

# Energy Efficiency of Radio Link Protocols in 3GPP Systems

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## Abstract

*The paper deals with data transfer techniques at the link layer, which have been specified in 3GPP to preserve information integrity over the wireless link. We consider the acknowledged transfer mode, which implements a selective ARQ protocol. We enhance the 3GPP specification with a control mechanism of the transmitter activity that allows the system to save radio resources as well as energy in the case of bad channel conditions. In this way, we can obtain a significant energy saving at the expense of the provided QoS. By developing a Markovian model of the ARQ scheme, we study the protocol behavior as channel characteristics change and we find a trade-off between traffic QoS and energy efficiency.*

## 1. Introduction

Recently, a great effort has been done to provide a common standard for next generation wireless networks. The Third Generation Partnership Project (3GPP) is currently producing technical specifications for a third generation mobile system based on both an evolved GSM network and novel radio access technologies [4]. Besides offering all GSM features, 3GPP specification based systems will offer advanced multimedia applications, mobile Internet services, and data communication with rates as high as 2Mbps.

We focus on the information transfer techniques specified in 3GPP at the link layer.

Several papers dealing with ARQ (Automatic Repeat Request) schemes have appeared in the literature. Performance analysis of ARQ protocols has been presented in [2, 6]. In [7], the authors have studied the trade-off between energy constraints and average traffic delay that can be achieved by dynamically adapting ARQ schemes to channel fading characteristics and traffic QoS (Quality of Service). Energy efficiency at the data link layer has been addressed also in [1, 8], where the behavior of ARQ protocols is studied when transmissions in the presence of disadvantageous channel conditions are avoided. A similar approach is used in [3],

where channel conditions and packet deadline constraints determine whether transmissions are deferred, as well as the best error-correcting code to select.

In this paper we build an ARQ scheme configuration by properly applying the control mechanisms defined in the 3GPP Radio Link Control (RLC) specification [4]. We provide an analytical model of the behavior of the ARQ scheme and we estimate its impact on typical QoS parameters for loss-sensitive services such as data file transfer. Besides the traditional QoS metrics for data traffic, the energy efficiency of the ARQ scheme is evaluated.

## 2. The ARQ Protocol

The reference network scenario assumed in the 3GPP specification of the RLC (Radio Link Control) protocol [4] consists of a mobile station and an access point to the terrestrial core network, communicating with each other through the radio channel. Mobile station and access point can be either transmitter or receiver entities.

According to [4], we denote by *PDU (Protocol Data Unit)* the data unit exchanged between the RLC layer and the MAC layer, and by *STATUS PDU* the data unit used by the receiver entity to send feedback information to the transmitter.

We focus on the acknowledged mode, which implements a selective ARQ protocol. In acknowledged mode, when the receiver has to request the retransmission of missing PDUs, it sends to the transmitter a STATUS PDU carrying a negative acknowledgement. Upon the reception of a negative acknowledgement, the sender retransmits only the PDUs that have been indicated as missing by the receiver. Retransmissions always have higher priority than data units transmitted for the first time. The sender can check on the receiver's status by *polling* the receiver. The receiver must reply to the sender's poll with a STATUS PDU, otherwise the transmitter keeps on polling the receiver until it receives a reply.

We consider that the loss of a PDU is detected either because an out-of-sequence data unit is delivered or none data unit is received by a certain time-out value. We denote by  $m$  the number of PDUs transmitted during the time delay

between the end of a PDU transmission and the reception of the STATUS PDU notifying that the PDU was lost.

We enhance the 3GPP specification with a control mechanism of the transmitter activity to let the system save radio resources as well as energy in the case of bad channel conditions. When the sender receives a STATUS PDU carrying a negative acknowledgement, it detects that the radio channel conditions are bad. At this point, two different modes of operation are possible: *greedy* or *saving* mode. In the case of greedy mode, the sender retransmits the missing data units at once and then goes on with the information transfer. In the case of saving mode, the sender stops transmitting PDUs and starts polling the receiver to probe the channel status; the sender starts retransmitting all missing data units only when the receiver replies to the poll. A similar approach was employed also in [1, 8].

