Abstract—Consider a wireless network of two tiers with different priorities: a primary tier and a secondary tier, which is an emerging network scenario with the advancement of cognitive radio technologies. The primary tier is constructed over static nodes of density $n$, which are randomly distributed and have an absolute priority to access the spectrum. The secondary tier contains mobile nodes of density $m = n^\beta$ with $\beta > 2$, which can only access the spectrum opportunistically. In the associated delay analysis, two mobility models are considered for the secondary nodes: an i.i.d. mobility model and a random walk model. We show that the primary tier can achieve delay scaling laws of $\Theta(1)$ and $\Theta(1/S)$ with the two mobility models, respectively, where $S$ is the random walk step size. Furthermore, we show that the primary tier can achieve a delay-throughput tradeoff of $D_p(n) = O(n\lambda_m(n))$ with $\lambda_p(n) = O(1/\log n)$ for the random walk model. The throughput and delay scaling laws for the secondary tier are also established, which are the same as those for a stand-alone mobile network.

I. INTRODUCTION

Inspired by the seminal work of Gupta and Kumar [1], the capacity of large-scale ad-hoc networks has been extensively studied in the literature [2]-[5]. For a wireless network with $n$ static nodes randomly deployed in a unit area, it is shown in [1] that the traditional multi-hop transmission strategy can achieve a per-node throughput scaling of $\Theta(1/\sqrt{n \log n})$. Such a throughput scaling can be improved when the nodes are able to move. It is shown in [3]-[5] that a per-node throughput scaling of $\Theta(1)$ is achievable in mobile networks by exploring two-hop transmission schemes. Unfortunately, the throughput improvement in mobile networks incurs a large packet delay [3]-[5], which is another important performance metric in wireless networks. In particular, it is shown in [3] that the constant per-node throughput is achieved at the cost of a delay scaling of $\Theta(n)$.

The aforementioned literature focuses on the delay and throughput scaling laws for a single network. Recently, the emergence of cognitive radio networks motivates people to extend the result from a single network to overlaid two-tier networks. Consider a licensed primary network and a cognitive secondary network coexisting in a unit area. The primary network has the absolute priority to use the spectrum, while the secondary network can only access the spectrum opportunistically to limit the interference to the primary network. Based on such assumptions, it is shown in [6]-[7] that both networks can achieve the same throughput and delay scaling laws as a stand-alone network. However, the existing results are obtained without considering possible positive interactions between the primary network and the secondary network. In practice, the secondary network, which is usually deployed after the existence of the primary network for opportunistic spectrum access, can transport data packets not only for itself but also for the primary network. As such, a natural question arises whether the throughput and/or delay performance of the primary network can be improved with the aid of the secondary network, while assuming the secondary network still capable of keeping the same throughput and delay scaling laws as the case where no supportive actions are taken between the two networks.

In [8], we defined a supportive two-tier network with a static primary tier and a static secondary tier as follows: The secondary tier is allowed to supportively relay the data packets for the primary tier in an opportunistic way, whereas the primary tier is only required to transport its own data. In this paper, we investigate the throughput and delay scaling laws for such a supportive two-tier network with a static primary tier and a mobile secondary tier. With the proposed two-hop transmission scheme for the secondary tier to relay the primary packets, we show that the achievable per-node throughput scaling for the primary tier can be improved to $\lambda_p(n) = \Theta(1/\log n)$. In the associated delay analysis, two mobility models are considered for the secondary nodes: the i.i.d. mobility model and the random walk (RW) model. We show that the primary tier can achieve delay scaling laws of $\Theta(1)$ and $\Theta(1/S)$ with the two mobility models, respectively, where $S$ is the RW step size. Furthermore, we show that the primary tier can achieve a delay-throughput tradeoff of $D_p(n) = O(n\lambda_m(n))$ with $\lambda(n) = O(1/\log n)$ for the RW model. The throughput and delay scaling laws for the secondary tier are also established, which are the same as those for a stand-alone mobile network.
for a stand-alone mobile network.

