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# On Multicast Capacity and Delay in Cognitive Radio Mobile Ad-hoc Networks

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***Abstract*—In this paper, we focus on the capacity and delay tradeoff for multicast traffic pattern in Cognitive Radio (CR) Mobile Ad-hoc Networks (MANET). In our system model, the primary network consisting of $n$ primary nodes, overlaps with the secondary network consisting of $m$ secondary nodes in a unit square. Assume that all nodes move according to an *i.i.d.* mobility model and each primary node serves as a source that multicasts its packets to $k_p$ primary destination nodes whereas each secondary source node multicasts its packets to $k_s$ secondary destination nodes. Under the *cell partitioned network model*, we study the capacity and delay for the primary networks under two communication schemes: *Non-cooperative Scheme* and *Cooperative Scheme*. The communication pattern considered for the secondary network is *Cooperative Scheme*. Given that $m = n^{\beta}$ ($\beta > 1$), we show that per-node capacity $O(1/k_p)$ and $O(1/k_s)$ are achievable for the primary network and the secondary network, with average delay $\Theta(n \log k_p)$ and $\Theta(m \log k_s)$, respectively. Moreover, to reduce the average delay in the secondary network, we employ a *Redundancy Scheme* and prove that a per-node capacity $O(1/k_s\sqrt{m \log k_s})$ is achievable with average delay $\Theta(\sqrt{m \log k_s})$. We find that the fundamental delay-capacity tradeoff in the secondary network is delay/capacity $\geq O(mk_s \log k_s)$ under both cooperative scheme and redundancy scheme.**

***Index Terms*—Cognitive Radio, Capacity Scaling, Network Delay**

## I. INTRODUCTION

Since the seminal work by Gupta and Kumar [1], the study of the capacity of wireless networks has received great attention. It is shown that the per-node capacity is $\Theta(1/\sqrt{n \log n})$ for *unicast traffic pattern*, where $n$ is the number of nodes in the network [1]. Compared with the unicast traffic pattern where packets are sent from a source node to another destination node, the *multicast traffic pattern* exhibits the following property: packets from source nodes are delivered to multiple destination nodes where some links can be shared by different destinations. Therefore, the multicast traffic pattern consumes less spatial and frequency resource required to establish communication among all the destinations.

Compared to the capacity scaling in static network models, mobility has been leveraged to improve the capacity bounds. In [2], Grossglauser *et al.* demonstrated that the per-node capacity $\Theta(1)$ is achievable under independent and identically distributed (i.i.d) mobility model. However, one significant performance metric in wireless networks, other than the throughput, is under-studied in [2], e.g., the *communication delay*. This motivated later research to explore the relationship between delay and throughput. In [3], Neely *et al.* studied the capacity-delay tradeoff in cell partitioned MANET by introducing the redundancy scheme which reduced delay by sacrificing capacity. They developed communication schemes to achieve per-node capacity $\Theta(1)$, $\Theta(\frac{1}{\sqrt{n}})$ and $\Theta(\frac{1}{n \log n})$ with average delay $\Theta(n)$, $\Theta(\sqrt{n})$ and $\Theta(\log n)$, respectively, which implies that the capacity-delay tradeoff has the characteristics that $\frac{delay}{capacity} > O(n)$. Later on, the capacity-delay tradeoff for unicast networks was thoroughly studied using various mobility models such as the random walk model [4], the random way point mobility model [5] and the constrained mobility model [6], [7].

For the multicast traffic pattern, Li *et al.* [8] studied the capacity in static networks where each node sends messages to $k-1$ destinations. Based on the interference model, they demonstrated that the per-node capacity is $\Theta(\frac{1}{\sqrt{kn \log n}})$ if $k = O(\frac{n}{\log n})$ whereas the per-node capacity is $\Theta(\frac{n}{\log n})$ when $k = \Omega(\frac{n}{\log n})$. This result can be seen as a generalization of two different traffic patterns: unicast [1] and broadcast [9]. Some relevant works can also be found in [10]-[14]. In [15], Wang *et al*. studied the capacity and delay tradeoff in cell partitioned MANET under a multicast traffic pattern. They proved that the per-node capacity and delay are $O(1/k)$ and $\Theta(n \log k)$ respectively if no redundant relay nodes are used, and $O(1/k\sqrt{n \log k})$ and $\Theta(\sqrt{n \log k})$ respectively otherwise.

All the aforementioned results focus only on the throughput scaling and delay analysis for a stand-alone network. Recently, the ever-growing demand for frequency resources has motivated the study of *cognitive radio* (CR) networks to efficiently utilize the idle spectrum in the time and space domain. CR networks consist of two different networks: *primary network* and *secondary network*. In CR networks, primary users have a higher priority when accessing the spectrum, while secondary users opportunistically access the licensed spectrum without deteriorating the performance of primary users. Specifically, the secondary network can have "vacuum" space to transmit when primary users are idle. Also, secondary nodes within the interference range of any primary nodes that are transmitting or receiving messages cannot have spectrum opportunities to transmit. Different from the stand-alone network, the interaction between primary and secondary users have to be considered when studying the throughput and delay scaling

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results in CR networks. Previous analysis for stand-alone networks is therefore not directly applicable to CR networks.

The study of capacity and delay scaling laws for both the primary and secondary network is a relatively new and challenging field. In [16] and [17], the authors investigated the capacity scaling of a homogeneous cognitive networks for unicast traffic by introducing a *preservation region* around primary receivers. Wang *et. al* [18] extended the CR network capacity scaling analysis to multicast traffic patterns under the Gaussian channel model. Interestingly, all these works showed that both the primary and secondary networks can achieve similar or the same performance bounds as if they can essentially be regarded stand-alone networks when the secondary network has a higher density than the primary one. Note that existing works mainly focus on static CR networks and, to the best of our knowledge, the performance of mobile CR networks has not been investigated before.

Motivated by the fact that mobility can dramatically enhance the throughput in stand-alone networks, we are interested in its impact on CR networks:

- What throughput and delay scaling law can be achieved under a multicast traffic pattern in Cognitive Radio Mobile Ad-hoc Networks (CR MANET)?
- What is the delay and capacity tradeoff characteristic in CR MANET?

In this paper, we first adopt a *non-cooperative scheme*[1] to investigate the achievable per-node capacity and delay for the primary network, where one source is supposed to send messages to $k_p$ destinations. We then consider the cooperative mode to give a unified presentation of the routing scheme. Next, we focus on the capacity and delay analysis for the secondary network under a *cooperative scheme* and a *redundancy scheme*[2], respectively. Finally, we introduce a *destination oriented redundancy scheme*[3] to efficiently utilize the network resources in the secondary network. The major contributions of this paper are as follows:

- We investigate the impact of mobility model for both the primary network and the secondary network. Transmission queues are employed to analyze the capacity and delay for CR MANET. Our results show that mobility can significantly enhance the capacity performance for both the primary and secondary networks.
- This paper is a nontrivial generalization of previous work since we directly study the capacity and delay under a multicast traffic pattern. Different with the mobility model studied in [19] and [20], where the primary nodes are static and only the secondary nodes have mobility, our model assumes that both the primary and secondary networks can have mobility. Our results can be specialized to the unicast and broadcast traffic by setting the number of destinations to be $1$ and $n-1$ for the primary network ($1$ and $m-1$ for the secondary network), respectively.
- We show that both the primary network and the secondary network can achieve the same throughput as the optimal one established for a stand-alone MANET in [15], if the number of secondary users $m$ is larger than that of primary users $n$ scaled by $m = n^{\beta}$ ($\beta > 1$). Specifically, under the cooperative scheme, the per-node capacity $O(1/k_p)$ and $O(1/k_s)$ are achievable for the primary network and the secondary network, with average delay $\Theta(n \log k_p)$ and $\Theta(m \log k_s)$, respectively.
- We introduce redundancy into the secondary network and prove that the tight bound of transmission delay can be reduced to $\Theta(\sqrt{m \log k_s})$ with an achievable per-node capacity $O(1/k_s\sqrt{m \log k_s})$ if there are redundant relay nodes. Moreover, we also proposed destination oriented redundancy scheme to utilize wireless resources efficiently in practical operation. We find that the fundamental capacity-delay tradeoff in the secondary network is characterized by delay/capacity $\geq O(mk_s \log k_s)$ under both the cooperative scheme and the redundancy scheme.

The rest of the paper is organized as follows. In section II, we introduce our network model and the main definitions. In section III, we present the communication schedules for both the primary and the secondary network. In sections IV and V, we give our main results of capacity and delay in the primary network and secondary network, respectively. Finally, we conclude this paper in section VI.

