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Broadcast Throughput Capacity of Wireless Ad Hoc Networks with Multipacket Reception

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***Abstract*—We study the broadcast throughput capacity of random wireless ad hoc networks when the nodes are endowed with multipacket reception (MPR) capability. We show that, in such networks, a per-node throughput capacity of $\Theta\left(R^2(n)\right)$ bits per second can be achieved as a tight bound (i.e., upper and lower bounds) for broadcast communication, where $R(n)$ is the receiver range that depends on the complexity of the nodes. Compared to ad hoc networks in which receivers decode at most one transmission at a time, the minimum capacity gain of MPR-based networks is $\Theta(\log n)$. This is attained when the minimum value for $R(n)$ is used, which equals the minimum transmission range needed to guarantee connectivity in the network ($r(n) = \Theta(\sqrt{\log n/n})$).**

I. Introduction

Gupta and Kumar [1] established that the per-node throughput capacity of wireless ad hoc network with multi-pair unicast traffic scales as $\Theta\left(1/\sqrt{n \log n}\right)$ when any receiver can successfully decode at most one packet at a time. Since then, researchers have studied the throughput capacity of wireless ad hoc networks for multicast and broadcast communication [2]–[5].

Without exploiting node mobility [6], in static networks, the only two possible approaches to increase the order capacity of an ad hoc network consist of increasing the amount of information in each relay by utilizing more bandwidth, or avoiding interference by increasing cooperation among nodes. Work has been carried out in both fronts. If bandwidth is allowed to increase proportionally to the number of nodes in the network [7], higher transport capacities can be attained for static wireless networks. Ozgur et al. [8] proposed a hierarchical cooperation technique based on virtual MIMO to achieve linear capacity scaling. Cooperation can also be extended to the simultaneous transmission and reception by adjacent nodes in the network, which can result in significant improvement in capacity [9].

Multipacket reception (MPR) is another cooperative technique that was first presented by Ghez et al. [10], [11]. MPR allows multiple nodes to transmit their packets simultaneously to the same receiver node, which can decode all these packets successfully. The ability of MPR-based networks to embrace interference contrasts with the traditional view in which a receiver is assumed to decode successfully at most one transmission at a time [1], which necessarily leads to interference avoidance.

In the context of MPR, multiple nodes cooperate to transmit their packets simultaneously to a single node using multiuser detection (MUD), directional antennas (DA) [12], multiple input multiple output (MIMO) techniques, or physical or analog network coding [13], [14]. Furthermore, Toumpis and Goldsmith [15] have shown that the capacity regions of ad hoc networks are significantly increased when multiple access schemes are combined with spatial reuse (i.e., multiple simultaneous transmissions), multi-hop routing (i.e., packet relaying), and successive interference cancelation (SIC). In our previous work [16], we have proved that the throughput capacity of a wireless network with MPR is $\Theta\left(R(n)\right)$ for multi-pair unicast applications. When $R(n) = \Theta\left(\sqrt{\log n/n}\right)$ to guarantee connectivity criterion, a gain of $\Theta(\log n)$ is achieved compared to the case in which network nodes can decode at most one transmission at a time [1].

The study of the broadcast capacity of wireless networks has also attracted considerable attention. Tavli [2] was the first to show a bound of $\Theta(1/n)$ for broadcast capacity of arbitrary networks. Zheng [3] derived the broadcast capacity of power-constrained networks, together with another metric called ”information diffusion rate” for single-source broadcast. The work by Keshavarz et al. [4] is the most general case of computing the broadcast capacity of a wireless network for any number of sources. Our work was inspired by some of the contributions in this paper.

The main contribution of this paper is to show that the per-source-destination broadcast capacity $C_B(n)$ of a wireless random ad hoc network in which receivers are endowed with MPR capability is tightly bounded by $\Theta(R^2(n))$ (upper and lower bounds) w.h.p. [1], where $R(n)$ is the reception range [9], [16] of a receiver. Furthermore, we note that when $R(n) = r(n) \geq \Theta\left(\sqrt{\log n/n}\right)$, the broadcast capacity has the minimum gain of $\Theta(\log n)$ compared to the broadcast capacity of a wireless random ad hoc network in which receivers can decode at most one packet at a time [4].

This paper is organized as follows. Section II describes the network model and definitions. The upper and lower bounds broadcast capacity of MPR-based networks is presented in Sections III and IV, respectively.

