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Analysis of Random Access Protocol and Channel Allocation Schemes for Service Differentiation in Cellular Networks

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ABSTRACT

In this work, the effect of the channel allocation scheme on the priority based Slotted ALOHA (S-ALOHA) random access protocol when blocked packets return to the network is presented. Service differentiation is considered for high and low priority users. Priority based S-ALOHA is implemented using a Geometric Backoff (GB) scheme by means of two retransmission probabilities. Two channel allocation schemes that implement priority queues for service differentiation in a TDMA based cellular network are considered: Bitmap Channel Allocation (BCA) and Uplink State Flag Channel Allocation (USFCA). In order to improve the system performance, new packet transmissions for low priority packets are differed (DFT) effectively increasing the throughput on the random access channel and reducing the average waiting time and access delay.

Keywords: Priority based Slotted ALOHA, Geometric Backoff (GB), Bitmap Channel Allocation (BCA), Uplink State Flag ChannelAllocation (USFCA).

1. INTRODUCTION

TDMA based cellular networks currently represent an important market share in mobile communications. Systems such as General Packet Radio Services (GPRS) and EGPRS (Enhanced GPRS) are still being used as the 2G and 3G networks respectively. Both GPRS and EGPRS are packet-switched systems that upgrades and uses the GSM infrastructure to offer data services in an efficient manner (Brasche and Walke, 1997). For simplicity, this work is focused on the GPRS system, but the mathematical analysis can easily be applied to EGPRS systems as well. GPRS offers data rates in the range of 14.4 kbps (single slot) and 115.2 kbps (multi-slot) depending on user terminal capabilities and system interference (Brasche and Walke, 1997). In such wireless networks, there is an increasing demand for multimedia traffic with different levels of Quality of Service (QoS). In particular, this paper focuses on two types of services: a) delay-sensitive services, which should be given higher priority, and b) non delay-services, which should be given a lower priority.

In the uplink, the GPRS MAC sublayer is based on the slotted ALOHA (S-ALOHA) random access packet reservation protocol (Brasche and Walke, 1997). It is important to mention that EGPRS also uses S-ALOHA like protocols for the uplink transmissions. In S-ALOHA, users that arrive to the system trying to reserve a data channel simply wait for the beginning of the next time slot and transmit their packet. If more than one user attempts to transmit a packet, then a collision will occur and the packets involved in the collision enter the backoff procedure in order to attempt a retransmission in a random time. If only one packet transmission attempt occurs in a time slot then it is received without any errors and the base station replies to the mobile with a positive acknowledge (ACK). Once the user has been successfully registered the packet is processed according to the channel allocation scheme. The rest of the paper is organized as follows: In Section II the analysis of the priority based S-ALOHA is presented, the channel allocation strategies are described in Section III and in Section IV numerical results are presented. Finally, some conclusions are obtained.

2. PRIORITY-BASED S-ALOHA

A partial DFT (Differed First Transmission) system is used, where new high priority packets are transmitted at the beginning of the next time slot while new low priority packets enter the backlog procedure with probability 1-τ_b and transmit at the beginning of the next time slot with probability τ_b. The new packet arrivals (packets that have not suffered any collision) follow a Poisson process with normalized rate of G_N packets per time slot. Packets that have suffered at least one collision are retransmitted according to a Geometric Backoff (GB) policy. High priority packets retransmit with probability τ_a until they are successfully received by the base station, while low priority packets retransmit with probability τ_b. It is assumed that there could be as much as M_a simultaneously backlogged high priority packets and as much as M_b simultaneously backlogged low priority packets in the system ($M_a = M_b = 250$) as it is done in (Rivero-Angeles et al., 2007).

After a successful packet registration, if there are neither available traffic channels nor any space at the buffers, the packet is blocked and has to enter the registration phase again. Blocked packets are considered as new packets at the registration phase. The total new packet arrival rate at the registration phase can be calculated as:

$$G_T = G_N + S/_{1-P_B} \qquad (1)$$

where S is the throughput of the S-ALOHA protocol, P_B is the blocking probability of the resource allocation scheme, $G_T = G_a + G_b$, G_a is the total high priority new packet arrival rate and G_b is the total low priority new packet arrival rate. The condition of the GPRS system considered is that when the prioritization scheme has a higher impact, that is, when most of the packets in the network are low priority packets, specifically $G_a = 0.1G_T$ ($G_b = 0.9G_T$), because under this condition few high priority packets have to contend with a high number of low priority packets and the system has to guarantee a lower access delay for these few packets over the rest of the packets in the network.