## II. Network Model

*Cell Partitioned Network Model*: Our network model is based on the model used in [3]. Consider a unit square with a co-existing primary network and secondary network, where the two networks share the same space, time and frequency domain but with different priorities in accessing the spectrum. The primary nodes and secondary nodes are distributed according to a *Homogeneous Poisson Process* (HPP) of density $n$ and $m$, respectively. We assume that $n$ and $m$ satisfy $m = n^{\beta}$ ($\beta > 1$), which indicates that the secondary network has a higher density than the primary network. It can be proved [21] that the total numbers of primary nodes and secondary nodes within the unit area are of order $\Theta(n)$ and $\Theta(m)$, respectively. For simplicity, we will assume that there are $n$ mobile primary nodes and $m$ mobile secondary nodes distributed over the square throughout the paper. We further divide the primary network into $w = \Theta(n)$ non-overlapping cells with equal area $\Theta(\frac{1}{n})$ and divide the secondary network into $c = \Theta(m)$ non-overlapping cells with equal area $\Theta(\frac{1}{m})$ as illustrated in Figure 1. The node density $\tau_p$ is $\frac{n}{w}$ for the primary network and $\tau_s$ is $\frac{m}{c}$ for the secondary network. Therefore, both $\tau_p$ and $\tau_s$ are of constant order $\Theta(1)$.

*Traffic Pattern*: In a multicast traffic pattern, we assume that there are a set $\mathcal{V}_p = \{v_p^1, v_p^2, \ldots, v_p^n\}$ of mobile primary nodes and another set $\mathcal{V}_s = \{v_s^1, v_s^2, \ldots, v_s^m\}$ of mobile secondary nodes in the unit square. For each multicast group in the primary network, there is a source node $v_i \in \mathcal{V}_p$ and $k_p$ destinations that are randomly and independently chosen. Multicast groups in the secondary network can be similarly defined.

[1]A non-cooperative scheme means that destinations cannot act as relays within the same multicast group. Otherwise, it is called a cooperative scheme.

[2]Redundancy scheme means that there can be multiple nodes acting as relays for a packet.

[3]Destination oriented redundancy scheme means that every destination that has received a packet can act as a relay for the packet.

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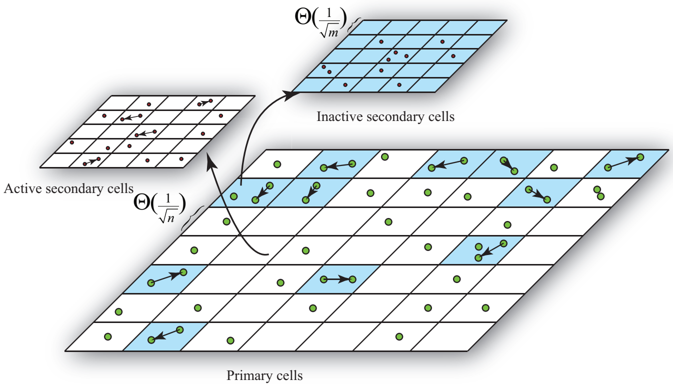


Fig. 1. Illustration of *cell partitioned network model:* the blue primary cells represent the active cells where a pair of primary nodes in a cell (denoted by green spots) are transmitting. No spectrum opportunities will be available for secondary nodes located in the region of active primary cells. Thus we color the secondary cells blue to indicate that they are inactive due to the presence of active primary cells. All the secondary nodes in the inactive secondary cells will buffer their packets without transmitting.

*Mobility Model*: Assuming that time is slotted, we adopt the ideal i.i.d. fast mobility model. The initial position of each node (primary or secondary) is equally likely to be in any of the (primary or secondary) cells independent of the other nodes' positions. At the beginning of the next time slot, nodes can roam to a new cell randomly in the network. Since we adopt the fast mobility model, the time it takes for a node to move from one cell to another has negligible delay. Under the mobility model, packets are carried by the nodes (either the source or relay nodes) until they reach their corresponding destination nodes.

*Interference*: In CR MANET, there are three kinds of interference: inter-cell interference, intra-cell interference and inter-network interference. To avoid intra-cell interference, we assume that each cell (primary or secondary) allows at most one transmission during a time slot. In order to mitigate inter-primary-cell interference, neighboring primary cells have to transmit over orthogonal frequency bands and four bands are enough for the whole primary network to ensure this condition [3]. The inter-secondary-cell interference can be avoided by adopting a 25-TDMA[4] schedule for the secondary network. Since the primary nodes have higher priority in using the spectrum, the secondary network has to operate without causing severe interference to the primary network. To limit the inter-network interference, no spectrum opportunities will be available for a secondary node if it resides in the region of an active primary cell. If a secondary node roams to an inactive secondary cell at a time slot, it will buffer its packets without transmitting.

*Capacity*: We assume that the exogenous rate of packets to each primary and secondary source node are both a *Bernoulli process* with rate $\lambda_p$ and $\lambda_s$ packets per slot, respectively. The network is stable when there exists a scheduling policy to ensure that the packet queue for each node will not approach infinity as time approaches infinity and each packet can be delivered to its $k$ ($k = k_p$ for the primary network and $k = k_s$ for the secondary network) distinct destinations. We define $\lambda_p$ and $\lambda_s$ as the achievable per-node capacity for the primary network and the secondary network, respectively. For other stochastic arrival process with the same average rate, the analysis can be treated similarly and the throughput will not change [3].

*Delay*: In the multicast communication pattern, the delay in the primary (secondary) network $\mathcal{D}_p$ ($\mathcal{D}_s$) is defined as the time interval between the time that the packet departs from the primary (secondary) source node, and the time that it arrives at all the $k_p$ ($k_s$) destination nodes.

*Transmission Queues*: We analyze the communication delay using queueing theory. For both the primary network and the secondary network, packets are transmitted through source-to-destination queues, source-to-relay queues and relay-to-destination queues according to their specific communication schemes.

*Knuth Notation*: Given two functions $f(n) > 0$, $g(n) > 0$: $f(n) = o(g(n))$ means $\lim_{n\to\infty} f(n)/g(n) = 0$; $f(n) = O(g(n))$ means $\lim_{n\to\infty} \sup f(n)/g(n) < \infty$; $f(n) = \omega(g(n))$ is equivalent to $g(n) = o(f(n))$; $f(n) = \Omega(g(n))$ is equivalent to $g(n) = O(f(n))$; $f(n) = \Theta(g(n))$ means $f(n) = O(g(n))$ and $g(n) = O(f(n))$.

The key notations used in this paper are listed in the following table.

TABLE I
NOTATIONS

| Notation | Definition |
|---|---|
| $n$ ($m$) | The number of primary (secondary) nodes. |
| $w$ ($c$) | The number of primary (secondary) cells. |
| $\tau_p$ ($\tau_s$) | The node density of each primary (secondary) cell. |
| $k_p$ ($k_s$) | The number of primary (secondary) destinations. |
| $\lambda_p$ ($\lambda_s$) | The throughput of primary (secondary) nodes. |
| $\mathcal{D}_p$ ($\mathcal{D}_s$) | The delay of primary (secondary) packets. |

## III. Communication Scheme

In this section, we will introduce the communication schemes for both the primary network and the secondary network. Since the primary network has a higher priority, it is oblivious to the existence of the secondary network. The secondary network adaptively chooses to transmit based on the given primary transmission scheme.

### A. Communication Scheme for the Primary Network

In the primary network, we assume that the packets are delivered using at most two hops. The source node either sends packets directly to all the destinations or to one of the relays. Then the relay will forward the packet to all the corresponding destinations. Each cell becomes active when at least one successful transmission can happen. In the following, we consider two schemes: non-cooperative scheme and cooperative scheme.

**Non-cooperative Scheme:**

[4]The TDMA scheme can also be 9-TDMA or 16-TDMA schemes, which is used for concurrently transmissions and since we focus on scaling performance, the constant will not affect our results.

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For an active cell containing at least two primary nodes, the transmissions are conducted in the following way.

1) If at least one primary source-destination pair can be found in the cell, then randomly pick one pair to finish the communication.
2) If no source-destination pair can be found in the cell, perform the following two schedules with equal probability:
   - *Source-to-Relay Transmission*: Randomly pick one source node as the sender. If at least one normal relay node[5] is available for the source node in the same cell, pick the relay node as the receiver to finish the transmission.
   - *Relay-to-Destination Transmission*: If one relay node, carrying a packet destined for a primary destination node, can be found in one cell and at least one corresponding "pristine" primary destination node [6] stays within the same cell, pick the relay node as the sender and one of these "pristine" destination nodes as the receiver to finish the transmission.
3) If neither of the above two items can be satisfied, no transmission will take place in this cell. A packet will be discarded whenever all its $k_p$ primary destinations have received it[7].