[1] We say that an event occurs with high probability (w.h.p.) if its probability tends to one as n goes to infinity. Θ, Ω and O are the standard order bounds.

II. Network Model, Definitions, and Preliminaries

We assume a random wireless ad hoc network with n nodes distributed uniformly in the network area. Our analysis is based on dense networks, where the area of the network is a square of unit value. All nodes use a common transmission range $r(n)$ for all their communications[2]. Our capacity analysis is based on extending the protocol model for dense networks introduced in [1].

The *protocol model* [1] is defined as follows: Node X_i can successfully transmit to node X_j if for any concurrent transmitter node $X_k, k \neq i$, we have $|X_i - X_j| \leq r(n)$ and $|X_k - X_j| \geq (1 + \Delta)r(n)$.

In wireless networks with MPR capability, the protocol model assumption allows a receiver to receive packets from multiple transmitters concurrently, as long as they are within a radius of $R(n)$ from the receiver and all other transmitting nodes have a distance to the receiver larger than $(1+\Delta)R(n)$. Note that the transmission range $r(n)$ is a random variable, while $R(n)$ in MPR is a predefined value that depends on the complexity of receivers. We assume that nodes cannot transmit and receive at the same time, which is equivalent to half-duplex communications [1]. The data rate for each transmitter-receiver pair is a constant value of W bits/second and does not depend on n. Given that W does not change the order capacity of the network, we normalize its value to 1.

The relationship between the receiver range used in the capacity computation for MPR-based wireless networks and the transmission range in [1] is defined as

$$R(n) = r(n) \geq \Theta\left(\sqrt{\frac{\log n}{n}}\right). \qquad (1)$$

Definition 2.1: Throughput broadcast capacity: In a wireless network with n nodes in which each source node transmits its packets to all n nodes, a throughput of $C_B(n)$ bits per second for each node is feasible if there is a spatial and temporal scheme for scheduling transmissions, such that by operating the network in a multi-hop fashion and buffering at intermediate nodes when awaiting transmission, every node can send $C_B(n)$ bits per second on average to all n nodes. That is, there is a $T < \infty$ such that in every time interval $[(i-1)T, iT]$ every node can send $TC_B(n)$ bits to all n nodes.

Definition 2.2: Order of throughput capacity: $C_B(n)$ is said to be of order $\Theta(f(n))$ bits per second if there exist deterministic positive constants c and c' ($c < c'$) such that

$$\begin{cases} \lim_{n\to\infty} \text{Prob } (C_B(n) = cf(n) \text{ is feasible}) = 1 \\ \lim_{n\to\infty} \text{Prob } (C_B(n) = c'f(n) \text{ is feasible}) < 1. \end{cases} \qquad (2)$$

Definition 2.3: Minimum Connected Dominating Set (MCDS $(R(n))$): A dominating set $(\text{DS}\,(R(n)))$ of a graph G is defined as a set of nodes such that every node in the graph G either belongs to this set or it is within a range $R(n)$ of one element of $\text{DS}(R(n))$. A connected dominating set $(\text{CDS}\,(R(n)))$ is a dominating set such that the subgraph induced by its nodes is connected. A Minimum Connected Dominating Set $(\text{MCDS}\,(R(n)))$ is a $\text{CDS}(R(n))$ of G with the minimum number of nodes.

Definition 2.4: Maximum Independent Set $(\text{MIS}\,(\Delta, r(n)))$: An Independent Set $\text{IS}(\Delta, r(n))$ of a graph G is a set of vertices in G such that the distance between any two elements of this set is greater than $r(n)$. The $\text{MIS}(\Delta, r(n))$ of G is an $\text{IS}(r(n))$ such that, by adding any vertex from G to this set, there is at least one edge shorter than or equal to $r(n)$.

We note that $\text{MIS}(\Delta, r(n))$ is a unique largest independent set for a given graph. Finding such a set in a general graph G is called the MIS problem and is an NP-hard problem. In [4], $\text{MIS}(\Delta, r(n))$ is used to describe the maximum number of simultaneous transmitters in plain routing scheme. We define a new concept, called Maximum MPR Independent Set (MMIS), to describe the same concept when MPR scheme is used.

