Performance Analysis of Mobile Hotspots with Heterogeneous Wireless Links

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***Abstract*— Mobile hotspot enabling Internet access services in moving vehicles is an important service for ubiquitous computing. In this paper, we propose an analytical framework for studying the packet loss behavior and throughput in a mobile hotspot with heterogeneous wireless links. We first develop a two-state Markov model for the integrated wireless wide area network (WWAN) and wireless local area network (WLAN). We then derive the expressions that describe the experienced packet loss probability, packet loss burst length, and throughput. Finally, we present simulation results to verify the accuracy of our analysis. It is concluded that adaptive and cross-layer approaches should be deployed to improve the performance of mobile hotspots.**

***Index Terms*— Mobile hotspot, integrated WWAN-WLAN link, Markov model, performance analysis.**

I. Introduction

WITH the advances of wireless access technologies and mobile Internet services, wireless local area network (WLAN)-based hotspot services in public areas (e.g., convention centers, cafes, airports, shopping malls, etc.) are being proliferated. In addition, the extension of hotpot services in moving vehicles such as subways, trains, buses, and ships is gaining much attention [1], [2]. The hotspot service in a mobile platform is also referred to as *mobile hotspot* [3], which is a novel concept to realize ubiquitous and always best connected (ABC) services in future wireless/mobile networks.

Figure 1 describes a typical network architecture for mobile hotspots [4], [5]. Within a moving vehicle, WLAN is used to connect a number of mobile nodes (MNs) to an access point (AP) or gateway. At the same time, wireless wide area network (WWAN) is employed for the connection between the AP and the base station (BS), which is in turn connected to the Internet through a wireline link. Packets sent from a correspondent node (CN) to an MN are first routed to the BS through the Internet, and then transmitted to the MN over the integrated WWAN-WLAN link. WLAN supports higher data rate than WWAN but it has a smaller service coverage than WWAN. By integrating these two technologies, WWAN provides an extended service coverage to the vehicle, and WLAN accommodates more users without excessive usage of the resource in WWAN. This mobile hotspot architecture also has other advantages. First, the aggregated traffic at the AP is transmitted to the BS through an antenna mounted on top of the vehicle which has better communication channels to the BS as compared to a channel between the BS and MNs. Second, the AP has less energy constraint than the MNs. Using the AP to relay the data to the BS can significantly save the energy consumption in MNs. Third, the AP has better knowledge of the mobility and location of the vehicle. Therefore, handoff management can be simple and efficient.

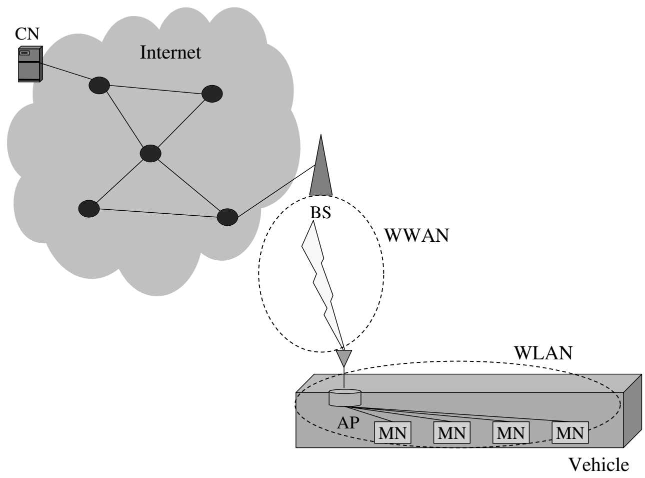

Fig. 1. Mobile hotspot architecture.

In order to deploy a mobile hotspot successfully, its performance should be thoroughly studied. Various research for mobile hotspots has been conducted: mobility management [6], [7], quality of service (QoS) support [4], link layer transmission technique [3], [8], gateway architecture [5], [9], and testbed implementation [10]–[12]. In these studies, performances have been analyzed through simulations or measurements. On the other hand, extensive studies have been done to analyze the performance of multi-hop wireless networks. However, these works are based on homogeneous multi-hop wireless links,

Manuscript received March 8, 2006; revised August 13, 2006 and October 31, 2006; accepted November 3, 2006. The editor coordinating the review of this paper and approving it for publication was M. Zorzi. This work has been supported in part by a Strategic Grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant No. STPGP 257682 and in part by the Korea Research Foundation Grant No. M01-2005-000-10073-0.

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Digital Object Identifier 10.1109/TWC.2007.060069.

and therefore they cannot be applied to mobile hotspots. To the best of our knowledge, there is no analytical study that specifically evaluates the performance of mobile hotspots with heterogeneous wireless links.

In this paper, we propose an analytical framework for studying the packet loss behavior and throughput in a mobile hotspot. We first develop a two-state Markov model which approximates the packet loss process in the integrated WWAN-WLAN link. Then, we derive the expressions that describe the experienced packet loss probability, packet loss burst length, and throughput. We present various numerical results to demonstrate the effects of the velocity of moving vehicle, the number of MNs within a vehicle, and wireless link conditions. In addition, simulation results are given to verify the accuracy of our analysis. The major contributions in this paper are three-fold: 1) we propose an analytical framework to evaluate the packet-level performance in mobile hotspots; 2) for the WLAN link, we introduce a novel analytical model describing packet transmission over a fading channel; and 3) based on the developed analytical framework, we present valuable numerical results and observations that give insights for further research issues.

The remainder of this paper is organized as follows. In Section II, the system model for a mobile hotspot is described. In Section III, the two-state Markov chain for the integrated WWAN-WLAN link is developed and the packet loss probability, packet loss burst length, and throughput are derived in Section IV. Various simulation results are presented in Section V. Finally, Section VI concludes this paper with future works.

II. System Description

For many Internet applications (e.g., web browsing and multimedia streaming), downlink traffic dominates uplink traffic. Therefore, we focus on the downlink transmission from the BS to the MN. A packet[1] is first transmitted over the WWAN link and then over the WLAN link. Since the data rate of the WLAN link is much higher than that of the WWAN link, the queueing delay at the AP queue is assumed negligible.

In WLAN, N saturated MNs (i.e., each MN always has a packet to send) are assumed to share the WLAN channel and transmission failures are due to either packet collision or channel fading. The IEEE 802.11 distributed coordination function (DCF) [13] is used for media access control. For WWAN, we consider a dedicated fading channel, and therefore transmission errors are only due to channel fading of the received signal strength. In addition, a truncated automatic repeat request (ARQ) scheme is used to recover transmission failures. Since packet losses in WWAN and WLAN are independent, we first model the packet losses in the WLAN link and WWAN link at the packet level in subsections II-A and II-B, respectively. And then, we develop an integrated WWAN-WLAN model in Section III.

