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A Low Complexity Algorithm for Statistically Based Estimation of Average IP Packet Delay in Cellular Data Networks

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Abstract. A new, low computation complexity technique for prediction of the average delay of IP packets, transported over cellular data networks with SR-ARQ loop, is presented in this paper. This prediction takes into account the SR-ARQ influence on the average IP packet delay, assuming that the MAC works with a static schedule policy (offering a fixed periodic access to radio resources). This assumption allows the use of this prediction as a link performance descriptor that is complementary to C/I, BER and BLER. A series of simulations and calculations have been performed to analyze the error introduced by the prediction. The results of these tests prove that the proposed method introduces a negligible prediction error, while the computation complexity is kept at a reasonable low level.

Keywords: ARQ, IP packet delay, wireless QoS.

1 Introduction

Wireless networks and in particular cellular networks are becoming a part of everyday life. Following the success of the GSM standard, the main vendors are working on deploying 2.5G and 3G networks while standardising 4G systems. On the other hand, more customers are tending to use wireless terminals as Internet access points. Thus there is a shift of cellular data networks to carrying IP traffic.

The Internet expansion has extended the variety of accessible services from traditional Internet services. Currently streaming and conversational types of traffic occupy a significant portion of the carried content. Since cellular data networks carry IP traffic, they will be soon be expected to deliver a satisfactory quality of the service for streaming and conversational services. Hence, some Quality of Service (QoS) mechanisms are essential to fulfill these expectations.

QoS is still a problematic issue in fixed networks, where the physical condition of the data link does not vary rapidly over the connection period. Therefore, to deploy QoS in networks that have a wireless link is a greater challenge. Thus, each parameter that describes the condition of a wireless data link enables the deployment of QoS in wireless networks.

Nowadays cellular data systems are likely to have an access to the following radio link performance parameters: Carrier to Interference Ratio (C/I), Bit Error Rate (BER) and Block Error Rate (BLER). The C/I parameter describes the strength of the transmitted signal compared to the total noise that this signal is exposed to. Hence, it is related to the physical properties of the radio channel. BER is a map of C/I on the error process of transmitted bits. Its value depends not only on the radio channel quality but also on the type of modulation than has been chosen for a particular connection. On the other hand BLER represents the error process of radio blocks, which are sets of bits with its own structure.

As can be noticed, the radio link is described well within the low levels of the protocol stack. However, there are no parameters that could describe the link performance at the IP level. These kinds of descriptors could be beneficial to the MAC scheduling algorithms, by helping to achieve better radio resource utilization. Additionally if a delay sensitive traffic, such as a streaming or a conversational one, is carried then the IP oriented radio link performance descriptor could help meet the QoS delay expectations. Moreover this descriptor can be used by Radio Resource Management block (RRM).

There are a few mechanisms affecting the delay of an IP packet in the wireless part of a cellular data network. The dominant two are, Medium Access Control (MAC) and Radio Link Control (RLC). The problem of improving throughput and delay performance in cellular data systems by modifying the MAC algorithms has been extensively investigated [7], [5], and will not be addressed in this paper. Instead, the focus of this paper is the influence of the RLC on the average IP packet delay. In particular, the problem of predicting the average IP packet delay is investigated when a Selective Repeat - Automatic Repeat reQuest (SR-ARQ) mechanism is deployed. The influence of SR-ARQ on the delay performance has been studied previously. However the main focus was placed on the delay of a single radio block [1], rather than the delay of an IP packet. Extended study addressing the problem of the delay experienced by a set of m radio blocks has been presented in [6]. This study assumed no influence from previous transmissions, as, all m radio blocks belonging to the analyzed set were assumed to have been transmitted consecutively at the first transmission attempt. Contrary to this, the work presented here takes into account the effect of already existing transmission on the IP packet delay.

The algorithm that predicts this delay should keep a balance between its complexity and accuracy. Low computation complexity is required because of the limited computation power of wireless terminals and due to the cost of the base station, which is proportional to its computation power. Additionally, the time of the computation should be kept as low as possible, since the prediction of an average IP packet delay is going to be used mainly in case of delay sensitive traffic. On the other hand, the accuracy of the prediction is an important issue and cannot be overshadowed by minimizing its complexity.

In this paper we propose a low complexity algorithm for estimation the average IP packet delay at Radio Link Control (RLC) layer in cellular data networks.

