Abstract. The Global System for Mobile Communications (GSM) Phase 2+ standard specifies a type of packet data service called General Packet Radio Service (GPRS). GPRS allows dynamic allocation of bandwidth resources. Wireless channels are allocated to a Mobile Station based on its demand. A communication session may last for an extended period of time with intermittent packet transmissions. This paper investigates the throughput and buffer utilization in a GPRS network under popular Internet traffic models, such as WWW and e-mail (SMTP) suppose the (Logical Link Control) LLC and (Radio Link Control/Medium Access Control) RLC/MAC layers in GPRS. The layers work either in acknowledged (Transparent) or not-acknowledged (non-Transparent) mode. We propose a new protocol for the acknowledged mode of LLC layer. We name this mechanism “channel dependent LLC protocol”. The new protocol dynamically takes into consideration the quality of wireless channel. When the channel is in good quality, the transmission is allowed. And the transmission can not take place while the channel is not in a good condition.

1 Introduction

The popularity of the Internet has resulted in a large number of services that are available online. These include, email, World Wide Web (WWW) browsing and streaming audio/video delivery. One factor that hinders the growth of wireless data communication is the inefficiency of circuit switched wireless networks for transporting packetized data.

Internet traffic is characterized by the ON/OFF behavior. Each communication session generally lasts for an extended time period. For example, a WWW browsing session may last for an hour or longer. During the session, a burst of packet arrivals (ON) is followed by a silent period (OFF). This ON/OFF pattern continues until the session terminates.

To allow for more efficient transportation of packet data traffic through the wireless network, an extension to the GSM standard called GPRS has been developed.

GPRS allows for the dynamic sharing of the wireless bandwidth among active Mobile Stations (MS). No dedicated channel is assigned to an MS for the duration of the communication session. An MS is allocated radio channels only when packets are available for immediate transmission. This results in better bandwidth utilization and lower communication cost.

This paper presents a study of the session throughput of the GPRS service under various traffic parameters and available buffer sizes. This analysis is based on a proposed "Channel-Dependent LLC protocol". Our results demonstrated that, depending on the traffic parameters, the proposed protocol has better throughput than conventional pure model.

In order to maximize user data throughput and decrease data-packet transfer time, the GPRS protocol stack should be optimally implemented. The protocol layers under consideration in this paper are the logical link control (LLC) and the Radio Link Control/Medium Access Control (RLC/MAC) layers.

In order to protect LLC peer-to-peer communication, Packet Data Units (PDUs) coming from higher layers are segmented into variable size LLC frames and 24 Cyclic redundancy-check (CRC) bits are added to every LLC frame for error detection. A stop-and-wait automatic repeat-request (ARQ) mechanism is implemented at the LLC to transmit any erroneous LLC frames, rendering to the LLC peer-to-peer link a high reliability. Each LLC frame is passed to the RLC/MAC layer, where it is further segmented into RLC/MAC blocks of fixed size depending on the channel coding scheme (CS) used at the physical layer. The RLC/MAC layer provides a selective ARQ mechanism for further error recovery over the radio interface (Um)[1,2,3].
This paper describes the interaction between the two ARQ mechanisms at the LLC and RLC/MAC layers, respectively. We assume that the LLC layer works in the acknowledged (ACK) mode so each LLC frame is acknowledged upon receiving it. One of objectives of this work is to define analytically closed form expressions that can be used for on-line quality-of-service (QOS) management. Their on-line estimation is crucial for network performance. We present a novel derivation of the ARQ parameters (that is, the number of retransmissions) at the LLC and RLC/MAC layers that strike a balance between the bandwidth efficiency within the GPRS access network and the efficiency over the Um.

Most of the papers published on LLC-RLC/MAC performance analysis in GPRS make use of numerical simulations to estimate the LLC throughput when the LLC works in non-acknowledgement mode [5]. Ludwig and Turina [6] derived a formula for the average LLC frame transfer delay at the RLC/MAC layer using an iterative method to calculate the RLC/MAC retransmission probability. They assume infinite number of RLC/MAC retransmissions per LLC frame. However their assumption is general and does not account for the LLC protocol.

In this paper we derive closed-form expressions under more realistic assumptions namely a finite number of retransmissions per LLC frame and a two-state radio channel model. Further in order to optimize radio resources, a channel dependent ARQ mechanism is introduced at the LLC layer.

This paper is organized as follows:

In Section two we introduce a novel LLC protocol that accounts for the radio channel status. The name of our proposed protocol is "Channel-Dependent LLC protocol". Section 3 describes the results of simulation. And finally conclusion is given in section 4.