[1]The term *frame* is referred to as a protocol data unit (PDU) in the data link layer and the term *packet* is referred to as a PDU in the transport layer. Since link layer fragmentation is not considered, these two terms are used interchangeably.

A. WLAN Link Model

Recently, the effects of channel fading in WLAN have been reported in several studies [14]–[16]. Through extensive experimentation, it is revealed that WLAN has considerable transmission errors due to channel fading, and the errors due to channel fading are dependent on physical layer parameters and become more severe when high data rates are employed. The well-known analytical model proposed by Bianchi [17] and its variants [18], [19] do not capture the impact of transmission errors. To remedy this problem, several analytical models [20], [21] have been proposed to capture the impact of transmission errors. However, these models are based on an independent packet loss assumption which does not portray the wireless fading channel well. To the best of our knowledge, little works have been done in modeling IEEE 802.11 WLANs that captures the impact of both correlated and uncorrelated transmission errors. In this subsection, we derive the expression for the packet loss probability of WLAN taking into account correlated transmission errors and packet collisions.

The WLAN correlated transmission error behavior can be approximated by using a discrete-time two-state Markov channel model [22], which has a good (g) state and a bad (b) state. A time slot in the Markov chain, $E[slot]$, is defined as the time interval between two consecutive backoff counter decrements [17], and it can be found in Appendix I. In general, the upper bound of $E[slot]$ equals the transmission time of a packet. The transmission time of a 1000-byte packet over the WLAN with 11 Mbps channel is less than 1 ms. On the other hand, a relative movement speed of the communicating devices or other objects in mobile hotspots (i.e., in-vehicle WLANs) is usually very low. In practice, the channel coherence time can be approximated as 42.3% of multiplicative inverse of the maximum Doppler frequency (a more conservative approximation) [23]. The maximum Doppler frequency of the fading channel, with user velocity of 5 m/s (18 km/hour) and carrier frequency of 2.4 GHz, is about 40 Hz. In that case, the channel coherence time is more than 10 ms. From this observation and other research [24], $E[slot]$ is generally much less than the WLAN channel coherence time. Therefore, it is reasonable to consider the state transitions of the Markov channel model after every time slot. In the bad state, a packet transmission fails while a packet transmission is successful in the good state if there is no collision. The transition probabilities of these states are given by the matrix

$$\mathbf{Q} = \begin{pmatrix} q_{bb} & q_{bg} \\ q_{gb} & q_{gg} \end{pmatrix}, \tag{1}$$

where q_{xy} is the transition probability from state $x \in \{b, g\}$ to state $y \in \{b, g\}$. Given an average error rate (π_b^{WLAN}), defined as the ratio of the number of erroneous packets to the total number of packets sent, and a burst length (l_B), defined as the average number of consecutive time slots in the bad state, the transition probabilities can be computed as

$$q_{bg} = \frac{1}{l_B} = 1 - q_{bb}$$

and

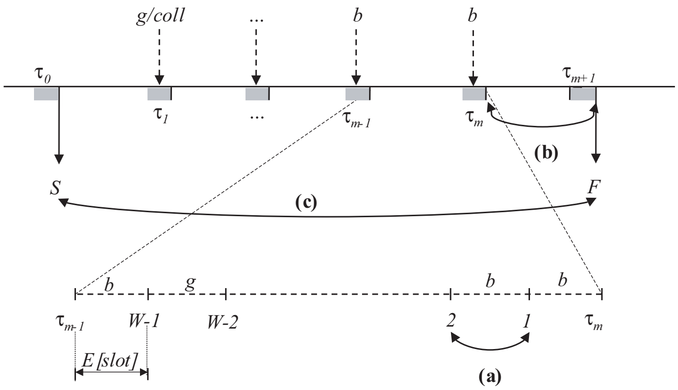


Fig. 2. Transmission success/failure behaviors in the IEEE 802.11 WLANs: (a) a slot, (b) a backoff stage, (c) a packet transmission interval. *coll*, S, and F represent collision, successful transmission, and failed transmission, respectively.

$$q_{gb} = \frac{\pi_b^{WLAN} q_{bg}}{1 - \pi_b^{WLAN}} = 1 - q_{gg}.$$

The fading parameters l_B and π_b^{WLAN} can be obtained from measurements or from wireless channel profiles by considering the physical characteristics of the channel and the physical layer modulation/coding schemes used [16]. How to obtain these parameters accurately is beyond the scope of this paper.

Figure 2 illustrates the transmission success/failure behaviors in the IEEE 802.11 basic access mode[2]. For tactical analysis, it is assumed that a packet transmission is successful when channel condition is good (g) and no collisions ($coll$) occur at the transmission time slot. A maximum of m retransmissions are attempted before the packet is aborted (i.e., after $m+1$ transmission failures). For every transmission failure, the sender defers its transmission for a random duration, i.e., backoff interval. In Figure 2, τ_{i+1} denotes the time slot where a packet transmission occurs at the ith backoff stage $(0 \le i \le m)$, where m is the transmission retry limit. Since the backoff stage length (in numbers of $E[slot]$) is uniformly chosen in the range [0,W_i-1], where $W_i = 2^i CW_{min}$ and CW_{min} is the minimum contention window size, the average length of the ith backoff stage (n_i) can be computed as $n_i = (W_i - 1)/2$.

Then, the transition probability from state $x \in \{b, g\}$ at time slot τ_i to state $y \in \{b, g\}$ at time slot τ_{i+1}, denoted by $q_{xy}^{(n_i)}$, can be obtained from elements in the n_i-step transition probability matrix,

$$\mathbf{Q}^{(n_i)} = \begin{pmatrix} q_{bb}^{(n_i)} & q_{bg}^{(n_i)} \\ q_{gb}^{(n_i)} & q_{gg}^{(n_i)} \end{pmatrix}. \tag{2}$$

As indicated before, a packet transmission fails when the channel is bad after winning channel contention or when a collision occurs in the good state. Since a packet loss occurs after $m+1$ consecutive transmission failures, there are 2^{m+1} possible unique sequences (traces) of the WLAN channel states for a packet loss event. Let $T_i \in \{(s_0, s_1, ...s_m)\}$ denote the ith trace of all possible traces, where $s_k \in \{b, g\}$ is the WLAN channel state in the kth transmission attempt. Then, the packet loss probability in the WLAN link is given by

$$\pi_F^{WLAN} = \sum_{i=1}^{2^{m+1}} \Theta(T_i) \cdot p^{N(T_i)}, \tag{3}$$

where p is the probability that a collision occurs when a packet is transmitted, $N(T_i)$ is the number of transmission attempts in the good channel state (or the number of packet collisions) in the trace T_i, and $\Theta(T_i)$ is the occurrence probability of trace $T_i = (s_0, s_1, ...s_m)$ which can be found as

$$\begin{aligned} \Theta(T_i) &= \pi_b^{WLAN} q_{bs_0}^{(0)} q_{s_0 s_1}^{(1)} ... q_{s_{m-1} s_m}^{(m)} \\ &+ \pi_g^{WLAN} q_{gs_0}^{(0)} q_{s_0 s_1}^{(1)} ... q_{s_{m-1} s_m}^{(m)}. \end{aligned} \tag{4}$$

$q_{xy}^{(i)}$ $(x, y \in \{b, g\})$ represents $q_{xy}^{(n_i)}$ in (2), and $\pi_b^{WLAN} = q_{gb}/(q_{gb} + q_{bg})$ and $\pi_g^{WLAN} = q_{bg}/(q_{gb} + q_{bg})$ are the steady state probabilities that the WLAN link conditions are bad and good, respectively.

