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Abstract: The stack protocol (called also tree protocol) can be used in order to introduce a priority mechanism on the random access stage in W-CDMA. Indeed, after second generation networks supporting voice service only, the third generation systems (UMTS) should offer more services with quality and priority. However, all priorities in the UMTS system are based on the dedicated channel and after the random access mechanism that use the weak access protocol: slotted aloha. In this paper, we analyze the possibility to apply the tree random access protocol for the W-CDMA part in the UTRA radio interface proposition. We study also a priority system applied on the random access directly. The analytical model use generating functions and an algebraic method in order to show the stack protocol performance. Also, numerical and simulation results are presented and show the predominance of this protocol compared with the slotted aloha mechanism.

Key-words: stack protocol, tree protocol, random access, slotted aloha, W-CDMA, UMTS

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Analyse du protocole en arbre pour un système W-CDMA avec priorité

Résumé : Dans cet article, nous étudions la possibilité d'appliquer le protocole en arbre pour améliorer la résolution de conflits sur l'accès aléatoire du système UMTS, lequel utilise le mécanisme "slotted aloha". Ce dernier exclut toute forme de priorité entre les utilisateurs. Nous montrerons également la manière dont on peut introduire la priorité au premier niveau de l'accés aléatoire à travers le protocole en arbre

Mots-clés : accés aléatoire, CDMA, protocole en arbre, UMTS

1 Introduction

Broadband communications in wireless networks are going to be developed in order to provide a larger bandwidth for multimedia applications. At the beginning of the third millenium, a large number of users will have access to third generation wireless systems such UMTS or IMT2000. Those systems can provide up to 2 Mbps for wireless transmissions and offer a multitude of Quality of Service (QoS) in terms of throughput, delay and priority [1].
Basically, the second layer in the UMTS architecture manages all services proposed in the UMTS [2]. The W-CDMA random access protocol based on the slotted aloha protocol does not consider any priority treatment for important traffic. The major aim in this protocol is to detect collision and try to resolve it. After the conflict resolution, the system dedicates channels upon service requirement by allocating a code, a spreading factor, and transport blocks. This allocation takes into account the importance of the type of traffic and consider the priority fixed by the user on both uplink and downlink direction. In short, all types of traffic are considered like equals from the priority point of view. So, a success access on the air interface is necessary before informing the system about the importance of the user traffic. Therefore, the introduction of an upstream priority system to introduce priority on the first stage of the access protocol is indispensable for a system based on guaranteed services.
From the random access protocol standpoint, the aloha protocol is the most basic protocol in the random access field. It consists of generating random time out, when a collision state is produced, and submitting a second access request after, when this time out is spending. More sophisticated mechanism was created to improve the performance of the aloha protocol. This used by W-CDMA is called "slotted aloha". The improvement is resumed by dividing the time into slots and each user can submit an access request only at the beginning of a slot. This must reduce the probability of collision between user requests. Anyway, the aloha protocol and all its variations presents a non-stability behavior with an infinite number of users [3].
On the other hand, the tree random access protocol [4, 5, 6] provides better performance of the aloha protocol. This protocol is stable and converges under infinite population conditions if the arrival rate of users per second does not exceeds a certain threshold. Several degrees of the tree protocol exist. In [7], Mathys and Flojolet show that best performances of the tree protocol are obtained by setting the degree at 3. In addition, the tree protocol offers more bandwidth than aloha protocol and reduce the delay for a user before acquiring a resource. This protocol was adopted for random access on cable TV (IEEE 802.14) [8, 9].
Our approach consists of using the tree protocol for W-CDMA random access and adding priorities in the protocol consideration (only two priorities will be introduced). Thus, The idea is to use two different CDMA codes for each priority and then the base station by distinguishing the priority can grant the first priority at the expense of the second one. Hence, in this paper, we show first the feasibility of such protocol applied to the W-CDMA random access. Then, we introduce the system priority to manage different traffic requirements.
This paper is organized as follows: Section 2 of this paper reviews briefly the aloha protocol and the random access mechanism in W-CDMA. It also introduces the tree protocol with priority enhancement; while Section 3 describes the analytical model used to study the performance of our proposal. Section 4 presents the numerical and simulation results.

2 W-CDMA random access description

2.1 Slotted aloha and random access in W-CDMA

The W-CDMA uses a slotted aloha scheme for its random access protocol [10]. As depicted in Figure 1, the time is divided into slots and each user can submit a transmission request only at the boundary of a slot. The random access request use the RACH (Random Access CHannel) logical channel. The RACH is carried by a Physical RACH (PRACH). The access request is composed of two parts: preamble part and message part. The preamble uses one of the 16 signatures available in each cell. Signatures are composed of 16 complex symbol, which is spread with a 256 chip real Orthogonal Gold code (for more details see: [11]). The structure of the random-access transmission is shown in Figure 2. The random-access transmission consists in one or several preambles of length 4096 chips and a message of length 10 or 20 ms. The use of several preambles is needed to find the exact power control level for the preamble transmission. In fact, preambles are sent with successive attempts by ramping the signal power until the reception of the acquisition indicator from the base station. When no acquisition is received after a certain number of attempts, the random access procedure fails.
The message is divided into two components: data part and control part that are sent in parallel in the I and Q components of the physical channel. The control part consists of pilot symbols and information on data rate transmission (see Figure 3). Hence, the random access protocol can support variable bite rate. The data part

