ABSTRACT

The authors consider connection-oriented wireless cellular networks such as IS-54, IS-95, GSM, and wireless ATM networks. These are connection-oriented digital networks which employ separate radio channels for the transmission of signaling information. A forward signaling channel is a common signaling channel assigned to carry the multiplexed stream of paging and channel-allocation packets from a base station to mobile stations. For wireless ATM networks, paging and virtual-circuit (VC) allocation packets are multiplexed across the forward signaling channels as part of the VC setup phase. A reverse signaling channel, which employs a contention-oriented medium access algorithm, is used by mobile stations to send channel-request and location-update packets. A location area is a region which includes a specified set of adjacent cells; it is used to track the location of mobile stations. Mobile units must re-register as they cross the boundary of a location area. The channel setup and paging response times are critical performance factors in the design of the signaling subsystem. A location area structure must be selected to ensure that acceptable levels of such performance functions are achieved. A network which employs small location-areas will experience a high rate of location updates, while larger location areas lead to higher traffic intensities of paging messages. In this article, combining the operation of forward and reverse signaling channels, the authors overview a method for calculating the performance behavior of signaling messages. Subsequently the impact of the location area structure on the performance of the signaling system is investigated.

Impact of the Location Area Structure on the Performance of Signaling Channels in Wireless Cellular Networks

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In this article we consider connection-oriented wireless cellular networks such as EIA/TIA (Electronics and Telecommunications Industry Associations) Interim Standard 54 (IS-54), EIA/TIA IS-95, European Global System for Mobile Communications (GSM), and wireless asynchronous transfer mode (ATM) networks [1-5]. These are connection-oriented digital networks which employ separate radio channels for the transmission of signaling information. A forward signaling channel (FSC) is a common signaling channel assigned to carry the multiplexed stream of paging (PG) and channel allocation (CA) packets from a base station (BS) to mobile stations (MSs). For wireless ATM networks, PG and virtual circuit (VC) allocation packets are multiplexed across the FSCs as part of the VC setup phase. PG packets are broadcast by the BS across the FSC to alert an MS to an incoming call. Upon receipt of a response from the destined mobile or a channel request (CR) from a call-initiating mobile, the BS selects a channel (identified as a traffic channel for a circuit-switched system and as a VC for an ATM network) to be allocated to the connection (when admitted), and transmits a CA packet across the FSC. On the other hand, a reverse signaling channel (RSC), which employs a contention-oriented medium access algorithm such as a slotted ALOHA protocol, is used by MSs to send CR and location update (LU) packets. An MS generates a CR packet in response to a page it receives, or when it wishes to initiate a new call connection. A LU packet is generated when the MS crosses the boundary of a location area (LA). This is done to alert the involved mobile switching centers to its change of location. In this manner, the location of the mobile (in reference to the LA in which it resides) is continually updated. The signaling flows across FSC and RSC are illustrated in Fig. 1.

Geographically, the region covered by a wireless cellular network is divided into LAs, and an LA consists of one or more adjacent cells (Fig. 2). An LA is the basic unit for mobility management. An MS must update its location information whenever it crosses the boundary of an LA. As the size of the LA increases, the uncertainty of the location of an MS rises. A PG packet destined for a mobile which is located in a specific LA is broadcast by all the BSs that belong to this LA (Fig. 3). As a result, the selection of a larger LA leads to an increase in the traffic intensity of broadcasted PG messages. In turn, the traffic intensity of LU messages is decreased.

In selecting the geographical span of the LA, it is necessary to incorporate the following factors:

- The channel setup time must be properly limited. To achieve acceptable quality-of-service levels, a traffic channel must be allocated in a timely fashion to accommodate newly initiated calls and re-registration requests.
- For calls destined to an MS, the BS broadcasts PG packets to alert the destined mobile. The destined MS then transmits across the RSC a CR packet. The latter also serves to acknowledge the transmission of the PG packet. The PG response time, which identifies the time elapsed from the moment a PG packet arrives at the BS to the moment a CR packet is successfully delivered to the BS, is a critical performance factor. To avoid excessive timeout rates by the call initiating party, and to yield acceptable circuit setup times, it is necessary to limit the PG response time.
- For calls initiated by a mobile, a CR is transmitted across the RSC to the cell's BS. Once a CR is received by the BS, a traffic channel is selected and a CA packet is sent.
in a high signaling load on the FSC(s). Thus, an LA structure must be suitably configured so that the relative loading of the associated FSC and RSC is balanced out.