The paper is structured as follows: Section 2 describes the process of transporting an IP packet over the wireless part of a cellular data network. Following that the methodology of analyzing the IP packet delay in a such connection is presented. Section 3 briefly describes the computation extensive method used for the prediction of this delay. In Section 4 the proposed low computation complexity algorithm is described and Section 5 shows the comparison between the calculated results and the simulation results. Finally Section 6 presents conclusions and some remarks.

2 IP packet delay analysis methodology [2]

In order to chose the methodology for the analysis of the IP packet delay, it is necessary to examine the nature of the process being investigating.

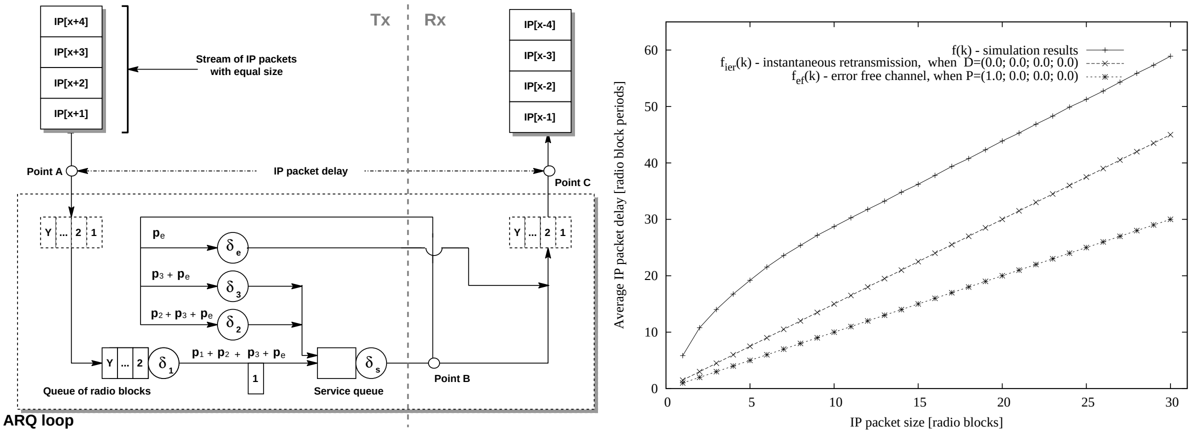
The process of transporting IP packets over the wireless part of the cellular networks relies on the protocol stack's structure. The generic wireless protocol stack consists of the following parts: Logical Link Control (LLC), RLC, MAC and the Physical Layer (PHY).

Firstly, every IP packet is mapped into an LLC frame - in the case presented here, each packet fits into one LLC frame. The LLC layer influence is omitted from this paper. Each LLC frame is fragmented into a number of radio blocks. The number of radio blocks required to transmit one LLC frame depends on the Modulation and Coding Scheme (MCS) used and the size of the particular packet. In the case of good radio channel conditions, the chosen MCS usually offers the highest payload with low protection against errors. In contrast, bad radio channel conditions forces the use of an MCS which has a small payload but strong protection against transmission errors. At the next step, the radio blocks are queued at the MAC and wait for access to the radio channel. Following that, a radio block is transmitted to a receiver through the PHY layer using the MCS selected previously by the RLC.

To separate the delay caused by the RLC from that caused by the MAC, the MAC's dynamical influence on the transmission rate has been omitted from this paper. Instead, it is assumed that every user has a fixed policy of obtaining access to the radio resources - in the case of GPRS it will be a fixed number of time-slots shared fairly with other users. This approach allows the RLC influence to be studied and allows the possible future development of MAC strategies that can compensate for these effects.

The influence of PHY layer on the transmission process is a more complex problem and is normally focused on modeling Bit Error Rates. However, due to the Forward Error Correction (FEC) mechanism implemented in the RLC it seems that the PHY can be considered as an entity for transporting radio blocks and having its own radio block error characteristic, dependent on the radio channel condition and chosen MCS.

So, in summary, LLC influence is omitted, while RLC influence is analyzed and it is the main topic of this methodology. On the other hand, MAC influence is neglected, whereas PHY influence is considered at the radio block level.



(a) Methodology description model

(b) Example of simulation results for $\overline{P}$ =(0.6;0.3;0.1;0) and $\overline{\Delta}$ =(0;8;13;0)

Fig. 1: Methodology description model and an example of simulation results.