Let $bw(t)$ and $bs(t)$ respectively denote the stochastic processes representing the backoff window size and the backoff stage for a given node at time t [18]. The packet transmission behavior can be described by a two-dimensional process as $\{bs(t), bw(t)\}$. Let $b_{i,k}$ be the stationary distribution of the Markov chain, i.e., $b_{i,k} = \lim_{t\to\infty} P\{bs(t) = i, bw(t) = k\}$. τ is the probability that a packet is transmitted in a randomly chosen slot and it is given by [18]

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1 - {p_f}^{m+1}}{1 - p_f} b_{0,0}, \tag{5}$$

where p_f is the packet transmission failure probability in a given slot. $b_{0,0}$ is given by (6) at the top of next page where m' is the number of contention window sizes (i.e., the maximum contention window size is $2^{m'}$) and W is the minimum contention window size.

To compute the packet transmission failure probability p_f, we use the same assumptions and notations as in [17], [18]. Even though we consider burst transmission errors in the derivation of π_F^{WLAN}, it is quite complicated to consider burst transmission errors in the derivation of p_f. Therefore, we assume that p_f is affected by independent transmission errors. This approximation can be acceptable since p_f mainly captures the average transmission failure rate. For instance, if we randomly sample an error sequence (i.e., τ_i in Figure 2), the average error rate of the sampled sequence remains the same as the original error rate and it is independent of the self-correlated coefficient of the original sequence. Furthermore, the transmission probability in the n_i-step transition matrix approaches the steady state probability (i.e., $q_{xy}^{(n_i)} \approx \pi_y^{WLAN}$) when n_i is sufficiently large. Note that the contention window size increases exponentially and CW_{min} is 32 in the IEEE 802.11b specification, which is sufficiently large for justifying the approximation. In Section V, we will validate this approximation through simulation. Given N saturated nodes, the collision probability p is given by $p = 1 - (1 - \tau)^{N-1}$. Then, the packet transmission failure probability, p_f, in a given

[2]Even though another access mode, request-to-send (RTS)/clear-to-send (CTS), is efficient to overcome the hidden-node problem, it is disabled in most products available in the current market [25]. Therefore, we assume the basic access mode.

$$b_{0,0} = \begin{cases} \frac{2(1-2p_f)(1-p_f)}{W(1-(2p_f)^{m+1})(1-p_f)+(1-2p_f)(1-{p_f}^{m+1})} & m \le m' \\ \frac{2(1-2p_f)(1-p_f)}{W(1-(2p_f)^{m'+1})(1-p_f)+(1-2p_f)(1-{p_f}^{m+1})+W2^{m'}{p_f}^{m'+1}(1-2p_f)(1-{p_f}^{m-m'})} & m > m' \end{cases}. \tag{6}$$

slot can be approximated as

$$p_f \approx \pi_b^{WLAN} + (1 - \pi_b^{WLAN})p. \tag{7}$$

Using (5), (6), and (7), p_f and p can be computed numerically. Once we obtain the packet transmission failure probability p_f and the collision probability p, we can use (3) to calculate the packet loss probability in WLAN, considering correlated channel fading.

B. WWAN Link Model

For the WWAN channel, a non-line-of-sight (NLOS) frequency-nonselective (flat) multipath fading channel with packet transmission rate (in packets/seconds) much higher than the maximum Doppler frequency (Hz) is considered. Given a modulation scheme, the dynamics of the fading channel can be characterized at the packet level. However, the performance analysis of high-level protocols becomes quite complex. As an alternative to this problem, a widely adopted two-state Markov channel model [26] is used to approximate the error process at the packet level. The discrete-time two-state Markov channel model has a *good* state and a *bad* state, i.e., packet error probability is 1 in the *bad* state and 0 in the *good* state. The time slot duration for the Markov chain equals the packet transmission time in WWAN. Let v and f_c be the velocity of a vehicle and the carrier frequency, respectively. The Doppler frequency f_d is given by $f_c v / v_c$, where v_c is the speed of light. Let F be the fading margin. Then the average transmission error probability is [26]

$$\pi_b^{WWAN} = 1 - e^{-1/F}. \tag{8}$$

Let $\mathbf{P} = \begin{pmatrix} p_{bb} & p_{bg} \\ p_{gb} & p_{gg} \end{pmatrix}$ be the WWAN link state transition matrix. The state transition probabilities are

$$p_{bb} = 1 - \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{1/F} - 1}$$

and

$$p_{gg} = \frac{1 - \pi_b^{WWAN}(2 - p_{bb})}{1 - \pi_b^{WWAN}},$$

where $\theta = \sqrt{\frac{2/F}{1-\rho^2}}$ and $\rho = J_0(2\pi f_d D)$. ρ is the Gaussian correlation coefficient of two samples of the complex amplitude in a fading channel with Doppler frequency f_d, which are sampled D seconds apart. $J_0(\cdot)$ is the Bessel function of the first kind and zero order, and $Q(\cdot, \cdot)$ is the Marcum Q function.

By deploying the truncated ARQ scheme, a sender retransmits a packet until the packet is successfully delivered, or drops the packet if the retry limit l (including the first transmission) is reached [27]. Consequently, the probability that a packet is lost in the WWAN link can be found as

$$\pi_F^{WWAN} = \pi_b^{WWAN} {p_{bb}}^{l-1}. \tag{9}$$

III. Integrated WWAN-WLAN Link Model

In this section, we use the parameters of the WWAN and WLAN models developed in Section II, and derive transition probabilities of the two-state Markov chain that describes the packet loss process in the integrated WWAN-WLAN link. The two-state Markov chain can be used to quantify the burstiness in packet losses, which is an important factor for dimensioning the BS buffer size and has significant impact on the performance of real-time transmission [28].