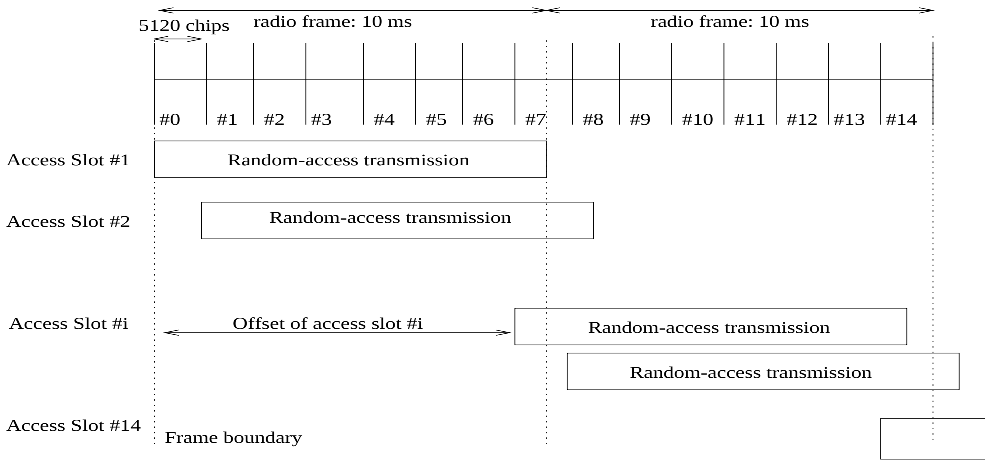

Figure 1: Access slots for random access protocol.

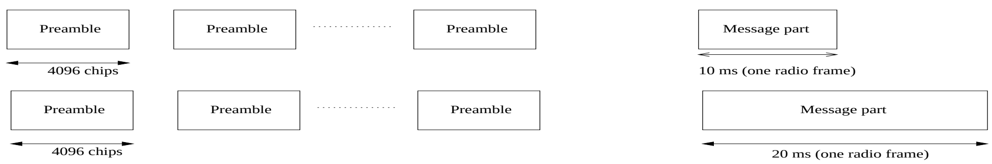

Figure 2: Structure of the random-access transmission.

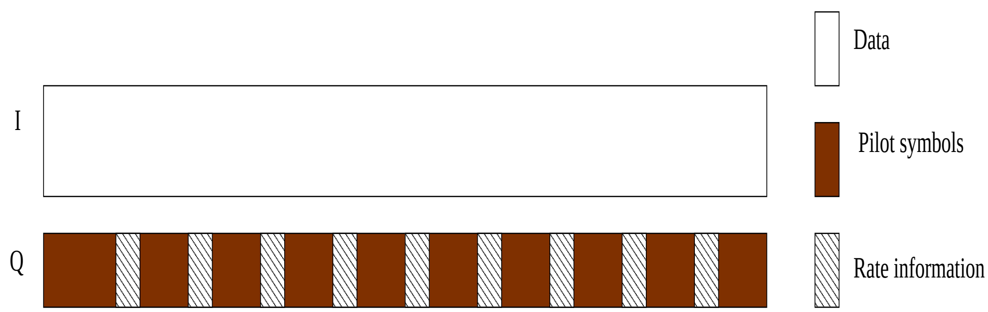

Figure 3: Message part.

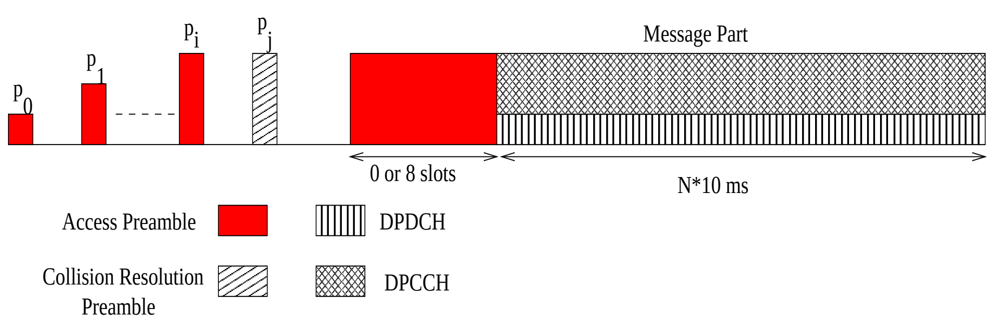

Figure 4: Structure of the CPCH random-access transmission.

carries the random access request or user packet. The spreading factor (SF) of the data part is limited to SF {256, 128, 64, 32} corresponding to channel bit rates of 15, 30, 60, and 120 kbps respectively [10].

When the user makes a random access request, he must acquire chip and frame synchronization to the target base station according to the cell search procedure [12]. Then, he obtains information about what random-access preamble codes are available in the cell from the broadcast cell channel (BCH). After acquiring information, the mobile station selects the spreading codes to be used for the preamble and message parts. The mobile station also selects the spreading factor (i.e., the channel bit rate) for the message part [12].
The user, next, estimates the downlink path loss and computes the required uplink transmit power to be used for the random access burst. At this moment, the user chooses randomly an access slot and transmits the preamble part. If the user does not detect any acquisition indicator with the selected signature, he retransmits the preamble part as mentioned above (see Figure 2). Then, the user sends the message part with the same signal power of the last preamble part. Finally, the physical layer indicates a "RACH message transmitted" to the second layer [12].
Evidently, no collision contention is applied on this random access mechanism. If any collision is happened (the probability is high under heavy traffic conditions), the message is loosed.
Another access procedure called Common Packet CHannel (CPCH) that applies a collision resolution by using an intermediary preamble before sending the message part. As depicted in Figure 4, first, several access preambles are transmitted for computing the power level and then a collision resolution preamble is sent. The base station will select a user for the transmission of its message part. Basically, when a user detects another signature that he transmitted, he stops the random access procedure. So, only the user with the adequate signature can submit the message part [12].

