Probabilistic QoS Guaranties and local scheduling studies in a Bluetooth piconet

Karima Maalaoui and Leila Azouz Saidane,

University of Manouba, Ecole Nationale des Sciences de l'Informatique, Tunisia

Summary

To ensure efficient communication in Bluetooth networks, there must be a good design of intra and inter-piconet scheduling solutions. We present a mathematical model for performance evaluation of a Bluetooth piconet, based on the M/G/1 queue with batch arrivals and vacation times.

We introduce a scheduling scheme that supports various traffics with QoS guaranties. We deal with two application constraints: the priority of a message and its end-to-end delivery deadline. We focus on two new local scheduling disciplines that we propose so far. The first is a combination of the class based priority queuing (PQ) and FIFO. The second is a combination of PQ and EDF. PQ is used between classes while FIFO and EDF are used within a class. We study these disciplines for providing Quality of Service (QoS) guarantees to various classes of soft real-time applications by using a probabilistic approach. Then we compute, for each discipline, the waiting time distribution to obtain the probability that the response time doesn't exceed a given deadline.

Key words:

Bluetooth, M/G/1, vacations, batch arrivals, FP/EDF, FP/FIFO, QoS, Scheduling.

1. Introduction

Bluetooth is emerging as an important standard [1] [2] for a low power, short range wireless access mechanism. The transmission rate is up to 1 Mbps. Concerning the time domain, the channel is divided into time slots of 625µs length, where a different hop frequency is used for each slot. A time-division duplex (TDD) scheme is used for full-duplex communications.

The devices can communicate with each other forming a network with up to eight nodes, called piconet. A multihop ad hoc network of piconets in which few devices are present in more than one piconet is referred to as a scatternet. A device that is a member of more than one piconet (referred to as a bridge) must schedule its presence in all of them. Within a piconet, one unit acts as a master and the others act as slaves which are time and hop synchronized to the master.

On a Bluetooth channel, time slots are divided into tow groups: master-to-slave slots (M/S) and slave-to-master slots (S/M). The master starts its packet transmission in even slots, while the slave starts its packet transmission in odd slots. A Bluetooth packet can be 1, 3 or 5 slots length. A slave can transmit a packet in the S/M slot only if it is polled by the master in the previous M/S slot. Between the master and a slave, synchronous and asynchronous connections can be established. Two types of synchronous connections exist: Synchronous Connection Oriented (SCO) and Extended SCO (eSCO) used for time bounded data, such as voice. For asynchronous connection there is only one type: Asynchronous Connection-Less (ACL) for data. In this paper, we consider ACL type of link.

In Bluetooth networks, there are three scheduling levels [3]: local, intra-piconet and inter-piconet scheduling. These levels are defined in [4] as follows: Local scheduling refers to the mechanism used to select one message on the local waiting queue of the Bluetooth device. Intra-piconet scheduling refers to the polling scheme (medium access) within a piconet. This scheme can be defined as the set of rules used to determine the way in which the master switches from one slave to another. Inter-piconet scheduling is the mechanism that determines the piconet where the bridging device must be present at a given time in a scatternet.

The Bluetooth specification [1] recommends the use of FIFO disciplines for local scheduling. But FIFO does not take into account deadline constraints. For medium access within a piconet, Bluetooth uses a polling scheme based on One Round Robin (1-RR): each slave is scanned once by cycle and two packet slots are assigned to it (one master-to-slave followed by one slave-to-master transmission). This scheduling mechanism can not support QoS requirements.

In order to support QoS sensitive applications such as streaming and voice, real-time constraints must be accounted for, by local and intra-piconet scheduling which affects the performances offered to traffics.

In this paper we are interested in local scheduling. We focus on two application constraints: the priority of a message and its end-to-end delivery deadline. We proposed two new local scheduling disciplines FP/FIFO and FP/EDF. We focus our interest to providing Quality of Service (QoS) guarantees to various classes of soft real-time applications by using a probabilistic approach. The

Manuscript received February 5, 2007
Manuscript revised February 25, 2007

waiting time distribution is then computed to obtain the probability that the response time doesn't exceed a given deadline.

We first present our mathematical model. Section 3 describes the steps for computing the mean waiting time for both FP/FIFO and FP/EDF policies. In section 4, we compute the response time distribution or both FP/FIFO and FP/EDF policies. Section 5 shows numerical results to compare the performances of both FP/FIFO and FP/EDF and we show how to provide a probabilistic QoS guarantee for flows, using the missing deadline probability. Finally, we conclude the paper and outline our future work.

