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Throughput and delay scaling laws for mobile overlaid wireless networks

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ABSTRACT

In this paper, we study the throughput and delay scaling laws over two coexisting mobile networks. The primary network consists of n randomly distributed primary nodes which can operate as if the secondary network is absent. However, the secondary network with a higher density $m=n^{\beta}$, $\beta>1$ is required to adjust its protocol. By considering that both the primary and the secondary networks move according to random walk mobility model, we propose a multi-hop transmission scheme, and show that the secondary network can achieve the same throughput and delay tradeoff scaling law as in stand-alone network $D_s(m)=\Theta(m\lambda_s(m))$. Furthermore, for primary network, it is shown that the tradeoff scaling law is given by $D_p(n)=\Theta(\sqrt{n\log n}\lambda_p(n))$, when the primary node is chosen as relay node. If the relay node is a secondary node, the scaling law is $D_p(n)=\Theta(\sqrt{n^{\beta}\log n}\lambda_p(n))$. The novelties of this paper lie in: (i) detailed study of the delay scaling law for the primary network in the complex scenario where both the primary and the secondary networks are mobile; (ii) the impact of buffer delay on the two networks due to the presence of preservation region. We explicitly analyze the buffer delay and obtain an expression as $D^{II}_{S_R}(m)=\Theta(1/\sqrt{n^{\beta-1}a_s(m)})$.

1. Introduction

1.1. Related work

The throughput scaling law of ad hoc wireless network has become an active research topic since the seminal work by Gupta and Kumar (2000). Gupta and Kumar (2000) introduced arbitrary network and random network for studying throughput scaling in a static wireless network. It is shown that a maximum per-node throughput of a static network with arbitrary topologies is $\Theta(1/\sqrt{n})$,[1] where n is the number of nodes in the network. For random network, the nodes were independently and uniformly distributed over an unit area, it is showed that per-node can achieve a throughput scaling law of $\Theta(1/\sqrt{n\log n})$. This means that as the number of nodes n increases, the per-node throughput decreases approximately as $1/\sqrt{n\log n}$. This is a pessimistic result as it may be not applicable to a larger networks. Grossglauser and Tse (2001) and Diggavi et al. (2002) showed that a constant per-node throughput scaling law $\Theta(1)$ can be achieved by exploiting node mobility under a two-hop relay scheme even when the number of nodes n tends to infinity. However, the throughput improvement is at the cost of increasing delay and Grossglauser and Tse (2001) does not provide any guarantee on the time that the packet takes to reach the destination.

In most applications, delay is also an important performance metric, and has great significance for networks with delay requirements e.g. in Neely and Modiano (2003), and Perevalov and Blum (2003). So throughput and delay tradeoff would be a better metric to evaluate the performance of the network. Bansal and Liu (2003) and Neely and Modiano (2003) studied the throughput and delay tradeoff in wireless ad hoc network and they established a fundamental delay/rate tradeoff curve that bounded the performance of any scheme. El Gamal et al. (2006b) developed transmission schemes for both static and mobile networks. They showed that for static network the optimal throughput and delay tradeoff is given by $D(n)=\Theta(n\lambda(n))$, where $\lambda(n)$ and $D(n)$ are the per-node throughput and delay, respectively. While for mobile network, if the throughput scaling is $\Theta(1/\sqrt{n\log n})$, the throughput and delay tradeoff is the same as in the static network. Garetto and Leonardi (2010) exploited a restricted mobility model which is usually found in practice with node heterogeneity. They intelligent schedule routing schemes which make use of the geographical information about the location most visited by a node, and showed that it is possible to achieve both constant capacity and constant delay.

Throughput and delay tradeoff is further discussed in Ying et al. (2008), Sharma et al. (2006), El Gamal et al. (2004, 2006a), de Moraes (2004), Sharma and Mazumdar (2004), and Ozgur and Leveque (submitted for publication). Recently, delay and throughput

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[1] We use the following notations throughout this paper: (1) $f(n)=O(g(n))$ means that there exists a constant c and integer N such that $f(n)<cg(n)$ for $n>N$; (2) $g(n)=\Omega(f(n))$ means that $f(n)=O(g(n))$; (3) $f(n)=\Theta(g(n))$ means that $g(n)=O(f(n))$ and $f(n)=O(g(n))$.

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tradeoff has been studied for an ad hoc network through nodes' mobility as MotionCast by Wang et al. (2011). They utilize redundant packets to realize the tradeoff and present the performance of the 2-hop relay algorithm without and with redundancy. However, all the above-mentioned literatures mainly focus on single network. In recent years, cognitive radio has been introduced as useful technology for secondary users to opportunistically access the unused primary spectrum in order to handle the severe under-utilization of license spectrum at a time or a location (Mitola, 2000). Huang and Wang (2011) studied the throughput and delay scaling of general cognitive networks, and show that secondary networks can obtain the same optimal performance as stand-alone networks when primary networks are classic static. Consider a scenario where a primary network and a secondary network coexist. Issues arise such as how will the throughput and delay tradeoff scaling law of the primary network be like; whether it is possible to improve the throughput of the primary network with the relaying help from the secondary nodes. What is the throughput and delay scaling of secondary network.