**Cooperative Scheme:**

According to the previous scheme, one primary destination node cannot serve as a relay for other destinations within the same multicast group. That is to say, a certain destination node either receives packets from corresponding source node or acts as a relay for other multicast groups. However, under the cooperative scheme, we will no longer discriminate between the destination nodes and normal relay nodes. The first node that the source delivers its packet to will be treated as a relay node irrespective of whether it is a destination node or not. Once a destination node is chosen as a relay node, it can send packets to other destination nodes (possibly within the same multicast group or not). Under the cooperative scheme for the primary network, the following two transmission patterns happen with equal probability:

1) *Source-to-Relay Transmission*: If one primary source node can be found in the cell and one relay node is available in the same cell, pick the source node as the sender and one relay node as the receiver to finish the transmission.
2) *Relay-to-Destination Transmission*: If one relay node, carrying a packet destined for primary destination nodes, can be found in this cell and meanwhile at least one corresponding "pristine" primary destination node resides within the same cell, pick the relay node as the sender and one destination node as the receiver to finish the transmission.

If neither of the above two items mentioned can be satisfied, no transmission will take place in this cell.

### B. Communication Scheme for the Secondary Network

Primary nodes have priority to access the channel. Secondary nodes should choose their action based on the activity of primary nodes. When primary nodes is transmitting in some primary cells, secondary nodes inside would keep silent. When primary nodes is silent, secondary nodes may transmit, when it will not cause severer interference to primary nodes. Since the density of secondary nodes is larger than that of primary nodes in order sense, the communication range employed by the secondary nodes can be much smaller than that of primary nodes. Therefore, the interference that secondary nodes cause can be tolerable for primary nodes if we schedule appropriately. And the schemes analyzed in Section V are all based on this main intuition.

From the capacity analysis for the primary network in section IV, we find that the cooperative scheme can achieve better performance than the non-cooperative scheme. Therefore, we only consider the cooperative scheme for the secondary network without considering the non-cooperative scheme further. The cooperative scheme in the secondary network is similar to that in the primary network.

Note that in the cooperative scheme, only one relay node is used for sending a single packet. For the secondary network, we further propose a *redundancy scheme* in order to reduce the delay, which allows more than one relay to be used for delivering a single packet. Then, we improve the redundancy scheme by avoiding the use of additional nodes other than the destination nodes which have received packets to serve as relays. This is referred to as *destination oriented redundancy scheme.* In this way, we are able to better utilize network resources under this scheme. This communication schedule will be discussed in more details later on in section V.

## IV. Capacity and Delay Analysis for the Primary Network

In this section, we will study the capacity and delay tradeoff in the primary network. Denote the probability that there are at least two primary nodes in one cell by $p_1$, which is given by

$$\begin{aligned} p_1 &= 1-(1-\frac{1}{w})^n - \binom{n}{1}\frac{1}{w}(1-\frac{1}{w})^{n-1} \\ &= 1-(1-\frac{1}{w})^n - \frac{n}{w}(1-\frac{1}{w})^{n-1} \\ &\sim 1-(1+\tau_p)e^{-\tau_p}. \end{aligned}$$

Denote the probability of finding a source-destination pair in the primary network by $p_2$. To get $p_2$, we need to model the primary nodes as mutually exclusive groups according to the following definition.

*Definition 1:* $\{k_p+1\}$**-grouped Primary Network**: For each source node $v_p^i \in \mathcal{V}_p$ in the primary network, we put it and its $k_p$ destination nodes into a group, denoted by $\mathcal{G}_p^i$.

[5]For a certain multicast group, all nodes in the area except for those destination nodes within this multicast group can be treated as normal relay nodes for this multicast group.

[6]A "pristine" primary destination node represents a destination node which has not received the desired packet, that the relay node is carrying. This is the same when we call a node as a "pristine" secondary destination node.

[7]The acknowledge information can be delivered when the source and destinations have transmission opportunities. Since this information size is very small compared to the packet size, its cost can be neglected.

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Then we will have $\frac{n}{k_p+1}$[8] groups over the whole primary network. We also assume that $\mathcal{G}_p^i \bigcap \mathcal{G}_p^j = \emptyset$, for $i \neq j$, and $i, j \in [1, \frac{n}{k_p+1}]$.

Note that in the $\{k_p+1\}$-grouped primary network, each node within $\mathcal{G}_p^i$ can be a source node or destination node. Thus, any two nodes from the same group are a source-destination pair. However, for any randomly chosen two nodes from different groups, they cannot be viewed as a source-destination pair. Then, we get

$$\begin{aligned} p_2 &= 1 - [(1-\frac{1}{w})^{k_p+1} + \binom{k_p+1}{1}\frac{1}{w}(1-\frac{1}{w})^{k_p}]^{\frac{n}{k_p+1}} \\ &= 1-(1-\frac{1}{w})^{\frac{nk_p}{k_p+1}}(1+\frac{k_p}{n})^{\frac{n}{k_p+1}} \\ &\sim \begin{cases} 1-e^{-\tau_p}e^{\tau} = 0, & \text{if } \ k_p = o(n); \\ 1-(1+\tau_p)e^{-\tau_p}, & \text{if } \ k_p = \Theta(n). \end{cases} \end{aligned}$$

### *A. Capacity and Delay Analysis of the Non-cooperative Scheme*

In this subsection, we will study the achievable capacity and communication delay in the primary network when destination nodes cannot relay packets to other destination nodes within the same multicast group. Our main results are presented in the following.

*Theorem 1:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, the achievable per-node capacity for the primary network under the non-cooperative scheme is $\lambda_p = O(1/k_p)$ with an average delay $\mathbf{E}[\mathcal{D}_p] = \Theta(n \log k_p)$.

*Proof:* In each time slot, a new packet arrives at a primary source node $v_p^i$ in the group $\mathcal{G}_p^i$ with rate $\lambda_p$. Denote the rate that the packet is transmitted to a primary destination node or handed over to a relay node by $\mathcal{R}_1$ and $\mathcal{R}_2$, respectively. Then we have

$$\lambda_p^o = \mathcal{R}_1 + \mathcal{R}_2.$$

Since the transmission of the source-to-relay and the relay-to-destination have equal probability, $\mathcal{R}_2$ is also equal to the rate at which the relay nodes are sending packets to the primary destinations. Thus, in every time slot, the total rate of transmission opportunities over the primary network is $n(\mathcal{R}_1 + 2\mathcal{R}_2)$. Meanwhile, a transmission occurs in any given cell with probability $p_1$. Hence we obtain

$$wp_1 = n(\mathcal{R}_1 + 2\mathcal{R}_2). \tag{1}$$

Similarly, since $p_2$ is the probability that a primary source-destination pair can communicate with each other in one cell, we have

$$wp_2 = n\mathcal{R}_1. \tag{2}$$

Combining Equations (1) and (2), we have

$$\mathcal{R}_1 = \frac{p_2}{\tau_p}; \quad \mathcal{R}_2 = \frac{(p_1 - p_2)}{2\tau_p}.$$

Then we obtain that the total service rate for one primary source queue is $\lambda_p^o = \frac{(p_1+p_2)}{2\tau_p}$.

[8]Here we assume that $n$ is divisible by $k_p+1$.

Now, we will deal with the traffic delay for the primary network using queueing theory techniques similar to [3][15]. There are two possible routing strategies for a primary packet to reach its destination: the 1-hop source-to-destination path and the 2-hop source-relay-destination path. For the first strategy, the source will transmit the packet to all the $k_p$ destinations directly and the delay consists of only the queueing delay at the source. For the second strategy, the packet will first sent to a relay and the relay will transmit the packet to all the $k_p$ destinations. Hence, delay is composed of the queueing delays at both the source and the relay nodes.

If one packet is directly sent from the source node to destination nodes, it will wait at the source for a time period $\mathcal{D}_{s\to d}^p$ before the source can find its corresponding destinations to forward this packet. Since a source node transmits packets to $k_p$ destinations for multicast traffic, we assume that there are $k_p$ identical copies of the packet in the buffer of the source node. Thus, we can model a source queue as a set of $k_p$ sub-queues, in which each sub-queue is intended for one destination. Since the rate of each sub-queue is assumed to be the same, and the transmission scheme is randomly operated for every sub-queue, the $k_p$ sub-queues can be seen as independent source-destination routings, as illustrated in Figure 2.