Let us consider a two-state Markov chain with failure (F) and success (S) states. A packet is successfully transmitted in state S whereas it is dropped in state F. Let r_{xy} be the transition probability from state $x \in \{F, S\}$ to state $y \in \{F, S\}$. Then, the transition matrix of the Markov chain is given by

$$\mathbf{R} = \begin{pmatrix} r_{FF} & r_{FS} \\ r_{SF} & r_{SS} \end{pmatrix}, \tag{10}$$

where $r_{FS} = 1 - r_{FF}$ and $r_{SF} = 1 - r_{SS}$. To characterize the integrated WWAN-WLAN link, we need to find expressions for transition probabilities r_{SS} and r_{FF}. From the WWAN and WLAN models characterized in Section II, the packet loss probability over the WWAN-WLAN link, P_l, can be computed as

$$P_l = \pi_F^{WWAN} + (1 - \pi_F^{WWAN}) \cdot \pi_F^{WLAN}. \tag{11}$$

Also, from the transition matrix $\mathbf{R}$, the packet loss probability over the WWAN-WLAN link can be computed as

$$P_l = \frac{1 - r_{SS}}{2 - r_{FF} - r_{SS}}. \tag{12}$$

By combining (11) and (12), r_{SS} can be found in terms of r_{FF}. Therefore, we only need to find the expression for r_{FF}.

Let X and Y denote two consecutive packet transmission events over the WWAN-WLAN link. Then, by definition, r_{FF} equals $\Pr(Y = F | X = F)$ and it can be written as

$$\Pr(Y = F | X = F) = \frac{\Pr(X = F, Y = F)}{\Pr(X = F)}, \tag{13}$$

where $\Pr(X = F, Y = F)$ is the joint probability that two consecutive packets are lost. $\Pr(X = F)$ is simply given by $\pi_F^{WWAN} + (1 - \pi_F^{WWAN}) \cdot \pi_F^{WLAN}$. To calculate $\Pr(X = F, Y = F)$, let A and B be the events that a packet is lost over the WWAN and WLAN links, respectively. Then, $\Pr(X = F, Y = F)$ is given by

$$\begin{aligned} \Pr(X = F, Y = F) &= \Pr(X = A, Y = A) \\ &+ \Pr(X = A, Y = B) \\ &+ \Pr(X = B, Y = A) \\ &+ \Pr(X = B, Y = B). \end{aligned} \tag{14}$$

A. *Expression for* $\Pr(X = A, Y = A)$

The event $(X = A, Y = A)$ represents that the first packet is lost over the WWAN link and the second packet is also lost over the WWAN link. The probability of the first packet loss is π_F^{WWAN}. Since the first packet is discarded at the WWAN link, the WWAN link condition during the last transmission of the first packet is bad. Therefore, the probability that the first transmission of the second packet fails is given by p_{bb}. Also, if all $l-1$ retransmissions fail, the second packet is discarded. Consequently, $\Pr(X = A, Y = A)$ is given by

$$\Pr(X = A, Y = A) = \pi_F^{WWAN} \cdot p_{bb} p_{bb}^{l-1}. \qquad (15)$$

B. *Expression for* $\Pr(X = A, Y = B)$

The event $(X = A, Y = B)$ refers to the case where the first packet is lost over the WWAN link and the second packet is lost over the WLAN link. Since the first packet is lost at the WWAN link, the WWAN link state at the lth transmission of the first packet is bad. To successfully transmit the second packet over the WWAN link, the WWAN link should be in the good state. Let ϕ_b be the probability that the second packet transmission over the WWAN link is successful given that the link state at the last trial of the first packet is bad. Then, ϕ_b is derived as

$$\begin{aligned} \phi_b &= p_{bg} + p_{bb}p_{bg} + {p_{bb}}^2 p_{bg} + \ldots + {p_{bb}}^{l-1} p_{bg} \\ &= p_{bg} \frac{1 - {p_{bb}}^l}{1 - p_{bb}} = 1 - {p_{bb}}^l, \end{aligned} \qquad (16)$$

where ${p_{bb}}^{i-1} p_{bg}$ represents the probability that the WWAN link state becomes good at the ith attempt $(1 \le i \le l)$. On the other hand, the probability that the second packet is lost over the WLAN link is π_F^{WLAN}. Consequently, $\Pr(X = A, Y = B)$ is derived as

$$\Pr(X = A, Y = B) = \pi_F^{WWAN} \cdot \phi_b \cdot \pi_F^{WLAN}. \qquad (17)$$

C. *Expression for* $\Pr(X = B, Y = A)$

In the event $(X = B, Y = A)$, the first packet is lost over the WLAN link and its probability is $(1 - \pi_F^{WWAN}) \cdot \pi_F^{WLAN}$. In this case, the WWAN link state at the last attempt of the first packet is good. However, the second packet is dropped at the WWAN link due to bad link condition. The probability for this event is $p_{gb}{p_{bb}}^{l-1}$. Consequently, $\Pr(X = B, Y = A)$ is given by

$$\Pr(X = B, Y = A) = (1 - \pi_F^{WWAN}) \cdot \pi_F^{WLAN} \cdot p_{gb}{p_{bb}}^{l-1}. \qquad (18)$$

D. *Expression for* $\Pr(X = B, Y = B)$

For the event $(X = B, Y = B)$, two consecutive packets are lost over the WLAN link. This implies that two consecutive packets are successfully transmitted over the WWAN link. Let ϕ_g be the probability that the second packet transmission over the WWAN link is successful given that the WWAN link state on the last transmission attempt of the first packet is good. Also let θ_F be the probability that the second packet is lost over the WLAN link when the first packet is lost over the WLAN link. Then, $\Pr(X = B, Y = B)$ is given by

$$\Pr(X = B, Y = B) = (1 - \pi_F^{WWAN}) \cdot \pi_F^{WLAN} \cdot \phi_g \cdot \theta_F. \qquad (19)$$

Similar to ϕ_b in (16), ϕ_g is obtained from

$$\begin{aligned} \phi_g &= p_{gg} + p_{gb}p_{bg} + p_{gb}p_{bb}p_{bg} + \ldots + p_{gb}{p_{bb}}^{l-2} p_{bg} \\ &= p_{gg} + p_{gb}p_{bg} \frac{1 - {p_{bb}}^{l-1}}{1 - p_{bb}} = p_{gg} + p_{gb}(1 - {p_{bb}}^{l-1}) \\ &= 1 - p_{gb}{p_{bb}}^{l-1}, \end{aligned} \qquad (20)$$

where p_{gg} is the probability that the WWAN link condition is good at the first transmission attempt and $p_{gb}{p_{bb}}^{i-2} p_{bg}$ is the probability of the event when the WWAN link becomes good at the ith transmission attempt $(2 \le i \le l)$.