2. Our Model

In this section, we present a model for both Bluetooth piconet and traffic within it. This model is used to evaluate the mean waiting time of a packet generated by a slave. We adopt:

Assumption 1: We assume that the master polls the slaves according to 1-RR. We assume also that the number of active slaves in a piconet is Ne. We note by Ne+1 the master index and 1..Ne the slaves indexes. As shown in figure 1, each slave i maintains a packet queue to transmit to the master, denoted Si→M. The master maintains one packet queue per slave i, denoted M→Si.

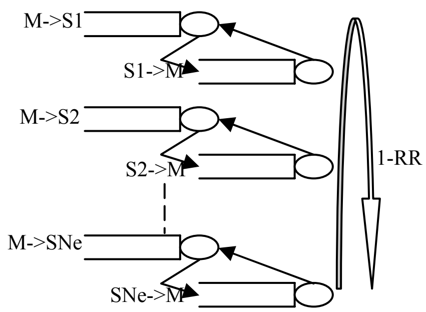

Fig. 1 Piconet queuing model.

Assumption 2: Time is assumed to be discrete equal to multiple time slots.

Assumption 3: The network is assumed to be reliable: neither network failures nor packet losses.

Assumption 4: We admit Zero-switchover-time model [5]: the time required for the master to travel between queues for polling is equal to zero.

Like the model described in [6] and [7], we denote by Xc the piconet service cycle time (the time needed by the master to serve all of its slaves once).

Assumption 5: We assume a grouped arrival of packets to the Baseband layer. This can be explained by the fact that the Bluetooth L2CAP layer provides the function of high levels PDU segmentation and reassembly. This segmentation will lead to a group of Baseband packets having 1, 3 or 5 slots each one. Moreover, L2CAP carries out the segmentation of a new high level package only when it completes the segmentation of the current package [1]. Therefore, L2CAP generates separately groups of packages where each group comes from the same higher level package. Thus, the packages belonging to the same group have the same characteristics: source, destination, type of traffic and priority.

In order to provide different delay treatment, we introduced priority levels and we determined scheduling scheme to guaranty that higher priority packets are served first. We assume that we have R priorities and K types of flow per priority.

Assumption 6: We assume that each slave, for each priority r and each type of flow k, generates bursts of packets that follow a Poisson distribution with arrival rate $\lambda_{r,k}$. Thus, the station of slave queue (Si→M), can be modeled via R queues and a Priority Queuing (PQ) scheduler as shown in Figure 2.

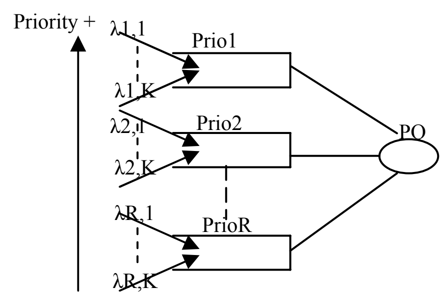

Fig. 2 Slave queue modeling

Let $G_{br,k}(z)$ be the probability generating function (PGF) of burst distribution length of priority r and type k (r ∈ 1..R and k ∈ 1..K). $\overline{B}_{r,k}$ is the corresponding mean length and $\overline{B}_{r,k}^{(2)}$ is the second factorial moment:

$$G_{br,k}(z) = \sum_{i=0}^{\infty} b_{r,k,i} z_i \quad ; \quad \overline{B}_{r,k} = G'_{br,k}(1) \quad \text{and}$$

$\overline{B}_{r,k}^{(2)} = G'_{br,k}(1) + G''_{br,k}(1)$ with $b_{r,k,i}$ the probability that the burst of priority r and type k contain i packets.

The polling in Bluetooth can be seen as a single server serving multiple queues. Thus, we can consider server vacation [8]. From a slave i point of view, even if its Si→M queue is full, it will be able to transmit only when it’s polled by the master. So, it must wait until all the other active slaves are polled.

Following all these considerations and assumptions, we will be able to model each Baseband queue, shown in

Figure 1, by an M/G/1 batch arrival queue with vacations, R priorities and K traffic types.