2 Proposing Cannel-Dependent LLC Protocol

In this Section we introduce a novel LLC protocol that accounts for the radio channel status. By means of a time-out error-recovery algorithm, the ARQ mechanism at the LLC layer attempts retransmission of an erroneous LLC frame only after a time interval, introducing a time diversity. This Channel-Dependent ARQ mechanism also increases MS battery lifetime by deferring transmission over a "bad" channel to a later time when the channel is likely to be in a "good" state.

Throughout this section, \( p_B \) denotes the Block Error Rate (BLER), \( n \) denotes the LLC frame size in RLC/MAC blocks, \( M \) is the maximum number of RLC/MAC block retransmissions per LLC frame and \( L \) is the maximum number of LLC retransmissions per LLC frame. Henceforth, the expression “RLC/MAC retransmission per LLC frame” denotes the retransmission of several RLC/MAC blocks belonging to the same LLC frame that have been reported as being in error by a negative acknowledgment (NACK). These blocks are selectively repeated. An LLC retransmission occurs only when the ARQ mechanism at the RLC/MAC layer fails to correct all the errors of an LLC frame within the maximum allowed number of RLC/MAC retransmissions.

We assume that radio channel is described by the Gilbert-Elliot model, which is a two-state Markov process. The two channel states are denoted by "bad" (where the block error rate (BLER) is equal to \( p_B \)) and "good" (where the BLER is zero), respectively [8].

Throughout this analysis, we consider that the errors over the radio channel in a bad state are independent. This is an optimistic assumption because, in general, errors over the radio channel occur in bursts. In a bad state errors may affect several RLC/MAC blocks in sequence. However, the probability of a deep rayleigh fade lasting more than 20 ms (that is more than one RLC/MAC block) is very low, so we neglect the correlation of errors over many RLC/MAC blocks.

We assume that the BLER is constant over the transmission of an LLC frame. This is a reasonable assumption, since the BLER is derived from a lognormal, slow-fading distribution of the carrier to interference ratio, \( C/I \), for which a slow fade can last several seconds [7].

First we calculate the probability that channel is in bad state. We show this probability with \( Pr( C/I < \text{Threshold} ) \). It is calculated as follow:

\[
Pr( C/I < \text{Threshold} ) = \frac{1}{\sigma c / I \sqrt{2\pi}} \int_{-\infty}^{\text{Threshold}} \exp\left[ -\frac{(x-C/I)^2}{2\sigma^2} \right] dx
\]

In this formula, \( \overline{C/I} \) and \( \sigma_{C/I} \) are mean and variance of \( C/I \) and "Threshold" is an indicator level for \( C/I \), if \( C/I \) value is less than threshold, Channel will vary from good state to bad state.
If we assume $C/I = 16$ dB, $\sigma_{C/I} = 7$ dB and $\text{Threshold} = 12$ dB then with respect to integration tables we have: $Pr( C/I < \text{Threshold}) = 0.3$

Now we calculate the probability that number of LLC frame transmissions across radio channel is $k$.

We show this probability with $Pr(k)$.

This probability consists of two parts: all RLC blocks have been received correctly in bad state or channel is in good state and hence no error has been occurred.

As we know, transmission of each RLC block is independent from other blocks. So for example, $P_{a}^{T}$ is probability that after second transmission, a RLC block is still in error and $1 - P_{a}^{T}$ is the probability that RLC block has been received correctly in one of two transmissions. (The first transmission has been accounted in calculation) $(1-P_{a}^{T})^{n}$ is probability that LLC frame has been received correctly after second transmission. In general we have:

$$Pr(k) = Pr( C/I < \text{Threshold}) \cdot [(1-P_{a}^{T})^{n} - (1-P_{a}^{T-1})^{n}]$$

So we can tell that the number of LLC frame transmissions is a random variable with PDF equal to $Pr(k) \cdot \sigma(k)$.

Cumulative Distribution Function (CDF) of $k$ can be obtained by using PDF as follows:

$$CDF(M) = \sum_{k=1}^{M} Pr(k)$$

Fig. 1-b shows the CDF of $k$ in RLC/MAC layer. Of course in this figure it is assumed that channel is in bad state. Also PDF of $Pr(k)$ is shown in Fig.1-a.

