sqrt{2}k \sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} \frac{8l}{2l-1} \right. \\
& \left. + k + C_2(n-k)\sqrt{\frac{\log n}{n}} \sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} (8l+1) \right) \\
=& \frac{1}{W_{\max}M(L-o(1))} r(n)c(n) \left(2\sqrt{2}k \sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} (4 \right. \\
& + \frac{4}{2l-1} \bigg) + k + \\
& \left. C_2(n-k)\sqrt{\frac{\log n}{n}} \sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} (8l+1) \right) \\
=& \frac{1}{W_{\max}M(L-o(1))} r(n)c(n) \left(2\sqrt{2}k\Theta \left(\sqrt{\frac{n}{\log n}} \right. \right. \\
& \left. + \log \left(\sqrt{\frac{n}{\log n}} \right) \right) + k \\
& \left. + C_2(n-k)\sqrt{\frac{\log n}{n}} \Theta \left(\frac{n}{\log n} \right) \right) \\
=& \frac{1}{W_{\max}M(L-o(1))} r(n)c(n) \left(2\sqrt{2}k\Theta \left(\sqrt{\frac{n}{\log n}} \right) \right. \\
& \left. + C_2(n-k)\Theta \left(\sqrt{\frac{n}{\log n}} \right) \right) \\
\overset{b}{=}& \frac{1}{W_{\max}M(L-o(1))} c(n)\Theta(\sqrt{\frac{\log n}{n}}) \\
& \left(2\sqrt{2}k\Theta \left(\sqrt{\frac{n}{\log n}} \right) + C_2(n-k)\Theta \left(\sqrt{\frac{n}{\log n}} \right) \right) \\
=& \frac{1}{W_{\max}M(L-o(1))} c(n) \left(2\sqrt{2}k + C_2(n-k) \right) \\
=& O(\frac{c(n)n}{W_{\max}}) = O(\frac{n}{T_{\max}})
\end{aligned} \tag{19}
$$

(a) is derived by replacing $W_l = T_l c(n)$ and (b) is derived by replacing $r(n)$ with $\Theta(\sqrt{\frac{\log n}{n}})$. L in this derivation is the average length of each unicast or the average length over all distances between k sources and the access node.

Second, we consider the case when $k = O\left(\sqrt{\frac{n}{\log n}}\right)$. From (18), we can see that the maximum traffic in the network still satisfies this condition. Thus, we can derive the same result as (19).

The case of $n-k$ =constant is straightforward since we can at most have one data sent to the access node when all the communications involve the access node.

Finally, from the analysis above, we derive a tight bound for the capacity.

Theorem 4.1: In a random ad hoc network, under the heterogeneous traffic pattern with one node performing as the destination for k source nodes and other nodes have unicast communications, the overall capacity is

$$
C = \begin{cases} \Theta\left(\sqrt{\frac{n}{\log n}}\right), & n-k \neq C_5,\ k = O(\sqrt{n\log n}) \\ \Theta\left(\frac{n}{k}\right), & n-k \neq C_5,\ k = \Omega(\sqrt{n\log n}) \\ \Theta(1). & \text{when } n-k = C_5 \end{cases}, \tag{20}
$$

Proof: We know that the capacity of this network is $\Theta(\frac{n}{T_{\max}})$, where $T_{\max} = k + C_2(n-k)\sqrt{\frac{\log n}{n}}$. Then it is straightforward to see that for different values of k, eq. (20) can be derived. ■

V. Discussion

Fig. 4 shows the throughput capacity of a wireless network obtained from (20) as a function of the number of sources for the access node. As the number of the sources for this access node k increases from 1 to $\Theta(\sqrt{n\log n})$, the capacity of the network is $\Theta(\sqrt{\frac{n}{\log n}})$ which is the well known result computed by Gupta and Kumar for homogeneous traffic model. We call this region as *Homogeneous Traffic* region. It is clear that the capacity of the network in this region is dominated by the uniform unicast traffic. Once the value of k passes this threshold of $\Theta(\sqrt{n\log n})$, the capacity of the network is $\Theta(\frac{n}{k})$ which is smaller than the capacity of the *Homogeneous Traffic* region. The capacity of the network is dominated by the access node which is the bottleneck in the network and we call this capacity region as *Heterogeneous Traffic* region. This result implies that for the cells near the access node, we should assign more resources (bandwidth or time) to guarantee the data rate for each traffic. Finally if the number of sources for the access node is such that $n-k = C_5$, then the capacity is $\Theta(1)$ which is the same as broadcast transport capacity [12]. Since the number of sources is relatively large in this case, we call this capacity region as *All to One Traffic* region. We can see that almost all of the nodes have traffic for the access node, thus, for the extreme case that all the nodes have traffic to the access node, at each time, only one node can transmit.

