Capacity of Wireless Networks with Heterogeneous Traffic under Physical Model

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***Abstract*—The throughput capacity of wireless ad hoc networks is derived when the traffic is heterogeneous but the node distribution is homogeneous. For the heterogeneous traffic we consider two types of traffic in the network, namely, unicast and data gathering communications. There are k sources that send different data to a single node and the rest of $n-k$ nodes in the network participate in unicast communications with a uniform assignment of source-destination pairs. Under the physical model, it is proved 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. The result demonstrates that the capacity is dominated by the maximum congestion in any area of the network. More specifically, 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 $k=\Omega(\sqrt{n\log n})$.**

I. Introduction

The scaling laws of wireless ad hoc networks with homogeneous traffic and uniform distribution have been extensively studies in the literature. Gupta and Kumar [1] evaluated the capacity of wireless ad hoc network with uniform traffic and showed that for the physical model, the lower bound of the capacity is $\Theta(\frac{n}{\sqrt{\log n}})$, but the upper bound is $\Theta(\sqrt{n})$. Later on, this capacity is closed by Franceschetti in [2]. The information theoretic capacity of wireless ad hoc networks with cooperation among nodes was investigated by Xie and Kumar [3], [4].

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. We have derived the capacity of wireless networks with heterogeneous traffic under the protocol model in [10]. This paper extends those results to physical model assumption.

Our paper provides the scaling laws of such network with heterogeneous traffic as a function of n and other network parameters under the physical model. The result indicates 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 the capacity should be achieved by all the nodes in the network. Clearly, the node with the highest traffic will dominate the capacity.

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

II. Wireless Network Model

Nodes are uniformly distributed in a dense network where the area of the network is a constant unit square. The heterogeneous traffic consists of data gathering traffic in which a single node (called the access node) 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]. This network model is shown in Figure 1.

The transmission range is 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 physical model, which is defined below.

Definition 2.1: Physical Model: Let $\{X_k; k\in\mathcal{K}\}$ be the subset of nodes simultaneously transmitting at the same time over a certain subchannel. All nodes in this subchannel choose a common power level P for all their transmissions. For each subchannel, the noise power is N. A node can transmit over several subchannels. A transmission from a node X_i, $i\in\mathcal{K}$,

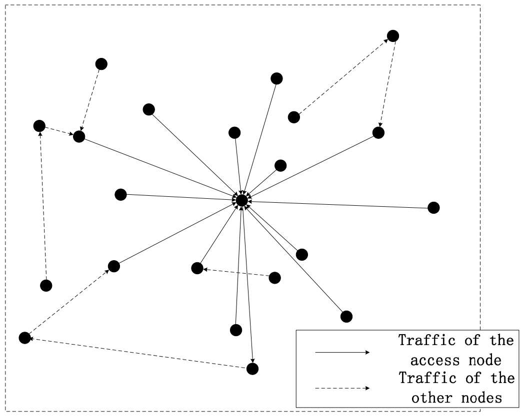

Fig. 1. The Network Model

is successfully received by a node $X_{i(R)}$ if

$$\frac{\frac{P}{|X_i - X_{i(R)}|^\alpha}}{N + \sum_{k \in \mathcal{K}, k \neq i} \frac{P}{|X_k - X_{k(R)}|^\alpha}} \geq \beta. \tag{1}$$

for every subchannel.

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

$$\begin{aligned} &\lim_{n\to\infty} \Pr(\lambda(n) = \sum_{i=1}^{n} \lambda_i(n) = cf(n) \text{ is feasible}) = 1; \text{ and} \\ &\liminf_{n\to\infty} \Pr(\lambda(n) = \sum_{i=1}^{n} \lambda_i(n) = c'f(n) \text{ is feasible}) < 1. \end{aligned} \tag{2}$$

One important assumption of our analysis is that the bandwidth for each traffic is assumed to be the same, which means that the bandwidth for each node is proportional to its traffic. In another word, the fairness for each flow is guaranteed. Let's define bandwidth W_i and traffic T_i for cell i, then

$$\frac{W_i}{T_i} = c(n), \tag{3}$$

where $c(n)$ is a pre-determined function of n.