Definition 2.5: Maximum MPR Independent Set $(\text{MMIS}\,(\Delta, R(n)))$: An MPR set is a set of nodes in G that contains one receiver node and all (transmitting) nodes within a distance of $R(n)$ from this receiver node. A Maximum MPR Independent Set $(\text{MMIS}\,(\Delta, R(n)))$ consists of the maximum number of MPR sets that simultaneously transmit their packets while MPR protocol model is satisfied for all these MPR sets. If we add any transmitter node from G to $\text{MMIS}(\Delta, R(n))$, there will be at least one MPR set that violates the MPR protocol model.

In this paper, $\overline{T}$ denotes the statistical average of T and $\#T$ defines the total number of vertices (nodes) in a tree T.

The distribution of nodes in random networks is uniform, so if there are n nodes in a unit square, then the density of nodes equals n. Hence, if $|S|$ denotes the area of region S, the expected number of the nodes, $E(N_S)$, in this area is given by $E(N_S) = n|S|$. Let N_j be a random variable defining the number of nodes in S_j . Then, for the family of variables N_j, we have the following standard results known as the Chernoff bounds [17]:

Lemma 2.6: Chernoff bound

- For any $\delta > 0$, $P[N_j > (1+\delta)n|S_j|] < \left(\frac{e^\delta}{(1+\delta)^{1+\delta}}\right)^{n|S_j|}$
- For any $0 < \delta < 1$, $P[N_j < (1-\delta)n|S_j|] < e^{-\frac{1}{2}n|S_j|\delta^2}$

Combining these two inequalities we have, for any $0 < \delta < 1$:

$$P[|N_j - n|S_j|| > \delta n|S_j|] < e^{-\theta n|S_j|}, \qquad (3)$$

where $\theta = (1+\delta)\ln(1+\delta) - \delta$ in the case of the first bound, and $\theta = \frac{1}{2}\delta^2$ in the case of the second bound.

Therefore, for any $\theta > 0$, there exist constants such that deviations from the mean by more than these constants occur with probability approaching zero as $n \to \infty$. It follows that we can get a very sharp concentration on the number of nodes in an area. Thus, we can find the achievable lower bound w.h.p., provided that the upper bound (mean) is given. In the next two sections, we first derive the upper bound, and then use the Chernoff bound to prove the achievable lower bound.

[2]In this paper, we assume receiver range is equal to transmission range

III. Upper Bound Broadcast Capacity with MPR

In this section, we compute the upper bound for MPR (i.e., the broadcast capacity of wireless networks when nodes are endowed with MPR capability). Note that $\overline{\#\text{MCDS}(R(n))}$ equals the average minimum number of retransmission required to broadcast a packet and $\overline{\#\text{MMIS}(\Delta, R(n))}$ is the average maximum number of successful simultaneous transmissions in the network. The following Lemma computes an upper bound as the ratio of $\overline{\#\text{MMIS}(\Delta, R(n))}$ to $\overline{\#\text{MCDS}(R(n))}$. In [4], $\overline{\#\text{MIS}(\Delta r(n))}$ is used to express the average maximum number of simultaneous transmissions without MPR instead of $\overline{\#\text{MMIS}(\Delta, R(n))}$.

Lemma 3.1: Per node broadcast capacity with MPR is upper bounded as $O\left(\frac{1}{n} \times \frac{\overline{\#\text{MMIS}(\Delta,R(n))}}{\overline{\#\text{MCDS}(R(n))}}\right)$.

Proof: We observe that $\overline{\#\text{MCDS}(R(n))}$ represents the total average number of channel usage required to broadcast information from a source. By Definition 2.1, the total broadcast capacity in the network is equal to $nC_B(n) = \sum_{i=1}^{n} \lambda^i(n)$. Denote by N_T the total number of broadcasted bits in $[0, T]$, then

$$nC_B(n) = \sum_{i=1}^{n} \lambda^i(n) = \lim_{T\to\infty} \frac{N_T}{T}. \quad (4)$$

Let $N_B(b)$ denote the total number of times any bit b is transmitted in order to broadcast to the network, then $N_B(b) \geq \overline{\#\text{MCDS}(R(n))}$. The total number of retransmissions for broadcast in $[0, T]$ is thus $N_T \times N_B(b)$. Since all broadcast packets are received in a limited time $T_{\max}$, at time $T + T_{\max}$ all transmissions of N_T bits are finished. Therefore,

$$\begin{aligned} \overline{\#\text{MMIS}(\Delta, R(n))} \times (T + T_{\max}) \geq & N_T \times N_B(b) \\ \geq & N_T \overline{\#\text{MCDS}(R(n))}. \end{aligned} \quad (5)$$