In this article, we study the design of the LA system by investigating the impact of the LA structure on the channel setup and PG response times. In the following section, we describe typical medium access protocols used for controlling the access of signaling packets to FSC and RSC. Next, we introduce a mobility model, which is used for the calculation of the LU rate. We then present the basic call- and mobility-related parameters. Using these parameters, we derive formulas for the calculation of PG and CR rates. After that, under the candidate multiplexing schemes (including scheduling policies which assign priority to either PG or CA packets), we present an analytical method for calculating the delay distributions of PG, CA, and LU packets. We next present an analytical method for the calculation of the distribution functions for the channel setup and PG response times. The section after that is devoted to numerical examples and performance comparisons, demonstrating the underlying trade-offs involved in the selection of the LA structure. Our analyses demonstrate the following results:

- The system's PG and LU rates highly affect the performance of the signaling system. A network which employs small LAs will experience a high rate of LUs, while large LAs lead to higher traffic intensities of PG messages. Hence, by properly selecting the size of the LA, a distinct performance behavior is achieved.

- The specific scheme used to multiplex PG and CA packets across the FSC(s) is also an important factor that must be considered in the selection of an LA structure. A multiplexing scheme that grants high access priority to PG packets is effective in reducing the PG packet delay incurred at the BS. On the other hand, this scheme can degrade the delay performance of the CA packets at the BS, which in turn results in a significant increase in the access time across the RSC. The latter is caused by the longer acknowledgment timeout periods and the resulting increase in the number of CR and LU packet retransmissions, induced by the increase in the CA packet delay at the BS. A multiplexing scheme that grants high access priority to CA packets reduces the CA packet delay incurred at the BS; however, when large LAs are considered, significant increases in PG packet delays can result.

- The performance behavior of the signaling system is affected by the bandwidth levels allocated to the FSC and RSC. For a selected LA structure, the data rates allocated to the FSC and RSC should be chosen so that neither exhibits a dominating congested (bottleneck) behavior.
DESCRIPTION OF THE MEDIUM ACCESS SCHEMES

The FSCs are used for the transport of PG and CA packets from the BS to the MSs. PG and CA packets are multiplexed and transmitted across these FSCs. Across these channels, we assume time to be divided into slots. To simplify the presentation, we assume that PG and CA packets have the same fixed length and that it takes a single time slot to transmit a packet. (A packet transmission starts at the beginning of a slot.) It is possible to multiplex PG packets and CA packets across the FSC in accordance with many different schemes [3]. In this article, we consider three multiplexing schemes denoted scheme PG, scheme CA, and scheme FCFS (first come first served). These multiplexing schemes are characterized by distinctive access priority assignments. Under scheme PG, high access priority is given to PG packets. A non-preemptive service discipline is used so that the transmission of a CA packet is not interrupted at the arrival of a PG packet. Under scheme CA, CA packets are granted high access priority. Under scheme FCFS, PG and CA packets are served according to the FCFS service discipline, so no access priority is given to any packet, and packets are served in order of arrival (Table 1).

An MS that wishes to set up a connection or update its location information generates a CR or an LU packet across the RSC, in accordance with a slotted ALOHA scheme. For such a channel, a time-slotted channel configuration is established. We assume that it takes a single time slot to transmit a CR (LU) packet. Our model for the slotted ALOHA scheme involves the following features:

- Whenever an MS generates a CR (LU) packet, the MS waits for a random time period before transmitting the CR (LU) packet.
- A CR (LU) packet transmission starts at the beginning of a slot.
- If an MS does not receive an explicit reply from the BS within an acknowledgment timeout period after sending a CR (LU) packet, the transmission of the CR is assumed to have failed. The MS then attempts to retransmit the CR (LU) packet at a randomly selected later time slot.
- The number of times an MS is permitted to retransmit a CR (LU) packet is limited to a prescribed level.

THE LOCATION AREA STRUCTURE AND A MOBILITY MODEL

The region covered by a wireless cellular network is divided into LAs. Each LA consists of multiple adjacent cells. We assume that a cell is geometrically represented as a disk of radius $r$ and that cells are identical in size. A BS is assumed to be located at the center of each cell. Given the number of cells per LA, the structure of an LA is designed so that its perimeter is minimized. In this fashion, given the number of cells per LA, the frequency of location updates by MSs is minimized. In this article, we use the following mobility model [6, 7].