The system can be modeled as a two dimensional Markov chain with states (i,j) where i is the number of high priority backlogged packets and j is the number of low priority backlogged packets in the system in the k^{th} slot and π_{ij} is the steady state probability of having i high priority backlogged packets and j low priority backlogged packets in a time slot. The transition probabilities from state (i,j) to state (k,l), $p_{ij,kl}$, are calculated in (2) considering that $0 \le i \le M_a$ and $0 \le j \le M_b$. A numerical solution method is used in order to find the steady state probabilities vector. The average throughput of the system is found in (3).

$$
p_{ij,kl}=\begin{cases}
0; & i,j,l=0,k=1 \text{ and } k=i,l<(j-1) \text{ and } k<(i-1),l=j \text{ and} \\
 & k\le(i-1),l\le(j-1) \text{ and } k<(i-1),l\ge(j+1) \\
G_b e^{-G_b}\left(1-\sigma_b\right)+\left[G_b^2 e^{-G_b}\sigma_b\left(1-\sigma_b\right)\right]e^{-G_a}; & i,j,k=0,l=1 \\
G_b\sigma_b e^{-G_T}\left[2-\left\{\left(1-\tau_b\right)^j+\left(1-\tau_a\right)^i\right\}\right]+ & \\
\left(1-\sigma_b\right)\left[G_b\left(1+G_a\right)e^{-(G_b+G_a)}+G_b^2 e^{-G_T}\sigma_b\left(1-\tau_a\right)^i\left(1-\tau_b\right)^j\right]; & k=i,l=(j+1) \\
e^{-G_T}\left[\left(G_a+\sigma_b G_b\right)\left(1-\tau_a\right)^i\left(1-\tau_b\right)^j+2-i\tau_a\left(1-\tau_a\right)^{i-1}\left(1-\tau_b\right)^j-j\tau_b\left(1-\tau_b\right)^{j-1}\left(1-\tau_a\right)^i\right]+ & \\
e^{-(G_a+G_b)}\left(1-\tau_a\right)^i j\tau_b\left(1-\tau_b\right)^{j-1}G_b\left(1-\sigma_b\right); & k=i,l=j \\
e^{-G_T}\left[\left(1-\tau_a\right)^i j\tau_b\left(1-\tau_b\right)^{j-1}\right]; & k=i,l=(j-1) \\
\dfrac{e^{-G_T}G_b^{l-j}}{(l-j)!}\left(1+G_b\sigma_b\left(1-\sigma_b\right)^{l-j}\right)+G_a e^{-G_a}\left(1-\sigma_b\right)^{l-j}; & k=i,l>(j+1) \\
e^{-G_T}\left[\left(1-\tau_a\right)^{i-1}i\tau_a\left(1-\tau_b\right)^j\right]; & k=(i-1),l=j \\
G_a e^{-G_T}\left[2-\left\{\left(1-\tau_b\right)^j+\left(1-\tau_a\right)^i\right\}\right]; & k=(i+1),l=j \\
\dfrac{e^{-G_T}G_a^{k-i}}{(k-i)!}; & k>(i+1),l=j \\
\dfrac{e^{-G_T}\left[G_a^{k-i}G_b^{l-j}\right]}{(k-i)!(l-j)!}; & k\ge(i+1),l\ge(j+1) \\
e^{-G_T}i\tau_a\left(1-\tau_a\right)^{i-1}\left(1-\tau_b\right)^j\dfrac{G_b^{l-j}}{(l-j)!}\left(1-\sigma_b\right)^{l-j}; & k=i-1,l\ge j+1
\end{cases} \tag{2}
$$

$$
\left[p_{ij,i(j-1)}+\sum_{k=i}^{M_a}\sum_{l=j}^{M_b}p_{ij,kl}\right]\pi_{ij}=p_{i(j+1),ij}\pi_{i(j+1)}+p_{(i+1)j,ij}\pi_{(i+1)j}+p_{(i+1)(j-1),ij}\pi_{(i+1)(j-1)},\quad \text{for } i=0,\ j=0,1
$$

