Delay Analysis for Packet Forward Scheme in Wireless Packet Networks

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Abstract

In a packet-switched wireless cellular network, a packet destined to a mobile station is queued at a base station and then broadcast over the base station's cell. When an active mobile station leaves a cell, there remain packets which are destined to the mobile and not yet delivered to it at the cell's base station. For applications which are sensitive to packet losses, such backlogged packets must be forwarded to the new base station. Otherwise, an end-to-end retransmission may be required. However, an increase in packet delay is incurred by employing the packet forward scheme, since a packet may be forwarded many times before it is delivered to the destined mobile station. For an enhanced quality-of-service level, it is preferred to reduce the packet delay time. In this paper, we develop an analytical approximation method for deriving mean packet delay times. Using the approximation and simulation methods, we investigate the effect of network parameters on the packet delay time.

1 Introduction

We consider packet-switched wireless cellular networks including wireless ATM networks [1] [3] [6]. At a base station, a packet destined to a mobile station is queued and then broadcast over the base station's cell through a wireless forward channel. When an active mobile station departs a cell, there may remain packets at the buffer of the cell's base station which are destined to the mobile and which have not yet been delivered to it [2]. Such packets are identified as backlogged packets. For applications which are sensitive to packet loss but are relatively tolerable to packet delay, (e.g., file transfer), it is not cost-effective to discard backlogged packets to the new base station. (An end-to-end retransmission may be required if the backlogged packets are discarded.) We thus consider a packet forward scheme under which all backlogged packets are forwarded to new base stations. By employing the packet forward scheme, we can avoid the loss of backlogged packets. However, since a packet may be forwarded many times before it is delivered to the destined mobile station, an increase in packet delay time is incurred. For an enhanced quality-of-service level, it is preferred to reduce the packet delay time.

In this paper, we develop an analytical approximation method for calculating the mean of the packet delay time. Using the approximation method as well as simulation method, we investigate the effect of network parameters, e.g., packet length, data rate on the wireless forward link, cell size, mobiile density, and mobile speed, on the distribution for the packet delay time.

In Section 2, we construct a mobility model, and characterize the probabilistic properties of the number of mobile stations resident in a cell and the mobile's cell departure process. We also describe an effective packet arrival rate by noting the influence of backlogged packets. In Section 3, by use of the effective arrival rate, an analytical approximation method is developed for the calculation of the mean packet delay time. Section 5 is devoted to numerical examples which exhibit the effect of network parameters on the packet delay time.

2 Model Description

The network service region is divided into cells. A base station is located in each cell. A cell is geometrically modeled as a disk of radius r and cells are assumed to be identical in size. Set v to be the average speed of mobile stations. Let C denote the cell sojourn time of a mobile. Then, based on the mobility model given in [2], the mean cell sojourn time is derived to be

$$E(C) = \frac{2}{\pi} \cdot \frac{2r}{v}. \tag{1}$$

We set the cell sojourn time to be governed by an exponential distribution with parameter η, where

$$\eta = \frac{\pi v}{4r}.$$

Let $N_{AMS}(t)$ denote the number of active mobile stations residing in a cell at time t. Let $\{E_n,\ n = 0, 1, \cdots\}$, $E_0 = 0$ a.s. and $\{H_n,\ n = 1, 2, \cdots\}$ denote the mobile's cell entrance and departure point processes. Suppose that the sequence $\{E_n,\ n = 0, 1, \cdots\}$ is a Poisson point process with parameter γ. Then, the process $\{N_{AMS}(t),\ t \geq 0\}$ is a version of the system-size process of an M/G/∞ queueing system with arrival rate γ and service time C. Thus, we have [4]

$$\lim_{t \to \infty} P(N_{AMS}(t) = m) = \frac{e^{-\gamma E(C)}[\gamma E(C)]^m}{m!}, \tag{2}$$

for $m = 0, 1, \cdots$. Define N_{AMS} as a random variable governed by the steady-state distribution in (2). Note that in the M/G/∞ queueing system [4],

$$\lim_{n\to\infty} P(H_{n+1} - H_n \le x) = 1 - e^{-\gamma x}$$

for $x > 0$. We approximate the sequence of cell departure times $\{H_n,\ n = 1, 2, \cdots\}$ to be a Poisson point process with parameter γ. Assume that mobile stations are uniformly distributed over the network service region. Let δ denote the average number of mobiles per unit area. Then, the average number of mobiles per cell is represented as $\delta \cdot \pi r^2$. From Equation (2), we have

$$\gamma = \frac{\delta \cdot \pi r^2}{E(C)} = \frac{\pi^2 \delta v r}{4}. \qquad (3)$$