Furthermore, the capacity we calculated is a normalized capacity by the maximum bandwidth. We can see without this normalization, the capacity of the network is $nc(n)$ which is not related to k (see Eqs. (16) and (19)). However, to achieve the same capacity for all nodes and for different

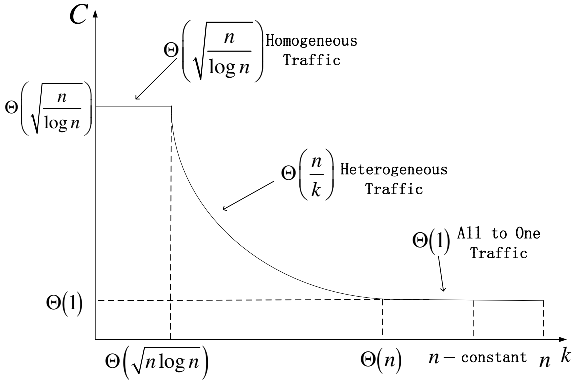

Fig. 4. The capacity result

values of k, we need to allocate more bandwidth to the more congested areas of the network. Fig. 5 demonstrates that in the *Homogenous Traffic* region, the maximum bandwidth needed is not related to k. However, in the *Heterogenous Traffic* region, the bandwidth grows linearly with k, which is the price for keeping the overall capacity the same. Finally, in the *All to One Traffic* region, the order of the maximum bandwidth does not change.

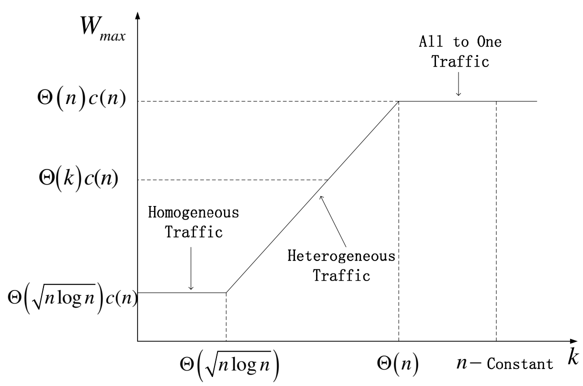

Fig. 5. The maximum bandwidth required corresponding to different k

VI. Conclusion

This paper presented the first closed-form scaling laws for the capacity of wireless ad hoc networks with heterogeneous traffic. More specifically, we assumed an access node with k sources choosing this node as destination and the rest of nodes in the network, having unicast communications. It was shown that the capacity of such heterogeneous networks is $\Theta(\frac{n}{T_{\max}})$. Equivalently, our derivations reveal that, when $n - k \neq$ constant, then the capacity is equal to $\Theta\left(\sqrt{\frac{n}{\log n}}\right)$ for $k = O(\sqrt{n \log n})$ and equal to $\Theta\left(\frac{n}{k}\right)$ for $k = \Omega(\sqrt{n \log n})$. Furthermore, when $n - k =$ constant, then the capacity is $\Theta(1)$. The results demonstrate that, as it should be expected, the capacity of a heterogeneous network is dominated by the maximum traffic (congestion) in any area of the network.

References

[1] P. Gupta and P.R.Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, March 2000.

[2] L.-L. Xie and P.R.Kumar, "A network information theory for wireless communication: Scaling laws and optimal operation," *IEEE Transactions on Information Theory*, vol. 50, no. 5, pp. 748–767, May 2004.

[3] ——, "On the path-loss attenuation regime for positive cost and linear scaling of transport capacity in wireless networks," *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2313–2328, June 2006.

[4] A. Zemlianov and G. de Veciana, "Capacity of ad hoc wireless networks with infrastructure support," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 3, pp. 657–667, March 2005.

[5] A. Keshavarz-Haddad and R. Riedi, "Bounds for the capacity of wireless multihop networks imposed by topology and demand," in *MobiHoc*, September 2007, pp. 256–265.

[6] F. Yu, V. Krishnamurthy, and V. C.M.Leung, "Cross-layer optimal connection admission control for varible bit rate multimedia traffic in packet wireless cdma networks," *IEEE Transactions on Signal Processing*, vol. 54, no. 2, pp. 542–555, February 2006.

[7] W. Liu, X. Chen, Y. Fang, and J. M. Shea, "Courtesy piggybacking: Supporting differentiated services in multiop mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 4, pp. 380–393, 2004.

[8] V. Rodoplu and T. H.Meng, "Core capacity of wireless ad hoc networks," in *The 5th International Symposium on Wireless Personal Multimedia Communications*, September 2002, pp. 247–251.

[9] M. Kyoung and V. Rodoplu, "Core capacity region of portable wireless networks," in *Globecom*, September 2004, pp. 256–265.

[10] F. Xue and P. R. Kumar, *Scaling Laws for Ad Hoc Wireless Networks: An Information Theoretic Approach*. NOW Publishers, 2006.

[11] B. Motwani and P. Raghavan, *Randomized Algorithms*. Cambridge University Press, 1995.

[12] D. Marco, E. J. Duarte-Melo, M. Liu, and D. L. Neuhoff, "On the many-to-one transport capacity of a dense wireless sensor network and the compressibility of its data," in *IPSN*, 2003.