From Fig.1 it is clear that for $k=7$ CDF tends to 1. But as we know, CDF is the probability of correct reception of LLC frame, so we choose optimum value for maximum transmission times of LLC frame in RLC/MAC layer equal to 7. This fact has been used in practical simulation. It is clear that $CDF(M)$ in (3) is probability of receiving a LLC frame correctly. We show this probability with $q$, so we have:

$$CDF(M) = 1 - Pr( C/I < \text{Threshold}) + Pr( C/I < \text{Threshold}) (1-P_{a}^{T})^{n} = q$$

Increasing of $q$ results in optimization of $M$. We can use calculus derivation of $q$ to optimize $M$:

$$M = \left[ \frac{Ln(1 - \frac{1}{A})}{Ln(P_{a}^{T})} \right] + 1$$

In this relation, $A$ is as follow:

$$A = \frac{q - 1 + Pr(C/I < (\text{Threshold}))}{Pr(C/I < \text{Threshold})}$$

We can indicate maximum of $Pr(k)$ from its graph. We can also find a value of $k$ that optimizes $Pr(k)$ by maximizing the (2). This optimum value of $k$, i.e. $k_{Opt}$ is as follow:

$$k_{Opt} = \left[ \frac{Ln\left(1 - \frac{1}{P_{a}^{T}}\right)}{Ln(P_{a}^{T})} \right] + 1$$

In this equation $\left[ x \right]$ stands for the greatest integer that is smaller than or equal to $x$.

$k_{Opt}$ is always greater than 1 because inside of $\left[ x \right]$ in (7) is positive.

Fig. 2 shows the relation between $n$ and $k_{Opt}$. But as we saw before, Fig.1 shows that $Pr(k)$ tends to 1 very quickly.
If we assume $PB = 0.2$, $n = 20$ and $k = k_{Opt} + 1 = 3$ then we get $CDF = 0.8$. In other word, 80% of RLC blocks are received in MS without error and only 3 retransmissions are needed. So we can assume that maximum number of LLC frame transmission in RLC/MAC layer is equal to optimum number of LLC frame transmissions:

$$M = k_{Opt}$$

(8)

Of course we can calculate $k_{Opt}$ from (7) on-line. This optimizes the use of radio channel and results in throughput balancing. In fact, (5) and (7) are equivalent to each other.
M parameter is very important in resource management. It can be used by admission control unit to provide desired quality of service. Here LLC timer is used to protect this connection. This timer fires when a LLC frame is sent to RLC/MAC layer. It’s value is:

\[
LLC_{\text{Timer}} = (Q+1) T_{RLC/MAC} + t
\]  

(9)

Where

\[
T_{RLC/MAC} = n \cdot E[R] \cdot T_{RLC-\text{TransDelay}} + D_{\text{NACK}} \cdot E[k]
\]  

(10)

and

\[
E[R] = \left( \Pr( C/I < \text{Threshold} ) \sum_{k=1}^{M} k(1 - p_B^k) p_B^{k-1} \right) + 1 - \Pr( C/I < \text{Threshold} )
\]  

(11)

Here, \( E[R] \) denotes the average number of retransmissions per RLC/MAC block; \( T_{RLC-\text{TransDelay}} \) is the transmission duration of an RLC/MAC block over the radio interface (18.46 ms); \( E[k] \) is mean of \( k \) and \( M \) is given in (8). \( D_{\text{NACK}} \), which is the time to receive and process a NACK (40 ms), includes the ACK/NACK processing delay at both the MS (10 ms) and BSS (10 ms) as well as the ACK/NACK transfer delay (20 ms) between the MS and the BSS. In (9) the term \( t \) is a positive constant introduced in order to avoid the fade on the radio channel at the next LLC retransmission. Thus for \( t>0 \) a time diversity is provided by the LLC time-out recovery mechanism. In practice \( t \) is set by measurement taken on the channel. For brevity, we have included the radio-across delay in the term \( t \) in (9). It is worth pointing out that the LLC frame queuing delay at the RLC/MAC layer- that is, the term \( Q \) in (9) – provides a natural, intrinsic time diversity. Thus, if an LLC transmission fails, the LLC will retransmit the erroneous LLC frame to the RLC/MAC layer. This LLC frame should wait in the RLC/MAC queue until all LLC frames in front of it are served. This queuing delay introduces an internal time diversity. However under a light and bursty traffic load, the queuing delay at the RLC/MAC layer could be very bad so that there is a need for the additional time diversity introduced by the term \( t \) in (9).

The LLC frame queuing delay at the RLC/MAC queue is explicitly taken into account in (9) by the presence of the factor \( Q \).

The time diversity introduced by this ARQ scheme increases MS battery lifetime by referring LLC frame transmission over a bad radio channel to a later time when the radio channel is likely to be in a good state. This reduces the number of LLC retransmissions at the expense of a slight increase in transfer delay due to the additional delay introduced by \( t \) in (9). Henceforth, we consider that \( t \) is large enough such that two consecutive LLC retransmissions are uncorrelated. Using this statistical independence of the LLC retransmissions, we next derive the LLC frame error rate.