3 Brute force solution[4]

Considering the IP packet delay mechanisms presented above, the process of transporting an IP packet is as follows. First an IP packet is mapped into a number of radio blocks. The number of radio blocks, called k, depends on the relationship between the size of the packet, IP_{size}, and the payload size of selected MCS, $RB_{Payloadsize}$, as shown in equation 1(c).

After mapping the packet into this number of radio blocks, these blocks are sent to a receiver over the radio channel. Some of them successfully reach the receiver at the first transmission attempt, but a fraction of these k radio blocks have to be transmitted two or three times before being successfully received. This creates the situation where 3^k different IP packet transmission scenarios exist.

The matrix $\mathbb{R}$ stores all possible scenarios. Each row, denoted by 'i', represents one possible transmission scenario, the columns, denoted 'j', show the order of radio blocks in the transmission buffer. Each element takes the value of the number of transmission attempts associated with the specific radio block within each scenario. Hence the matrix has the form, shown in equation 2 (a). Where $r_{i,j}$ represents the number of transmission attempts experienced by j'th radio block of the i'th possible retransmission scenario. In the case of a retransmission free scenario, all $r_{i,j}$ of a particular 'i' will be equal to one. On the other hand, $i \in \{1, 2, 3, \cdots, 3^k\}$ represents one of the 3^k possible scenarios of transporting an IP packet which has a size of k radio blocks. And finally, $j \in \{1, 2, 3, \cdots, k\}$ represents the position of the radio block in the transmission queue, in the i'th transporting scenario.

Knowing all possible scenarios, we can now create a vector of order 3^k, denoted by $\overline{S}$, that stores probabilities of occurrence for each scenario. The probability of the i'th transmission scenario occurring is the product of the probabilities of successful transmission of all its constituent radio blocks.

The probabilities of successful transmission of a radio block at a particular attempt is stored in the vector $\overline{P}$, which is one of the initial parameters. However, these probabilities have to be linked appropriately with the status of a particular radio block. Therefore, the matrix $\mathbb{R}$, is used to determined the number of transmission attempts associated with this particular radio block. Consequently, each element of $\mathbb{R}$ is an index of an element of vector $\overline{P}$. Hence, $\overline{S}$ has the form shown in equation 2 (b). Where, $s_i^r = \prod_{j=1}^{k} p_{r_{i,j}}$ represents the probability that i'th constellation of radio blocks will occur during the transmission of IP packet.

Since all possible scenarios have to be considered, the natural representation of the total delay is a vector that stores delays for every possible constellation of k radio blocks. Thus, the vector $\overline{\Delta}_{Total}$ shown in equation 2 (c) is created. Where, the vector size is 3^k and δ_i^{Total} represents the delay of an IP packet when its radio blocks have experienced the transmission attempt scenario stored the i'th row of the $\mathbb{R}$ matrix.

The approximation of b can be easily calculated as it represents the effective radio resource occupation. Therefore, $\overline{b} = \sum_{m=1}^{3} (p_m \cdot m)$, where p_m are the values taken from $\overline{P}$ vector. This summation is limited up to three, because of the assumption that only three transmission attempts for a particular radio block are allowed.

The second fraction of the step progress function cannot be found in the same way. Therefore, the C and D parameters are going to be approximated by using two points from "brute force" method. These points are $(x, \overline{f_{BF}(x)})$ and $(y, \overline{f_{BF}(y)})$, where x and y represent an IP packet size not larger than 5. Thus, the computation complexity of the "brute force" method associated with these two points is kept relatively small.

Because the C and D parameters are going to be approximated on the basis of x and y and their values can vary, then in order to be more precise about the combination of x and y used for a particular approximation approach the lower indexes are added to their name. Thus, C and D approximated on the basis of x and y are $\overline{C_{x,y}}$ and $\overline{D_{x,y}}$ respectively. Hence, if the value of x is chosen as one and the value of y is chosen as two, then they will have the following form $\overline{C_{1,2}}$ and $\overline{D_{1,2}}$.