2.2 Tree protocol with priority access

The tree algorithm is used for resolving collision on the W-CDMA air interface. The idea of this protocol is to submit a random access preamble and wait a acknowledgment from the medium manager (in our case, the medium manager is the base station). Indeed, the user sets his stack level to 0 and starts transmission of the preamble at the beginning of the nearest access slot. Basically, if a negative acknowledgment is done, all users consider that there is a collision of different requests. When a collision happens between a certain number of users, each user generates randomly a value x, $x \in [0, N-1]$ (x is a stack level during the next slot, N is the degree of the tree protocol or the number of split levels, in our case $N = 3$ (see [13, 14, 7]). A user transmits only if his level $x = 0$. If the user is alone on the access slot, the base station will acknowledge the user for the random access. Else, when several users generate exactly the same value x, there will be once again a collision. Hence, the same procedure will be applied again.
An example is shown in Figure 5. The collision resolution is depicted in a tree diagram. This example uses a 2-degree tree protocol. In this Figure, four users a, b, c, and d are in collision on the same random access slot. All users try to generate values between 0 and 1. We suppose that a and b generate 0 and c and d generate 1. So, a and b are in collision on the first slot and c and d are also in collision on the second one. More again, users generate values. In a first time a and b obtain the same value (for x) and after they are separated on two different slots by generating different x values. Meanwhile, a new user called e tries to access to the medium. The same treatment is done for this new client, as depicted in Figure 5. On the other hand, when a, b, and e successfully transmit their preambles, c and d apply the same procedure and at eventually, they transmit their preambles.
Table 1 illustrates the virtual stack that describes the protocol functioning of this example. Only clients situated on the first row of the stack can submit a random access request. When a slot is in collision, all users with level $x > 0$ increment their level by $N - 1$ (in this example N=2), change their position and go deeper in the stack. In a case of a free slot or a slot with a successful transmission, all users in the stack reduce there level by 1.
Now, we present an adaptation of the tree protocol to work in a W-CDMA context. Basically, we do not modify or add requirements compared with existing mechanism. Figure 6 exhibits the priority introduction in the random-access procedure. Referring to UMTS specifications [10, 12], access preamble signatures can be divided into several sets. Each set is equivalent to an access priority. The acquisition indicator can acknowledge each priority by using the same signature of the access priority preamble (typically, other users that using different signatures understand that the medium is not free).
First, the user selects a signature from all available signatures of the requiring priority (this information can be available on the Broadcast Channel (BCH)). Second, the user submits its preamble on the air interface and waits for the acknowledgment on the AICH (Acquisition Indicator CHannel). The base station manages the user priority. If no superior priority that requires a free slot, the base station sends a positive acknowledgment. When a positive AICH is receiving (left side of Figure 6), the user sends the random-access message. Obviously,

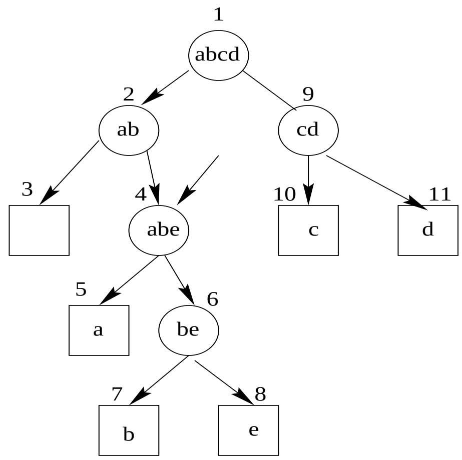

Figure 5: The resolution collision tree.

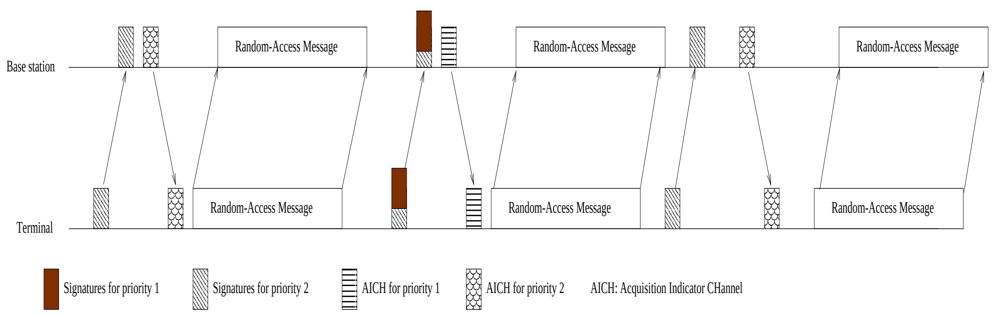

Figure 6: Example of a tree protocol transmission in W-CDMA.

Slot	1	2	3	4	5	6	7	8	9	10	11
Channel	$\times$	$\times$		$\downarrow\times$	$\uparrow$	$\times$	$\uparrow$	$\uparrow$	$\times$	$\uparrow$	$\uparrow$
	$abcd$	ab	$\emptyset$	abe	a	be	b	e	cd	c	d
Stack	–	cd	ab	cd	be	cd	e	cd	–	d	–
	–	–	cd	–	cd	–	cd	–	–	–	–

$\times$: collision; $\uparrow$: success; $\downarrow$: arrival

Table 1: The protocol stack.

collision between users using the same signature (users of the same priority class) is resolved by the tree protocol procedure, e.g. users will generate a random value etc ...

When several simultaneous transmissions of different priority requests, the base station will distinguish the priority thanks to the signature (information about signature partitioning can be found on the BCH). The right side of Figure 6 displays a collision between two priorities: first and second. The base station sends a positive AICH only for the first priority. The user of the second priority, by seeing the positive AICH modulated with another signature, will stop transmission and leaves the medium for the transmission of the first priority message not changing his level x. Then, he can restart the access procedure on the next access slot.