By combining the two previous equations, we have

$$\begin{aligned} C_B(n) &= \frac{1}{n} \times \lim_{T\to\infty} \frac{N_T}{T} \\ &= \frac{1}{n} \times \lim_{T\to\infty} \frac{N_T}{T + T_{\max}} \\ &\leq \frac{1}{n} \times \frac{\overline{\#\text{MMIS}(\Delta, R(n))}}{\overline{\#\text{MCDS}(R(n))}}, \end{aligned} \quad (6)$$

which proves the lemma. ■

We need to compute the upper bound of $\overline{\#\text{MMIS}(\Delta, R(n))}$ and the lower bound of $\overline{\#\text{MCDS}(R(n))}$ and then combine them with Lemma 3.1 to compute the upper bound broadcast capacity for MPR.

Lemma 3.2: The average number of nodes in a broadcast tree with receiver range $R(n)$ has the following lower bound:

$$\overline{\#\text{MCDS}(R(n))} \geq \Theta\left(R^{-2}(n)\right) \quad (7)$$

Proof: We first divide the network area into square cells. Each square cell has an area of $\frac{R(n)^2}{2}$ which makes the diagonal length of square equal to $R(n)$ as shown in Fig. 1. Under this condition, connectivity inside all cells is guaranteed and all nodes inside a cell are within reception range of each other. We build a cell graph over the cells that are occupied with at least one vertex (node). Two cells are connected if there exist a pair of nodes, one in each cell, that are less than or equal to $R(n)$ distance apart. Because the whole network is connected when $R(n) = r(n) \geq \Theta\left(\sqrt{\log n/n}\right)$, it follows that the cell graph is connected [18], [19].

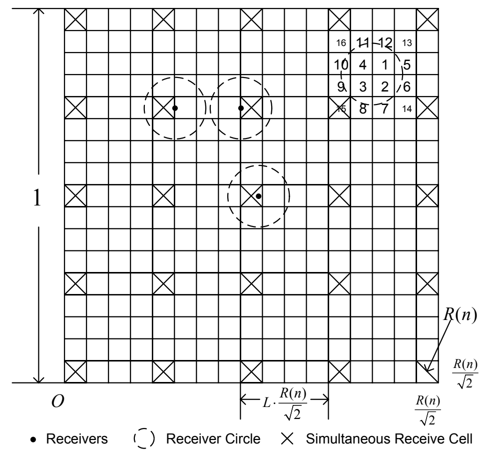

Fig. 1. Cell construction of wireless dense ad hoc networks

From Definition 2.3, every node has to be covered by a MCDS. It has been shown [18] that if $R(n)$ satisfies the connectivity criterion, then each cell has at least one node w.h.p., which implies that all cells in the network are covered by the MCDS. For any receiver with $R(n)$ as its receiver range, it can cover at most 12 (in some literature they use 16) cells that is shown in the upper right corner in Fig. 1. Therefore, to cover all $\left(R(n)/\sqrt{2}\right)^{-2}$ cells in the networks, the number of nodes in MCDS has to be at least $\left(R(n)/\sqrt{2}\right)^{-2}/12$. Hence, the lower bound for MCDS is given by

$$\overline{\#\text{MCDS}(R(n))} \geq \Theta\left(R^{-2}(n)\right), \quad (8)$$

which proves the Lemma. ■

Lemma 3.3: The average number of maximum MPR independent sets that transmit simultaneously is upper bounded by

$$\overline{\#\text{MMIS}(\Delta, R(n))} \leq \Theta(n). \quad (9)$$

Proof: We want to find out the maximum simultaneous MPR set of transmitters in this dense network. From the protocol model for MPR, the disk with radius $R(n)$ centered at any receiver should be disjoint from the other disks centered at the other receivers. We demonstrate it by contradiction. If the disks of different receivers overlap, then there exists some transmitters that are within the receiver range of two receiver nodes. Based on the definition of MPR, these nodes in the overlapping areas will send two different packets at any time to their corresponding receivers, which is in contradiction with the fact that each node can only transmit one packet at a time. That means the disk with radius $R(n)$ centered at any receiver should be disjoint.