Let p1, p3 and p5, the probabilities that an ACL packet covers one, three and five slots. There are other packet types like NULL (when slave-to-master queue is empty) and POLL (when master-to-slave queue is empty). These types of packets cover only one slot. We note by $G_p(z)$ the probability generating function (PGF) of packet length distribution.

$$G_p(z) = P1z + P3z^3 + P5z^5$$

The probability that a Si→M queue is not empty is:

$$P_u = \sum_{r=1}^{R} \sum_{k=1}^{K} \lambda_{r,k} \overline{B}_{r,k} \overline{Xc} \cdot$$

The probability that a M→Si queue is not empty is:

$$P_{di} = \sum_{r=1}^{R} \sum_{k=1}^{K} \lambda_{r,k} P_{Ne+1,i}^{r,k} \overline{B}_{r,k} \overline{Xc}$$

The PGF's downlink and uplink communications are:

$$G_u(z) = (P_u p_1 + (1-P_u))z + P_u p_3 z^3 + P_u p_5 z^5$$

$$G_{di}(z) = (P_{di} p_1 + (1-P_{di}))z + P_{di} p_3 z^3 + P_{di} p_5 z^5$$

Thus, the PGF of the service cycle time is:

$G_{Xc}(z) = \prod_{i=1}^{Ne} G_u(z)\, G_{di}(z)$, Its mean is $\overline{Xc} = G'_{Xc}(1)$

In the same way, the PGF of the vacation time is:

$G_V(z) = \prod_{i=1}^{Ne-1} G_u(z) \prod_{i=1}^{Ne} G_{di}(z)$, Its mean is $\overline{V} = G'_V(1)$.

3. Mean waiting time

In this section we evaluate the mean waiting time of a packet generated by a slave. We first evaluate it in the case of FP/FIFO discipline. Then we introduce a dynamic local scheduling based on FP/EDF.

3.1 FP/FIFO local scheduling

Let $\overline{W}_{r,k}$ be the mean waiting time of a packet belonging to a burst g of priority r and type k (r = 1..R and k = 1..K) generated by a slave i in its Si→M queue. $\overline{W}_{r,k}$ can be decomposed as:

- The waiting time of the first packet in the burst g: $\overline{W}_{rk,g}$
- The necessary time to serve all packets previous to the considered one belonging to the same burst g.

$$\overline{W}_{r,k} = \overline{W}_{rk,g} + \overline{N}_{p,rk} \overline{Xc} \quad (1)$$

Where $\overline{N}_{p,rk}$ is the mean number of packets preceding the considered one in the same burst of priority r and type k. $\overline{W}_{rk,g}$ can also be decomposed as:

- The residual service time of the burst being served (if there is one). This burst can be of priority $\geq$ r.
- The necessary time to serve all bursts of priority $\leq$ r that came before the burst g.
- The necessary time to serve all bursts of priority < r that came after the burst g but before the beginning of its service.

$$\overline{W}_{rk,g} = \overline{W}_0 + \overline{W}_{vr} + \overline{W}_{pr} \quad (2)$$

Which gives equation (3) as we've developed it in [15].

$$\overline{W}_{rk,g} = \frac{\overline{W}_0 + \sum_{s=1}^{r} \sum_{\substack{i=1 \\ (s,i)\neq(r,k)}}^{K} \rho_{s,i} \overline{W}_{si,g}}{1 - \rho_{r,k} - \sum_{s=1}^{r-1} \sum_{i=1}^{K} \rho_{s,i}} \quad (3)$$

This is a system of K equations with the variables $\overline{W}_{rk,g}$ that can be resolved using Maple.

Finally, we can compute $\overline{W}_{r,k}$ using equation 1, where

$$\overline{N}_{p,rk} = \frac{\overline{B}_{r,k}^2 - \overline{B}_{r,k}}{2\overline{B}_{r,k}}$$

3.2 FP/EDF local scheduling

In what follows, we are going to evaluate the mean waiting time of an ACL packet using FP/EDF scheduling instead of FP/FIFO discipline. EDF is used to improve the Bluetooth performances in case of real-time traffic streams with deadline constraints. We assume that each device in the piconet generates real-time applications belonging to R priorities and K types of flows in each priority. We choose the Earliest Deadline First (EDF) dynamic priority discipline to manage messages of the same priority and having different types.

Assumption 7: We assume that all packets in a burst and all bursts in the same type of flow have the same relative deadline. This is explained by the fact that all packets in a burst have the same parameters and come from the same application PDU.

We note by $d_{r,k}$ the relative deadline of a burst of priority r and type k. By convention, we label the flows such that if i < j then $d_{r,i} < d_{r,j}$ for each priority r. $\delta_{r,j,i} = d_{r,j} - d_{r,i}$. We note by $\tau_{r,i}$ the arrival time of a burst with priority r and type i.