Suppose an MS enters a cell at time 0. We set the initial location of the MS (at time 0) to be a uniformly distributed random vector on the cell's boundary. Let $V$ denote the speed of the MS at time 0. We set $V$ to be uniformly distributed in $[v_{\text{min}}, v_{\text{max}}]$. The moving direction of the MS is identified by the angle $\theta$ which is measured (in a counterclockwise sense) with respect to the line leading to the center of the cell from the initial location of the MS. The angle $\theta$ is set to be a uniformly distributed random variable in $[-\pi/2, \pi/2]$. We assume that the moving speed and direction of the MS are determined at time 0, and do not change until the MS departs the cell [6]. Let $S$ denote the sojourn time of the MS in the cell. (The cell sojourn time is defined as the time elapsed from the instant the MS enters the cell to the instant the MS departs the cell.) From trigonometric calculations, we obtain the distribution function for the cell sojourn time $S$. From the distribution function for $S$, we calculate the mean of the cell sojourn time to be

$$E(S) = \frac{4r}{\pi} \log \left( \frac{v_{\text{max}}}{v_{\text{min}}} \right).$$

We model the sequence of cell entrance times of MSs as a Poisson point process with parameter $\gamma$ (i.e., intercell entrance times are assumed to be statistically independent and identically distributed random variables governed by an exponential distribution with mean $1/\gamma$). Then the number of MSs residing in a cell has the same statistics as the statistics of the system size of an $M/G/\infty$ queuing system with arrival rate $\gamma$ and service time $S$. From $M/G/\infty$ queuing system analysis [5], we conclude that, in steady state, the number of MSs per cell is governed by a Poisson distribution with mean $n_{MS} = \gamma \cdot E(S)$.

SIGNALLING TRAFFIC RATES FOR PAGING, CHANNEL REQUEST, AND LOCATION UPDATE Messaging

As stated in the first section, an MS generates a CR packet when the MS is paged or initiates a call, and an LU packet when the MS crosses the boundary of an LA. A PG packet is broadcasted by all BSs residing in an LA across their FSCs. We introduce the following basic parameters:

- $\lambda_{\text{AMTC}}$: mobile terminating call rate (calls/MS/unit-time)
- $\lambda_{\text{AMOC}}$: mobile originating call rate (calls/MS/unit-time)
- $\lambda_{\text{CBC}}$: cell boundary crossing rate (crossings/MS/unit-time)

The cell boundary crossing rate is defined as the average number of cell boundary crossings per MS in a time unit. Using the mobility model presented in the third section, where we have defined the average number of MS's entering a cell per unit-time as $\gamma$, we have

$$\lambda_{\text{CBC}} = \frac{\gamma}{n_{MS}} E(S),$$

where the mean cell sojourn time $E(S)$ is given by Eq. (1).

The PG rate represents the average number of PG packets which arrive at a BS during a time unit. Let $\lambda_{\text{PG}}$ denote the PG rate at a cell. Then we have

$$\lambda_{\text{PG}} = \lambda_{\text{AMTC}} \cdot n_{MS} \cdot n_{C},$$

where $n_{MS}$ is the average number of MSs per cell and $n_{C}$ is the number of cells per LA. When an MS crosses the boundary of an LA, the MS must report its location information to the BS (which then forwards the registration data to the new LA's mobile switching center). For this purpose, the MS requests a traffic channel (or a VC) by sending an LU packet to its BS across the RSC. We define the LU rate as the average number of LU packets received by a BS per time unit. Let

Table 1. Multiplexing schemes.

<table>
<thead>
<tr>
<th>Multiplexing schemes</th>
<th>Access priority</th>
<th>Service discipline</th>
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<tr>
<td>Scheme PG</td>
<td>Paging</td>
<td>Non-preemptive</td>
</tr>
<tr>
<td>Scheme CA</td>
<td>Channel allocation</td>
<td>Non-preemptive</td>
</tr>
<tr>
<td>Scheme FCFS</td>
<td>None</td>
<td>FCFS</td>
</tr>
</tbody>
</table>
\( \lambda_{LU}^k \) denote the location update rate received by a BS resident at the \( k \)th cell of an LA. Then the LU rate is expressed as [4]

\[ \lambda_{LU}^k = c_k \cdot \lambda_{BC} \cdot \lambda_{MS}. \]  