When an active mobile station leaves a cell, some of the packets destined to the mobile may remain at the cell's base station. These backlogged packets are forwarded to a new base station. As a result, there are primary arrivals of packets as well as secondary arrivals of backlogged packets at a base station. Let λ denote the primary arrival rate at a base station. Assume that traffic flow from a base to mobile stations residing in the base station's cell is evenly distributed to these mobiles. Let $\hat{\lambda}$ denote the arrival rate of packets destined to an active mobile station. Then,

$$\lambda = \hat{\lambda} \cdot E(N_{AMS}). \qquad (4)$$

Assume that at a base station, packets are served in a FCFS discipline and the packet service time is equal to the packet transmission time, denoted by τ. Without loss of generality, we set $\tau = 1$. Let X_t denote the the number of packets waiting or in service at a base station at time t. Then, X_{H_n-} represents the number of packets at the base station right before the nth cell departure time. Let B_n denote the number of backlogged packets at the nth cell departure time. Since backelogged packets are immediately removed from the queue, we obtain

$$X_{H_n+} = X_{H_n-} - B_n$$

for $n = 1, 2, \cdots$. Let B denote a random variable such that

$$P(B = m) = \lim_{n\to\infty} P(B_n = m) \qquad (5)$$

for $m = 0, 1, \cdots$. Since the mobile entrance rate is equal to the mobile departure rate and the traffic flow is evenly distributed to mobiles, the secondary arrival rate at a base station is equal to $\gamma \cdot E(B)$, where γ is the mobile departure rate. Let λ^* denote the packet arrival rate at a base station. Then, we have

$$\lambda^* = \lambda + \gamma E(B). \qquad (6)$$

We assume that the sequence of packert arrival times at a base station is a Poisson point process with parameter λ^*.

3 Packet Delay Analysis

Under the packet forward scheme, every backlogged packet is forwarded to a new base station. Thus, a packet may be forwarded to a new base station many times until the packet is delivered to the destined mobile station. We define the delay time of a packet to be the time elapsed from the moment the packet primarily arrives at a base station to the moment it finally departs to the destined mobile station. When a packet arrives at a base station, the packet is either backlogged (and consequently, forwarded to a new base) or successfully transmitted to the destination. Suppose that a packet is forwarded N_{FW} times before it is delivered to the destined mobile station. Let U_k denote the time the packet stays at the kth base station it visits for $k = 1, \cdots, N_{FW}$. Then, U_k is the time elapsed from the instant the packet arrives at the kth base station to the instant it is backlogged there. Let V denote the time the packet spends at the last base station it visits. Note that the time V is equal to the sum of the packet's waiting time and service time at the last base. Let D denote the delay time of the packet. Then,

$$D = \sum_{k=1}^{N_{FW}} U_k + V. \qquad (7)$$

We assume that the times $U_1, U_2, \cdots$ are mutually independent and identically distributed. We also assume that the packet is backlogged independently at each base and the probabilities that the packet is backlogged at the bases are identical. Set ϵ to represent such probability, identified as backlog probability. Then, the number of packet forwards, denoted by N_{FW} has a geometric distribution with parameter ϵ, i.e.,

$$P(N_{FW} = m) = (1 - \epsilon)\epsilon^m \qquad (8)$$

for $m = 0, 1, \cdots$. To derive an approximate expression of the mean packet delay time, we consider the following processes.

Let $\{Q_k,\ k = 0, 1, \cdots\}$, $Q_0 = 0$ a.s. be a renewal point process such that

$$Q_{k+1} - Q_k \stackrel{d}{=} C$$

for all $k = 0, 1, \cdots$, where C is the cell sojourn time. Let K_t denote the forward recurrence time associated with the process $\{Q_k,\ k = 0, 1, \cdots\}$ at time t, i.e.,

$$K_t = Q_{k^*} - t,$$

where $k^* = \min\{k : Q_k > t\}$. Then, we have the following renewal equation [5]

$$\begin{aligned} P(K_t \le y) &= P(K_t \le y,\ Q_1 > t) \\ &\quad + \int_0^t P(K_{t-s} \le y)\, dP(Q_1 \le s). \quad (9) \end{aligned}$$

From Key renewal theorem [5], we have

$$\lim_{t\to\infty} P(K_t \le y) = \frac{1}{E(Q_1)} \int_0^y P(Q_1 > x)\, dx. \qquad (10)$$