;

$$
\left[p_{ij,i(j-1)}+p_{ij,(i-1)j}+\sum_{k=i}^{M_a}\sum_{l=j}^{M_b}p_{ij,kl}+\sum_{l=j+1}^{M_b}p_{ij,(i-1)l}\right]\pi_{ij}=p_{i(j+1),ij}\pi_{i(j+1)}+p_{(i+1)j,ij}\pi_{(i+1)j}
$$

$$
+\sum_{x=0}^{i}\sum_{y=0}^{j}p_{xy,ij}\pi_{xy}+\sum p_{(i+1)l,ij}\pi_{(i+1)l},\qquad \text{for } i=0,\ j\ge 2\cup i\ge 2,\ j=0\cup i\ge 1,\ j\ge 1;
$$

$$
\left[p_{ij,(i-1)j}+\sum_{k=i}^{M_a}\sum_{l=j}^{M_b}p_{ij,kl}+\sum_{l=j+1}^{M_b}p_{ij,(i-1)l}\right]\pi_{ij}=p_{i(j+1),ij}\pi_{i(j+1)}+p_{(i+1)j,ij}\pi_{(i+1)j},
$$

for $i=1,\ j=0$;

$$
S=\sum_{i=0}^{M_a}\sum_{j=0}^{M_b}e^{-G_T}\left(1-\tau_a\right)^i\left(1-\tau_b\right)^j e^{G_b(1-\sigma_b)}\left[G_a+\left\{\frac{\sigma_b}{1-\sigma_b}\left(1-e^{-G_b(1-\sigma_b)}\right)\right\}+\frac{i\tau_a}{\left(1-\tau_a\right)}+\frac{j\tau_b}{\left(1-\tau_b\right)}\right]\pi_{ij} \tag{3}
$$

where $\pi_{i,j}$ is calculated using the normalization equation:

$$\sum_{i=0}^{M_a}\sum_{j=0}^{M_b}\pi_{ij}=1 \qquad (4)$$

Throughput for high priority and low priority packets can be calculated similarly. The average access delay is derived in (5) according to (Yang and Yum, 2003).

$$E_{a,b}\left[D\right]=\frac{T_{slot}}{2\tau_{a,b}}\left[\frac{2\left(1+\tau_{a,b}\right)}{P_{success}}+\tau_{a,b}-2\right] \qquad (5)$$

where T_{slot} is the duration of the slot in the S-ALOHA protocol in the GPRS system with a value of 4.615 msec, $\tau_{a,b}$ is the retransmission probability for high (*a*) or low (*b*) priority packets. Additionally, τ_b is calculated in order to maintain the random access channel stable and a total arrival rate (new plus backlogged packets) equal to 1, then: $\tau_b = {}^{(1-G_T)}\!/_{\alpha i+j}$.

3. CHANNEL ALLOCATION SCHEMES

Two channel allocation schemes are considered, the complete analysis can be found in (Chia and Chang, 2006): a) Bitmap Channel Allocation (BCA), where a successful packet transmission by the mobile unit at the registration phase is processed by the GPRS network which returns a message with the *allocation bitmap* indicating the allocated data traffic channels, the network allocates the radio resources in full amount requested by the mobile. Hence, when all traffic channels are assigned out, new uplink requests need to wait until a transmitting packet completes its service. B) Uplink State Flag Channel Allocation (USFCA), where a successful packet transmission by the mobile unit at the registration phase is processed by the GPRS network which returns a message with the *USF-for-each-timeslot-number* indicating the specific value for each data channel allocated to the uplink packet request. The network broadcasts a USF value at each downlink radio block. In the next uplink radio block, the mobile assigned with the same USF value can transmit for one radio block. Hence, the network can schedule an uplink packet to transmit at the next radio block and a transmitting packet can be suspended at the end of the radio block even if it has not ended its session. Using BCA, the network cannot suspend the transmission of a packet under service. With USFCA however, the network can suspend a transmission of a non-priority packet, put it back to the priority queue and start transmitting a new priority packet.