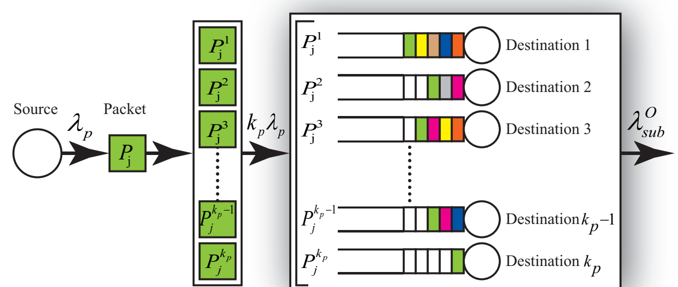


Fig. 2. Illustration of the source-to-destination transmission process in the primary network under the non-cooperative scheme.

Denote the delay in each routing by $\mathcal{D}_{s\to d}^j$. Then we have

$$\mathcal{D}_{s\to d}^p = \max_{1\le j\le k_p}\{\mathcal{D}_{s\to d}^j\}.$$

To calculate the delay in this scenario, we first obtain the input and output rate for each source-to-destination sub-queue in the following lemma.

*Lemma 1:* Each source-to-destination sub-queue is a $M/M/1$ queue corresponding to one destination node with input rate $\lambda_{sub}^i = \frac{\lambda_p \mathcal{R}_1}{\lambda_p^o}$ and service rate $\lambda_{sub}^o = \frac{\mathcal{R}_1}{k_p}$.

*Proof:* It is clear that the probability that the packet will be sent directly from the source to the destination is $\frac{\mathcal{R}_1}{\lambda_p^o}$. Hence, the input rate of each sub-queue is

$$\lambda_{sub}^i = \lambda_p p_{s\to d} = \frac{\lambda_p \mathcal{R}_1}{\lambda_p^o}.$$

The output rate of each sub-queue is equal to the communication rate of a source-to-destination pair $\lambda_{sub}^o = \frac{\mathcal{R}_1}{k_p}$ because

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the $k_p$ destinations are equally likely to get the packet directly from the source. ■

Thus, the expected queueing time for each sub-queue is $\frac{1}{\lambda_{sub}^o - \lambda_{sub}^i}$. To obtain the maximum expected queueing time for all the sub-queues, we first introduce the following lemma [15].

*Lemma 2:* Suppose $X_1, X_2, \ldots, X_k$ are continuous i.i.d exponential random variables with expectation of $1/a$. Denote $X_{\max} = \max\{X_1, X_2, \ldots, X_k\}$, then

$$\mathbf{E}\{X_{\max}\} = \begin{cases} \Theta(1/a), & k = 1 \\ \Theta(\log k/a), & k > 1 \end{cases}.$$

Therefore, we can conclude that

$$\mathcal{D}_{s\to d}^p = \begin{cases} \Theta\left(\frac{1}{\frac{\mathcal{R}_1}{k_p} - \frac{\lambda_p \mathcal{R}_1}{\lambda_p^o}}\right), & k_p = 1 \\ \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_1}{k_p} - \frac{\lambda_p \mathcal{R}_1}{\lambda_p^o}}\right), & k_p > 1 \end{cases}. \tag{3}$$

On the other hand, if the packet is transmitted through a relay node, the relay node will hold the packet and transmit the packet to all destinations. We denote the delay from source to relay by $\mathcal{D}_{s\to r}^p$ and the delay from relay to destination by $\mathcal{D}_{r\to d}^p$. Then we have the following lemma.

*Lemma 3:* In the first phase of the 2-hop routing strategy under the non-cooperative scheme, the expected delay before a primary source node can find a normal relay node to send a packet is equal to $1/(R_2 - \lambda_p \frac{R_2}{\lambda_p^o})$.

*Proof:* The probability that a packet is handed over by a relay in the primary network is $\frac{\mathcal{R}_2}{\lambda_p^o}$. Thus, for a source node with input rate $\lambda_p$, the rate that the packets will be delivered to a relay is $\lambda_p \frac{\mathcal{R}_2}{\lambda_p^o}$. Also note that the available service rate for a source to a relay is $R_2$. Therefore we conclude this lemma. ■

Next, we will calculate the delay in the second phase $\mathcal{D}_{r\to d}^p$. Note that the probability that the packet is sent to a relay node is $p_{s\to r}^i = \frac{\mathcal{R}_2}{\lambda_p^o (n-k_p-1)}$, because all these $n - k_p - 1$ primary nodes outside the group $\mathcal{G}_p^i$ are equally likely to be chosen as a relay under the non-cooperative scheme. Then the input rate for a relay-to-destination queue in the primary network $\lambda_r^i$ is

$$\lambda_r^i = \lambda_p p_{s\to r}^i = \frac{\lambda_p \mathcal{R}_2}{\lambda_p^o (n - k_p - 1)}.$$

Hence, similar to the previous discussion, we can model this process as a packet transmitted through $k_p$ independent sub-queues and each destination is associated with one fixed sub-queue, as shown in Figure 3.

Thus, using the same technique as in the previous analysis, the input rate of one sub-queue is $k_p \lambda_r^i$ and the output rate is $\frac{\mathcal{R}_2}{n-k_p-1}$ because one primary node can relay packets for all the other $n - k_p - 1$ nodes except the $k_p + 1$ nodes in its group. Therefore, the expected queueing time for each sub-queue in the relay node is $\frac{1}{\frac{\mathcal{R}_2}{n-k_p-1} - k_p \lambda_r^i}$. By Lemma 2, we can obtain

$$\mathcal{D}_{r\to d}^p = \begin{cases} \Theta\left(\frac{1}{\frac{\mathcal{R}_2}{n-k_p-1} - k_p \lambda_r^i}\right), & k_p = 1 \\ \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_2}{n-k_p-1} - k_p \lambda_r^i}\right), & k_p > 1 \end{cases}. \tag{4}$$

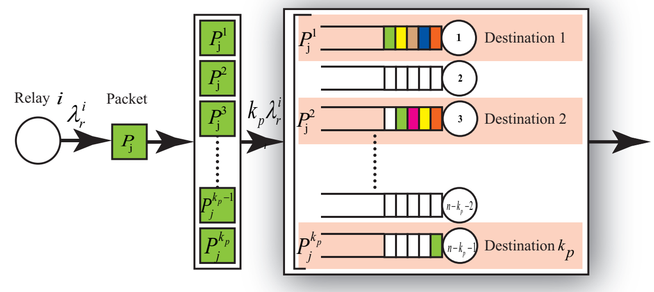


Fig. 3. Illustration of the relay-to-destination transmission process in the primary network under the non-cooperative scheme.

Combining Lemma 1, Lemma 2 and Equation (4), we can obtain that the total expected delay for the primary network under multicast traffic ($k_p > 1$) is

$$\begin{aligned} \mathbf{E}[\mathcal{D}_p] &= \frac{\mathcal{R}_1}{\lambda_p^o} \mathcal{D}_{s\to d}^p + \frac{\mathcal{R}_2}{\lambda_p^o} (\mathcal{D}_{s\to r}^p + \mathcal{D}_{r\to d}^p) \\ &= \frac{\mathcal{R}_1}{\lambda_p^o} \cdot \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_1}{k_p} - \frac{\lambda_p \mathcal{R}_1}{\lambda_p^o}}\right) \\ &\quad + \frac{\mathcal{R}_2}{\lambda_p^o}\left(\frac{1}{\mathcal{R}_2 - \lambda_p \frac{\mathcal{R}_2}{\lambda_p^o}} + \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_2}{n-k_p-1} - k_p \lambda_r^i}\right)\right) \\ &= \frac{1}{\lambda_p^o} \cdot \Theta\left(\frac{\log k_p}{\frac{1}{k_p} - \frac{\lambda_p}{\lambda_p^o}} + \frac{\log k_p}{\frac{1}{n-k_p-1} - \frac{k_p \lambda_r^i}{\mathcal{R}_2}}\right). \end{aligned} \tag{5}$$

Note that $\lambda_r^i = \frac{\lambda_p \mathcal{R}_2}{\lambda_p^o (n-k_p-1)}$. Since the input rate of a stable queue must be smaller than its output rate, we have

$$\begin{cases} \frac{1}{k_p} > \frac{\lambda_p}{\lambda_p^o}; \\ \mathcal{R}_2 > \lambda_p \frac{\mathcal{R}_2}{\lambda_p^o}; \\ \frac{\mathcal{R}_2}{n-k_p-1} > k_p \lambda_r^i = \frac{k_p \lambda_p \mathcal{R}_2}{\lambda_p^o (n-k_p-1)}. \end{cases}$$

The constraint of the above three inequalities allows the per-node capacity $\lambda_p = O(1/k_p)$ and delay $\mathbf{E}[\mathcal{D}_p] = \Theta(k_p \log k_p) = \Theta(n \log k_p)$.