Thus, it is clear that, in a dense network, there are $\pi n R^2(n)$ transmitters for each receiver node with receiver range of

$R(n)$. Since MPR protocol model requires a minimum distance between receiver nodes, it follows that each receiver node requires an area of at least $\pi\left(R(n)+\frac{\Delta R(n)}{2}\right)^2$. It is easy to show that there are a total of at most $\frac{n}{\left(1+\frac{\Delta}{2}\right)^2}$ nodes in this network which provides the order upper bound of $\Theta(n)$ for $\#\text{MMIS}(\Delta, R(n))$. ■

Combining Lemmas 3.1, 3.2, and 3.3, we state the upper bound of broadcast capacity with MPR in the following theorem.

Theorem 3.4: Per node broadcast capacity for MPR is upper bounded as $O\left(R^2(n)\right)$.

IV. Lower Bound Broadcast Capacity with MPR

We now provide an achievable lower bound for broadcast capacity using a TDMA scheme similar to the approaches presented in [18], [19].

To satisfy the MPR protocol model, we should design a communication scheme for the network in groups of cells such that there is enough separation for simultaneous transmission. Let L represents the minimum number of cell separations in each group of cells that allows simultaneous successful communication as shown for one example of $L = 4$ in Fig. 1. Utilizing the MPR protocol model, L should satisfy

$$L = \left\lceil 1 + \frac{R(n) + (1+\Delta)R(n)}{R(n)/\sqrt{2}} \right\rceil = \lceil 1 + \sqrt{2}(2+\Delta) \rceil. \quad (10)$$

Let us divide time into L^2 time slots and assign each time slot to a single group of cells. If L is large enough, interference is avoided and the MPR protocol model is satisfied. We know from the MPR protocol model that the minimum distance between two receiver node should be $(2+\Delta)R(n)$. By comparing this distance with $(L-1)\frac{R(n)}{\sqrt{2}}$ which is the distance between two receiver node in our TDMA scheme and using Eq. 10, it is clear that the MPR protocol model is satisfied with this scheme. It can be shown in the upper middle two circles in Fig. 1.

Using this TDMA scheme, we can derive an achievable broadcast capacity for MPR. The following Lemma demonstrates that this TDMA scheme with parameter L does not change the order of the broadcast capacity of a wireless network.

Lemma 4.1: The capacity reduction caused by the proposed TDMA scheme is a constant factor and does not change the order of broadcast capacity for the network.

Proof: The TDMA scheme introduced above requires cells to be divided into L^2 groups, such that only nodes in each group can communicate simultaneously. Eq. (10) demonstrates that the upper bound of L is not a function of n and is only a constant factor. Because the proposed TDMA scheme requires L^2 channel uses, it follows that this TDMA scheme reduces the capacity by a constant factor. ■

Next we prove that, when n nodes are distributed uniformly over a unit square area, we have simultaneously at least $\frac{1}{(LR(n)/\sqrt{2})^2}$ circular regions in Fig. 1, each one contains $\Theta(nR^2(n))$ nodes w.h.p.. The objective is to find the achievable lower bound using the Chernoff bound, such that the distribution of the number of nodes in each receiver range area is sharply concentrated around its mean, and hence in a randomly chosen network, the actual number of simultaneous transmission occurring in the unit space is indeed $\Theta(n)$ w.h.p. similar to Lemma 3.3 for the upper bound analysis.

Lemma 4.2: Each receiver in the cross sign in Fig. 1 with circular shape of radius $R(n)$ contains $\Theta(nR^2(n))$ nodes w.h.p. and uniformly for all values of $j, 1 \le j \le \frac{1}{(LR(n)/\sqrt{2})^2}$.

This Lemma can be expressed as

$$\lim_{n\to\infty} P\left[\bigcap_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} |N_j - E(N_j)| < \delta E(N_j)\right] = 1, \quad (11)$$

where N_j is the number of transmitter nodes in the receiver circle of radius $R(n)$ centered at the receiver j, $E(N_j)$ is the expected value of N_j, and δ is a positive small value arbitrarily close to zero.