The rest of the paper is organized as follows. The system model is described in Section II. The proposed protocols for the primary and secondary tiers are described in Section III. The delay and throughput scaling laws for the primary tier are derived in Section IV. The delay and throughput scaling laws for the secondary tier are studied in Section V. Finally, Section VI summarizes our conclusions.

II. SYSTEM MODEL

Consider a two-tier network with a static primary tier and a mobile secondary tier over a unit square. We first describe the network model, the interaction model between the two tiers, and the mobility models for the secondary tier. Then we give the definitions of the throughput and delay.

A. Network Model

Consider two network tiers over a unit square. The nodes of the primary tier, so-called primary nodes, are distributed according to a Poisson point process (PPP) of density \( n \) and randomly grouped into one-to-one source-destination (S-D) pairs. Likewise, the nodes of the secondary tier, so-called secondary nodes, are distributed according to a PPP of density \( m \) and randomly grouped into S-D pairs. We assume that the density of the secondary tier is higher than that of the primary tier, i.e.,

\[
m = n^\beta
\]

(1)

where we consider the case \( \beta \geq 2 \). The primary tier and the secondary tier share the same time, frequency, and space, but with different priorities to access the spectrum. The former one is the licensed user of the spectrum and thus has a higher priority; and the latter one can only opportunistically access the spectrum to limit the resulting interference to the primary tier.

For the wireless channel, we only consider the large-scale pathloss and ignore the effects of shadowing and small-scale multipath fading. As such, the channel power gain \( g(r) \) is given as

\[
g(r) = r^{-\alpha}
\]

(2)

where \( r \) is the distance between the transmitter (TX) and the corresponding receiver (RX), and \( \alpha > 2 \) denotes the pathloss exponent.

B. Interaction Model

As shown in the previous work \[6\] \[7\], although the opportunistic data transmission in the secondary network does not degrade the scaling law of the primary network, it may reduce the throughput in the primary tier by a constant factor due to the fact that the interference from the secondary network to the primary network cannot be reduced to zero. To completely compensate the throughput degradation or even improve the throughput scaling law of the primary tier in the two-tier setup, we could allow certain positive interactions between the two tiers. Specifically, we assume that the secondary nodes are willing to act as relay nodes for the primary tier, while the primary nodes are not assumed to do so. When a primary source node transmits packets, the surrounding secondary nodes could pretend to be primary nodes to relay the packets. Specifically, the received packets are stored in the secondary nodes and delivered to the corresponding primary destination node only when the secondary nodes move into the neighboring area of the destination node. As such, the primary tier is expected to achieve better throughput and/or delay scaling laws. Note that, these “fake” primary nodes do not have the same priority as the real primary nodes in terms of spectrum access, i.e., they can only use the spectrum opportunistically in the same way as a regular secondary node. The assumption of allowing packet exchanges between the two tiers is the essential difference from the models in \[6\] \[7\].

C. Mobility Model

We assume that the positions of the primary nodes are fixed whereas the secondary nodes stay static in one primary time slot\(^2\) and change their positions at the next slot. In particular, we consider the following two mobility models for the secondary nodes.

Two-dimensional i.i.d. mobility model \[3\]: The secondary nodes are uniformly and randomly distributed in the unit area at each primary time slot. The node locations are independent of each other, and independent from time slot to time slot, i.e., the nodes are totally reshuffled over each primary time slot.

Two-dimensional RW model \[4\] \[5\]: We divide the unit square into \( S \) small-square RW-cells, each of them with size \( S \). The RW-cells are indexed by \( (x, y) \), where \( x, y \in \{1, 2, \cdots, 1/\sqrt{S} \} \). A secondary node that stays in a RW-cell at a particular primary time slot will move to one of its eight neighboring RW-cells at the next slot with equal probability (i.e., 1/8). For the convenience of analysis, when a secondary node hits the boundary of the unit square, we assume that it jumps over the opposite edge to eliminate the edge effect \[4\] \[5\]. The nodes within a RW-cell are uniformly and randomly distributed. Note that the unit square are also divided into primary cells and secondary cells in the proposed protocols as discussed in Section III, which are different from the RW-cells defined above. In this paper, we only consider the case where the size of the RW-cell is greater than or equal to that of the primary cell.