Since the "brute force" method has a low complexity for small IP packets, then the calculation of the step delay progress for such packets will not require greater computation complexity. Thus, the "brute force" method is used to calculate the step delay progress. Therefore, $\overline{\Delta f_{BF}(k)} = \overline{f_{BF}(k)} - \overline{f_{BF}(k-1)}$. By combining this with the equation 6 it is possible to create two independent equations for two approximation points $(x, \overline{f_{BF}(x)})$ and $(y, \overline{f_{BF}(y)})$.

$$\overline{f_{BF}(x)} - \overline{f_{BF}(x-1)} - \overline{b} = \overline{C_{x,y}} \cdot e^{-\overline{D_{x,y}} \cdot x} \tag{7}$$

$$\overline{f_{BF}(y)} - \overline{f_{BF}(y-1)} - \overline{b} = \overline{C_{x,y}} \cdot e^{-\overline{D_{x,y}} \cdot y} \tag{8}$$

After a few mathematical operations.

$$\overline{D_{x,y}} = \frac{ln(\overline{f_{BF}(y)} - \overline{f_{BF}(y-1)} - \overline{b}) - ln(\overline{f_{BF}(x)} - \overline{f_{BF}(x-1)} - \overline{b})}{x-y} \tag{9}$$

$$\overline{C_{x,y}} = (\overline{f_{BF}(x)} - \overline{f_{BF}(x-1)} - \overline{b}) \cdot e^{\overline{D_{x,y}} \cdot x} \tag{10}$$

Thus, the final form of $f(k)$ approximation function, based on $(x, \overline{f_{BF}(x)})$ and $(y, \overline{f_{BF}(y)})$ points, denoted as $\overline{f_{CD_{x,y}}(k)}$, has the following form.

$$\overline{f_{CD_{x,y}}(k)} = \overline{f_{BF}(1)} + \sum_{n=2}^{k} \left(\overline{C_{x,y}} \cdot e^{-\overline{D_{x,y}} \cdot n} + \overline{b} \right) \tag{11}$$

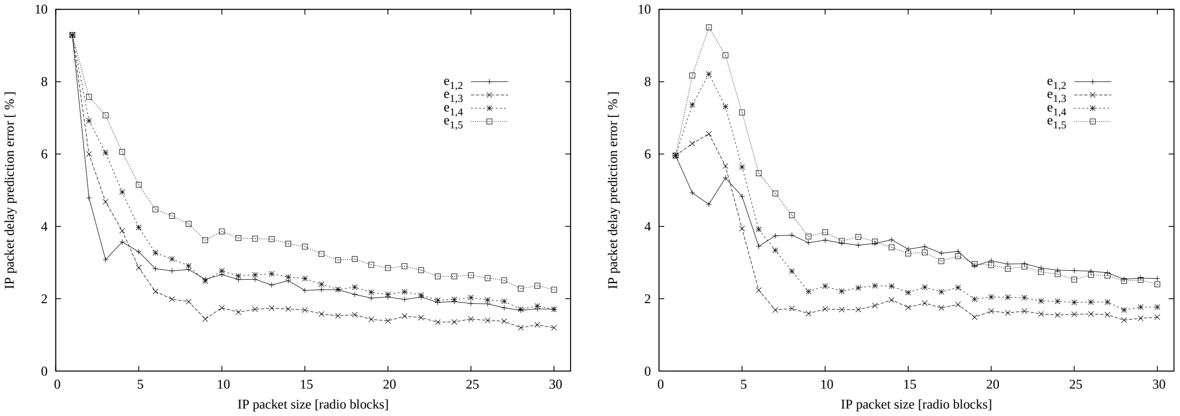
5 Results

Since x and y can take any value between one and five there is a set of different solutions for the C and D parameters. This will affect the final version of the approximation function. Therefore, there is a need to test different combinations of x and y values and find a one that introduces the smaller error between the delay function $f(k)$, obtained from simulation, and the prediction of this function $\overline{f(k)}$, obtained from the analytical solution.

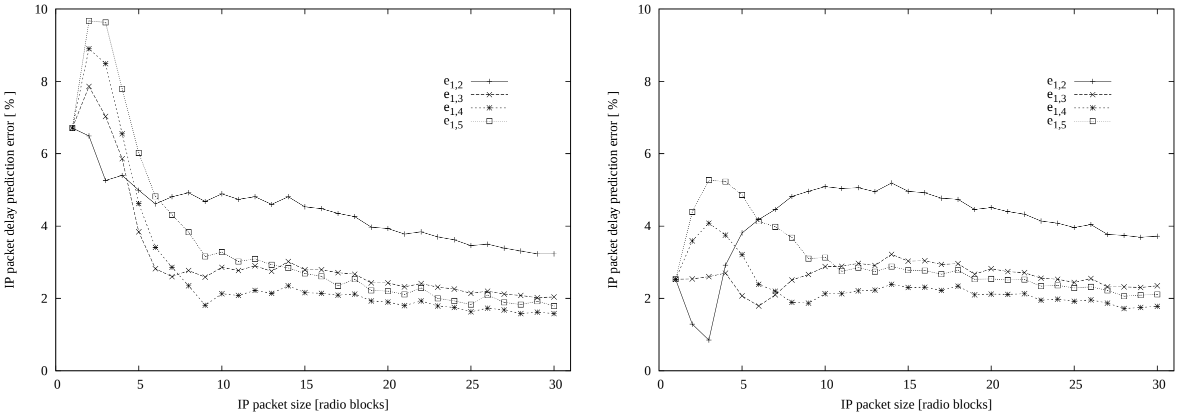
To do that a series of tests have been performed, with different possible radio channel conditions, described by the vector $\overline{P}$, and different ARQ feedback loop delays, described by the vector $\overline{\Delta}$.