This concludes the proof of Theorem 1. ■

Note that while the network performance remains almost the same when $k_p$ varies, the transmission flow goes through different paths. To give a more simplified and elegant routing scheme, we further assume that each destination can also act as a relay for the other destinations in the same group, and we call this as the cooperative scheme in the following subsection.

### *B. Capacity and Delay Analysis of the Cooperative Scheme*

In this subsection, we utilize the cooperation among destinations within the same multicast group and show that the routing scheme can be presented in a unified form while keeping the performance remain the same. Under the cooperative scheme, packets can be transmitted only through the 2-hop source-to-relay-to-destination pattern. The difference from the previous subsection is that the relay node for each packet is selected from $n - 1$ nodes rather than from $n - k_p - 1$

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nodes. Our main results under this scenario are presented in the following theorem.

*Theorem 2:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, the achievable per-node capacity for the primary network is $\lambda_p = O(1/k_p)$ with average delay $\mathbf{E}[\mathcal{D}_p] = \Theta(n \log k_p)$ under the cooperative scheme.

*Proof:* The proof is similar as that of Theorem 1. To avoid confusion, we will adopt the same mathematical symbols as the previous subsection. Since only the 2-hop source-to-relay-to-destination pattern is available under the cooperative scheme, we have $\mathcal{R}_2 = \lambda_p^o = \frac{p_1}{2\tau_p}$. For the source-to-relay delay $\mathcal{D}_{s\to r}^p$, we have the following lemma.

*Lemma 4:* In the first phase of 2-hop routing strategy under the cooperative scheme, the expected delay before a primary source node can find a relay node to send a packet is

$$\mathcal{D}_{s\to r}^p = \frac{1}{\mathcal{R}_2 - \lambda_p \frac{\mathcal{R}_2}{\lambda_p^o}}. \tag{6}$$

*Proof:* The proof is quite similar to that of Lemma 3 and we omit it here. ■

Now we will discuss the delay in the second phase $\mathcal{D}_{r\to d}^p$. Under the cooperative scheme, when destination nodes can serve as relay nodes for any multicast group, the input rate for a relay-to-destination queue $\lambda_r^i$ is

$$\lambda_r^i = \frac{\lambda_p}{n-1}.$$

If a destination node is chosen as a relay node, then it only needs to transmit packets to the remaining $k_p - 1$ destination nodes. Otherwise, a normal relay node must send packets to all the $k_p$ destination nodes. It is clear that whether $k_p - 1$ or $k_p$ destination nodes that are supposed to receive the packet makes no difference to the delay in an order sense. Therefore, we assume that a relay node has to relay packets for $k_p$ destination nodes regardless of whether it is a destination node or not. Hence, using the same technique as the previous subsection, we have that the input rate for a sub-queue is $k_p\lambda_r^i$ and the output rate is $\frac{\mathcal{R}_2}{n-1}$. Therefore, the expected queueing time for each sub-queue in the relay node is $\frac{1}{\frac{\mathcal{R}_2}{n-1} - k_p\lambda_r^i}$. According to Lemma 2, we can obtain

$$\mathcal{D}_{r\to d}^p = \begin{cases} \Theta\left(\frac{1}{\frac{\mathcal{R}_2}{n-1} - k_p\lambda_r^i}\right), & k_p = 1 \\ \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_2}{n-1} - k_p\lambda_r^i}\right), & k_p > 1 \end{cases}. \tag{7}$$

Combining Equations (6) and (7), we have that the total expected delay under multicast traffic ($k_p > 1$) is

$$\begin{aligned} \mathbf{E}[\mathcal{D}_p] &= \mathcal{D}_{s\to r}^p + \mathcal{D}_{r\to d}^p \\ &= \frac{1}{\mathcal{R}_2 - \lambda_p \frac{\mathcal{R}_2}{\lambda_p^o}} + \Theta\left(\frac{\log k_p}{\frac{\mathcal{R}_2}{n-1} - k_p\lambda_r^i}\right). \end{aligned} \tag{8}$$

From Equation (8), it is clear that the following two inequalities should hold:

$$\begin{cases} \lambda_p < \lambda_p^o; \\ k_p\lambda_r^i \sim \frac{\lambda_p k_p}{n-1} < \frac{\mathcal{R}_2}{n-1}. \end{cases}$$

From the above two inequalities, it is easy to see that the per-node capacity $O(1/k_p)$ is achievable under the cooperative scheme regardless of the order of $k_p$. Note that the expected delay $\mathbf{E}[\mathcal{D}_p]$ is still in the order of $\Theta(n \log k_p)$, which implies that cooperative schemes use a simplified algorithm while keeping a same performance as non-cooperative schemes. ■

## V. Capacity and Delay Analysis for the Secondary Network

In this section, we will discuss the capacity and delay tradeoff in the secondary network. Unlike the scheme in the primary network, a node in the secondary network can only opportunistically transmit whenever it is outside the region of active primary cells. For these active secondary cells, we adopt a 25-TDMA scheme to avoid interference. In the following, we first analyze the expected capacity and delay under the cooperative scheme. We then introduce the redundancy scheme and destination oriented redundancy scheme to help reduce the delay and efficiently utilize the network resources for the secondary network.

### A. Capacity and Delay Analysis of the Cooperative Scheme

The following lemma indicates that, with the communication schemes defined previously, the secondary nodes (whether source nodes or relay nodes) have opportunities to deliver their packets. Later we prove that the whole secondary network appears to have the same capacity and delay performance as a stand-alone MANET in the order sense.

*Lemma 5:* With the proposed communication scheme, the following two results hold:

1) In each time slot, a constant fraction of the secondary cells is outside the region of active primary cells, which can be scheduled successfully for transmission.
2) Each individual secondary cell has a constant probability for spectrum access to transmit.

*Proof:* Let $c_q(n)$ be the fraction of primary cells with $q$ nodes ( $q \geq 0$ ). According to Lemma 1 in [22], $c_q(n) = e^{-1}/q!$ w.h.p.. Then $1 - 2e^{-1} \approx 0.26$ fraction of the primary cells contains at least two primary nodes w.h.p.. This implies that the remaining fraction of primary cells may not be active and this allows the secondary nodes access to the spectrum for transmitting. Thus, we conclude the first part of the lemma.

The above part implies a constant transmission opportunity for the overall secondary cells. We have to further consider the transmission opportunity of each individual secondary cell. Recall that the secondary network adopts a 25-TDMA scheme with adjacent-neighbor communication. In each primary time slot, we have a complete secondary TDMA frame in our communication scheme. Each active secondary cell will be assigned with at least one active secondary TDMA slot within each secondary frame. This completes the proof. ■

*Lemma 6:* The total service rate for a secondary source queue is $\lambda_s^o = \frac{p_3}{2\tau_s}$, where $p_3 \sim 1 - (1+\tau_s)e^{-\tau_s}$.

*Proof:* Denote the probability that there are at least two secondary nodes in one cell by $p_3$. Then we have $p_3 = 1 - (1-\frac{1}{c})^m - \binom{m}{1}\frac{1}{c}(1-\frac{1}{c})^{m-1} \sim 1 - (1+\tau_s)e^{-\tau_s}$.

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Similar to the cooperative scheme in the primary network, packets are transmitted only through the 2-hop source-relay-destination paths under the cooperative scheme in the secondary network. Since the transmission for source-to-relay and relay-to-destination have equal probability, $\lambda_s^o$ is also equal to the rate at which the relay nodes are sending packets to the secondary destinations. Thus, in every time slot, the total rate of transmission opportunities over the secondary network is $2m\lambda_s^o$. Meanwhile, a transmission occurs in any given cell with probability $p_3$. Hence, we obtain

$$cp_3 = 2m\lambda_s^o. \tag{9}$$

Therefore, the total service rate for a secondary source queue is $\lambda_s^o = \frac{p_3}{2\tau_s}$. ∎

Our results on achievable per-node capacity and transmission delay are given in the following.

*Theorem 3:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, the achievable per-node capacity for the secondary network under the cooperative scheme is $\lambda_s = O(1/k_s)$ with average delay $\mathbf{E}[\mathcal{D}_s] = \Theta(m \log k_s)$.

*Proof:* For the 2-hop source-relay-destination communication strategy, both the queueing time at the secondary source node and relay node are accounted for in the delay. We denote the delay in first phase (from a secondary source node to a relay node) by $\mathcal{D}_{s\to r}^s$ and delay in second phase (from a relay node to all the $k_s$ secondary destination nodes) by $\mathcal{D}_{r\to d}^s$. Then, similar to Lemma 3 in previous section, we have the following lemma.