Observe that the energy cost of polls and STATUS PDUs are negligible compared to the cost of transmitting PDUs.

At the cost of a higher energy consumption, greedy mode is more reactive than saving mode to changes in the channel conditions, and therefore is able to provide better QoS. In order to dynamically trade-off between the needs of providing QoS and saving energy, we introduce a control mechanism on the sender such that if the number of PDUs in the transmission buffer is less than a given threshold  $T_h$ , the sender operates in saving mode, otherwise it enters greedy mode.

### 3. A Model of the ARQ Scheme

We consider an asymmetric traffic pattern, with the network access point transmitting information to the mobile station; thus, with reference to the ARQ scheme described above, the access point acts as sender while the mobile station acts as receiver. (Notice however that the proposed model can represent the reverse situation as well.)

We develop a discrete-time Markov chain (DTMC) model of the system, in which the time is slotted according to the PDU transmission time  $\Delta$ . The model focuses on the following aspects of the system: the traffic generator, which models the arrival process of PDUs to the RLC layer, the transmission buffer, and the radio channel.

The traffic generator is modeled as a discrete-time *on-off* process with time granularity equal to the PDU transmission time,  $\Delta$ . During *on* periods, the traffic generator is *active* and one PDU is generated every time slot; whereas during *off* periods, the generator is *idle* and no PDUs are generated.

Traffic sources are characterized by the average *off* period,  $T_{off}$ , and by the traffic load normalized to the system capacity,  $\rho$ . The average *on* period,  $T_{on}$ , is then equal to  $\rho T_{off}/(1 - \rho)$ . The parameters of the traffic generator are the probability that the generator switches on during a time slot,  $\alpha = \Delta/T_{off}$ , and the probability that it switches off,  $\beta = \Delta/T_{on}$ .

The radio channel behavior is represented by a Markov model [8] with two states, *good* and *bad*, representing the state of the channel during the transmission time of one PDU. We denote the transition probability from state *good* to state *bad* by  $p$  and from state *bad* to state *good* by  $q$ ;  $p$  and  $q$  depend on the steady-state data unit error rate  $\epsilon$ , and on the normalized Doppler frequency. The steady-state data unit error rate can be written as a function of the fading margin  $F$  as follows [8]:  $\epsilon = 1 - e^{-1/F}$ . Clearly, high values of  $F$  represent good channel conditions, while low values of fading margin correspond to a high data unit error rate.

In constructing the ARQ model, the following assumptions are introduced: *i*) there is not a maximum number of retransmissions per PDU; *ii*) STATUS PDUs are always correctly received; *iii*) mobile stations consume a constant level of power in receiving mode; thus, modeling the battery behavior we can neglect the capacity-rate effect [5].

### 3.1 Analytical Model

We describe the DTMC model for the case with  $m$  equal to 1. In order to model the system behavior, the following dynamics have to be carefully described: *i*) the PDU generation process, *ii*) the buffer occupancy, *iii*) the working mode of the transmitter and *iv*) the channel state.

Accordingly, let the DTMC state be defined by the vector  $\bar{s} = (g, b, t, t^-, c, c^-)$  where

- $g$  is the state of the traffic generator, which is either active, denoted by  $A$ , or idle, denoted by  $I$ ,  $g \in \{A, I\}$ ;
- $b$  is the buffer occupancy in number of PDUs,  $b$  can assume all integer values between 0 and  $B$ ;
- $t$  is the state of the transmitter, either active or idle; when active, the transmitter is sending PDUs over the radio channel; the transmitter is idle when it has no PDUs to transmit or when, being in saving mode, it has detected bad channel conditions,  $t \in \{A, I\}$ ;
- in slot  $n$  the value of  $t^-$  denotes the state that the transmitter assumed in slot  $n - 1$ ,  $t^- \in \{A, I\}$ ;
- $c$  is the channel state,  $c \in \{good, bad\}$ ;
- in slot  $n$  the value of  $c^-$  denotes the state that the channel assumed in slot  $n - 1$ ,  $c^- \in \{good, bad\}$ .