Since the cell sojourn time C has an exponential distribution with parameter η, we calculate

$$\lim_{t\to\infty} P(K_t \le y) = 1 - e^{-\eta y} \tag{11}$$

for $y > 0$. Set K to be a random variable governed by the exponential distribution in (11). Let $\{\hat{D}_n,\ n = 1, 2, \cdots\}$ denote the sequence of delay times at an M/D/1 queueing system with arrival rate λ^* and service time 1. Let $\hat{D}$ denote a random variable governed by the steady-state distribution for the sequence $\{\hat{D}_n,\ n = 1, 2, \cdots\}$. Then, the Laplace-Stieltjes transform of the distribution function for $\hat{D}$ is calculated to be

$$G_{\hat{D}}(s) = \frac{(1-\lambda^*)se^{-s}}{\lambda^* e^{-s} - \lambda^* + s} \tag{12}$$

for $Re(s) \ge 0$. From Equation (12), the mean of $\hat{D}$ is also calculated to be

$$E(\hat{D}) = 1 + \frac{\lambda^*}{2(1-\lambda^*)}. \tag{13}$$

Suppose that the process $\{Q_k,\ k = 0, 1, \cdots\}$ is the sequence of cell departure times associated with an active mobile station. Suppose that a packet destined to the mobile arrives at a base station at time t. If the packet stays at the base more than K_t, then the packet must be backlogged. Otherwise, the packet must be delivered to the destination. Recall that the random variable $\hat{D}$ represent the delay time of an M/D/1 queueing system with arrival rate λ^* and service time 1 at steady-state. Assume that the sum of the packet's waiting time and service time at the base station has the same probabilistic properties as the random variable $\hat{D}$. Then, based on the above observation and assumption, we make the following approximations:

$$\begin{aligned} \epsilon &= P(\hat{D} > K) \\ V &\overset{d}{=} \hat{D} \cdot I_{\{\hat{D} \le K\}} \\ U_k &\overset{d}{=} K \cdot I_{\{K \le \hat{D}\}} \end{aligned} \tag{14}$$

for $k = 1, 2, \cdots$. From Equations (7) and (14), we obtain the mean packet delay time

$$\begin{aligned} E(D) &= \frac{\epsilon}{1-\epsilon} E(U_k) + E(V) \\ &= \frac{\epsilon}{1-\epsilon} E(\hat{D} I_{\{\hat{D} \le K\}}) + E(K I_{\{K \le \hat{D}\}}), \end{aligned} \tag{15}$$

where the backlog probability ϵ is calculated to be

$$\epsilon = P(\hat{D} > K) = E(e^{-\eta \hat{D}}) = G_{\hat{D}}(\eta).$$

(Note that $G_{\hat{D}}(s)$ is the Laplace-Stieltjes transform of the distribution function for $\hat{D}$ in (12).) The expected values in Equation (15) are also calculated as follows:

$$\begin{aligned} E(\hat{D} I_{\{\hat{D} \le K\}}) &= \frac{1}{\eta} - \frac{1}{\eta} G_{\hat{D}}(\eta) - E(\hat{D} e^{-\eta \hat{D}}) \\ E(K I_{\{K \le \hat{D}\}}) &= E(\hat{D} e^{-\eta \hat{D}}), \end{aligned} \tag{16}$$

where we may approximate

$$E(\hat{D} e^{-\eta \hat{D}}) \approx E(\hat{D}) e^{-\eta E(\hat{D})}.$$

Note that the function $xe^{-\eta x}$ is neither convex nor concave so that such approximate expression does not provide upper or lower bound.

4 Numerical Examples

In this section, we illustrate the effect of network parameters on the packet delay time, by using the analytical approximation method. The parameter values selected in the illustrations are summarized in Table 1.

In Figure 1, we demonstrate the effect of the traffic load per active mobile station on the mean packet delay time, where the data rate on the forward channel is fixed to be 10 Mbps and the packet length is assumed to be 500 bits. The cell radius, active mobile density and average mobile speed are set to be 10 m, 0.01 /m^2 and 5 km/hour, respectively. We observe that as the traffic load increases, the mean delay time increases. An increase in traffic load contributes to an increase in primary arrival rate. Futhermore, such increase invokes an increase in average number of backlogged packets at a mobile's cell departure time, which results in an increase in secondary arrival rate at a base station.