D. Throughput and Delay

The throughput per S-D pair (per-node throughput) is defined as the average data rate that each source node can transmit to its chosen destination as in \[6\] \[7\], which is a function of network density. Besides, the sum throughput is defined as the product between the throughput per S-D pair and the number of S-D pairs in the network. In the following, we use \( \lambda_p(n) \) and \( \lambda_s(m) \) to denote the throughputs per S-D pair for the primary tier and the secondary tier, respectively; and we use \( T_p(n) \) and \( T_s(m) \) to denote the sum throughputs for the primary tier and the secondary tier, respectively.

The delay of a primary packet is defined as the average number of primary time slots that it takes to reach the primary destination node after the departure from the primary source node. Similarly, we define the delay of a secondary packet as the average number of secondary time slots for the packet to travel from the secondary source node to the secondary

\(^2\) As we will see in Section III, the data transmission is time-slotted in the primary and secondary tiers.
destination node. We use $D_p(n)$ and $D_s(n)$ to denote packet delays for the primary tier and the secondary tier, respectively. For simplicity, we use a fluid model [5] for the delay analysis, in which we divide each time slot to multiple packet slots and the size of the data packets can be scaled down with the increase of network density.

III. NETWORK PROTOCOLS

In this section, we describe the proposed protocols for the primary tier and the secondary tier, respectively. The primary tier deploys a similar time-slotted multi-hop transmission scheme to those for the primary network in [6] [7], while the secondary tier adapts its protocol to the primary transmission scheme. In the following, we use $p(E)$ to represent the probability of event $E$, and claim that an event $E_n$ occurs with high probability (w.h.p.) if $p(E_n) \to 1$ as $n \to \infty$.

A. The Primary Protocol

The main sketch of the protocol is given as follows:

i) Divide the unit square into small-square primary cells with size $a_p(n)$. In order to maintain the full connectivity within the primary tier even without the aid of the secondary tier, we have $a_p(n) \geq 2\log n/n$ such that each cell has at least one primary node w.h.p..

ii) Group every 64 primary cells into a primary cluster. The cells in each primary cluster take turns to be active in a round-robin fashion. We divide the transmission time into TDMA frames, where each frame has 64 primary time slots that correspond to the number of cells in each primary cluster. Note that the number of primary cells in a primary cluster has to be no less than 64 such that we can appropriately arrange the preservation regions and the collection regions, which will be formally defined in the next section for the secondary protocol.

iii) Define the data path along which the packets are routed from the source node to the destination node: The data path follows a horizontal line and a vertical line connecting the source node and the destination node, which is the same as that defined in [6] [7]. Pick an arbitrary node within a primary cell as the designated relay node, which is responsible for relaying the packets of all the data paths passing through the cell.

iv) When a primary cell is active, each primary source node in it takes turns to transmit one of its own packets with probability $p$. Afterwards, the designated relay node transmits one packet for each of the S-D paths passing through the cell. The above packet transmissions follow a TDMA pattern within the active primary time slot, which is divided into packet slots. Each source node reserves a packet slot no matter it transmits or not. If the designated relay node has no packets to transmit, it does not reserve any packet slots. For each packet, if the destination node is found in the adjacent cell, the packet will be directly delivered to the destination. Otherwise, the packet is forwarded to the designated relay node in the adjacent cell along the data path. At each packet transmission, the TX node transmits with power of $P_{a_p^2}(n)$, where $P$ is a constant.

v) We assume that all packets for each S-D pair are labelled with serial numbers (SNs). The following handshake mechanism is used when a TX node is scheduled to transmit a packet to a destination node: The TX sends a request message to initiate the process; the destination node replies with the desired SN; if the TX has the packet with the desired SN, it will send the packet to the destination node; otherwise, it stays idle. As we will see in the proposed secondary protocol, the secondary relay nodes will take advantage of the above handshake mechanism to remove the outdated (already-delivered) primary packets from their queues. We assume that the length of the handshake message is negligible compared to that of the primary data packet in the throughput analysis for the primary tier as discussed in Section IV.