III. The Upper Bound of the Capacity

In this section, we compute the upper bound of the capacity. From [1] and [2], we know that the minimum transmission range under the physical model is $\Theta\left(\frac{1}{\sqrt{n}}\right)$. Therefore, the maximum number of hops for each source-destination pair is $\frac{L-o(1)}{r(n)} = \Theta(\sqrt{n})$. Note that there are at most n source-destination pairs in the network. Thus, the total traffic is

$$\sum_l T_l = \Theta(n\sqrt{n}). \tag{4}$$

We know that each transmission consumes a disk of radius $\Theta(r(n))$ and these disks are disjoint. Note that all the traffic are carried by these disjoint disks and the bandwidth distributed to each cell is proportional to the traffic. Therefore, the upper bound of the capacity is given by

$$\begin{aligned} C_{\text{upper}} &= \frac{\text{the sum of traffic for all nodes}}{\text{the average number of hops for source-destination pairs}} \\ &\quad \times \frac{1}{\text{maximum bandwidth expansion}}, \\ &= \frac{1}{W_{\max}} \cdot \frac{\sum_{l=1}^{n} W_l}{\frac{L-o(1)}{r(n)}} = \frac{1}{W_{\max}} \cdot \frac{\sum_{l=1}^{n} T_l c(n)}{\frac{L-o(1)}{r(n)}}, \\ &= \frac{1}{T_{\max} c(n)} \cdot \frac{\Theta(n\sqrt{n}c(n))}{\frac{L-o(1)}{\frac{1}{\sqrt{n}}}} = \Theta\left(\frac{n}{T_{\max}}\right), \end{aligned} \tag{5}$$

where $W_{\max}$ is the maximum bandwidth and $T_{\max}$ is the maximum traffic for a cell in the network.

IV. The Lower Bound of the Capacity

For 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, the routing protocol and scheduling are defined 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 [11]. 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. The side length of each cell d_n is selected as $\Theta(r(n)) = C_1\sqrt{\frac{\log n}{n}}$ [1], where C_1 is a positive constant. For the rest of j nodes with unicast traffic where $1 \leq j \leq n-k$, 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 [11] with some modifications to take into account the heterogeneity of the traffic.

B. The Lower Bound of the Capacity

For the lower bound of the capacity, we will introduce a specific network structure which divides the network into square cells. To guarantee the connectivity in the network, the side length of each cell is chosen as $\Theta\left(\sqrt{\frac{\log n}{n}}\right)$. We will show that the lower bound of the capacity is still $\Theta\left(\frac{n}{T_{\max}}\right)$.

1) Case of $n-k=\Omega\left(\sqrt{n\log n}\right)$: From [10], it can be deduced that the number of lines passing through a cell with distance x from the access node is upper bounded as

$$T_l < \begin{cases} \dfrac{2d_n k}{(2l-1)\frac{\sqrt{2}d_n}{2}} + C_2(n-k)\sqrt{\dfrac{\log n}{n}} & l \neq 0 \\ k + C_2(n-k)\sqrt{\dfrac{\log n}{n}} & l = 0 \end{cases} \tag{6}$$

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, as mentioned before, 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 node as shown in Fig. 2, 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

$$\frac{W_0}{T_0} = \frac{W_1}{T_1} = ... = \frac{W_{\Theta(\sqrt{\frac{n}{\log n}})}}{T_{\Theta(\sqrt{\frac{n}{\log n}})}} = c(n). \tag{7}$$

Note that $W_0 = W_{\max}, T_o = T_{\max}$. This assumption basically means that more bandwidth is provided to a cell with higher traffic[1].

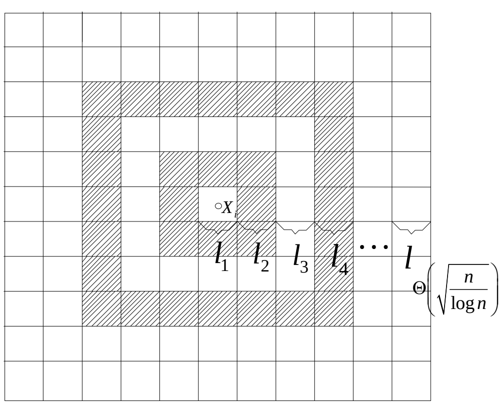

Fig. 2. The layers around access node X_i

For the Physical Model, it is important to show that under the schedule given in Section IV-A, the required SINR threshold β can be guaranteed. We can consider that all the interference comes from cells that are active at the same time. It is obvious to see that there are at most $8k$ interfering cells from the kth layer of the network. Moreover, the distance from an interfering cell is at least $k\sqrt{M}s_n - s_n$, where M is the number of non-interference groups and s_n is the side length of each cell.