The probability that after \( M \) RLC/MAC retransmissions there are still RLC/MAC blocks in error belonging to the same LLC frame of size \( n \) is equal to:

\[
P_M = Pr( C/I < \text{Threshold} ) \left[ 1-(1-P_M^n)^n \right] \cong n \cdot P_M^n \cdot Pr( C/I < \text{Threshold} )
\]  

(12)

Where the approximation is valid for \( P_M^n << 1/n \). Thus, \( P_M \) is the probability of RLC/MAC failure, which leads to an LLC retransmissions of the whole LLC frame; then the RLC/MAC process is repeated. In other word, \( P_M \) is the LLC frame error rate seen at the LLC layer. Therefore, the LLC peer-to-peer link has an error probability of \( P_M \), we can see from (12) that the reliability of the LLC peer-to-peer link increases as \( M \) increases for a fixed LLC frame size \( n \). As the number of RLC/MAC retransmissions per LLC frame, \( M \), increases, then the probability of RLC/MAC failure, \( P_M \), decreases; therefore, fewer LLC retransmissions(L) are necessary per LLC frame. Thus, for large \( M \) and for a radio channel in a bad state, the radio channel is heavily loaded with RLC/MAC retransmissions. This leads to poor radio efficiency and a waste of MS battery lifetime. On the other hand, a very small number of RLC/MAC retransmission, \( M \), gives rise to many LLC retransmissions (large \( L \)), which consequently leads to heavy network load over the Gb and A-bis interfaces. Here Gb refers to the interface between the BSS and the Serving GPRS Support node (SGSN), while A-bis are the interface between the Base Transceiver Station (BTS) and the Base Station Controller (BSC). This also increases the LLC frame transfer delay.

In counterbalance, the efficiency over the radio interface is increased due to the inherent time diversity of the LLC retransmission process (that is, it’s basis on time-out). We believe that \( M \) strikes a balance between the number of LLC retransmissions and the number of RLC/MAC retransmissions.
3 Results

We simulate a GPRS network in which the following parameters are existed. There are 100 MSs in each cell, each cell has 8 Packet data Channels (PDCH) for data frames, a 10 second timer is set for retransmission. The L parameter is considered 3. The channel quality is given by the ratio of the Carrier to the Interference (C/I). Fig.3 shows the session throughput for C/I=16 and 8 dB and compare the new protocol with the conventional one. Fig.3-a shows that the new proposed protocol does not produce big advantage over the conventional protocol. Fig.3-d shows that when there is enough buffer space then the proposed protocol enhances the session throughput. The channel quality (C/I) in heavy traffic situation influences the retransmission in the proposed protocol. Fig.3 (a,b,c,d) shows this influence quantitatively.

The coding schemes have strong correlation with the channel quality. In other word a strong coding scheme improve the throughput in a low quality channel. We investigate the effect of coding schemes in Fig.4. This figure shows that the proposed protocol works well in heavy traffic both for CS-1, which is a strong coding scheme, and CS-4, which is a no-Coding scheme.

Fig.3. Comparison of channel effect in Conventional and proposed LLC protocols in various buffer sizes
4 Conclusion

The channel quality plays a crucial role in the session throughput of GPRS network. A low quality channel makes the LLC and RLC/MAC layers retransmit the frames and blocks several times. The channel quality does not enter into conventional LLC protocol. We have included the channel quality into the protocol and compared the results with conventional one. Our results show that the new proposed protocol greatly enhances the session throughput in heavy traffic. We have also investigated the effect of the coding schemes on the throughput. It is shown that using the new protocol and a strong coding scheme increases significantly the session throughput.

References

1. European Telecommunication Standards Institute :Digital Cellular Telecommunications System (Phase 2+), General Packet Radio Service (GPRS), Mobile Station (MS) – Base Station System (BSS) Interface Radio Link Control/Medium Access Control (RLC/MAC) Protocol. EN 301 349 (GSM 04.60) Ver. 6.3.0 (1999)
2. European Telecommunication Standards Institute :Digital Cellular Telecommunications System (Phase 2+), General Packet Radio Service (GPRS), Mobile Station (MS) – Serving GPRS Support Node (MS-SGSN) Logical Link Control (LLC) Layer Description. TS 101351 (GSM 04.64) Ver. 6.3.0 (1999)
3. European Telecommunication Standards Institute :Digital Cellular Telecommunications System (Phase 2+), General Packet Radio Service (GPRS), Multiplexing and Multiple Access on the Radio Path. (GSM 05.02) Ver. 6.0.0 (1998)
4. European Telecommunication Standards Institute :Digital Cellular Telecommunications System (Phase 2+), Channel Coding. EN 300 909 (GSM 05.03) Ver. 6.2.0 (1999)