Note that running of the above protocol for the primary tier is independent of whether the secondary tier is present or not. When the secondary tier is absent, the primary tier can achieve the throughput scaling law given in [1]. When the secondary tier is present as shown in Section IV, the primary tier can achieve a better throughput scaling law with the aid of the secondary tier.

B. The Secondary Protocol

Next we describe the protocol for the secondary tier. We start by defining the separation threshold time of random walk, which will be used in the description of the secondary protocol. The separation threshold time is defined as [10]

$$\tau = \min \{ t : s(t) \leq e^{-1} \}$$

(3)

where $s(t)$ measures the separation from the stationary distribution at time $t$, which is given by

$$s(t) = \min \left\{ s : p(x,y),(u,v)(t) \geq (1-s)\pi(u,v), \right.$$}

(4)

for all $x, y, u, v \in \{1, 2, \cdots, 1/\sqrt{S}\}$

where $p(x,y),(u,v)(t)$ denotes the probability that a secondary node hits RW-cell $(u, v)$ at time $t$ starting from RW-cell $(x, y)$ at time 0, and $\pi(u,v) = S$ is the probability of staying at RW-cell $(u, v)$ at stationary state. We have $\tau = \Theta(1/S)$ [10].

We assume that the secondary nodes have the necessary cognitive features to “pretend” as primary nodes such that they could be chosen as the designated primary relay nodes within a particular primary cell. As shown by Lemma 2 in Section IV, a randomly selected designated relay node for the primary packet in each primary cell is a secondary node w.h.p.

To limit the interference to primary transmissions, we define a preservation region as nine primary cells centered around an active primary TX and an extra layer of protection strip with width $1/m$, shown as the square with dashed edges in Fig. 1. The secondary nodes perform the following two operations according to whether they are in the preservation regions or not:

i) If a secondary node is in a preservation region, it is not allowed to transmit packets. Instead, it receives the packets from the active primary transmitters and store them in the buffer for future deliveries. Each secondary node maintains $Q$ separate queues for each primary S-D pair. For the i.i.d. mobility model, we take $Q = 1$, i.e., only one queue is needed for each primary S-D pair. For the RW model, $Q$ takes the value of $\tau$ given by (3). The packet received at time slot $t$ is considered to be ‘type $k$’ and stored in the $k$th queue, if $\lfloor \frac{t}{\tau} \rfloor \mod Q = k$, where $\lfloor x \rfloor$ denotes the flooring operation.
ii) If a secondary node is not in a preservation region, it transmits the primary and secondary packets in the buffer. In order to guarantee successful deliveries for both primary and secondary packets, we evenly divide the secondary S-D pairs into two classes: Class I and Class II. Define a collection region as nine primary cells and an extra layer of protection strip with width $1/m$, shown as the square with dotted edges in Fig. 1, where the collection region is located between two preservation regions along the horizontal line and they are not overlapped with each other. In the following, we describe the operations of the secondary nodes of Class I based on whether they are in the collection regions or not. The secondary nodes of Class II perform a similar task over switched timing relationships with the odd and even primary time slots.

• If the secondary nodes are in the collection regions, they keep silent at the odd primary time slots and deliver the primary packets at the even primary time slots to the primary destination nodes in the sink cell, which is defined as the center primary cell of the collection region. In a particular primary time slot, the primary destination nodes in the sink cell take turns to receive packets following a TDMA pattern. For a particular primary destination node at time $t$, we choose an arbitrary secondary node in the sink cell to send a request message to the destination node. The destination node replies with the desired SN, which will be heard by all secondary nodes within the nine primary cells of the preservation region. These secondary nodes remove all outdated packets for the destination node, whose SNs are lower than the desired one. For the i.i.d. mobility model, if one of these secondary nodes has the packet with the desired SN and it is in the sink cell, it sends the packet to the destination node. For the RW model, if one of these secondary nodes has the desired packet in the $k$th queue with \( k = \{ \lfloor \frac{t}{
} \rfloor \mod Q \} \) and it is in the sink cell, it sends the packet to the destination node. At each transmission, the secondary node transmits with the same power as that for a primary node, i.e., \( P_{\text{sec}}(n) \).