In order to derive the expression θ_F, let us consider the WLAN model developed in Section II, where a transmission failure over the WLAN link is caused by a collision or transmission error. Let $T_i|s_0 = x$ be a trace with $s_0 = x \in \{b, g\}$, where s_j is the WLAN link state at the jth transmission attempt. Similarly, $T_i|s_m = x$ represents a trace with $s_m = x \in \{b, g\}$. Then, θ_F is represented by (21) at the top of next page where $\omega_b = \sum_i \Theta(T_i|s_m = b) \cdot p^{N(T_i|s_m = b)}$ and $\omega_g = \sum_i \Theta(T_i|s_m = g) \cdot p^{N(T_i|s_m = g)}$. That is, ω_b and ω_g are the probabilities that the last transmission failure of the first packet in the WLAN link is due to transmission error and collision, respectively. In (21), the first term refers to the case that the second packet is lost over the WLAN link when the last transmission of the first packet fails due to bad link condition. The second term represents that the second packet is lost over the WLAN link when the first packet fails at the last transmission attempt due to collision. $\Theta_b(\cdot)$ and $\Theta_g(\cdot)$ are the occurrence probabilities when the WLAN link states at the last transmission of the previous packet (i.e., τ_0 in Figure 2) are known as bad and good, respectively. For a given $T_i = (s_0, s_1, \ldots, s_m)$, they are defined as $\Theta_b(T_i) = q_{bs_0}^{(0)} q_{s_0 s_1}^{(1)} \ldots q_{s_{m-1} s_m}^{(m)}$ and $\Theta_g(T_i) = q_{gs_0}^{(0)} q_{s_0 s_1}^{(1)} \ldots q_{s_{m-1} s_m}^{(m)}$.

IV. Performance Analysis

We have developed an analytical channel model for an integrated WWAN-WLAN link. In this section, we use this model to study the performance of multimedia traffic (e.g., data, video, etc.) in mobile hotspots. To facilitate the performance study of multimedia traffic, we derive expressions that describe the packet loss probability, packet loss burst length, and channel throughput of the developed channel model.

The packet loss probability (P_l) is defined as the probability that a packet is lost over the integrated WWAN-WLAN link, which can be obtained from (11). The packet loss burst length (L_b) is defined as the average number of consecutive packet losses in the WWAN-WLAN link. From Section III, the packet loss burst length can be found as

$$L_b = \sum_{i=1}^{\infty} i \cdot {r_{FF}}^{i-1}(1 - r_{FF}) = \frac{1}{(1 - r_{FF})}. \qquad (22)$$

The channel throughput (T) is defined as the amount of actual data (payload) for a packet transmission through

$$\begin{aligned}\theta_F &= (\sum_i \Theta_b(T_i|s_0=b)\cdot p^{N(T_i|s_0=b)} + \sum_i \Theta_b(T_i|s_0=g)\cdot p^{N(T_i|s_0=g)})\cdot \frac{\omega_b}{\omega_b+\omega_g}\\ &+ (\sum_i \Theta_g(T_i|s_0=b)\cdot p^{N(T_i|s_0=b)} + \sum_i \Theta_g(T_i|s_0=g)\cdot p^{N(T_i|s_0=g)})\cdot \frac{\omega_g}{\omega_b+\omega_g}. \end{aligned} \quad (21)$$

the integrated WWAN-WLAN link per unit time. It can be computed as

$$T = \frac{\pi_S P}{t_{wireless}}, \quad (23)$$

where $t_{wireless}$ is the expected channel usage time for a packet transmission and P is the packet payload size (i.e., actual data transmitted). π_S is the steady state probability of the channel being in the success (S) state. Hence, $\pi_S P$ represents the expected payload bits transmitted by a packet transmission. From (10), π_S can be computed as

$$\pi_S = \frac{r_{FS}}{r_{FS}+r_{SF}}. \quad (24)$$

$t_{wireless}$ can be calculated by (25) at the top of next page where t_L^{WWAN} and t_L^{WLAN} are the average latencies for a packet loss over the WWAN and WLAN links, respectively. On the other hand, t_S^{WWAN} and t_S^{WLAN} are the average latencies for a successful transmission over the WWAN and WLAN links, respectively. π_F^{WLAN} and π_F^{WWAN} are respectively defined in (3) and (9). Note that the first, second, and third terms in the right-hand side of (25) are respectively correspond to the cases when a packet is lost in the WWAN link, a packet is successfully transmitted in the WWAN link but then lost in the WLAN link, and a packet is successfully transmitted both in the WWAN and WLAN links.

The latency when a packet is lost over the WWAN link is given by

$$t_L^{WWAN} = lD. \quad (26)$$

where D is the time slot duration in the WWAN link. Similarly, the latency for a lost packet over the WLAN link is the sum of time slots during $m+1$ backoff stages and therefore it is given by

$$t_L^{WLAN} = \sum_{j=0}^{m} \frac{W_j-1}{2}\cdot E[slot]. \quad (27)$$

From the system description, l transmissions are performed before a packet is finally discarded over the WWAN link. Intuitively, the first transmission attempt is always performed regardless of the transmission result. On the other hand, the probability that a successfully transmitted packet performs the ith ($i \geq 2$) transmission attempt in the WWAN link is given by $\pi_b^{WWAN}\cdot {p_{bb}}^{i-2} - \pi_F^{WWAN}$. Since the time slot duration in the WWAN link is D, the average latency for a packet to be successfully transmitted over the WWAN link can be computed as

$$t_S^{WWAN} = D + \sum_{i=2}^{l} \frac{\pi_b^{WWAN}\cdot {p_{bb}}^{i-2} - \pi_F^{WWAN}}{1-\pi_F^{WWAN}}\cdot D. \quad (28)$$

The latency for a packet to be successfully transmitted over the WLAN link can also be calculated in a similar way. In the WLAN link, at least one transmission is always completed so that $(W_0-1)/2$ slots are required with probability 1. Let Q_k be the kth trace when a successfully transmitted packet over the WLAN link reaches the jth backoff stage, where $1 \leq j \leq m$ and $Q_k = (s_0, s_1, ..., s_{j-1})$. The trace space size of Q_k is 2^j. The probability that a successfully transmitted packet performs the jth retransmission is given by

$$\sum_{k=1}^{2^j} \Theta(Q_k) p^{N(Q_k)} - \pi_F^{WLAN},$$

where $\Theta(\cdot)$ and $N(\cdot)$ are as defined in Section II. The average time duration at the jth backoff stage is $E[slot]\cdot(W_j-1)/2$, where $E[slot]$ is the average slot length and W_j is the contention window size at the jth backoff stage. Then, the latency for a packet to be successfully transmitted over the WLAN link can be calculated as (29).