The $\overline{P}$ is represented in five forms, and each of them represents different radio channel conditions. The first case, called T0, represents a situation where only 10 percent of radio blocks have to be retransmitted, while the following cases T1, T2, T3 and T4 represent worsening retransmission scenarios. For T0 the radio channel vector is $\overline{P} = [0.9; 0.07; 0.03; 0.0]^T$, which means that we assume that 90 percent of radio blocks will reach the receiver at the first transmission attempt, 7 percent at the second attempt, and 3 percent at the third attempt. The last position is zero and it indicates that in this scenario there is no errors experienced by any of the radio blocks after the second retransmission. The other cases, T1 to T4, can be interpreted in the same way. The other radio channels vectors are the following: T1 - $\overline{P} = [0.6; 0.3; 0.1; 0.0]^T$, T2 - $\overline{P} = [0.3; 0.4; 0.3; 0.0]^T$, T3 - $\overline{P} = [0.1; 0.3; 0.6; 0.0]^T$ T4 - $\overline{P} = [0.03; 0.07; 0.9; 0.0]^T$.

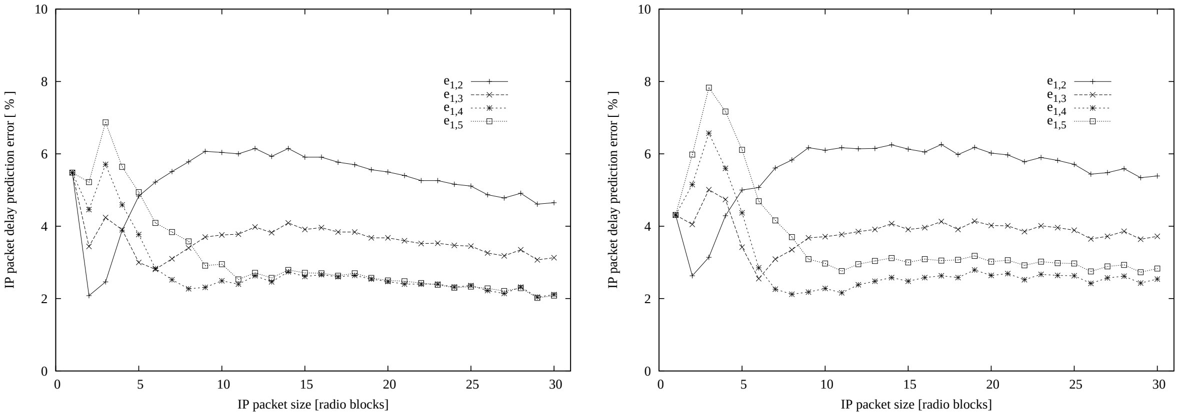
The $\overline{\Delta}$ is chosen to have several forms, to test the method under different ARQ loop delay properties. These values are the following: (a) $\overline{\Delta} = [0; 8; 13; 0]^T$, (b) $\overline{\Delta} = [0; 14; 19; 0]^T$, (c) $\overline{\Delta} = [0; 13; 23; 0]^T$, (d) $\overline{\Delta} =$



(a) $\overline{\Delta}$ =(0;8;13;0) (b) $\overline{\Delta}$ =(0;14;19;0)



(c) $\overline{\Delta}$ =(0;13;23;0) (d) $\overline{\Delta}$ =(0;19;29;0)



(e) $\overline{\Delta}$ =(0;18;33;0) (f) $\overline{\Delta}$ =(0;24;39;0)

Fig. 2: IP packet delay prediction error averaged over fife radio channel conditions, T0, T1, T2, T3, T4 for different ARQ loop delay conditions, $\overline{\Delta}$.

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