3 Analytical model

3.1 Traffic model

We consider a broadcast system with two Poisson flows of packets. Packets of different flows have different priorities. The input flow rates of first and second priority packets are respectively λ_1 and λ_2. We suppose that

the packets of first priority get the access to the channel using the free access stack algorithm with three split levels.
We do not repeat the rules of the stack algorithm. We call by k-session a sequence of slots that starts with a slot where k packets are transmitted (a k-collision) and there exists a "virtual" packet with stack level $x = 1$; the end of k-session coincides with the end of the slot after which a "virtual" packet level becomes equal to 0. We call k-sessions, $k \geq 1$, by busy sessions. A sequence of several busy sessions that follows a 0-session and is followed by a 0-session is called a busy period.
Our first model of a system with two flows is a model where the second priority packets are transmitted during the slots when non of first priority packets is transmitted. The packets of second priority get the access to the channel "between" the slots with first priority packets transmission, also using the free access stack algorithm with 3 split levels. The rigorous analytical investigation of such system seems difficult, because the distribution of idle slots in stack algorithm is not known. Note that while both input flows are Poisson, different intervals between idle slots (of first priority transmission) cause a "bursty" second priority flow upon the idle slots. Compared with delay of a Poisson flow with the same mean rate, a bursty flow has a larger delay.
Apparently using asymptotical approach, it is possible to investigate analytically the case of small values of λ_1. But we are interested in a more general case. In general case, simulations are used to estimate the delay of the second priority packets and the throughput of the full flow.
We consider analytically a second model that can give the upper bound of mean delay and the lower bound of throughput for the first model. Namely, we assume that second priority packets can be transmitted only between the busy periods, that is, during the sessions of multiplicity 0 (it is assumed that a base station broadcasts a special information indicating the end of a session). The second priority packets also use stack algorithm following the usual stack algorithm rules during the slots that do not belong to the busy periods of the first flow stack algorithm. It is plain that there exist a difference between the performance of algorithms for two types of packets: for the first priority packets, the stack memory and a packet level change at the beginning of every slot, while for the second priority stack, its memory does not change during the busy sessions of the first stack. As a simplifying assumption, we assume that the mobile node population is virtually infinite (infinite population model [15]).

3.2 Priority 1 model

This section is a simple remainder about the work done in [6, 7, 16].
We denote as a priority 1 session the time period between two consecutive slots where the stack counter of priority 1 is zero.
Let H_k^1 being the average length in slots of a random priority 1 session which starts with a collision of k mobile nodes.
Following [6, 7], we have

$$\begin{aligned} H_0^1 &= H_1^1 = 1 \\ H_k^1 &= 1 + \frac{1}{3^k} \sum_{k_1,k_2=0}^{k} \binom{k}{k_1 k_2} \sum_{l=0}^{\infty} (H_{k_1+l}^1 + H_{k_2+l}^1 + H_{k-k_1-k_2+l}^1) q_1^1(l) \end{aligned} \tag{3.2.1}$$

with

$$q_m^i(k) = e^{-m\lambda} \frac{(m\lambda_1)^k}{k!} \tag{3.2.2}$$

Let $P_{k,m}^1$ be the probability a random priority 1 session starting with a collision of multiplicity k has a length of exactly m slots.

$$\begin{aligned} P_{0,m}^1 &= P_{1,m}^1 = \delta(m = 1) \\ P_{k,m}^1 &= 0 \qquad \text{for } m < k+1, \text{ and } k > 1 \\ P_{k,m}^1 &= \sum_{k_1,k_2=0}^{k} \binom{k}{k_1 k_2} \frac{1}{3^k} \sum_{l_1=0}^{\infty} q_1^1(l_1) \sum_{m_1}^{m-2} P_{k_1+l_1,m_1}^1 \sum_{l_2=0}^{\infty} q_1^1(l_2) \\ &\times \sum_{m_2}^{m-m_1-1} P_{k_2+l_2,m_2}^1 \sum_{l_3=0}^{\infty} q_1^1(l_3) P_{k-k_1-k_2+l_3,m-m_1-m_2-1}^1 \end{aligned} \tag{3.2.3}$$

where $\delta(F)$ matches Kronecker symbolism, *i.e.* $\delta(F)=0$ when F is false and $\delta(F)=1$ when F is true.

3.3 Priority 2 model

We call priority 2 slot, the period between two slots where priority 2 nodes are authorized to transmit, *i.e.* when the priority 1 stack counter is zero and no priority 1 node transmits. We denote by Y the length in slot of a priority 2 slots and Y_m the probability that a priority 2 slot is of length equal to m slots. According to the memoryless property of Poisson traffic, the length of priority 2 slots are i.i.d.
According to the previous section, we have

$$\begin{aligned} Y_m = P(Y=m) &= \delta(m=1)e^{-\lambda_2} + (1-e^{-\lambda_2}) \sum_{m_1+m_2=m} Q^*_{m_1} Y_{m_2} \\ &= \delta(m=1)e^{-\lambda_2} + \sum_{m_1 \geq 1}^{m-1} Q_{m1} Y_{m-m_1} \end{aligned} \tag{3.3.1}$$

with

$$Q(m) = \sum_{k=0}^{\infty} q_1^1(k) P^1_{k,m} \tag{3.3.2}$$

$$Q^*(m) = \frac{\sum_{k=1}^{\infty} q_1^1(k) P^1_{k,m}}{1-e^{-\lambda_1}} \tag{3.3.3}$$

We denote as a priority 2 session, the time period between two consecutive slots where nodes of priority 2 are authorized to transmit and the stack counter of priority 2 is zero. A priority 2 session is made of an integer number of priority 2 slots.
Let H_k^2 be the average number of priority 2 slots contained in a random priority 2 session starting with a collision of k mobile nodes of priority 2.