Vu et al. (2007) proposed a single-hop transmission scheme to study the throughput scaling law under a given primary outage constraint. Jeon et al. (submitted for publication) considered a multi-hop transmission scheme, they assumed that the secondary nodes know the locations of the primary nodes (both the transmitter (TX) and the receiver (RX)). Based on the prelocation theory, both networks can achieve the same throughput scaling laws as in stand-alone network if the secondary network is denser than the primary network. Gao et al. (submitted for publication) investigated the throughput and delay scaling laws of primary and secondary networks in the following two scenarios: (1) both the two networks are static; (2) the primary network is static and the secondary network is mobile. They showed that the static primary network can achieve a scaling law of $D_p(n)=\Theta(\sqrt{n^\beta \log n}\, \lambda_p(n))$, where $\beta \geq 2$ and the throughput and delay scaling law for the secondary network is the same as in the stand-alone network. However, the delay scaling laws for primary and secondary networks are not discussed in detail in aforementioned literatures.

1.2. Motivation and contributions

This paper completes the analysis of throughput and delay tradeoff scaling laws for mobile overlaid networks where the initial part of the work has been published in Zhang and Yeo (2010). We consider that both the primary and the secondary networks are mobile. The secondary nodes know the locations of the primary TXs, and are allowed to relay the primary packet while the primary nodes are required to transmit their own packets. The complexity will increase, as both the primary and the secondary networks are mobile. It is necessary to analyze how much mobility affects the network performance and determine the probability that the secondary node suffers from the preservation region. A related issue is how long it takes for a packet to go out of the preservation region. We introduce a modified multi-hop transmission scheme similar to scheme-3A in El Gamal et al. (2006b) to analyze the throughput and delay scaling laws for primary and secondary networks. Our major contributions are outlined as follows:

(1) We consider the scenario that both the primary and the secondary nodes are mobile, which is more general in reality. In particular, we consider that the nodes perform independent random walk mobility model.
(2) We explicitly calculate the exact expressions of packet delay for the primary and secondary networks which is not done in Jeon et al. (submitted for publication), and Gao et al. (submitted for publication). The delay has a significant relationship with the choice of relay node. We assume that if the packets reach their destination via secondary relay nodes, where the delay has two components: (i) *hop delay*, which is the expected number of hop a packet taken from source to destination and (ii) *buffer delay*, which is the hop time a packet spends when the secondary node is in the preservation region. We establish exact expressions for these two parts of delay, and bound the delay performance for primary network depending on the relay node chosen. Analysis of the packet delay is perhaps one of the most important contributions of this paper.
(3) Note that in Gao et al. (submitted for publication), the authors pointed out that the results held only when the density of secondary network is much higher than the primary network (i.e. the secondary network has a density of $m=n^\beta$ where $\beta>2$). In our paper $\beta>1$ is enough for the results to be satisfied, which is one improvement over Gao et al. (submitted for publication).
(4) Finally, we show that the throughput of mobile primary network can be further improved with the relaying help from the secondary nodes, and the mobile secondary network can obtain a throughput scaling which is the same as in stand-alone network.

1.3. Paper outline

The rest of this paper is organized as follows. Section 2 presents the network model, definitions, main assumptions and a review of the random walk mobility model. The proposed protocols for the primary and secondary networks are outlined in Section 3. The key part: the throughput and delay tradeoff scaling laws for the primary and secondary networks are obtained in Sections 4 and 5, respectively. Finally, we end this paper with conclusion in Section 6.

2. System model

2.1. Network model

Consider the scenario that the primary and secondary networks coexist over a unit area (Jeon et al., submitted for publication). The n primary nodes are initially independent and identically distributed (i.i.d.) and randomly grouped into one-to-one Source–Destination (S–D) pair. We assume a denser secondary network i.e. $m=n^\beta$ where $\beta>1$ (Jeon et al., submitted for publication). Initially, the secondary nodes are likely to be i.i.d. and grouped into one-to-one S–D pair at random. The primary and secondary networks share the same channel time, frequency and space, but they have different priorities to access the spectrum. The primary nodes are the license holders and have a higher priority to use the spectrum, while the secondary nodes exploit the existence of spectrum holes opportunistically. The secondary nodes can relay the primary packet to the destination, while the primary nodes do not relay the secondary packet.

For wireless channel, loss can be due to shadowing and multipath fading. We only consider loss due to the effect of distance between TX and RX. Thus the power gain is given as $g(r)=r^{-\alpha}$, where r represents the distance between the TX and RX, and $\alpha>2$ denotes the path loss exponent.

We define the data rate for each transmit pair based on the famous Shannon Capacity, which is similar to Vu et al. (2007) and Yin et al. (2011). Let N_p and N_s denote the number of active primary and secondary TXs that communicate simultaneously. So the data rate of the ith primary TX can be given as

$$R_p(i)=\log\left(1+\frac{P_p(i)g(\|X_{p,tx}(i)-X_{p,rx}(i)\|)}{N_0+I_p(i)+I_{sp}(i)}\right) \quad (1)$$

where $\|\cdot\|$ denotes the norm operation; $P_p(i)$ is the transmitting power of ith primary TX; $X_{p,tx}(i)$ and $X_{p,rx}(i)$ represent the locations