• If the secondary nodes are not in the collection regions, they keep silent at the even primary time slots and transmit secondary packets at the odd primary time slots as follows. Divide the unit square into small-square secondary cells with size \( a_s(m) = 1/m \) and group every 64 secondary cells into a secondary cluster. The cells in each secondary cluster take turns to be active in a round-robin fashion. Divide the transmission time into TDMA frames, where each frame has 64 secondary time slots that correspond to the number of cells in each secondary cluster. The secondary frame has the same length as that of one primary time slot. In a particular active secondary cell, we could use Scheme 2 in [5] to transmit secondary packets with power of \( P_{\text{sec}}(m) \) within the secondary tier.

IV. DELAY AND THROUGHPUT ANALYSIS FOR THE PRIMARY TIER

In this section, we first derive the throughput and delay scaling laws for the primary tier and then present the delay-throughput tradeoff.
w.h.p. from Lemma 2. As such, when a primary cell is active, the current primary time slot is only used for the primary source nodes in the primary cell to transmit their own packets w.h.p. Therefore, the achievable throughput per S-D pair is of \( \Theta(pK/(n\alpha_p(n))) = \Theta(1/(n\alpha_p(n))) \) w.h.p. Since the total number of primary nodes in the unit square is of \( \Theta(n) \) w.h.p., we have \( T_p(n) = \Theta(n\lambda_p(n)) = \Theta(1/a_p(n)) \) w.h.p. This completes the proof.

By setting \( a_p(n) = 2\log n/n \), the primary tier can achieve the following throughput per S-D pair and sum throughput w.h.p.:

\[
\lambda_p(n) = \Theta(1/\log n)
\]

and

\[
T_p(n) = \Theta(n/\log n).
\]

B. Delay Analysis for the Primary Tier

We focus on the delay performance of the primary tier with the aid of the secondary tier. From the proposed protocols, we know that the primary tier asymptotically pours all the primary packets into the secondary tier w.h.p., i.e., the primary packets reach their destinations via secondary relay nodes w.h.p.. As such, the delay has two components: i) the hop delay, which is the transmission time for one hop (either from a primary source node to a secondary relay node or from a secondary node to a primary destination node), and ii) the queueing delay, which is the time a packet spends in the relay-queue at a secondary node until it is delivered to its destination. The hop delay is one primary time slot, which can be considered as a constant independent of \( m \) and \( n \). Next, we quantify the primary-tier delay performance by focusing on the expected delay of the relay-queue based on the two mobility models described in Section II.C.

1) Two-Dimensional i.i.d. Mobility Model: We have the following theorem regarding the delay of the primary tier.

**Theorem 2:** With the protocols given in Section III, the primary tier can achieve the following delay w.h.p. when \( \beta \geq 2 \).

\[
D_p(n) = \Theta(1). \tag{9}
\]

**Proof:** According to the secondary protocol, the \( m \) secondary nodes act as relays, each of them with a separate queue for each of the primary S-D pairs. Therefore, the queueing delay is the expected delay at such a relay-queue. By symmetry, all such relay-queues incur the same delay w.h.p.. For convenience, we fix one primary S-D pair and consider the \( m \) secondary nodes together as a virtual relay node without the need of identifying which secondary node is used as the relay. As such, we can calculate the expected delay at a relay-queue by analyzing the expected delay at the virtual relay node. Denote the selected primary source node, destination node, and the virtual relay node as S, D, and R, respectively. To calculate the expected delay at the virtual relay node, we have to characterize the arrival and departure processes. A packet arrives at R when a) the primary cell containing S is active, and b) S transmits a packet. According to the primary protocol in Section III, the primary cell containing S becomes active every 64 primary time slots. Therefore, we consider 64 primary time slots as an observation period, and the arrival process is a Bernoulli process with rate \( p \). Similarly, packet departure occurs when a) D is in a sink cell, and b) at least one of the relay nodes that have the desired packet for D is in the sink cell containing D. Let \( q \) denote the probability that event b) occurs, which can be expressed as