Observe that, in order to properly take into account the delay between the transmission of a PDU and its acknowledgement ( $m = 1$ ), the introduction of some memory about the past history of the system is necessary; therefore, we introduced the variables  $t^-$  and  $c^-$ .

Let  $P(\bar{s}, \bar{d})$  denote the probability that the chain moves in one-step from source state  $\bar{s}$  to destination state  $\bar{d}$ . In

determining probabilities  $P(\bar{s}, \bar{d})$ 's observe that the behaviors of the channel and of the traffic generator are independent of the rest of the system; thus, their stochastic description can be *a-priori* specified by input parameters. On the contrary, changes in the transmitter mode and in the buffer occupancy can be deterministically derived from the actual state of the system and from the channel and generator behavior. Hence, we write the following expressions

$$P(\bar{s}, \bar{d}) = P\{g : g_s \rightarrow g_d\} \cdot P\{c : c_s \rightarrow c_d\} \cdot \delta(\bar{s}, \bar{d})$$

with  $\bar{s} = (g_s, b_s, t_s, t_s^-, c_s, c_s^-)$   
and  $\bar{d} = (g_d, b_d, t_d, t_d^-, c_d, c_d^-)$

where

- $P\{g : g_s \rightarrow g_d\}$  is the probability that the traffic generator changes from  $g_s$  to  $g_d$ , with  $g_s, g_d \in \{A, I\}$ ;
- $P\{c : c_s \rightarrow c_d\}$  is the probability that the channel state changes from  $c_s$  to  $c_d$ , with  $c_s, c_d \in \{good, bad\}$ ;
- $\delta(\bar{s}, \bar{d})$  is an indicator, which is equal to 1 if state  $\bar{d}$  is a possible successor of state  $\bar{s}$ ; and equal to 0 otherwise.

As already mentioned,  $P\{g : g_s \rightarrow g_d\}$  and  $P\{c : c_s \rightarrow c_d\}$  are independent of the state of the system. Changes in the state of the traffic generator determine changes in the value of  $g$ ,

$$P\{g : I \rightarrow A\} = \alpha \quad \text{and} \quad P\{g : A \rightarrow I\} = \beta.$$

The value of  $c$  changes according to the two-state model of the channel,

$$P\{c : good \rightarrow bad\} = p \quad \text{and} \quad P\{c : bad \rightarrow good\} = q.$$

The state variables  $t^-$  and  $c^-$  are, by definition, determined by the value of  $t$  and  $c$  in the previous slot, so that for each transition we have  $t_d^- = t_s$  and  $c_d^- = c_s$ .

Changes in the value of  $t$  and  $b$  depend deterministically on the channel and generator behavior, as well as on the current state.

Let us first focus on the saving mode of the transmitter.

Since  $m = 1$ , the transmitter chooses its working mode according to the most recent estimate of the channel state, which is the value of  $c^-$ . If during slot  $n$ , while the transmitter is active and sending a PDU, a STATUS PDU arrives notifying that the PDU sent in slot  $n - 1$  is missing, then the transmitter completes the current PDU transmission and switches to idle at the beginning of slot  $n + 1$ . Thus, in saving mode from states  $\bar{s}$  with  $t = A$  and  $c^- = bad$  the chain moves to states with  $t_d = I$ .

On the contrary, if the transmitter is idle in slot  $n$ , it sends a short poll message at the beginning of slot  $n$ , receives a STATUS PDU still in slot  $n$  and switches to active at the

beginning of slot  $n + 1$ . These are the transitions from states  $\bar{s}$  with  $t = I$  and  $c = good$ , to states with  $t_d = A$ .