Thereafter, for each specific node i, we can calculate a lower bound on the achieved SINR as shown below.

$$\begin{aligned} \frac{\frac{P}{|X_i - X_{i(R)}|^\alpha}}{N + \sum_{k\in\mathcal{K}, k\neq i}\frac{P}{|X_k - X_{i(R)}|^\alpha}} &\overset{(a)}{\geq} \frac{\frac{P}{(2\sqrt{2}s_n)^\alpha}}{N + \sum_{k=1}^{\infty} 8k\frac{P}{(k\sqrt{M}s_n - s_n)^\alpha}} \\ &= \frac{\frac{P}{(2\sqrt{2})^\alpha}}{Ns_n^\alpha + \frac{8P}{M^{\frac{\alpha}{2}}}\sum_{k=1}^{\infty}\frac{1}{(k-\frac{1}{\sqrt{M}})^\alpha}} \end{aligned} \tag{8}$$

Figure 3 shows the relationship between traffic in a cell and allocated bandwidth as described in Eq. (7). Since each layer of cells has different bandwidth requirement, therefore only portion of the transmitted signal in a layer will interfere with adjacent cells. For example, when $T_k \geq T_i$, the interfering portion of bandwidth for the cells in layer i from cells in layer k is at most T_i. Similarly, when $T_k < T_i$, the interfering bandwidth for the cells in layer i from cells in layer k is at most T_k. So for each subchannel, the interference may come from part of every layer of the network that is active at the same time. Since in the inequality (a) in Eq. (8), we calculate the entire signal power while only portion of it may interfere with i, then this value is the lower bound.

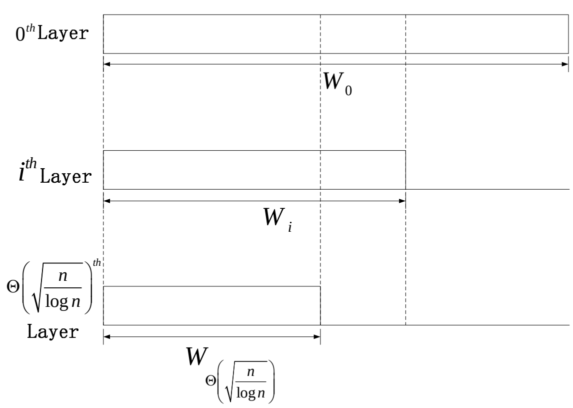

Fig. 3. The distribution of the bandwidth in different cell layers of the network.

The summation in the denominator converges to a constant value when $\alpha > 2$ as described below.

$$\begin{aligned} &\sum_{k=1}^{\infty}\frac{1}{(k-\frac{1}{\sqrt{M}})^\alpha} \\ &= \sum_{k=1}^{\infty}\frac{1}{(k-\frac{1}{\sqrt{M}})^{\alpha-1}} + \frac{1}{\sqrt{M}}\sum_{k=1}^{\infty}\frac{1}{(k-\frac{1}{\sqrt{M}})^{\alpha-1}} \end{aligned}$$

[1] The bandwidth allocation in this paper is based on the common definition of throughput capacity that is utilized in literature. Under this assumption, the achievable througput capacity is based the fact that all the nodes in the network achieve the same rate. However, if one changes this definition of capacity and allows different nodes to have different throughput capacity, then the bandwidth allocation should accordingly changes in order to achieve the highest possible throughput.