$$\begin{aligned} H_0^2 &= H_1^2 = 1 \\ H_k^2 &= 1 + \frac{1}{3^k} \sum_{k_1,k_2=0}^{k} \binom{k}{k_1 k_2} \sum_{l=0}^{\infty} (H^2_{k_1+l} + H^2_{k_2+l} + H^2_{k-k_1-k_2+l}) q_l(\lambda_2, Y) \end{aligned} \tag{3.3.4}$$

with

$$q_l(\lambda_2, Y) = \sum_{m=1}^{\infty} Y_m q_m^2(l) \tag{3.3.5}$$

3.4 Maximum throughput analysis

In [6], it is shown that the maximum value attainable by λ_1 in a stable system is $\lambda_{\max} \approx 0.401599$, in this section, we will determine via analytical means the maximum value attainable by λ_2 when $\lambda_1 < \lambda_{\max}$. For example, it is expected that when $\lambda_1 = 0$, the maximum attainable value of λ_2 is $\lambda_{\max}$, and when λ_1 tends to $\lambda_{\max}$, the maximum attainable value of λ_2 tends to 0.
We denote as $H^{\langle 2 \rangle}(z) = \sum_{n\geq 0} H_n^2 \frac{z^n}{n!} e^{-z}$. In [17], we call $H^{\langle 2 \rangle}(z)$ the Poisson generating function of the sequence $\{H_n^2\}_{n\in N}$ since the coefficient $\frac{z^n}{n!}e^{-z}$ is exactly the n-th coefficient of a Poisson distribution of parameter z. In the following, we assume that quantity z is a complex number and $H^{\langle 2 \rangle}(z)$ is an analytical function of z.
The generating function $H^{\langle 2 \rangle}(z)$ satisfies the functional equation

$$H^{\langle 2 \rangle}(z) = 1 + 3\mathbf{T}H^{\langle 2 \rangle}(z) - 3\mathbf{T}H^{\langle 2 \rangle}(0)(1+z)e^{-z} - 3(\mathbf{T}H^{\langle 2 \rangle})'(0) z e^{-z} \ , \tag{3.4.1}$$

where $\mathbf{T}f(z) = \sum_{m\geq 0} Y_m f(z/3 + m\lambda_2)$ and $(\mathbf{T}H^2)'(.)$ is the first derivative of $\mathbf{T}H^{\langle 2 \rangle}(.)$.
We need the following technical lemma:

Lemma 1 *Let $f(z)$ and $g(z)$ be analytical functions. Assume that $g(z) = O(z^2)$ when $\Re(z) \to \infty$ and $f(z) - 3\mathbf{T}f(z) = g(z)$, then the following equality holds:*

$$f(z) = f(0) + zf'(0) + \sum_{n=0}^{\infty} 3^n(\mathbf{T}^n g(z) - \mathbf{T}^n g(0) - z(\mathbf{T}^n g)'(0) \ , \tag{3.4.2}$$

And the above series converges in $O(3^{-n})$

Proof: We derive twice to obtain $f''(z) - \frac{1}{3}Tf''(z) = g''(z)$. Using an argument detailled in [16], we also have that $g(z) = O(1)$ when $\Re(z) \to +\infty$. We can formally invert the identity $f''(z) - \frac{1}{3}\mathbf{T}f''(z) = g(z)$ by $f''(z) = \sum_{n\geq 0} \frac{1}{3^n}\mathbf{T}^n g''(z)$ as long the later series converges. Indeed, we have

$$\begin{aligned} \mathbf{T}^n g''(z) &= \sum_{m_0} \cdots \sum_{m_{n-1}} Y_{m_0} \cdots Y_{m_{n-1}} g''(\frac{z}{3^n} + m_0 + \cdots + \frac{m_{n-1}}{3^{n-1}}) \\ &= \sum_{m_0} \cdots \sum_{m_{n-1}} Y_{m_0} \cdots Y_{m_{n-1}} O(1) = O(1) \ . \end{aligned} \tag{3.4.3}$$

Integrating twice

$$\begin{aligned} f(z) =& f(0) + zf'(0) + \int_0^z \int_0^y f''(y)dy \\ =& f(0) + zf'(0) + \sum_{n\geq 0} 3^n(\mathbf{T}^n g(z) - \mathbf{T}^n g(0) - z(\mathbf{T}^n g)'(0)) \end{aligned} \tag{3.4.4}$$

which terminates the proof of the lemma.
In the sequel, we denote by $\mathbf{R}g(z)$ the function $\sum_{n\geq 0} 3^n(\mathbf{T}^n g(z) - \mathbf{T}^n g(0) - z(\mathbf{T}^n g)'(0))$.
Using the above lemma on Equation (3.4.1) and using the fact that $H^{\langle 2\rangle}(0) = 1$ and $(H^{\langle 2\rangle})'(0) = 0$, it comes that:

$$H^{\langle 2\rangle}(z) = 1 - 3\mathbf{T}H^{\langle 2\rangle}(0)(\mathbf{R}e_1(z) + \mathbf{R}e_2(z)) - 3(\mathbf{T}H^{\langle 2\rangle})'(0)\mathbf{R}e_2(z) \ , \tag{3.4.5}$$

where $e_1(z) = e^{-z}$ and $e_2(z) = ze^{-z}$.

Theorem 1 *The maximum value of λ_2 for a given $\lambda_1 < \lambda_{\max}$ is the first non-negative root in λ_2 of $D(\lambda_1, \lambda_2)$, where*

$$\begin{aligned} D(\lambda_1, \lambda_2) =& (1 + 3\mathbf{T}\mathbf{R}e_1(0) + 3\mathbf{T}\mathbf{R}e_2(0)) \times (1 + 3(\mathbf{T}\mathbf{R}e_2)'(0)) - \\ &- 9(\mathbf{T}\mathbf{R}e_2(0)) \times ((\mathbf{T}\mathbf{R}e_1)'(0) + (\mathbf{T}\mathbf{R}e_2)'(0)) \ . \end{aligned} \tag{3.4.6}$$