When in greedy mode, the transmitter is always active. Therefore, states with  $t = I$  and  $b > 0$  are not possible.

The buffer dynamics are governed by the PDU generation process and by the successful transmission of PDUs over the radio channel. In particular, PDUs are generated one per slot when the traffic generator is active (states with  $g = A$ ) and they are successfully transmitted if the transmitter is active and the channel is good. A successful PDU transmission in slot  $n - 1$  is notified during slot  $n$  and removed from the buffer only at the beginning of slot  $n + 1$ ; i.e., during a transition from  $\bar{s}$  to  $\bar{d}$  a PDU is removed from the buffer if  $t^- = A$  and  $c^- = good$ . We adopt the convention that at the beginning of a slot, the generation of a new PDU precedes the removal of a PDU from the buffer. This implies, for example, that the transition from state  $(g, B, A, A, c, good)$  to state  $(g, B - 1, A, A, c_d, c)$  corresponds to a PDU loss and to a successful transmission.

By employing standard techniques, we compute the steady-state probability vector  $\Pi = \{\pi(\bar{s})\}$ , where  $\pi(\bar{s})$  denotes the steady-state probability of  $\bar{s}$ .

Notice that the model can be extended to take into account values of  $m$  which are greater than 1. In these cases, the state definition has to include the information about the transmitter and the channel state for the past  $m$  time slots.

## 4 QoS Performance of Data Traffic

In this section, we employ the proposed model to assess the impact of the ARQ scheme on the QoS of loss-sensitive data traffic services such as data file transfer.

In Sec. 3 we described the dynamic of the traffic generator as independent of the system performance. However, an accurate description of the system for data services has to take into account the implicit feedback which the system performance has on the traffic generator. In particular, the traffic generator is going to be active until all the PDUs corresponding to the current file are successfully transferred.

We take this phenomenon into account in the following way. Neglecting losses due to the wired network, we assume that all PDUs which are lost due to buffer overflow, have to be regenerated. Let  $N$  be the number of PDUs corresponding to a file to be transferred, and let also  $P_L$  be the probability that a PDU is lost, due to buffer overflow. At steady-state we expect:  $T_{on}(1 - P_L)/\Delta = N$ .

While  $N$  is *a-priori* specified, both  $T_{on}$  and  $P_L$  depend on the system performance. We derive them by means of a fixed-point procedure. Furthermore, in order to have an even more realistic description of a data traffic source, in loss states we forbid that the generator switches to the *off* state. In these cases, in fact, the generator has at least one data unit to regenerate.

In the case of data traffic, performance of the ARQ scheme can be expressed in terms of PDU loss probability, throughput, and energy consumption.

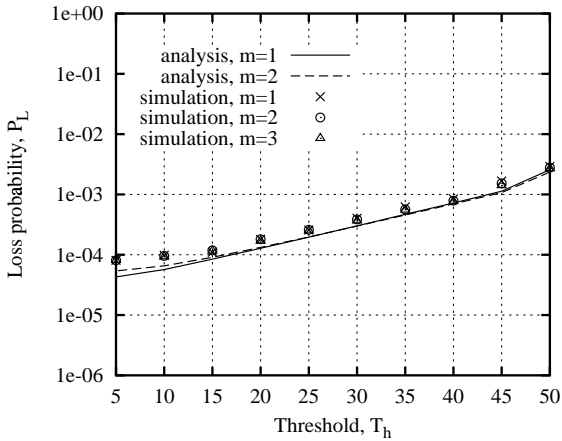
The PDU loss probability  $P_L$  is the probability that a PDU can not be accommodated in the buffer,

$$P_L = \frac{1}{\rho} \sum_{\mathcal{T}_L} P(\bar{s}, \bar{d}) \pi(\bar{s})$$

where  $\mathcal{T}_L$  is the set of transitions from  $\bar{s}$  to  $\bar{d}$ , which cause losses and  $\rho$  is the normalized traffic load.