\[
q = 1 - (1 - a_p(n))^M = 1 - e^{-M\alpha_p(n)}, \tag{10}
\]

\[
\sim 1 - e^{-M\alpha_p(n)}, \tag{11}
\]

and

\[
q \to 1, \text{ as } n \to \infty, \text{ for } \beta \geq 2, \tag{12}
\]

where \( f \sim g \) means that \( f \) and \( g \) have the same limit when \( n \to \infty \).

Next we need to verify that the relay-queue at each of the \( m \) secondary nodes is stable over time. Note that every secondary node removes the outdated packets that have the SNs lower than the desired one for D when it jumps into the sink cell containing D. Since the queueing length at R can be upper-bounded by one, the length of the relay-queue at any secondary node can be upper-bounded by

\[
E\{W_1\} = 64 \frac{1 - p}{q - p} \to 64, \text{ as } n \to \infty, \tag{13}
\]

where \( E\{\cdot\} \) denotes the expectation and the factor 64 is the length of one observation period. Note that the queueing length of this asymptotically Bernoulli/Deterministic queue is at most one primary packet w.h.p..

Next we need to consider the relay-queue at each of the \( m \) secondary nodes when \( n \) is large. As such, when an event of interest occurs, we have

\[
\frac{1}{1 - a_p(n)} = \Theta(1), \tag{14}
\]

where \( n \) can be considered as an upper-bound for the inter-visit time of the primary cell containing D, since \( (1 - a_p(n))^n \to 0 \) as \( n \to \infty \). Thus, the relay-queues at all secondary node are stable over time, which completes the proof.

2) Two-Dimensional RW mobility Model: For the RW model, we have the following theorem regarding the delay of the primary tier.

**Theorem 3:** With the protocols given in Section III, the primary tier can achieve the following delay w.h.p. when \( \beta \geq 2 \).

\[
D_p(n) = \Theta(1/S) = O(1/a_p(n)) \tag{15}
\]

where \( \tilde{S} \geq a_p(n) \).

**Proof:** Like the proof in the i.i.d. mobility case, we fix a primary S-D pair and consider the \( m \) secondary nodes together as a virtual relay node. Denote the selected primary source node, destination node, and the virtual relay node as S, D, and R, respectively. Based on the proposed secondary protocol in Section III, each secondary node maintains \( Q = \tau \) queues for each primary S-D pair. Equivalently, R also maintains \( Q \) queues for each primary S-D pair. Therefore, the packet arrive at time \( t \) is stored in the \( k \)th queue, where \( k = \lfloor t/\tau \rfloor \mod \tau \). By symmetry, all such queues incur the same expected delay. Without loss of generality, we analyze the expected delay of the \( k \)th queue by characterizing its arrival and departure
processes. A packet that arrives at time \( t \) enters the \( k \)th queue when a) the primary cell containing \( S \) is active, b) \( S \) transmits a packet, and c) \( \left\lfloor \frac{t}{q_0} \right\rfloor \mod \tau = k \). Consider \( 64\tau \) primary time slots as an observation period. The arrival process is a Bernoulli process with arrival rate \( p \). Similarly, a packet departure occurs at time \( t \) when a) \( D \) is in a sink cell, b) at least one of the relay nodes that have the desired packet for \( D \) is in the sink cell containing \( D \), and c) \( \left\lfloor \frac{t}{q_0} \right\rfloor \mod \tau = k \). Let \( q \) denote the probability that event b) occurs during one observation period, which can be expressed as

\[
q = 1 - \left( 1 - \sum_{i \in I} p_0 \frac{\text{dist}(x_i, y_i)}{\text{dist}(x_d, y_d)} (t_d) \right), \tag{16}
\]