Let $\overline{W}_{r,k}$ be the mean waiting time of a packet belonging to a burst g of priority r and type k (r=1..R et k=1..K) in the S→M queue.

$\overline{W}_{r,k}$ can be decomposed as :

- The waiting time of the first packet in the burst g
- The necessary time to serve all packets previous to the considered packet in the same burst.

$$\overline{W}_{r,k} = \overline{W}_{rk,g} + \overline{N}_{p,rk}\,\overline{Xc} \tag{4}$$

Where $\overline{N}_{p,rk}$ is the mean number of packets preceding the considered one in the same burst of priority r and type k.

Computing $\overline{W}_{rk,g}$: The first packet in a burst of priority r and type k has to wait for the residual service time of the burst being served (if there is one), then continues to wait for the servicing of all priority bursts existing in the queue at arrival time or arriving at the waiting time of our considering burst. Hence, by reference to [10]

$$\overline{W}_{rk,g} = \overline{W}_0 + \sum_{s=1}^{R}\sum_{i=1}^{K}(\overline{N}_{rk,si} + \overline{M}_{rk,si})\overline{B}_{s,i}\overline{X}_c \tag{5}$$

Where $\overline{N}_{rk,si}$ is the mean number of bursts of priority s and type i which have been arrived before the tagged burst g and which have been served prior to it. $\overline{M}_{rk,si}$ is the mean number of bursts of priority s and type i which have been arrived after the tagged burst g, and which have been served prior to it.

Equation (5) gives the expression of $\overline{W}_{rk,g}$ as we've shown it in [15]:

$$\overline{W}_{rk,g} = \left[\frac{1}{\sum_{s=1}^{r-1}\sum_{i=1}^{K}\rho_{s,i}}\right]\times$$

$$\left[\frac{\overline{W}_0}{1-\rho_r} + \sum_{s=1}^{r-1}\sum_{i=1}^{K}\rho_{s,i}\overline{W}_{si,g} - \sum_{i=k+1}^{K}\rho_{r,i}\min(\overline{W}_{ri,g},\delta_{r,i,k}) + \sum_{i=1}^{k}\rho_{r,i}\min(\overline{W}_{rk,g},\delta_{r,k,i})\right] \tag{6}$$

4. Waiting time distribution

In this section we evaluate the waiting time distribution of a packet of priority r and type k, generated by a slave, in cases of FP/FIFO and FP/EDF local queue disciplines.

4.1. FP/FIFO local scheduling

Let $W^*_{r,j}(s)$ be the LST of the waiting time of a packet belonging to a burst g of priority r and type k (r = 1..R and k = 1..K) generated by a slave i in its Si→M queue.

Authors of [12] had shown that, for a M/G/1 system with vacations, the waiting time in a queue can be decomposed in tow independent variables: the waiting time in a M/G/1 queue without vacation + an additional time witch is dependant only on the vacation period.

$$W^*_{r,j}(s) = (W^{r,j,g}_{M/G/1})^*(s) * W^*_1(s)$$

By reference to [11], we have: $W^*_1(s) = \dfrac{1-V^*(s)}{s\overline{V}}$

In order to find $(W^{r,j,g}_{M/G/1})^*(s)$, we classed messages to [8]:

- Priority messages: messages of priority 1, 2, …, r.
- Ordinary messages: messages of priority r+1, …, R.

We use the following notations:

- $\lambda_{k,i}$: The arrival rate of a packet of priority r and type i.
- $\lambda^+_r = \sum_{k=1}^{r}\sum_{i=1}^{K}\lambda_{k,i}$, $\lambda^-_r = \sum_{k=r+1}^{R}\sum_{i=1}^{K}\lambda_{k,i}$, $\lambda_r = \sum_{i=1}^{K}\lambda_{r,i}$
- $\rho_{k,i} = \lambda_{k,i}\overline{B}_{k,i}\overline{X}_c$, $\rho^+_r = \sum_{k=1}^{r}\sum_{i=1}^{K}\rho_{k,i}$, $\rho^-_r = \sum_{k=r+1}^{R}\sum_{i=1}^{K}\rho_{k,i}$, $\rho = \sum_{k=1}^{R}\sum_{i=1}^{K}\rho_{k,i}$
- $G_{b,r,j}(z)$: The PGF of burst distribution length of priority r and type k. $\overline{B}_{r,j}$ is the corresponding mean length.
- $B^+_r(s) = \dfrac{1}{\lambda^+_r}\sum_{k=1}^{r}\sum_{i=1}^{K}\lambda_{k,i}G_{b,k,i}(X^*_c(s))$
- $\theta^+_{r-1}(s)$: the solution of the equation : $\theta^+_{r-1}(s) = B^+_{r-1}(s+\lambda^+_{r-1}-\lambda^+_{r-1}\theta^+_{r-1}(s))$
- $\sigma_{r-1} = s+\lambda^+_{r-1}-\lambda^+_{r-1}\theta^+_{r-1}(s)$