Proof: Using Equation (3.4.5), it comes that

$$\mathbf{T}H^{\langle 2\rangle}(z) = 1 - 3\mathbf{T}H^{\langle 2\rangle}(0)(\mathbf{T}\mathbf{R}e_1(z) + \mathbf{T}\mathbf{R}e_2(z)) - 3(\mathbf{T}H^{\langle 2\rangle})'(0)\mathbf{T}\mathbf{R}e_2(z) \ , \tag{3.4.7}$$

substituting $z = 0$ gives the identity

$$(1 + 3\mathbf{T}\mathbf{R}e_1(0) + 3\mathbf{T}\mathbf{R}e_2(0))\mathbf{T}H^{\langle 2\rangle}(0) + 3(\mathbf{T}\mathbf{R}e_2(0))(\mathbf{T}H^{\langle 2\rangle})'(0) = 1 \tag{3.4.8}$$

Derivating (3.4.7) gives the second identity

$$3((\mathbf{T}\mathbf{R}e_1)'(0) + (\mathbf{T}\mathbf{R}e_2)'(0))\mathbf{T}H^{\langle 2\rangle}(0) + (1 + 3(\mathbf{T}\mathbf{R}e_2)'(0))(\mathbf{T}H^{\langle 2\rangle})'(0) = 0 \tag{3.4.9}$$

Together, identities (3.4.8) and (3.4.9) form a linear system where the only unknown are $\mathbf{T}H^{\langle 2\rangle}(0)$ and $(\mathbf{T}H^{\langle 2\rangle})'(0)$; the other $\mathbf{T}\mathbf{R}e_i(0)$'s and derivative are constant depending on λ_1 and λ_2 via the application of operators $\mathbf{T}$ and $\mathbf{R}$ over functions $e_1(z)$ and $e_2(z)$:

$$\begin{bmatrix} 1 + 3\mathbf{T}\mathbf{R}e_1(0) + 3\mathbf{T}\mathbf{R}e_2(0) & 3\mathbf{T}\mathbf{R}e_2(0) \\ 3(\mathbf{T}\mathbf{R}e_1)'(0) + 3(\mathbf{T}\mathbf{R}e_2)'(0) & 1 + 3(\mathbf{T}\mathbf{R}e_2)'(0) \end{bmatrix} \times \begin{bmatrix} \mathbf{T}H^{\langle 2\rangle}(0) \\ (\mathbf{T}H^{\langle 2\rangle})'(0)) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{3.4.10}$$

The determinant of the system is $D(\lambda_1, \lambda_2)$. As long $D(\lambda_1, \lambda_2) \neq 0$, by application of Cramer resolution, the system has a finite solution, which proves that the system is stable. When $D(\lambda_1, \lambda_2) = 0$, the solution becomes infinite and the system is unstable, which terminates the proof of the theorem.

Remark: the unconditional average priority 2 session lengh is $\mathbf{T}H^{\langle 2\rangle}(0)$ priority 2 slots.

3.5 Delay model

The delay analysis of the first priority packets is already done in [16]. Now, we turn to packets of the second flow when $\lambda_2 > 0$.
Let $d_{2,l},\ l > 0$ be the average delay in priority 2 slots of a second priority packet that is transmitted for the first time in the beginning of a priority 2 session starting with a collision of multiplicity l. Quantities $d_{2,l}$ satisfy the system

$$\begin{aligned} d_{2,1} &= 1 \\ d_{2,l} &= 1 + 3^{-l} \sum_{0\le l_1,l_2,\ l_1+l_2\le l,\ i\ge 0} \binom{l}{l_1, l_2} Q_2(i_1)\Big[\frac{l_1}{l} d_{2,l_1+i_1} \\ &+ \sum_{i_2\ge 0} Q_2(i_2)\Big(\frac{l_2}{l}(H_{2,l_1+i_1} + d_{2,l_2+i_2}) \\ &\sum_{i_3\ge 0} Q_2(i_3)\frac{l-l_1-l_2}{l}(H_{2,l_1+i_1} + H_{2,l_2+i_2} + d_{2,l-l_1-l_2+i_3}\Big)\Big]. \end{aligned} \tag{3.5.1}$$

The mean delay $D^{(2)}$ of the second priority virtual packet is

$$D^{(2)} = \frac{E(Y^2)}{2E(Y)} + \frac{\sum_{k,l\ge 0} Q_2(k) s_{1,k}(l)(d_{2,l+1} - 1)}{\sum_{l=0} Q_2(l) H'_{2,l}}, \tag{3.5.2}$$

where $s_{2,k}(l)$ is the mean number of slots with transmission of l second flow packets in a session of the second flow starting with a collision of multiplicity k. The values $s_{1,k}(l)$ satisfy the system

$$\begin{aligned} &s_{2,0}(l) = \delta_{0,l},\ s_{2,1}(l) = \delta_{1,l}, \\ s_{2,k}(l) = \delta_{k,l} + 3^{-l} &\sum_{0\le k_1,k_2,\ k_1+k_2\le k,\ i\ge 0} \binom{k}{k_1, k_2} Q_2(i)(s_{2,k_1+i}(l) + s_{2,k_2+i}(l) + s_{2,k-l_k-k_2+i})(l),\ k > 1. \end{aligned} \tag{3.5.3}$$