Proof: From Chernoff bound in (3), for any given $0 < \delta < 1$, we can find $\theta > 0$ such that

$$P\left[|N_j - E(N_j)| > \delta E(N_j)\right] < e^{-\theta E(N_j)}. \quad (12)$$

Thus, we can conclude that the probability that the value of the random variable N_j deviates by an arbitrarily small constant value from the mean tends to zero as $n \to \infty$. This is a key step in showing that when all the events $\bigcap_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} |N_j - E(N_j)| < \delta E(N_j)$ occur simultaneously, then all N_js converge uniformly to their expected values. Utilizing the union bound, we arrive at

$$\begin{aligned} & P\left[\bigcap_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} |N_j - E(N_j)| < \delta E(N_j)\right] \\ = \;& 1 - P\left[\bigcup_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} |N_j - E(N_j)| > \delta E(N_j)\right] \\ \ge \;& 1 - \sum_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} P\left[|N_j - E(N_j)| > \delta E(N_j)\right] \\ > \;& 1 - \frac{1}{(LR(n)/\sqrt{2})^2} e^{-\theta E(N_j)}. \end{aligned} \quad (13)$$

Since $E(N_j) = \pi n R^2(n)$, then we have

$$\lim_{n\to\infty} P\left[\bigcap_{j=1}^{\frac{1}{(LR(n)/\sqrt{2})^2}} |N_j - E(N_j)| < \delta E(N_j)\right] \ge 1 - \lim_{n\to\infty} \frac{1}{(LR(n)/\sqrt{2})^2} e^{-\theta\pi n R^2(n)} \quad (14)$$

When $R(n)$ satisfies connectivity criterion, then $\lim_{n\to\infty} \frac{e^{-\theta\pi n R^2(n)}}{R^2(n)} \to 0$, which concludes the proof. ■

This lemma proved that w.h.p., there are indeed $\Theta(n)$ transmitter nodes inside $\frac{1}{(LR(n)/\sqrt{2})^2}$ circles centered around receiver nodes with radius $R(n)$. Combining Lemmas 4.1 and 4.2, we have the following achievable lower bound.

Theorem 4.3: The achievable lower bound for broadcast capacity with MPR is

$$C_B(n) = \Omega\left(R^2(n)\right). \tag{15}$$

Proof: From the fact that our TDMA scheme does not change the order capacity (Lemma 4.1), we conclude that at any given time there are at least $\Omega(R^{-2}(n))$ simultaneous cells, each one receives information from $\Omega(R^2(n)n)$ transmitters simultaneously. Hence, from the Lemma 4.2, the total number of allowed simultaneous transmission is $\Omega(n)$.

There are $\frac{1}{(R(n)/\sqrt{2})^2}$ cells in the unit square network area. For broadcasting, every cell receives the broadcast packet from a neighbor cell and relays it to the next adjacent cell. The number of relaying is at most $\Theta\left(R^{-2}(n)\right)$ in order to guarantee all the nodes receive the packet from source. In other words, each broadcasting session requires $\Theta\left(R^{-2}(n)\right)$ relaying. Since the network can support $\Theta(n)$ simultaneous transmissions, therefore, the total broadcast capacity for this network is given by $\Omega\left(\frac{n}{R^{-2}(n)}\right)$.

Accordingly, the lower bound of the per-node capacity is given by $\Omega\left(R^2(n)\right)$, which proves the lemma. ∎

From Theorems 3.4 and 4.3 and connectivity criterion in Eq. (1), the tight bound broadcast capacity of MPR can be given in the following theorem.

Theorem 4.4: Per node broadcast capacity of MPR is

$$C_B(n) = \Theta\left(R^2(n)\right), \tag{16}$$

where $R(n) \geq \Theta\left(\sqrt{\log n/n}\right)$.

This result implies that the broadcast capacity for MPR system increases by increasing the receiver range. This is in sharp contrast with simple routing techniques. The main reason for this difference is that strong interference from adjacent nodes is embraced with MPR, rather than avoided.

V. Conclusion

We showed that using multipacket reception (MPR) in wireless networks renders a $\Theta\left(R^2(n)\right)$ bits per second broadcast capacity for both lower and upper bounds. $R(n)$ is the receiver range, which depends on the complexity of the receiver and connectivity condition in the network. If the receiver range has the minimum value to guarantee connectivity, MPR achieves $\Theta(\log n)$ gain compared with the case of broadcasting when receivers can decode at most one transmission at a time [4]. By increasing the receiver range, the broadcast capacity with MPR increases.

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