V. Simulation Results

To validate analytical results, simulations are performed using the *ns-2* simulator [29]. For realistic simulations, we use continuous-time two-state error models for the WWAN and WLAN links. That is, the durations of the good and bad states are drawn from exponential distributions where the average durations correspond to those in the discrete-time two-state error model used in the analytical model. The following parameters are used for our simulation and analytical results, unless otherwise explicitly stated. The carrier frequency (f_c) of the WWAN link is 900 MHz. The WWAN bandwidth is assumed to be 400 Kbps and the payload size is fixed to 250 bytes. Hence, the transmission time (D) of a packet over the WWAN link is 5 msec. The default values (i.e., the values used if they are not explicitly stated) for velocity (v) and fading margin (F) are 10 m/s and 10 dB, respectively. Regarding the WLAN link, the transmission error rate (π_b^{WLAN}) and burst error length (l_B) are 0.01 and 1000 slots, respectively. The default values of retransmission limits for the WWAN and WLAN links, l and m, are 4. Note that $m = 4$ is less than the value in the IEEE 802.11 specification. This is because we focus on time-sensitive multimedia applications in this paper, and thus a larger m is not appropriate due to a long end-to-end delay and delay jitter even though it can reduce the packet loss rate. The number of MNs within a vehicle is varied from 1 to 20 and its default value is 10. The parameters for WLAN follow those of the IEEE 802.11b specification in [18] and the data rate is 11 Mbps. To obtain more accurate results, the simulation is conducted for 100 packets and repeated 100 times with different random seeds.

A. *Effects of v and N*

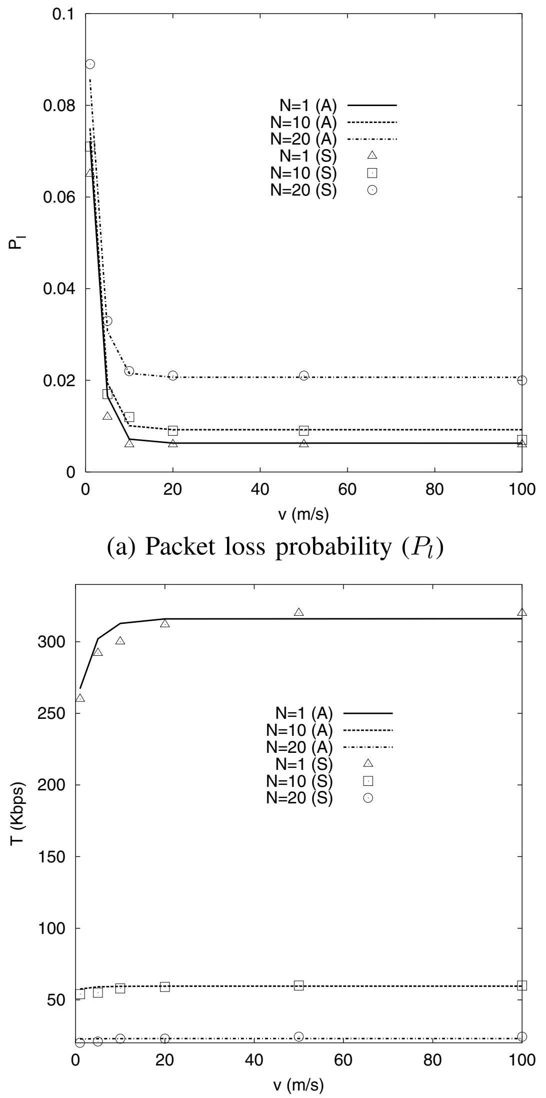
Figure 3(a) shows the effect of velocity (v) on the packet loss probability (P_l) for different numbers of MNs. It can

$$\begin{aligned} t_{wireless} &= \pi_F^{WWAN} \cdot t_L^{WWAN} + (1-\pi_F^{WWAN})\pi_F^{WLAN} \cdot (t_S^{WWAN} + t_L^{WLAN}) \\ &+ (1-\pi_F^{WWAN})(1-\pi_F^{WLAN}) \cdot (t_S^{WWAN} + t_S^{WLAN}). \end{aligned} \tag{25}$$

$$t_S^{WLAN} = \frac{W_0 - 1}{2} \cdot E[slot] + \sum_{j=1}^{m} \frac{W_j - 1}{2} \cdot \frac{\sum_{k=1}^{2^j} \Theta(Q_k) p^{N(Q_k)} - \pi_F^{WLAN}}{1 - \pi_F^{WLAN}} \cdot E[slot]. \tag{29}$$

be seen that, from both simulation and analytical results, P_l decreases as v increases. This observation can be explained as follows. When v increases, the Doppler frequency increases (i.e., the WWAN link's coherence time decreases) which in turn reduces the burstiness of the transmission errors in the WWAN link. Since there is a finite number of retransmission attempts in the WWAN link, P_l decreases as v increases. It can also be seen that P_l remains fairly constant when v exceeds a certain value. In addition, Figure 3(a) indicates that P_l increases as N increases. This is due to the fact that transmission errors in the WLAN link are fairly steady; therefore, the number of competing nodes (N) is an important factor affecting the packet loss probability. In other words, as the number of nodes serviced by a single AP in a mobile hotspot increases, the packet losses due to frequent collisions also increase.

Figure 3(b) shows the impact of velocity on the channel throughput (T). It can be seen that, as v increases, T increases and tends to a value close to the WWAN link bandwidth (i.e., 400 Kbps) when N = 1. However, T remains almost unchanged for N equal to 10 and 20. The observation implies that the packet loss probability and throughput in mobile hotspots, which are deployed in fast moving vehicles (e.g., 430 km/h in Maglev trains [30]), are not severely affected by the WWAN link condition. Thus, handoff and packet collision are likely to be the dominant sources of packet losses. To reduce packet losses due to handoff latency, Fast Handover for Mobile IPv6 [31] can be utilized. On the other hand, to mitigate the impact of N, it is necessary to employ good admission control algorithms [32] or to use multiple APs within a mobile hotspot [33]. From Figure 3, even though analytical and simulation results are mostly consistent, there is some discrepancy between them when N is small and v is low. This discrepancy can be explained as follows: 1) since $E[slot]$ is much less than the packet transmission time for a small N, we need to observe more channel conditions at the first time slot for a packet transmission in order to derive a more accurate packet loss probability; and 2) since the channel coherence time is long for low v, the approximation of independent transmission errors for p_f and p may lead to certain errors.



(a) Packet loss probability (P_l)

(b) Throughput (T)

Fig. 3. Effect of v and N on P_l and T (A: Analysis, S: Simulation).