The values $H'_{2,l}$ satisfy the system 3.3.4 with $a_l = 1,\ l \ge 0$.
The mean time $T(2)$ a packet of the second flow stays in the system is

$$T(2) = (1 - e^{-\lambda_1}) D_w^{(2)} + D^{(2)} \tag{3.5.4}$$

4 Numerical and simulation results

Numerical resolution of the determinant of equation 3.4.10 is plotted on Figure 7. The line on the figure represents $\lambda_1 = \lambda_1$. We define the function $\lambda_{2,max}(\lambda_1)$ as the maximum value of λ_2 than occurs when the rate of first priority traffic is λ_1. The upper curve shows the behavior of the stack protocol in two-priority conditions. As for the one-priority stack protocol, the maximum value of $\lambda = \lambda_1 + \lambda_{2,max}(\lambda_1)$ is near 0.4. This value guarantees the protocol convergence under infinite population conditions. When λ_1 increases the value of $\lambda_{2,max}(\lambda_1)$ decreases in order to produce a stable value for the sum. Note that for a big value of λ_1, the convergence of the protocol is very slow and needs a high computing power to find the stable value.
We can also observe on the figure that the summation of both $\lambda_1,\ \lambda_2$ can reach a bigger value than the theoretical maximum value (0.4). This is due to the virtual non-collision scenario between first and second priority. In fact, when two users from different classes are in collision, they use two different signatures and the collision is automatically resolved by giving priority to the first traffic attempts. Therefore, when using a two-priority system, more collisions can be managed with same bandwidth.
The mean of session length can be computed as follows:

$$\begin{aligned} E[H^2] &= E[Y] \sum_{k,m} P(Y = m) q_m^2(k) H_k^2 \\ &= \sum_m m P(Y = m) \sum_{k,m} P(Y = m) q_m^2(k) H_k^2 \\ &= \sum_m m Y_m \sum_{k,m} Y_m q_m^2(k) H_k^2 \end{aligned} \tag{4.0.5}$$

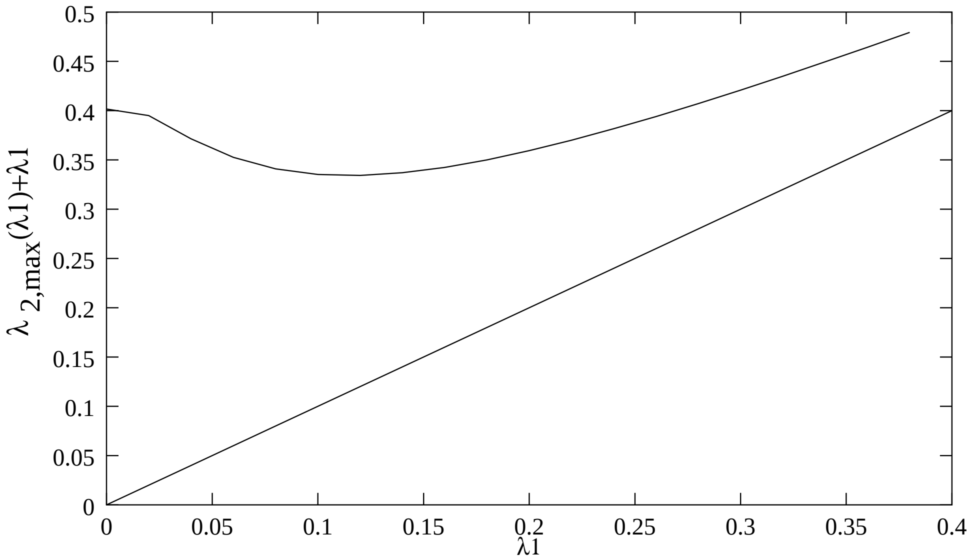

Figure 7: Stability area of the 2-priority stack protocol.

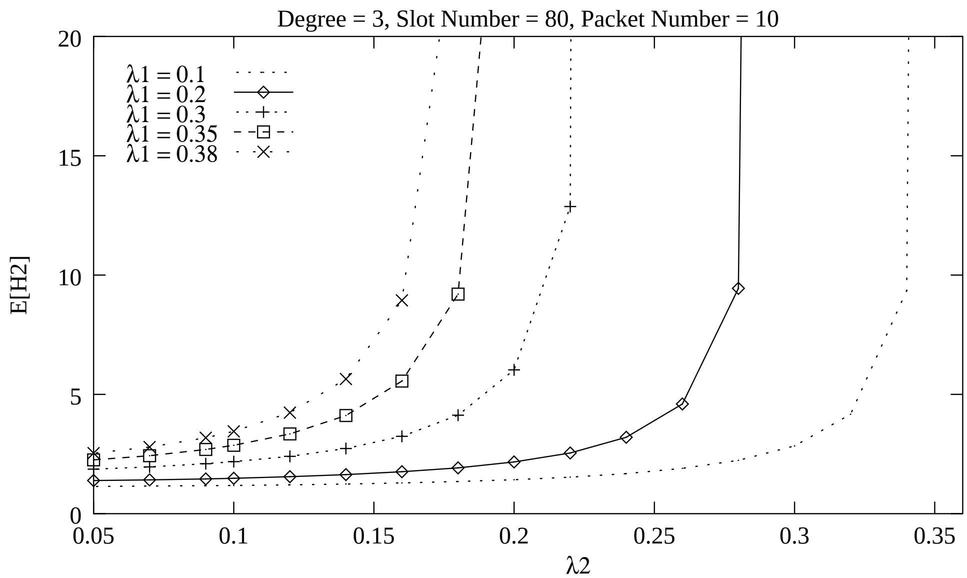

Figure 8: Length average of priority 2 session.

Figure 8 depicts the length average in slots of priority 2 session versus λ_2. This figure is plotted by resolving the Equation 4.0.5. Several curves are shown according to different values of λ_1. The convergence of the session length confirms the stability of the stack protocol when $\lambda_1 + \lambda_2$ is inferior than 0.4. For all curves, the summation of λ_1, λ_2 reach the same maximum value. When the incoming number of first priority user decreases, the protocol can authorize more second priority users.
Simulation results are exhibited in Figure 9. Here, results indicate the delay that a user must wait before acquiring a system access (i.e. the delay of the session resolution). Simulation model is based on two Poisson traffic with arrival rate λ_1 and λ_2. The W-CDMA random access protocol is also simulated with only one priority (slotted aloha protocol does not support more than one priority). Figure 9 shows clearly the predominance of the stack protocol comparing to the W-CDMA RACH. At 0.15, the W-CDMA RACH displays a non-stability behavior. On the other way, the stack protocol guarantees stability until a maximum of 0.4 for arrival rates. In addition, simulation results correspond perfectly to theoretical and numerical analysis. Indeed, the summation of λ_1 and λ_2 reach always a maximum value of 0.4.