where the coefficient \( c_k \) represents the fraction of the length of the boundary of the \( k \)th cell, which is also part of the boundary of the LA, relative to the perimeter of the cell. The coefficient \( c_k \) is determined by the number of cells per LA and the position of the \( k \)th cell in the LA. Note that an MS engaged in an active call while crossing an LA boundary can utilize its allocated traffic channel for the transmission of its LU message. Hence, such an MS may not generate LU signaling messages across an RSC. Since at any time only a small fraction of the mobiles are engaged in a call, the ensuing reduction in signaling flows is hereby neglected. One can, however, readily incorporate this traffic rate modification into the analysis. When a call active MS crosses a cell boundary, its connection (circuit or VC) is handed over from the old BS to the new BS. The resulting handover signaling traffic, flowing from and to an in-call handheld-over MS, is assumed to be carried along the allocated forward and reverse traffic channels, or across other assigned channels which are not part of the above-mentioned FSC and RSC. The CR rate is equal to the average number of CA packets transmitted in a cell per time unit, excluding the CA packets produced by transmissions. Let \( \lambda_{CR} \) denote the CR rate at a cell. Then we have

\[ \lambda_{CR} = (\lambda_{MTC} + \lambda_{MOC}) \cdot \lambda_{MS}. \]  

We observe that as the number of cells per LA increases, the average PG rate in an LA increases, while the average LU rate in an LA decreases.

**DELAY ANALYSIS FOR THE FORWARD SIGNALING CHANNEL**

The region covered by a wireless cellular network is partitioned into cells, and a BS is located in each cell. Across each FSC, the BS in a cell delivers a multiplexed stream of PG and CA packets to MSs residing in the cell. A PG packet is assumed to have the same length as a CA packet. We assume that time is divided into slots and that a slot duration is equal to the packet transmission time. We set the slot duration time to be \( \tau_{FSC} \). We consider the three multiplexing schemes, PG, CA, and FCFS, described in the second section. Suppose that \( c \) FSCs are supported at the BS. We assume that PG and CA packets are uniformly distributed to these \( c \) FSCs at the BS. At the BS, for each FSC, the arrival streams of CA packets and PG packets are modeled as independent geometric point processes. Let \( r_{PG} \) and \( r_{CA} \) denote the arrival rate of PG and CA packets for an FSC, respectively. The packet arrival rate is measured as the average number of packet arrivals per time slot, so a PG (CA) packet arrival occurs in a slot with probability \( r_{PG} \) (\( r_{CA} \)), and no packet arrival occurs with probability \( 1 - r_{PG} \) (\( 1 - r_{CA} \)). Note that the arrival stream of the PG (CA) packets at the BS is equally divided into \( c \) substreams, and each substream is directed to an FSC. For the calculation of the PG and CA packet delay distributions under schemes PG and CA, we use a completion time analysis method [7]. The completion time of a packet is defined as the sojourn time of the packet at the top of its queue; that is, it represents the time elapsed from the instant a packet is placed at the head of the queue to the instant it is transmitted across the channel. Under scheme PG, the variable representing the number of CA packets waiting or in service at the BS can be modeled as the system size of a Geom/Geom/1 queueing system in which the arrival rate is \( r_{CA} \) and the service time is the CA packet’s completion time. The latter is noted to be governed by a geometric distribution. Let \( D_{PG} \) and \( D_{CA} \) denote the delay times of PG and CA packets in steady state. Then

\[ D_{PG} = \tau_{FSC} \text{ a.s.}, \]

\[ D_{CA} = \tau_{FSC} \text{ a.s.}, \]

for \( n \geq 1 \). Note that the random variable \( D_{CA} \) exists if \( r_{CA} < 1 \). Under scheme CA, CA packets are granted high access priority. Interchanging the roles of PG and CA packets under scheme PG, we obtain

\[ P(D_{PG} = n \cdot \tau_{FSC}) = \left[ \frac{1 - r_{CA}}{1 - r_{PG} - r_{CA}} \right] \left[ \frac{r_{PG} + r_{CA}}{1 - r_{PG}} \right]^{n-1}, \]

for \( n \geq 1 \). Note that the random variable \( D_{PG} \) exists if \( r_{PG} + r_{CA} < 1 \). Under scheme FCFS, access priority is given to neither PG nor CA packets. These packets are served under an FCFS service discipline. Using a Markov chain-based analysis method, we derive the steady state delay time distribution [9]. Note that PG and CA packets can arrive simultaneously at the BS, and may be directed to the same FSC. In this case, we assume random service ordering for these packets (i.e., a packet is served first with probability 0.5). Then we have

\[ P(D_{PG} = n \cdot \tau_{FSC}) = \left[ \frac{1 - r_{CA}}{2} \right] (1 - r_{PG})^{n-1} I_{[n \geq 1]} + \frac{r_{PG}}{2} - (1 - r_{PG})^{n-2} I_{[n \geq 2]}, \]

where

\[ r = \frac{r_{PG} \cdot r_{CA}}{(1 - r_{PG})(1 - r_{CA})}. \]