$$\leq \frac{1}{(k-\frac{1}{\sqrt{M}})^{\alpha-1}} + \int_{1-\frac{1}{\sqrt{M}}}^{\infty} \frac{1}{x^{\alpha-1}}$$
$$+ \frac{1}{\sqrt{M}} \left(\frac{1}{(k-\frac{1}{\sqrt{M}})^{\alpha}} + \int_{1-\frac{1}{\sqrt{M}}}^{\infty} \frac{1}{x^{\alpha}} \right)$$
$$= \frac{1}{(1-\frac{1}{\sqrt{M}})^{\alpha-1}} + \frac{\left(1-\frac{1}{\sqrt{M}}\right)^{-(\alpha-2)}}{\alpha-2}$$
$$+ \frac{1}{\sqrt{M}} \frac{1}{(1-\frac{1}{\sqrt{M}})^{\alpha}} + \frac{1}{\sqrt{M}} \frac{\left(1-\frac{1}{\sqrt{M}}\right)^{-(\alpha-1)}}{\alpha-1}$$
$$= \text{constant} \tag{9}$$

It is clear from these results that when M is sufficiently large, then the SINR of an arbitrary subchannel can be made larger than the specific threshold β to satisfy the *Physical Model* (1).

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

$$C_{\text{lower}} = \frac{1}{MW_{\max}} \left(\sum_{l=1}^{\Theta(\sqrt{\frac{n}{\log n}})} \frac{8lW_l}{T_l} + \frac{W_0}{T_0} \right) \cdot \Theta(\log n),$$
$$= \frac{1}{MW_{\max}} \left(\sum_{l=0}^{\Theta(\sqrt{\frac{n}{\log n}})} 8lc(n) + c(n) \right) \cdot \Theta(\log n),$$
$$= \frac{1}{MW_{\max}} \cdot \Theta(\frac{n}{\log n} + \sqrt{\frac{n}{\log n}}) \cdot \Theta(\log n) \cdot c(n),$$
$$= \Omega(\frac{c(n)n}{W_{\max}}) = \Omega(\frac{n}{T_{\max}}), \tag{10}$$

where M is the TDMA parameter that is required to separate cells in order to satisfy the physical 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 $n-k = o\left(\sqrt{n \log n}\right)$: Under this condition, clearly most of the traffic is contributed by the access node and since each source is sending different packet to the access node, the achievable 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 achievable lower bound.

Theorem 4.1: The achievable lower bound for a heterogeneous traffic with maximum number of traffic of $T_{\max}$ in a cell can be given as follows.

$$C_{\text{lower}} = \begin{cases} \Omega(\frac{n}{T_{\max}}) & \text{when } n-k = \Omega\left(\sqrt{n \log n}\right) \\ \Omega(1) & \text{when } n-k = o\left(\sqrt{n \log n}\right) \end{cases} \tag{11}$$

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

Theorem 4.2: 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

$$C = \Theta\left(\frac{n}{T_{\max}}\right) \tag{12}$$

V. Discussion

Eq.(6) provides the value of $T_{\max}$ when k is small value compared to n. But when k is a large number, i.e., $n-k = o\left(\sqrt{n \log n}\right)$, then the dominant traffic in the network is the data gathering traffic and for computation of $T_{\max}$, one can ignore the contribution of unicast traffic. Under this assumption, then the data gathering traffic provides the maximum traffic for the access node, i.e., $T_{\max} = k$. Thus, Eq. (12) becomes

$$C = \begin{cases} \Theta\left(\sqrt{\frac{n}{\log n}}\right), & k = O(\sqrt{n \log n}) \\ \Theta\left(\frac{n}{k}\right), & k = \Omega(\sqrt{n \log n}) \end{cases} \tag{13}$$

Fig. 4 shows the throughput capacity of a wireless network obtained from (13) as a function of the number of sources for the access node k. When k increases from 1 to $\Theta(\sqrt{n \log n})$, the capacity of the network is dominated by the unicast traffic and it is equal to the well known result computed by Gupta and Kumar for unicast communications as $\Theta(\sqrt{\frac{n}{\log n}})$. This region is called unicast region. Once the value of k passes this threshold of $\Theta(\sqrt{n \log n})$, the capacity of the network is equal to $\Theta(\frac{n}{k})$ and it is affected by both the unicast and data gathering traffics. 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 when $k = \Theta(n)$, 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.