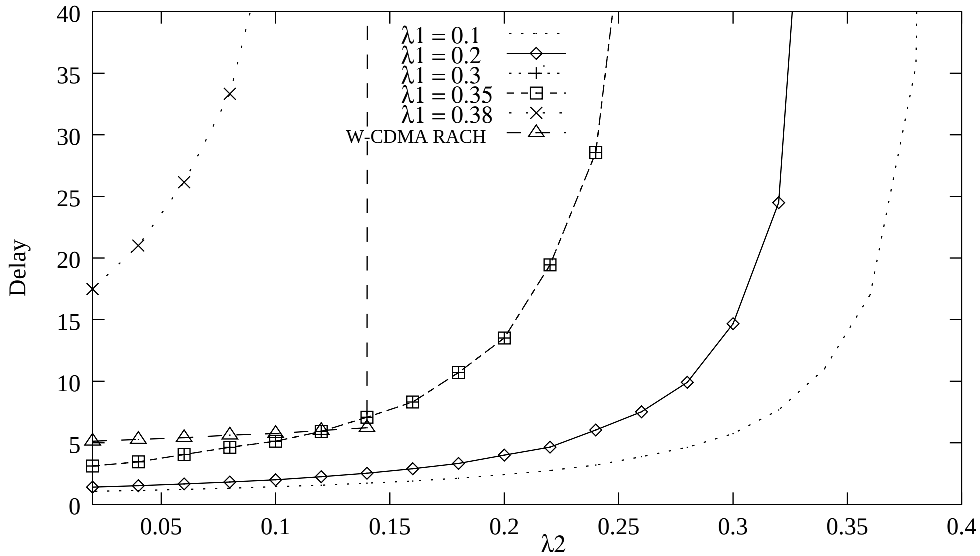

Figure 9: Mean delay before acquiring a channel.

5 Conclusion

In order to apply a priority system in future generation mobile networks at the random access level, a demonstration of the stack protocol with priority resolution is presented. The idea is resumed into the possibility to integrate a kind of quality of service mechanism at the first stage of the access system, and especially in the UMTS network that based on a guaranteed service principal. The stack protocol is analyzed and compared to the slotted aloha that used for the W-CDMA part in the UMTS systems. The major objective of this paper is to show the importance of the access mechanism in a QoS based system. Only two-priority tree protocol is presented but, of course, more service classes can be integrated.

References

[1] E. Dahlman, B. Gudmundson, M. Nilsson, and J. Skold, "Umts/imt2000 based on wideband cdma," *IEEE Communications magazine*, pp. 70–80, sep. 1998.

[2] ETSI, "Umts terrestrial radio access (utra); concept evaluation," Tech. Rep. TR 101 146 V3.0.0, ETSI, 1997. http://www.etsi.org.

[3] G. Fayolle, E. Gelembe, and J. Labetoulle, "Stability and optimal control of the packet switching broadcast channel," *JACM*, vol. 24, pp. 375–386, 1977.

[4] J. I. Capetanakis, "Tree algorithms for packet broadcast channels," *IEEE Transactions on Information Theory*, vol. IT-25, pp. 505–515, 1979.

[5] B. S. Tsybakov and V. A. Mikhailov, "Tree synchronous packet access in a broadcast channel with feedback," *Probl. Inform. Transmission*, vol. 14, pp. 259–280, 1979.

[6] B. S. Tsybakov and N. Vvedenskaya, "Random multiple access stack algorithms," *Probl. Inform. Transmission*, vol. 16, pp. 230–243, 1980.

[7] P. Mathys and P. Flojolet, "Q-ary collision resolution algorithms in random-access systems with or blocked channel access," *IEEE Transactions on Information Theory*, vol. IT-31, pp. 217–243, 1985.

[8] I. P. . W. Group, "Ieee p 802.14 cable-tv functional requirements and evaluation criteria," Tech. Rep. 94-002R2, IEEE, March 1995. http://www.walkingdog.com/catv/public.html.

[9] N. Golmie, Y. Saintillan, and D. H. Su, "A review of contention resolution algorithms for of ieee 802.14 networks," *IEEE Communications Surveys*, pp. 2–12, First Quarter 1999.

[10] T. R. WG1, "Physicals channels and mapping of transport channels onto physicals channels (fdd)," Tech. Rep. TS 25.211, 3GPP, dec. 1999. http://www.3gpp.org.

[11] T. R. WG1, "Spreading and modulation (fdd)," Tech. Rep. TS 25.213, 3GPP, dec. 1999. http://www.3gpp.org.

[12] T. R. WG1, "Physical layer procedures (fdd)," Tech. Rep. TS 25.214, 3GPP, dec. 1999. http://www.3gpp.org.

[13] N.D.Vvedenskaya and B.S.Tsybakov, "Random multiple access of packets at a channel with errors," *Probl. Inform. Transmission*, vol. 19, no. 2, 1983.

[14] N.D.Vvedenskaya and B.S.Tsybakov, "Packet delay in the case of multiple access stack algorithm," *Probl. Inform. Transmission*, vol. 20, no. 2, 1984.

[15] J. Massey, *Collision-resolution algorithms and random-access communications.* Longo ed, 1981. CISM Courses and Lectures.

[16] G. Fayolle, P. Flajolet, M. Hofri, and P. Jacquet, "Analysis of a stack algorithm for random multiple-access communication," *1985*, vol. IT-31, pp. 244–254, IEEE Trans Information Theory.

[17] P. Jacquet and W. Szpankowski, "Analytical depoissonization and its applications," *Theoretical Computer Science*, vol. 201, pp. 1–62, 1998.

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