**PERFORMANCE ANALYSIS FOR THE REVERSE SIGNALING CHANNEL**

CR and LU packets generated by an MS are transmitted across the RSC. The latter employs a slotted ALOHA multiple access scheme. The delay-throughput performance of slotted ALOHA systems was studied extensively (e.g., [3, 10]). In this section, we present an expression for the delay-throughput performance of the RSC. The results of this section will be used for the analysis of the channel setup time and PG response time presented in the next section.

We define \( \lambda_{RSC} \) to denote the rate of CR and LU packets transmitted across a cell’s RSC (including CR and LU rates incurred due to retransmissions). A packet’s transmission across the RSC may fail due to the occurrence of a collision or an acknowledgment timeout. A packet collides with others when more than one MS simultaneously transmits packets. An acknowledgment timeout takes place when the MS does not receive an explicit reply from the BS within the acknowledgment timeout period. Let \( p_{COL} \) denote the collision probability for a packet transmitted across the RSC, and \( p_{TO} \) denotes the timeout probability for a noncolliding packet. Let \( t_{TO} \) and \( t_{PRO} \) denote the length of the acknowledgment timeout period and the propagation delay across the FSC or RSC (we assume

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CHANNEL SETUP TIME AND 
PAGING RESPONSE TIME ANALYSIS

To request a traffic channel assignment, an MS generates a CR or LU packet and transmits it across the RSC. The BS acknowledges the request (if it is successful) by sending a CA packet to the MS. (We assume here that the BS has a sufficient number of traffic channels. This provides a conservative estimate on the signaling traffic intensity.) The channel setup time, denoted by $T_{CS}$, is defined to be the time elapsed from the moment an MS generates a CR or LU packet to the moment the MS receives the corresponding CA packet from the BS (Fig. 4). It serves as a measure of delay performance in the establishment of connections for mobile originating calls and for location update transactions. Note that the channel setup time is defined only for non-blocked CRs and LUs.

Let $U$ denote the length of the random time period an MS should wait before transmitting a CR or LU packet. We set $U$ to have a discrete uniform distribution in $\{U_{\text{min}} \leq U \leq U_{\text{max}}\}$. Then, we have the following expression for the channel setup time $T_{CS}$:

$$T_{CS} = \sum_{n=1}^{N_R} [U_n + \tau_{RSC} + t_{TO}] + U + \tau_{RSC} + t_{PRO} + D_{CA} + t_{PRO}. \quad (15)$$

where $N_R$ represents the number of packet retransmissions incurred in the admission of a primary CR or LU, $\{U_n, n \geq 1\}$ represents a sequence of i.i.d. random variables governed by distribution for $U$, and the random variable $D_{CA}$ is the delay time of a CA packet which is delivered to the MS within the acknowledgment timeout period. The random variable $N_R$ has a normalized truncated geometric distribution:

$$P(N_R = n) = \frac{(1-p_F)(p_F)^n}{1-(p_F)^{N_R}}, \quad 0 \leq n \leq N_R. \quad (16)$$

for $0 \leq n \leq N_R$. The distribution for $D_{CA}$ under each multiplexing scheme is given in [7, 9]. Let $T_{CS}^k$ denote the overall channel setup time in an LA. Then we set

$$P(T_{CS} \leq x) = \sum_{N_R = 1}^{N_R} P(N_R = n) \sum_{k=1}^{N_C} P(T_{CS}^k \leq x), \quad (17)$$

where $T_{CS}^k$ represents the channel setup time at the $k$th cell of an LA. For calls destined to a mobile, the BS broadcasts $P_G$.
packets in the LA, and the destined MS subsequently sends across a RSC a CR packet as a positive acknowledgment. The PG response time, denoted by $T_{PR}$, is defined to be the time elapsed from the instant a PG packet arrives at the BS to the instant a CR packet is successfully (i.e., experiencing no collisions across the RSC as well as requiring the corresponding CA packet to arrive at the destined MS within the prescribed acknowledgment timeout period) delivered to the BS (Fig. 5). This PG response time serves as a measure of delay performance for the establishment of connections for mobile terminating calls, accounting for the time elapsed until the BS can notify the call originator about its success in contacting the destined MS.