Figure 4 plots the packet loss burst length (L_b) over the WWAN-WLAN link as a function of v. When $v < 5$ m/s, L_b is drastically reduced as v increases. However, L_b increases with v when 5 m/s $< v <$ 20 m/s and L_b becomes stable for $v >$ 20m/s. This interesting observation can be explained as follows. By (13) and (22), L_b can be written as a function of π_F and $\Pr(X = F, Y = F)$, i.e., $L_b = \pi_F/(\pi_F - \Pr(X = F, Y = F))$. Since π_F is more sensitive to the channel coherence time than $\Pr(X = F, Y = F)$, π_F is more drastically reduced than $\pi_F - \Pr(X = F, Y = F)$ with v when $v <$ 5 m/s. Accordingly, L_b decreases as v increases. On the other hand, when v exceeds 5 m/s, $\Pr(X = F, Y = F)$ becomes almost stable. Therefore, L_b can be represented in the form $f(x) = x/(x-a) = 1+a/(x-a)$, where $f(x)$, x and a correspond to L_b, π_F, and $\Pr(X = F, Y = F)$, respectively, and a is a constant. As mentioned before, π_F is reduced as v

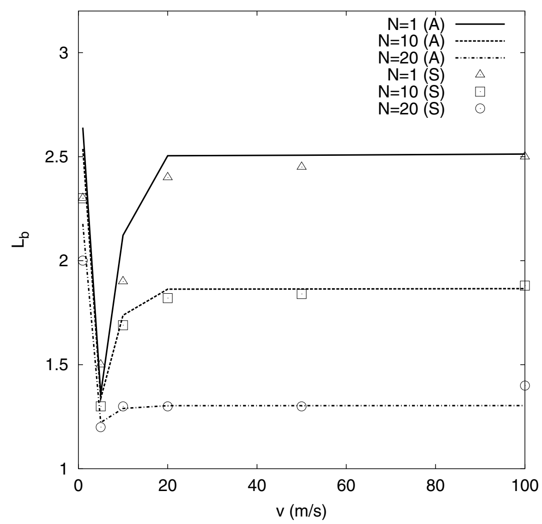


Fig. 4. L_b vs. v (A: Analysis, S: Simulation).

increases. Consequently, L_b increases as v increases because $f(x)$ is a decreasing function of $x > a$. However, if v exceeds 20m/s, the reduction of π_F is also negligible. Therefore, L_b does not further increase.

Figure 4 also shows that L_b is reduced as N increases. Since $\Pr(X = F, Y = F)$ is mainly affected by the fading process in the WWAN and WLAN links, it is rarely affected by N. Therefore, $\Pr(X = F, Y = F)$ can be considered as a constant with respect to N and thus L_b can be represented as a decreasing function of π_F, similar to $f(x)$. Since π_F increases with N, L_b is reduced as N increases.

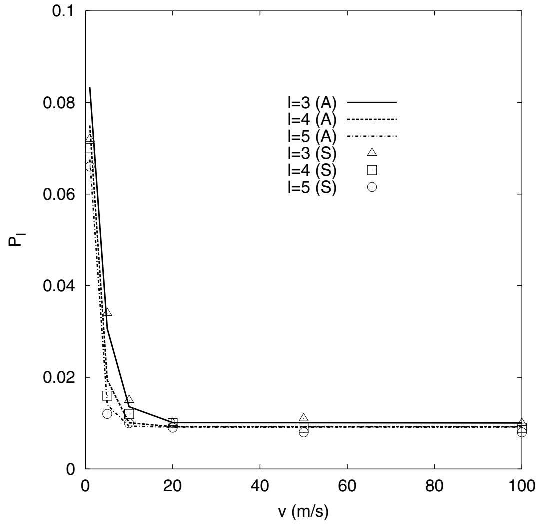
B. Effects of l and m

As described before, link layer retransmission mechanisms are employed to achieve reliable transmission. Retransmissions up to $l - 1$ and m are supported in the WWAN and WLAN links, respectively. Figure 5 shows the effects of l and m on P_l.

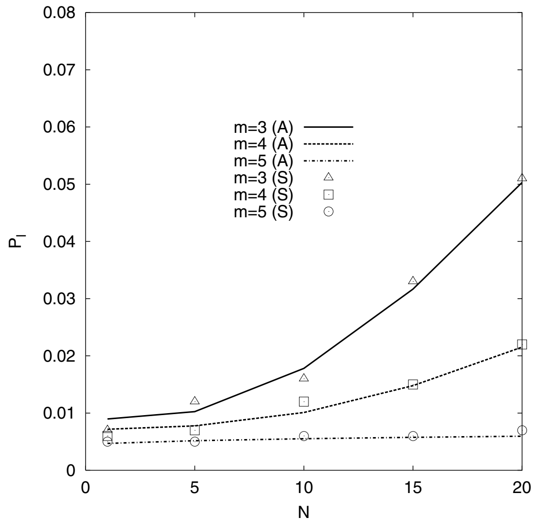
It can be seen that P_l is reduced when a large l is employed. However, the effect of l becomes insignificant at a high value of v. As v increases, the coherence time in the WWAN link apparently decreases. Therefore, burst transmission errors in the WWAN link are infrequent when v is high, and thus the reduction of P_l by employing a large l is not noticeable. Similarly, P_l can be reduced by increasing m as shown in Figure 5(b). In the WLAN link, more packets are lost due to collisions when N is large. Therefore, the effectiveness of a large m on P_l becomes apparent as N increases.

C. Effect of Wireless Link Condition

Wireless links are characterized by variable link conditions, so that wireless link conditions have significant effects on P_l and T. Figure 6 illustrates the effect of the WWAN link condition. To change the transmission error probability in the WWAN link, the fading margin F is varied. As F decreases, more packets are lost due to high transmission error probability in the WWAN link. On the other hand, since T is inversely proportional to P_l, it increases with F. However,



(a) Effect of l



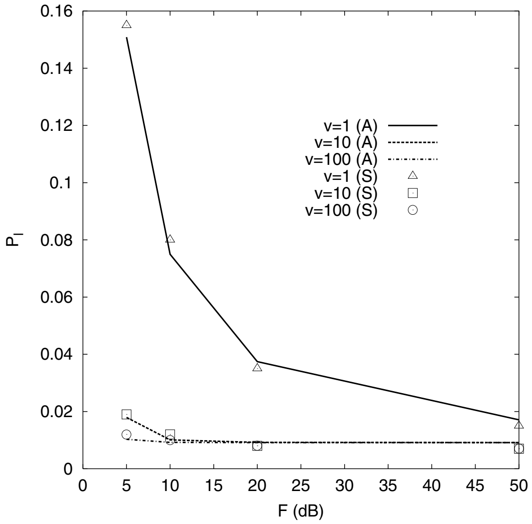
(b) Effect of m

Fig. 5. Effect of l and m on P_l (A: Analysis, S: Simulation).