*Lemma 7:* In the first phase of the cooperative scheme in the secondary network, the expected delay for a secondary source to send one packet to a relay node equals $\frac{1}{\frac{c_1}{25}p_3 - \lambda_s}$, where $c_1 (0 < c_1 < 1)$ is a constant.

*Proof of Lemma 7:* Since a secondary frame is divided into 25 sub-frames, the transmission rate for a secondary cell decreases by a factor of 25. Moreover, according to Lemma 5, there is a constant fraction of secondary cells in the unit area that can access the spectrum. Here we use the constant $c_1$ to represent the overall likelihood that the secondary cells will be successfully scheduled during one second. Therefore, the input rate and output rate for a secondary source-to-relay queue are $\lambda_s$ and $\frac{c_1}{25}\lambda_s^0$, with average delay $\frac{1}{\frac{c_1}{25}\lambda_s^0 - \lambda_s}$.

Now, we need to get the delay in the second phase $\mathcal{D}_{r\to d}^s$. Note that a secondary node relays a packet from a secondary source node with rate $\lambda_s^i = \frac{\lambda_s}{m-1}$ because all the secondary nodes are equally likely to be chosen as a relay. For a relay-to-destination sub-queue, there will be $k_s$ or $k_s - 1$ sources, depending on whether the relay is also a destination for the packet. Let us regard the input rate for a relay-to-destination sub-queue to be $k_s\lambda_s^i$.

The output rate of one sub-queue is $\frac{c_1\lambda_s^o}{25(m-1)}$ because one secondary node can relay packets destined for all the other $m-1$ nodes with equal probability. Therefore, the expected queueing time for each sub-queue in the relay node is $\frac{1}{\frac{c_1\lambda_s^o}{25(m-1)} - k_s\lambda_s^i}$. By Lemma 2, we can obtain

$$\mathcal{D}_{r\to d}^s = \begin{cases} \Theta\left(\frac{1}{\frac{c_1\lambda_s^o}{25(m-1)} - k_s\lambda_s^i}\right), & k_s = 1 \\ \Theta\left(\frac{\log k_s}{\frac{c_1\lambda_s^o}{25(m-1)} - k_s\lambda_s^i}\right), & k_s > 1 \end{cases}. \tag{10}$$

Combining Lemma 6 and Equation (10), we have the total expected delay for the secondary network under multicast traffic ($k_s > 1$) as

$$\begin{aligned} \mathbf{E}[\mathcal{D}_s] &= \mathcal{D}_{s\to r}^s + \mathcal{D}_{r\to d}^s \\ &= \frac{1}{\frac{c_1}{25}\lambda_s^0 - \lambda_s} + \Theta\left(\frac{\log k_s}{\frac{c_1\lambda_s^o}{25(m-1)} - k_s\lambda_s^i}\right). \end{aligned} \tag{11}$$

To make sure that the number of packets waiting to be transmitted in each queue does not increase to infinity with time, the following two constraints must be satisfied.

$$\begin{cases} \lambda_s < \frac{c_1}{25}\lambda_s^0; \\ \frac{c_1\lambda_s^o}{25(m-1)} > k_s\lambda_s^i. \end{cases}$$

From the above two inequalities, we obtain $\lambda_s < \frac{c_1\lambda_s^o}{25k_s}$. Thus, the per-node capacity $\lambda_s = O(1/k_s)$ and average delay $\mathbf{E}[\mathcal{D}_s] = \Theta(m \log k_s)$ are achievable for the secondary network. ∎

Note that in our system model and communication scheme, the primary network and secondary network achieve per-node capacity $O(1/k_p)$ and $O(1/k_s)$, respectively. Therefore, the co-existence and mutual interference do not affect throughput scaling for cognitive networks.

### B. Capacity and Delay Analysis of the Redundancy Scheme

In this part, we will discuss the capacity and delay tradeoff when more than one secondary node can serve as a relay, i.e., the redundancy scheme, for the secondary network.

Intuitively, the time needed for a packet to reach its destinations can be reduced by repeatedly sending this packet to many other secondary nodes, i.e., using more than one node as a relay. In this way, the chances that some node carrying an original or duplicate version of the packet finds a destination will increase. Thus, it is supposed that adopting the redundancy scheme can reduce communication delay although this may not help to improve the network throughput. Previous works [3] and [15] have also introduced the redundancy scheme for a stand-alone ad hoc network in which the source node sends packets to more than one relay node. In CR networks, the redundancy scheme is also applicable for both the primary network and the secondary network. However, considering that secondary nodes suffer from a larger average-delay than the primary nodes, we shall introduce this redundancy scheme to the secondary network to help effectively reduce its end-to-end delay.

Here, we first show the lower bound of the average delay, which is given in the following.

*Theorem 4:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, no communication scheme with redundancy can achieve an average delay lower than $O(\sqrt{m \log k_s})$ for the secondary network.

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*Proof:* We prove this result by considering an ideal situation where the secondary network has only a single secondary source node that sends a packet to $k_s$ destinations. The optimal scheme for the source is to send duplicate versions of the packet whenever it meets any node that has never received the packet before. These nodes then act as relays to transmit the packet to the destinations once they enter the same cell as the destinations'.

During the time slots $\{1, 2, \ldots, i\}$, let $\vartheta_j$ be the total number of intermediate relay nodes at the beginning of time slot $j$ $(1 \leq j \leq i)$. Clearly, $\vartheta_1 \leq \vartheta_2 \leq \cdots \leq \vartheta_i$ since the number of relays is non-decreasing over time. Note that a relay can only be generated by the secondary source node, hence at most one node can be a new relay in every time slot. Thus, $\vartheta_i \leq i$ for all $i \geq 1$. Furthermore, denote the probability that a destination node can meet at least one relay node during time slots $\{1, 2, \ldots, i\}$ by $p^{(i)}$, we have

$$\begin{aligned} p^{(i)} &= 1 - \prod_{j=1}^{i}(1-\frac{1}{c})^{\vartheta_j} \\ &\leq 1 - (1-\frac{1}{c})^{i^2}. \end{aligned}$$

However, a destination node that encounters a relay does not necessarily ensure the transmission can be scheduled since the secondary cell in which they meet may not be active during that slot. Similar to previous discussion in Lemma 7, a constant $\frac{c_1}{25}$ should be factored in. Hence, the probability that a destination node can successfully receive a packet from a relay during time slots $\{1, 2, \ldots, i\}$ is $c_1 p^{(i)}/25$. Then, we have

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &\geq 1 - (\frac{c_1}{25}p^{(i)})^{k_s} \\ &\geq 1 - (\frac{c_1}{25})^{k_s}(1-(1-\frac{1}{c})^{i^2})^{k_s} \\ &\sim 1 - (\frac{c_1}{25})^{k_s}(1-e^{-\tau_s\frac{i^2}{m}})^{k_s}. \end{aligned} \tag{12}$$

Let $i = \sqrt{\frac{m\log k_s}{\tau_s}}$ and $k_s \to \infty$, we obtain that

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &\geq 1 - (\frac{c_1}{25})^{k_s}(1-e^{-\log k_s})^{k_s} \\ &= 1 - (\frac{c_1}{25})^{k_s}(1-\frac{1}{k_s})^{k_s} \geq 1 - \frac{c_1}{25}e^{-1}. \end{aligned}$$

Therefore, the average delay in the secondary network with redundancy satisfies

$$\begin{aligned} \mathbf{E}[\mathcal{D}_s] &\geq \mathbf{E}\{\mathcal{D}_s | \mathcal{D}_s \geq i\} Pr(\mathcal{D}_s \geq i) \\ &\geq (1 - \frac{c_1}{25}e^{-1})\sqrt{\frac{m\log k_s}{\tau_s}} \end{aligned} \tag{13}$$

as both $m$ and $k_s$ approach infinity, which concludes the theorem. ■

To achieve the above lower bound of the average delay, we propose the following *redundancy scheme* for the secondary network.

**Redundancy Scheme:** For an active secondary cell containing at least two secondary nodes, the following two transmission patterns have with equal probability:

1) *Source-to-Relay Transmission*: Randomly choose a secondary node as the source node to transmit and one other secondary node as the receiver. If the source node has forwarded the duplicate of the packet to at least $\sqrt{m\log k_s}$ distinct relays (possibly be some of the destinations), the packet is removed from the buffer of source node.
2) *Relay-to-Destination Transmission*: If one relay node, carrying a packet destined for secondary destination nodes, can be found in the cell and meanwhile at least one corresponding "pristine" secondary destination node resides within the same cell, pick the relay node as the sender and the destination node as the receiver to finish the transmission. A packet will be removed when all its $k_s$ destinations have received it.

We now state the following result.