The total number of data channels (*C*) is set to be 4 used in a practical GPRS network (Chia and Chang, 2006). When all the GPRS data channels are assigned, additional uplink packet requests are put in a priority queue of size *B* maintained by the network, *B* is also set to be 4. In the priority queue packets of the same priority will be served on a First Come First Served (FCFS) basis. When the priority queue is full, new requesting packets are blocked as explained in Section II.

4. NUMERICAL RESULTS AND CONCLUSIONS

The new packet arrival rate, G_N, at the random access channel is set to be 0.2 packets per time slot. In Figure 1, the system performance for both the random access procedure and the channel allocation schemes is presented. Total throughput, *S*, increases as the value of $\boldsymbol{\sigma}_b$ increases because more low priority packet transmissions are allowed with a low collision probability as it is seen by the increasing low priority packets throughput, S_b,; this is done by choosing a value of τ_b that maintains the access channel stable as explained at the end of Section II. However, the value of $\boldsymbol{\sigma}_b$ should not be too high because as the total throughput increases the blocking probability, P_B, also increases. High priority packets throughput, S_a, is decreased as the value of $\boldsymbol{\sigma}_b$ is increased because the total arrival rate is increased and the collision probability increases. However, this decrement on the throughput is very small (from 0.4145 to 0.41) and does not have an impact on the total average waiting time, $E[D]$, since it can be seen that it is kept constant for any value of τ_b. For low priority packets, the average total waiting time is considerably decreased as the value of $\boldsymbol{\sigma}_b$ increases. Then a GPRS network operator can decide the blocking probability acceptable for data packet users or an average waiting time acceptable for low priority packets and choose the value of τ_b accordingly.

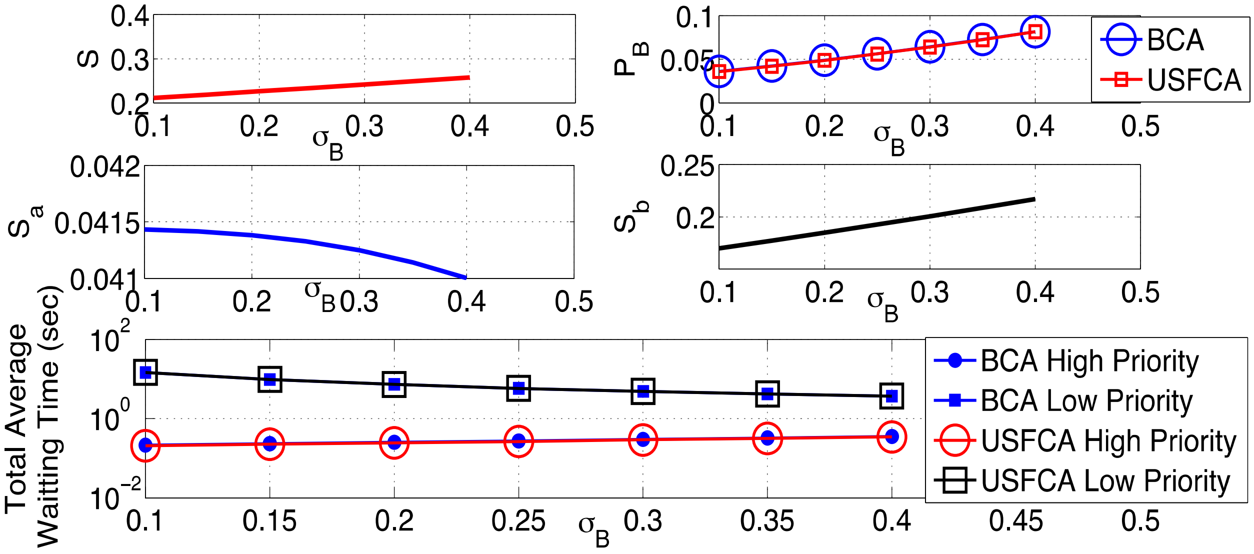

Figure 1. System performance for different values of σ_b.

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