Throughput,  $X$ , can be computed by summing the probabilities of the states in which a successful PDU transmission occurs; similarly, including the unsuccessful transmissions, the average number of total PDU transmissions,  $T$ , is the sum of the probabilities of all states in which a transmission is attempted. Then, the average number of transmissions per PDU is  $R = T/X$ .

By assuming that the receiver listens to the channel only during the sender's transmissions, the energy consumed per data unit at the mobile station in receiving mode is  $E_c = P_{rx} \Delta R$ , with  $P_{rx}$  being the power consumption in receiving mode.

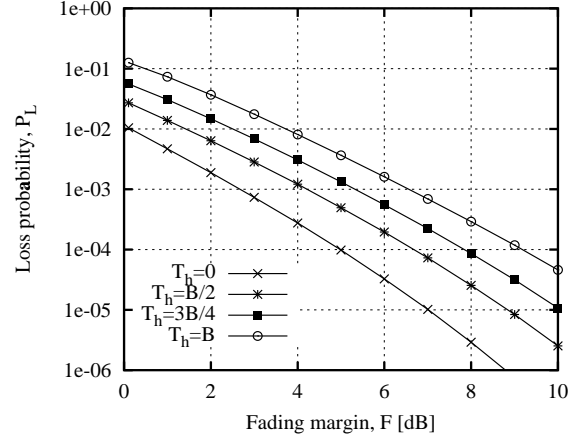


**Figure 1. Data traffic loss probability as a function of threshold  $T_h$ . Analytical and simulation results are compared.**

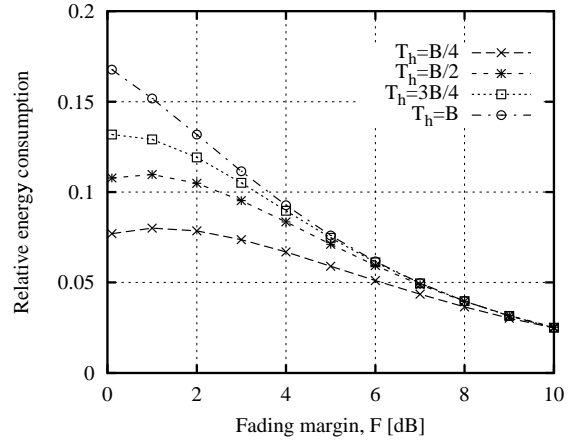
#### 4.1 Numerical Results

We assume that the average size of the file to be transferred over the radio channel is equal to 4 MB, the peak rate is equal to 384 Kbps, while the average load is a varying parameter of the system. The normalized Doppler frequency of the radio channel is equal to 0.2, and the power consumed in receiving mode is normalized to the transmission power and is assumed to be equal to 0.25.

We first validate our model by comparing analytical results to simulation results. The main objective of the validation is to assess the impact of the fixed-point procedure



**Figure 2. Data traffic loss probability as a function of fading margin  $F$  and for different values of threshold  $T_h$ .**

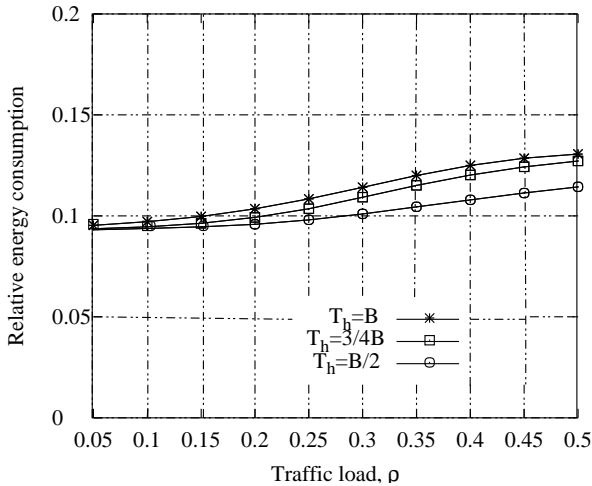


**Figure 3. Relative energy consumption at the mobile station as a function of fading margin  $F$  and for different values of threshold  $T_h$ .**