*Theorem 5:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, the achievable per-node capacity for the secondary network is $O(1/k_s\sqrt{m\log k_s})$ with an average delay $\mathbf{E}[\mathcal{D}_s] = O(\sqrt{m\log k_s})$ under the redundancy scheme.

*Proof:* Under the redundancy scheme, the expected time required for a certain packet to reach its corresponding $k_s$ destinations $\mathbf{E}[\mathcal{D}_s]$ is less than $\mathbf{E}[\mathcal{D}_s^1] + \mathbf{E}[\mathcal{D}_s^2]$, where $\mathbf{E}[\mathcal{D}_s^1]$ represents the expected time required to distribute the duplicates to $\sqrt{m\log k_s}$ different nodes, and $\mathbf{E}[\mathcal{D}_s^2]$ is the expected time required to reach all the $k_s$ destinations given that $\sqrt{m\log k_s}$ relays are holding the packet. We then derived upper bounds on $\mathbf{E}[\mathcal{D}_s^1]$ and $\mathbf{E}[\mathcal{D}_s^2]$, respectively.

$\mathbf{E}[\mathcal{D}_s^1]$ bound: During the time interval from 1 to $\mathcal{D}_s^1$, there are at least $m - \sqrt{m\log k_s}$ secondary nodes that do not have the packet. Hence, in every time slot, the probability that at least one of these nodes is located in the same cell as the source is at least $1-(1-\frac{1}{c})^{m-\sqrt{m\log k_s}}$. At every time slot in the duration $\mathcal{D}_s^1$, a source node can deliver a duplicate packet to a new node with probability of at least $p^*$ given by

$$p^* \geq \frac{c_1}{25}\alpha_1\alpha_2(1-(1-\frac{1}{c})^{m-\sqrt{m\log k_s}}),$$

where $\alpha_1$ is the probability that the source is selected to be the transmitting node in the cell, and $\alpha_2$ is the probability that this source is chosen to operate the "source-to-relay" transmission which is equal to 1/2. According to Lemma 6 in [3], $\alpha_1 \geq 1/(2+\tau_s)$. Thus,

$$p^* \to \frac{c_1}{25}\frac{1-e^{-\tau_s}}{4+2\tau_s}$$

as $m$ approaches infinity.

The average time for a duplicate packet to reach a new relay is upper bounded by $1/p^*$. Since there are $\sqrt{m\log k_s}$ duplicates to be transmitted, in the worst case, $\sqrt{m\log k_s}$ of these times are required. Therefore, $\mathbf{E}[\mathcal{D}_s^1]$ is upper bounded by $\sqrt{m\log k_s}/p^*$. Hence, we have $\mathbf{E}[\mathcal{D}_s^1] \leq \frac{25}{c_1}\frac{4+2\tau_s}{1-e^{-\tau_s}}\sqrt{m\log k_s}$.

$\mathbf{E}[\mathcal{D}_s^2]$ bound: At every time slot in the duration of $\mathcal{D}_s^2$, there are at least $\sqrt{m\log k_s}$ nodes holding the duplicates of the packet. The probability that at least one other node is in the same cell as the destination is $1-(1-\frac{1}{c})^{m-1}$. Each time slot, a destination node can successfully receive a duplicate

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packet from one of these relay nodes with probability of at least $p^{**}$ given by

$$p^{**} = \frac{c_1}{25}\beta_1\beta_2\beta_3(1-(1-\frac{1}{c})^{m-1}),$$

where $\beta_1$ is the probability that the destination is selected from all the other nodes in the same cell to be the receiver, $\beta_2$ is the probability that the sender is chosen to operate the "relay-to-destination" transmission which is equal to 1/2, and $\beta_3$ represents the possibility that the sender is one of these $\sqrt{m\log k_s}$ nodes possessing a duplicate packet intended for the destination. Similarly, we have $\beta_1 \geq 1/(2+\tau_s)$ and $\beta_3 = \sqrt{m\log k_s}/(m-1) \geq \sqrt{\log k_s/m}$. Thus,

$$p^{**} \to \frac{c_1}{25}\frac{1-e^{-\tau_s}}{4+2\tau_s}\sqrt{\log k_s/m}$$

as $m$ approaches infinity. The average time that a single destination node receives a duplicate packet destined for it is upper bounded by $1/p^{**}$. The time needed for all the $k_s$ destination nodes to receive the packet is the maximum of them. Using Lemma 9, $\mathbf{E}[\mathcal{D}_s^2]$ is upper bounded by $\log k_s/p^{**}$. Hence, we have $\mathbf{E}[\mathcal{D}_s^2] \leq \frac{25}{c_1}\frac{4+2\tau_s}{1-e^{-\tau_s}}\sqrt{m\log k_s}$.

Finally, according to Lemma 2 in [3], the total delay can be upper bounded by $\mathbf{E}[\mathcal{D}_s] = O(\sqrt{m\log k_s})$ and we obtain an achievable per-node capacity $O(1/k_s\sqrt{m\log k_s})$. ■

*Theorem 6:* In a cell-partitioned network with overlapping $n$ primary nodes and $m$ secondary nodes, the achievable per-node capacity for the secondary network is $O(1/k_s\sqrt{m\log k_s})$ with average delay $\mathbf{E}[\mathcal{D}_s] = \Theta(\sqrt{m\log k_s})$ under the redundancy scheme.

*Proof:* This can be directly obtained by combining Theorem 4 and Theorem 5. ■

### *C. Capacity and Delay Analysis of Destination Oriented Redundancy Scheme*

The above mentioned redundancy scheme can effectively reduce the end-to-end delay. However, the shortcoming is that repeatedly sending one packet to more than one relay node can consume more network resources and increase the interference level. To account for this, we improve the original redundancy scheme and propose a novel redundancy scheme, named the *Destination Oriented Redundancy Scheme*, which not only reduces delay but also better utilizes the network resources.

**Destination Oriented Redundancy Scheme**:

For an active secondary cell containing at least two secondary nodes, the following two transmission patterns have equal probability.

1) *Source-to-Relay Transmission*: Choose the first node that the secondary source node meets as a relay irrespective of whether it is a destination node or not. Pick the source node as the sender and the relay node as the receiver to finish the transmission.
2) *Relay-to-Destination Transmission*: If one relay node, carrying a packet destined for secondary destination nodes, can be found in this cell and meanwhile at least one corresponding "pristine" secondary destination node resides within the same cell, pick the relay node as the sender and the destination node as the receiver to finish the transmission. For the destination nodes which have received the packet, they can also serve as relay nodes to conduct the relay-to-destination transmission.

In the above mentioned scheme, to reduce the delay by bringing in redundancy, we allow the destination nodes who have received the message to perform as relay nodes. Note that at most one node besides the source and $k_s$ destinations is chosen as a relay, hence we do not introduce extra relay nodes to relay the packet, utilizing the network resources more efficiently.

With this new redundancy scheme, we show that the lower bound of communication delay for secondary network is $O(\sqrt{m\log k_s})$ if we allow only one transmission in one time slot. However, if we assume that all the available transmissions among different active cells can be conducted in one time slot, we prove that the lower bound of communication delay is $O(\frac{m\log k_s}{k_s})$. Formally, we define these two communication patterns as *Destination Oriented Solo-redundancy Scheme* (use "Solo-redundancy Scheme" for short) and *Destination Oriented Ensemble-redundancy Scheme* (use "Ensemble-redundancy Scheme" for short), respectively.

*Definition 2:* **Solo-redundancy Scheme** refers to the scheme when at most one destination node within the same multicast group is allowed to receive packets in one time slot, even though there may be more than one active cell in which a packet from a certain source secondary node can be sent to a "pristine" secondary destination node. Whereas the **Ensemble-redundancy Scheme** allows all the available transmissions within the same multicast group among different active cells to be conducted in one time slot.

*Theorem 7:* When $k_s = \Omega(\sqrt{m\log k_s})$, the lower bound of communication delay in the secondary network under the destination oriented redundancy scheme is

1) $\mathcal{B}_1 \triangleq \Omega(\sqrt{m\log k_s})$ if we adopt the solo-redundancy scheme.
2) $\mathcal{B}_2 \triangleq \Omega(\frac{m\log k_s}{k_s})$ if we adopt the ensemble-redundancy scheme.