Using the random variable $N_{k}$, whose distribution is given by Eq. (16), we have

$$T_{PR} = [DPG + TPRO] + \sum_{i=1}^{N_{k}} [U + RSC + T_{TO}] + [U + RSC + FPRO].$$

where $DPG$ is the PG packet delay time at the BS and its distribution function is given by Eqs. (6) and (7). Let $T_{PR}$ denote the overall PG response time in an LA. Then we write

$$P(T_{PR} \leq x) = \frac{1}{N_{k}} \sum_{i=1}^{N_{k}} P(T_{PR}^{k} \leq x),$$

where $T_{PR}^{k}$ represents the PG response time at the $k$th cell of an LA.

**Numerical Examples**

In the seventh section, we have presented analytical techniques for deriving statistical properties of the overall channel setup time ($T_{CS}$) and PG response time ($T_{PR}$). These random variables depend on network parameters such as mobile terminating call rate ($\lambda_{MTT}$), mobile originating call rate ($\lambda_{MOC}$), and cell boundary crossing rate ($\lambda_{BCR}$). In this section, we present examples illustrating the behavior of the mean and standard deviation functions of these times with respect to the number of contained in an LA. (We consider a fixed value for the cell radius.) We use

$$E(T_{CS}) + 3 \cdot \sqrt{Var(T_{CS})} \quad \text{and} \quad E(T_{PR}) + 3 \cdot \sqrt{Var(T_{PR})}$$

as indicators of the probabilistic peak levels of the channel setup time and PG response time, respectively.

For the examples presented in this section, we adopt the following criterion for the length of the acknowledgment timeout period ($T_{TO}$) and for the threshold for the number of retransmissions ($n_{R}$). We set $T_{TO}$ to be the minimum value which guarantees that in any cell of an LA, the timeout probability ($P_{TO}$) does not exceed 1 percent. We also set $n_{R}$ to be equal to the minimum value, which guarantees that, in any cell of an LA, the blocking probability does not exceed 1 percent.

In Figs. 6 and 7, using the parameter values shown in Table 2, we demonstrate the behavior of the peak levels of the channel setup and PG response times, with respect to the number of cells included in an LA.

In Fig. 6, we observe that under scheme PG, in which high-access priority to the FSC is given to PG packets, for small LA regions, the peak levels of the channel setup time increase as the LA size decreases. In this domain, the higher LU levels dominate system behavior. For large LA regions, this peak level increases as the LA size increases. In the latter case, the PG rate becomes the dominant factor. Under scheme FCFS, the peak levels of the channel setup time show a similar trend. However, under scheme CA, in which CA packets are granted higher access priority, this peak performance level decreases as the LA size increases. This is explained by noting that
under scheme CA, the CA packet delay at the BS is not affected by the increase in the PG rate, since CA packets are granted higher priority in accessing the FSC. For the network setup under consideration, scheme CA exhibits the best performance among the three multiplexing schemes evaluated here.

In Fig. 7, we demonstrate the behavior of the PG response time as the LA size is increased. For small LA regions, the LU rate is the dominant factor, so the PG response time decreases as the LA size increases for all FSC multiplexing schemes. However, in this range, the increased PG packet intensity does not affect the access delay of CA packets under scheme CA, and consequently does not lead to access delay degradations across the RSC. As a result, the PG response time function under scheme CA monotonically decreases as the LA size increases. Induced by the same considerations, we note in Fig. 8 that the length of the acknowledgment timeout period as the LA size increases is not affected under scheme CA, while it increases under scheme PG.

We consider next another wireless network configuration whose parameters are given by Table 3. These parameter values are extracted from [3, 11]. Under the Table 3 setup, the network is characterized by a larger cell radius, higher MS speed levels and a lower call traffic intensity. We vary the length of the slot duration time across the RSC in comparison with the slot duration time across the FSC. This may correspond to having RSC and FSC packets of different length or to configurations which operate these signaling channels at different data rates.