introduced in order to take into account the feedback which the system performance has on the traffic generator. A synchronous simulator was developed for the analytical model validation. The simulator accurately describes the proposed system configuration. It comprises a detailed description of the regeneration mechanism of lost PDUs; while it shares with the analytical approach all the other assumptions listed in Sec. 3.

Analysis and simulation results are compared in Fig. 1. PDU loss probability,  $P_L$ , is plotted versus increasing values of threshold  $T_h$ , with buffer capacity  $B = 50$  PDUs, traffic load  $\rho = 0.25$ , and fading margin  $F = 1$  dB. Analytical results are derived for  $m = 1$  as well as for  $m = 2$ ; in both cases they are accurate when compared to simulation predictions.

Due to the state space explosion problem, the model becomes exceedingly complex for  $m > 2$ . However, from



**Figure 4. Relative energy consumption at the mobile station as a function of threshold  $T_h$  and for different values of  $\rho$ .**

simulation results with  $m = 3$  it can be seen that  $m$  does not have a relevant impact on system performance. Thus, there is no loss in generality showing the following results for the case  $m = 1$  only. Also, because of space limitation and since loss probability is typically one of the most critical performance metrics, we do not validate the model for other performance measures.

When designing a system with the objective of providing QoS guarantees for data traffic, we usually aim at satisfying constraints on loss probability. From Fig. 1 observe that, under the considered traffic scenario, changes of the value of  $T_h$  turn into changes of the loss probability over a range of more than one order of magnitude. The selection of small values of  $T_h$  which provide small values of  $P_L$ , however, may not always be a good designing choice since it results in large energy consumption.

Fig. 2 shows the impact of fading margin  $F$  on the loss probability for different values of  $T_h$ ,  $B = 40$ , and  $\rho = 0.25$ . As expected, the fading margin has a remarkable impact on  $P_L$ . Again,  $T_h$  can be chosen so that given the channel conditions, the desired loss probability is guaranteed. For example, knowing that the fading margin is going to be no smaller than 4 dB we can provide loss probability guarantees between  $1e-2$  and  $5e-4$  only by changing the value of  $T_h$ .

As already mentioned, the choice of  $T_h$  trades-off between QoS performance and energy consumption. Fig. 3 reports the relative energy consumption per PDU, i.e., the difference between energy consumption per PDU in greedy and in saving mode at the receiver, normalized with respect to the energy consumption per PDU in greedy mode. The relative energy consumption is plotted as a function of fading margin  $F$  and for different values of threshold  $T_h$ . For low values of  $F$ , a significant reduction in energy con-

sumption is obtained when saving mode is applied since the number of unsuccessful transmissions performed in greedy mode is quite high. We observe that up to 16% improvement in energy consumption can be achieved by properly choosing  $T_h$ .

Fig. 4 shows the relative energy consumption per PDU as a function of the traffic load  $\rho$ . Curves are obtained for fading margin  $F = 3$  dB and for different values of the threshold. An improvement in energy consumption is achieved by using saving mode for any value of traffic load, and the benefit of saving mode grows as the traffic load increases.

## 5 Conclusions

In this paper we presented a configuration of the ARQ protocol defined in 3GPP specifications, and we introduced a control mechanism of the transmitter activity. The transmitter enters greedy or saving mode depending on the value of a threshold on the buffer occupancy. A Markov model was developed to study the system performance as the channel fading conditions vary. Results derived for loss-sensitive traffic showed that, by changing the buffer threshold, a trade-off between loss probability and energy consumption can be found.

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