In Figure 2, we show the mean packet delay time with respect to the cell radius. In this figure, the data rate of 1 Mbps and the packet length of 500 bits are assumed. Also, the mobile density and mobile speed are set to be 0.01 /m^2 and 5 km/hour. The mean delay time is observed to increase as the cell radius increases. Since the traffic load per active mobile is fixed here, the primary arrival rate increases as the cell radius increases. On the other hand, the probability that a packet is backlogged decreases. In the environment given in Figure 2, however, the former is the dominant factor in the mean delay time. As a result, the mean packet delay time increases as the cell radius increases.

In Figure 3, the mean packet delay time is illustrated with respect to the average mobile speed. In this figure, the data rate and packet length are set to 10 Mbps and 10000 bits. The cell radius and mobile density are also fixed to 10 m and 0.01 /m^2, respectively. We observe that the mean packet delay time increases as the average speed increases. The average mobile speed has no effect on the average number of active mobiles in a cell and the primary arrival rate, since the traffic load per active mobile is fixed. On the other hand, the mobile's cell departure rate increases as the average speed increases. Consequently, an increase in secondary arrival rate is incurred by an increase in average mobile speed.

Finally, we observe that the mean values obtained by the approximation method are highly close to the corresponding simulation results in Figures 1, 2 and 3.

Table 1: Network Parameter Values in Section 4

parameter	
data rate on forward channel	1, 10 Mbps
packet length	500, 10000 bits
traffic load per active mobile	0-300 kbps
cell radius	10-100 m
active mobile density	0.01, 0.1, 1 /m^2
average mobile speed	5-100 km/hour

5 Conclusions

In this paper, we considered packet-switched wireless cellular networks. For applications which are sensitive to packet loss but are relatively tolerable to packet delay, we investigated a packet forward scheme in which all packets backlogged at a mobile's cell departure time are forwarded to a new base station. To evaluate the packet delay time under the packet forward scheme, we developed an analytical approximation method for calculating the mean packet delay time. Using the analytical approximation method, we investigated the effect of network parameters on the mean packet delay time. Our observations are as follows:

1. An increase in traffic load for active mobile station induces not only an increase in primary arrival rate but also an increase in secondary arrival rate incurred by forwarding backlogged packets. Thus, the effect of the packet forward scheme on the packet delay time is more significant under higher traffic load.
2. As the cell size increases, the average number of mobiles residing in a cell and the mobile's cell departure rate increase. When the traffic load per active mobile is fixed, as the cell size increases, both of the primary and secondary arrival rates increase, while the probability for a packet to be backlogged decreases. In a practical range of network parameters, the former is dominant. Hence the mean packet delay time increases as the cell size increases.
3. The average mobile speed does not affect the average number of active mobiles in a cell. However, as the speed increases, the mobile's cell departure rate increases. As a result, the average forwarding number for a packet increases. Thus, the mean packet delay time increases as the average mobile speed increases.

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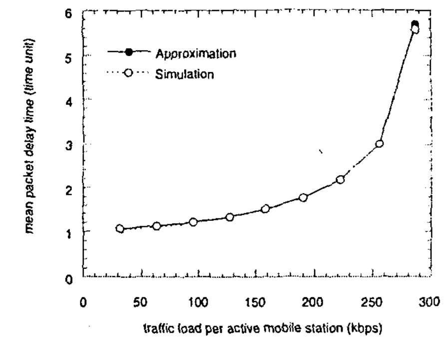

Figure 1: Mean packet delay time with respect to traffic load per active mobile station

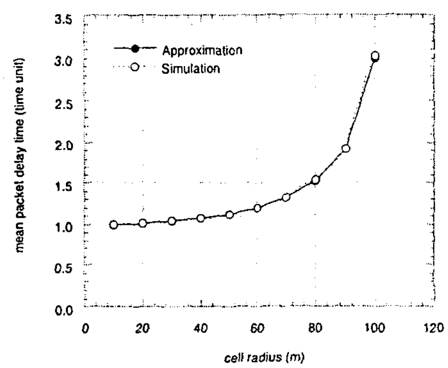

Figure 2: Mean packet delay time with respect to cell radius

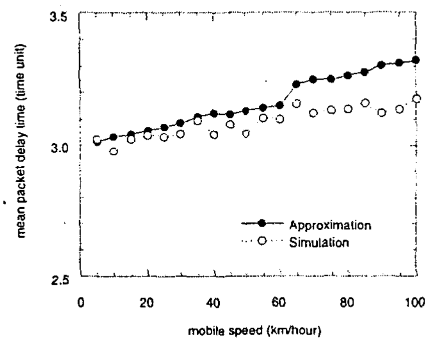

Figure 3: Mean packet delay time with respect to average mobile speed