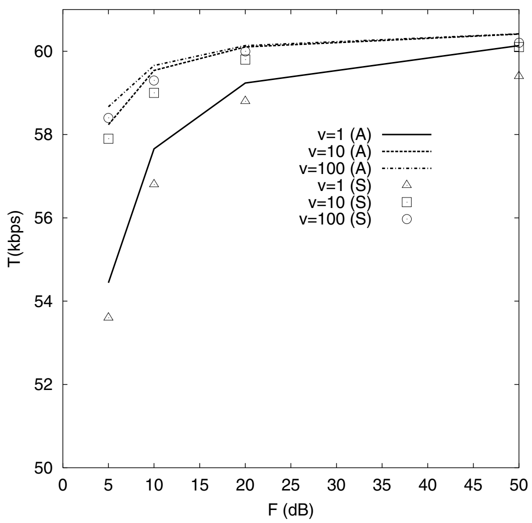
this trend is not clear when v is high. As mentioned before, if v is high, the burstiness of WWAN transmission errors is negligible. Since most non-bursty WWAN transmission errors can be recovered using ARQ, the effect of the WWAN transmission error probability is not significant for a high value of v.

As shown in Figure 7, the effect of π_b^{WLAN} becomes clearer when l_B is high. Specifically, the approximate increasing rates in P_l are 0.01 and 0.68 when l_B is 100 and 1000, respectively. On the other hand, T is drastically reduced as π_b^{WLAN} increases especially when l_B is high. From Figures 6 and 7, it can be concluded that a mechanism which adapts to the wireless link conditions is needed to improve the packet-level performance in terms of the packet loss probability and throughput. Since wireless link conditions can be estimated using the information available at the physical and MAC layers, cross-layer coupling should be considered in designing an adaptive mechanism.

Figure 8 demonstrates the effects of π_b^{WLAN} and l_B in the packet loss burst length (L_b). When l_B is 100, the packet loss

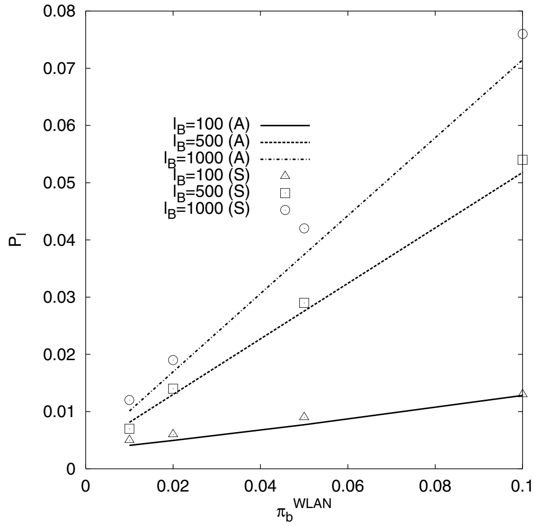


(a) Packet loss probability (P_l)

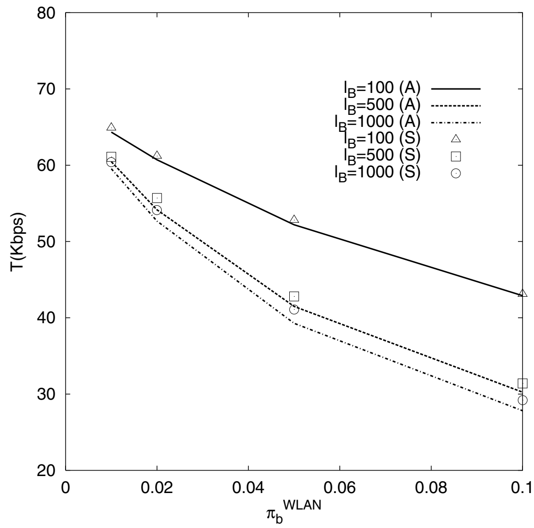


(b) Throughput (T)

Fig. 6. Effect of WWAN link condition on P_l and T (A: Analysis, S: Simulation).



(a) Packet loss probability (P_l)



(b) Throughput (T)

Fig. 7. Effect of WLAN link condition on P_l and T (A: Analysis, S: Simulation).

burstiness is negligible, i.e., L_b is almost 1.0. However, when l_B is 500 or 1000, an apparent L_b larger than 1.0 is observed.

VI. Conclusion

In this paper, we have proposed a two-state Markov model for the integrated WWAN-WLAN link in mobile hotspots, which characterizes the packet-level behavior. Using the proposed model, we have analyzed the packet loss probability, packet loss burst length, and throughput of the integrated WWAN-WLAN link. Through analytical and simulation results, the effects of various parameters such as the velocity, wireless link conditions, and retransmission limits have been investigated. It is concluded that adaptive and cross-layer approaches are necessary in order to improve the packet-level performance in mobile hotspots. In our future works, we will exploit the TCP/TFRC performances and adaptive multimedia streaming protocols for mobile hotspots.

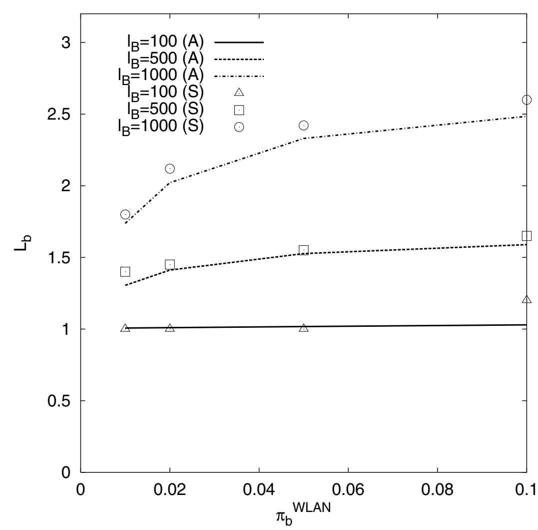


Fig. 8. L_b vs. π_b^{WLAN} (A: Analysis, S: Simulation).

APPENDIX I
DERIVATION OF $E[slot]$

The average slot length $E[slot]$ is given by [18],

$$E[slot] = (1 - P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1 - P_S) T_C,$$

where σ is the time duration of an empty slot. $P_{tr} = 1-(1-\tau)^n$ is the probability that there is at least one transmission in a given time slot. P_S is the probability that the transmission is successful and is calculated as $P_S = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \cdot \pi_g^{WLAN}$, where π_g^{WLAN} is the steady state probability of a good WLAN link condition. T_S and T_C are respectively time durations that the WLAN link is sensed busy during a successful packet transmission and during a collided frame transmission, and they are given by

$$T_S = DIFS + H + P + \delta + SIFS + ACK + \delta$$

and

$$T_C = DIFS + H + P + SIFS + ACK,$$

where δ is the propagation delay. $DIFS$ and $SIFS$ represent DCF inter frame space and small inter frame space, respectively. H, P, ACK are respectively the transmission times for the header, payload, and ACK frame.

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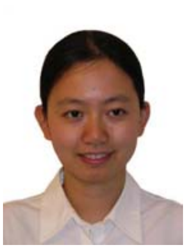

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