*Proof:* We start with the proof of the first item in Theorem 7. Suppose during the time slots $\{1,2,\ldots,i\}$, there are $\psi_i$ ($\psi_i \leq k_s$) destination nodes that have received the packet. Denote the number of destination nodes who have received the message in time slot $j$ ($1 \leq j \leq i$) by $\psi_j$. It is clear that $\psi_1 \leq \psi_2 \leq \cdots \leq \psi_i$. Furthermore, denote the probability that one destination node has not received the packet during the time slots $\{1,2,\ldots,i\}$ by $p^{\S}$. Then $p^{\S}$ satisfies

$$\begin{aligned} p^{\S} &= \prod_{j=1}^{i}(1-\frac{1}{c})^{\psi_j} \\ &= (1-\frac{1}{c})^{\sum_{j=1}^{i}\psi_j} \geq (1-\frac{1}{c})^{i\psi_i}. \\ &\geq (1-\frac{1}{c})^{i^2} \\ &\quad (\text{ since } \psi_i \leq i \text{ under } \textit{solo redundancy scheme} \text{ ).} \end{aligned}$$

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Then we have

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &\geq 1 - [\frac{c_1}{25}(1-p^{\S})]^{(k_s-\psi_i)} \\ &\geq 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} [1-(1-\frac{1}{c})^{i^2}]^{(k_s-\psi_i)} \\ &\sim 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} (1-e^{-\tau_s \frac{i^2}{m}})^{(k_s-\psi_i)}. \end{aligned} \tag{14}$$

We choose $i = \sqrt{\frac{m \log k_s}{\tau_s}}$. Substituting the value of $i$ into Equation (14), we obtain that

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &\geq 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} (1-e^{-\log k_s})^{(k_s-\psi_i)} \\ &= 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} (1-\frac{1}{k_s})^{(k_s-\psi_i)} \\ &\geq 1 - e^{-1}. \end{aligned}$$

Therefore, the expected communication delay in the secondary network under *solo-redundancy scheme* satisfies

$$\begin{aligned} \mathbf{E}[\mathcal{D}_s] &= \mathbf{E}\{\mathcal{D}_s|\mathcal{D}_s \geq i\}Pr(\mathcal{D}_s \geq i) + \mathbf{E}\{\mathcal{D}_s|\mathcal{D}_s < i\}Pr(\mathcal{D}_s < i) \\ &\geq \mathbf{E}\{\mathcal{D}_s|\mathcal{D}_s \geq i\}Pr(\mathcal{D}_s \geq i) \\ &\geq (1-e^{-1})\sqrt{\frac{m \log k_s}{\tau_s}} \\ &\sim \Omega(\sqrt{m \log k_s}). \end{aligned}$$

Thus, we prove the first claim in Theorem 7. Next we prove the second claim. In this scenario, we have that $p^{\S}$ satisfies

$$\begin{aligned} p^{\S} &= \prod_{j=1}^{i}(1-\frac{1}{c})^{\psi_j} \\ &= (1-\frac{1}{c})^{\sum_{j=1}^{i}\psi_j} \geq (1-\frac{1}{c})^{i\psi_i} \\ &\geq (1-\frac{1}{c})^{ik_s}. \\ &\text{( since } \psi_i \leq k_s \text{ is always satisfied )} \end{aligned} \tag{15}$$

Then we have

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &= 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} (1-p^{\S})^{(k_s-\psi_i)} \\ &\geq 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} [1-(1-\frac{1}{c})^{ik_s}]^{(k_s-\psi_i)} \\ &\sim 1 - \left(\frac{c_1}{25}\right)^{(k_s-\psi_i)} (1-e^{-\tau_s \frac{ik_s}{m}})^{(k_s-\psi_i)}. \end{aligned} \tag{16}$$

Here, we choose $i = \frac{m \log k_s}{\tau_s k_s}$. Substituting that value into Equation (16), we obtain

$$\begin{aligned} Pr(\mathcal{D}_s \geq i) &\geq 1 - \frac{c_1}{25}^{(k_s-\psi_i)} (1-e^{-\log k_s})^{(k_s-\psi_i)} \\ &\geq 1 - e^{-1}. \end{aligned}$$

Hence, the expected communication delay in the secondary network under *ensemble-redundancy scheme* satisfies

$$\begin{aligned} \mathbf{E}[\mathcal{D}_s] &\geq \mathbf{E}\{\mathcal{D}_s|\mathcal{D}_s \geq i\}Pr(\mathcal{D}_s \geq i) \\ &\geq (1-e^{-1})\frac{m \log k_s}{\tau_s k_s} \\ &\sim \Omega(\frac{m \log k_s}{k_s}). \end{aligned}$$

Note that under *ensemble-redundancy scheme*, more transmissions are allowed in one time slot compared to *solo-redundancy scheme*, thus the delay in *ensemble-redundancy scheme* should be smaller than that in the *solo-redundancy scheme* correspondingly. Therefore, the two delay lower bounds $\mathcal{B}_1$ and $\mathcal{B}_2$ should satisfy $\mathcal{B}_1 > \mathcal{B}_2$, which is in consistence with our results. ∎

## VI. Conclusion and Discussion

### A. Comparison with Previous Work

Compared with the multicast capacity of static CR networks developed in [18], we find that the capacity performance is better when nodes are mobile. Also, different with the partial mobility model studied in [19] and [20], which requires the primary nodes to be static and only the secondary nodes are allowed to move, our model allows both the primary and secondary networks to be mobile. Moreover, compared with the results of CR network under unicast traffic in [20], we find that the capacity diminishes by a factor of $1/k_p$ and $1/k_s$ for the primary network and the secondary network respectively under the cooperative scheme, as shown in Table II. This is because we need to forward a packet to $k_p$ primary destinations (or $k_s$ secondary destinations). Particularly, if $k_p = \Theta(1)$ and $k_s = \Theta(1)$, our results can be specialized to the unicast traffic; if $k_p = \Theta(n)$ and $k_s = \Theta(m)$, our results can be specialized to the broadcast traffic.

TABLE II
COMPARISONS

| | Unicast, Static | Unicast, Mobile | Multicast, Mobile |
|---|---|---|---|
| Capacity | $\frac{1}{\sqrt{nk_p}}$, $\frac{1}{\sqrt{mk_s}}$ | 1, 1 | $\frac{1}{k_p}$, $\frac{1}{k_s}$ |
| Delay | $\sqrt{nk_p}$, $\sqrt{mk_s}$ | $n$, $m$ | $n \log k_p$, $m \log k_s$ |

Furthermore, we find that although redundancy can reduce the transmission delay in the secondary network, it will lead to a decrease in the capacity. The tradeoff between the delay and capacity always satisfies delay/capacity $\geq O(mk_s \log k_s)$ under both the cooperative scheme and the redundancy scheme in the secondary network. However, if we schedule the transmission in the secondary network by multiple unicast from source to $k_s$ destinations, the capacity will diminish by a factor of $k_s$ and the delay will increase by a factor of $k_s$, which indicates that the delay-capacity tradeoff becomes delay/capacity $\geq O(mk_s^2)$ in CR MANET. This demonstrates that our tradeoff is better than that of directly extending the tradeoff for unicast to multicast.

### B. Rationality of System Model

In our system model, we consider an ideal i.i.d fast mobility model, which allows nodes to choose new locations every timeslot from overall cells in the network. Actual mobility maybe better characterized by *Brownian motion* or *Random Walk* mobility model, where nodes' mobility is limited. However, analysis under the ideal i.i.d mobility model provides a significant insight on capacity and delay performance in the

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limit of infinite mobility [3]. Under the i.i.d mobility model, all the nodes' locations can not be predicted from time to time, hence the communication schemes are required to be more robust and adaptable. Compared with other communication schemes, our schemes need less current and future information about users' locations. In addition, it has been proven in [3] that the network capacity and delay using an i.i.d mobility model is equivalent to the capacity and delay of the networks using other random mobility models under given constraints.

### C. Future Work

In this work, we have achieved a "harmonious" co-existence of the primary network and the secondary network by assuming primary nodes confine their interference to one cell. For a more general and practical network, we can introduce a "guard zone" to limit the interference received by primary and secondary nodes. The analysis of capacity and delay under this network model will be considered in future work. Additionally, the per-node capacity under the destination oriented redundancy scheme in CR MANET remains unknown.

## VII. Acknowledgment

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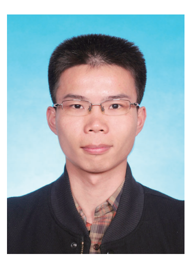

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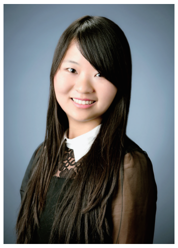

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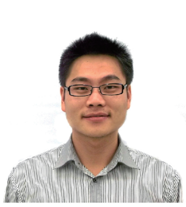

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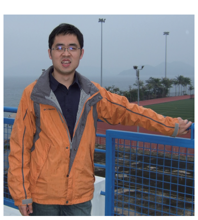

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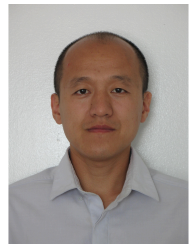

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