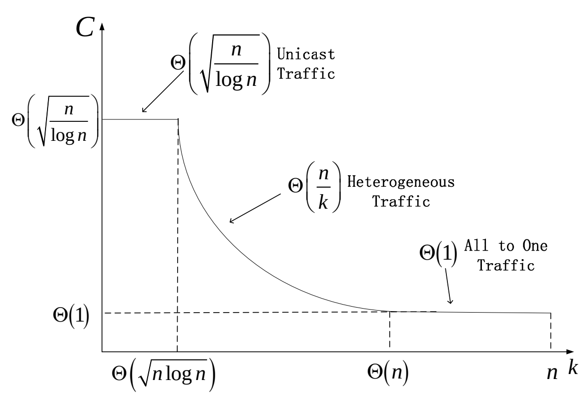

Fig. 4. The capacity result

The nodes with higher traffic consume more power for transmission of information. Our goal is to demonstrate the relationship between k and maximum required power. From (8), it is easy to observe that the minimum transmit power P for each subchannel to guarantee the SINR $\geq \beta$ condition is

$$P_{\text{min}} = \Theta(s_n^{\alpha}) = \Theta\left(\left(\frac{\log n}{n}\right)^{\frac{\alpha}{2}}\right). \tag{14}$$

Thus, the maximum required power is

$$P_{\text{max}} = P_{\text{min}} W_{\text{max}} = P_{\text{min}} T_{\text{max}} c(n). \tag{15}$$

Combining the above result with Eq. (6), we arrive at

$$P_{\text{max}} = \begin{cases} \Theta\left(\frac{(\log n)^{\frac{\alpha}{2}+\frac{1}{2}}}{n^{\frac{\alpha}{2}-\frac{1}{2}}}\right) c(n), & k = O(\sqrt{n \log n}) \\ \Theta\left(\frac{(\log n)^{\frac{\alpha}{2}}}{n^{\frac{\alpha}{2}}}\right) kc(n), & \Omega(\sqrt{n \log n}) = k = O(n) \\ \Theta\left(\frac{(\log n)^{\frac{\alpha}{2}}}{n^{\frac{\alpha}{2}-1}}\right) c(n). & k = \Theta(n) \end{cases}, \tag{16}$$

Figure 5 shows the order of the maximum power as a function of k. It is clear that the node with the maximum required power is the access node since it carried more traffic than any other node in the network. In the unicast traffic region, the order of the maximum power for the access node is not growing because the unicast traffic is the dominant traffic. In the homogeneous traffic region, as k increases, the traffic for the access node increases and accordingly, this node requires more transmit power. In the final region of all to one traffic, the traffic in the network is dominated by the data gathering scheme and the access node carries majority of the traffic in the network. The maximum transmit power is achieved in this region because the traffic for the access node has reached its order upper bound traffic. These results imply that if the traffic for the access node is restricted with $k = O(\sqrt{n \log n})$, then the optimal power consumption for the access node can be attained.

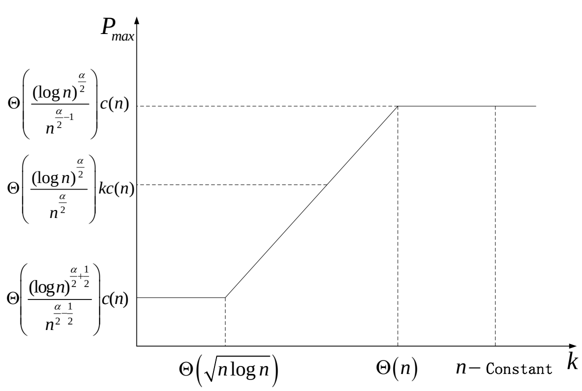

Fig. 5. The Growth of Power as a function of k

VI. Conclusion

This paper presents a closed-form scaling law for the capacity of wireless ad hoc networks with heterogeneous traffic under physical model. More specifically, a combination of unicast communications and data gathering has been chosen for this paper. It is shown that the capacity of such heterogeneous network is $\Theta(\frac{n}{T_{\text{max}}})$. Further, 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 $k = \Omega(\sqrt{n \log n})$. The results confirms our intuition that the capacity of a heterogeneous network is dominated by the maximum traffic (congestion) in any area of the network.

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