In Fig. 9, we compare the peak levels of the PG response time under schemes PG and CA, when the slot duration time across the FSC is fixed, and the ratio of the FSC and RSC slot duration times is varied (being set equal to 1 and 8). This figure shows that as the RSC slot duration time decreases, the peak level of the PG response time decreases under scheme PG as well as under scheme CA. Such a reduction in the peak level of the PG response time is more pronounced under scheme PG. When the ratio of the FSC and RSC slot duration times is set equal to 8, in contrast with the result obtained under the previous example (Fig. 7), the peak level of the PG response time realized under scheme PG is now lower than the peak level exhibited by scheme CA. This is explained by noting that the shorter RSC slot times have led to a significant reduction in RSC access delays. The latter leads to a large decrease in the PG response time.

In Figs. 10 and 11 we show the variation of the peak levels of the channel setup time under scheme PG and of the PG response time under scheme CA, with respect to the ratio of slot duration times across the FSC and the RSC. The parameter set in Table 3 is used in these figures. Two values for the number of FSCs are considered (1 and 5). The LA size is set at a fixed level. In Fig. 10, the LA size is set equal to 91 cells. We observe that the increase in RSC bandwidth leads to reduced channel setup time values. An increase in the number of FSCs can be used to effectively reduce this peak level when the allocated RSC data rate level is low. The higher number of FSCs contributes to a decrease in the CA packet delay level at the BS. However, the impact of such a contribution is negligible when the RSC is allocated a sufficiently high bandwidth level.

In Fig. 11, we observe that the allocation of a larger number of FSCs yields a noticeable impact on the PG response time performance when high RSC data rates are assigned. For this illustrative network, since large LA regions are configured, the PG packet delay at the BS is a dominant delay performance factor. Hence, the PG response time level can effectively be reduced by properly increasing the number of FSCs utilized.

<table>
<thead>
<tr>
<th>Table 3. Parameter values for Figs. 9 and 11.</th>
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<td>Mobile terminating call rate</td>
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<td>Mobile originating call rate</td>
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<tr>
<td>Cell radius</td>
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<tr>
<td>Average number of MSs per call</td>
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<td>Average speed of MS</td>
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<td>Maximum speed of MS</td>
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<tr>
<td>Minimum speed of MS</td>
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<tr>
<td>Slot duration time (FSC)</td>
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<tr>
<td>Slot duration time (RSC)</td>
</tr>
<tr>
<td>Number of forward signaling channels</td>
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<tr>
<td>Length of random time period</td>
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<td>Propagation delay</td>
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CONCLUSIONS

In this article, focusing on the delay-throughput behavior of the FSC and RSC used by connection-oriented digital wireless cellular networks, we have investigated the impact of the LA structure on key connection setup delay measures. The latter consists of the channel setup time and PG response time. In order to calculate the distributions of these performance functions, we employ the following modeling elements:

- The LA size affects the PG and LU rates. We employ a mobility model to analytically calculate the ensuing LU rates.
- We evaluate the throughput of the RSC as a function of the PG and CR rates under prescribed limits on the maximum number of retransmissions and the maximum time an MS is ready to wait for a response.
- For the FSC, we consider several multiplexing schemes for the transmission of PG and CA packets. Two key access priority assignments are used for accessing an FSC. We present an analytical method for calculating the distribution functions of queuing delays incurred by these packets at the BS.

We present examples which illustrate the performance analysis method outlined here and discuss the underlying considerations to be used for the optimal selection of the LA structure. These examples demonstrate the following points:

- The optimal LA structure which minimizes the average (or peak) level of the channel setup time (or PG response time) under the scheme in which high priority is given to PG packets is different from that obtained under the scheme that grants high priority to CA packets. Also, under any multiplexing scheme, the LA structure which minimizes the peak level of the channel setup time is not necessarily the same as that which minimizes the peak level of the PG response time.
- The multiplexing scheme which grants high access priority to CA packets is superior to that which allocates high priority to PG packets when the average and peak levels of the channel setup time are considered as key performance measures. On the other hand, when assessing the average and peak levels of the PG response time, no particular multiplexing scheme exhibits uniformly superior performance. When a sufficient bandwidth level is allocated to the RSC, the scheme in which high priority is given to PG packets exhibits better performance. Otherwise, scheme CA provides better delay performance behavior.
- An optimal selection of the LA structure can be made so that efficient utilization levels of the FSC and RSC are achieved. Also, for a given LA configuration, the FSC and RSC capacities and access protocol parameters can be chosen to yield desired channel setup and PG response time behavior.

REFERENCES


BIographies

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