\[
\geq 1 - \left( 1 - q_0 (1 - e^{-1}) \right) S^M, \tag{17}
\]

\[
\sim 1 - e^{-q_0 (1 - e^{-1}) S} m \lambda, \tag{18}
\]

\[
\rightarrow 1, \quad n \rightarrow \infty, \quad \beta \geq 2, \tag{19}
\]

where \( I \) denotes the set of the secondary nodes that have the desired packet and belong to Class I (Class II) if \( D \) is in a sink cell at (even) odd time slots; \( (x_i, y_i) \) represents the index of the RW-cell, in which the \( i \)th secondary node in \( I \) is located when \( S \) sends the desired packet; \( (x_d, y_d) \) is the index of the RW-cell, in which \( D \) is located; \( t_d \) stands for the difference between the arrival time and the departure time for the desired packet, which can be lower-bounded by \( 64/(\tau - 1) \); and \( q_0 \) denotes the probability that a secondary node is within the sink cell containing \( D \) when it moves into RW-cell \( (x_d, y_d) \), which is given by \( q_0 = c_0(n)/S \). As such, the departure process is an asymptotically deterministic process with departure rate \( q = 1 \).

Let \( W_2 \) denote the delay of the queue at the virtual relay node based on the RW model. Thus, the queue at the virtual relay node is an asymptotically Bernoulli/deterministic queue, with the queueing delay given by

\[
E[W_2] = 64\tau \frac{1 - p}{q - p} \sim 64\tau = \Theta \left( \frac{1}{S} \right), \tag{20}
\]

where the factor \( 64\tau \) is the length of one observation period. Since \( S \geq c_0(n) \), we have \( E[W_2] = O \left( 1/c_0(n) \right) \).

Using the similar argument as in the i.i.d. case, we can upper-bound the length of the \( k \)th relay-queue at any secondary node by (14) for any \( k \). Thus, the relay-queues at all secondary nodes are stable, which completes the proof.

\section*{C. Delay-Throughput tradeoff for the Primary Tier}

For the RW model, we have the following delay-throughput tradeoff for the primary tier by combining (5) and (15).

\[
D_p(n) = O \left( n \lambda_p(n) \right), \quad \text{for} \quad \lambda_p(n) = O \left( 1/\log n \right). \tag{21}
\]

We see that the delay-throughput tradeoff for the primary tier with the aid of the secondary tier is even better than the optimal delay-throughput tradeoff given in [5] for a static stand-alone network.

\section*{V. DELAY AND THROUGHPUT ANALYSIS FOR THE SECONDARY TIER}

In this section, we give the throughput and delay scaling laws for the secondary tier without proofs due to space limit, with the details appearing in the journal version.

\section*{Theorem 4:} With the protocols given in Section III, the secondary tier can achieve the following throughput per S-D pair and sum throughput w.h.p.

\[
\lambda_s(m) = \Theta(1) \quad \text{and} \quad T_s(m) = \Theta(m). \tag{22}
\]

Next, we provide the delay scaling laws of the secondary tier for the two mobility models as discussed in Section II.C.

\section*{Theorem 5:} With the protocols given in Section III, the secondary tier can achieve the following delay w.h.p. based on the i.i.d. mobility model.

\[
D_s(m) = \Theta(m). \tag{23}
\]

\section*{Theorem 6:} With the protocols given in Section III, the secondary tier can achieve the following delay w.h.p. based on the RW model.

\[
D_s(m) = \Theta \left( m^2 S \log \frac{1}{m} \right). \tag{24}
\]

Note that (24) is a generalization result for \( S = 1/m \). When \( S = 1/m \), the delay \( D_s(m) = \Theta(m \log m) \) is the same as that in [5].

\section*{VI. CONCLUSION}

In this paper, we studied the throughput and delay scaling laws for a supportive two-tier network, where the mobile secondary tier is willing to transport packets for the static primary tier. When the secondary tier has a much higher density, the primary tier can achieve a better throughput scaling law and a better delay-throughput tradeoff compared to non-interactive overlaid networks.