We obtain, by reference to [8], in our case of M/G/1 batch arrival queue with vacations, R priorities and K traffic types:

$$(W_{M/G/1}^{r,j,g})^*(s) = \frac{(1-\rho)\sigma_{r-1} + \sum_{k=r+1}^{R}\sum_{i=1}^{K}\lambda_{k,i}[1-G_{b,k,i}(X_c^*(\sigma_{r-1}))]}{s-\lambda_r+\lambda_r G_{b,r,j}(X_c^*(\sigma_{r-1}))} \times \frac{1-G_{b,r,j}(X_c^*(s))}{\overline{B}_{r,j}(1-X_c^*(s))}$$

Thus:

$$W_{r,j}^*(s) = \frac{(1-\rho)\sigma_{r-1} + \sum_{k=r+1}^{R}\sum_{i=1}^{K}\lambda_{k,i}[1-G_{b,k,i}(X_c^*(\sigma_{r-1}))]}{s-\lambda_r+\lambda_r G_{b,r,j}(X_c^*(\sigma_{r-1}))} \times \frac{1-G_{b,r,j}(X_c^*(s))}{\overline{B}_{r,j}(1-X_c^*(s))} \times \frac{1-V^*(s)}{s\overline{V}}$$

4.2. FP/EDF local scheduling

In this section, we want to find the distribution of the waiting time for the packet of priority r and type k, in case of the FP/EDF scheduling. FP is applied between priorities and EDF is applied between bursts of same priority but belonging to different types. The packets of the same burst are served in FIFO discipline.

We note by $W_{r,k}^*(s)$, the LST of the waiting time distribution of a packet belonging to a burst g of priority r and type k. this time can be decomposed as:

- The necessary time to serve all packets previous to the considered packet in the same burst, its LST is noted by $W_{G,rk}^*(s)$
- The waiting time of the first packet in the considered burst g, its LST is noted by $W_{gv,rk}^*(s)$

Let: $W_{r,k}^*(s) = W_{gv,rk}^*(s) * W_{G,rk}^*(s)$.

Where: $W_{G,rk}^*(s) = \frac{1-G_{b,r,k}(X_c^*(s))}{\overline{B}_{r,k}(1-X_c^*(s))}$

Computing $W_{gv,rk}^*(s)$: We have shown that the waiting time in the M/G/1 queue with vacations can be decomposed as:

$$W_{gv,rk}^*(s) = \frac{1-V^*(s)}{s\overline{V}} * W_{g,rk}^*(s)$$

where : $W_{g,rk}^*(s)$: the LST of the waiting time distribution of the first packet in a burst of priority r and type k for a M/G/1 batch arrival queue without vacations and with FP/EDF scheduling between bursts.

Computing $W_{g,rk}^*(s)$

When a burst g of priority r and type k arrives, it has to wait:

1. The residual service time of the burst being served (if there is one).
2. The necessary time to serve all waiting bursts prior to it, that came before the burst g.
3. The necessary time to serve all bursts prior to it, that came at the waiting time of the burst g.

The waiting time of a burst g of priority r and type k can be decomposed as: [8], [13], [14]

- $W_{g,rk}^+$: The waiting time generated by all bursts founded in the queue when g arrives and which will be served before it. These are bursts of categories 1) and 2). We note by $\widetilde{W}_{g,rk}^+$ this time and $(W_{g,rk}^+)^*(s)$ its LST.
- The waiting time generated by all bursts which will arrive to the system during $W_{g,rk}^+$ and will be served before g. These are bursts of category 3).

Compution $(W_{g,rk}^+)^*(s)$*:* In order to find $(W_{g,rk}^+)^*(s)$, we will consider all bursts founded in the system at the arrival time of the considered burst g.

The considered burst g must wait until serving all bursts founded in the system which will be served before it. Hence, we can consider that these bursts are served in FIFO order [8]. Then, we introduce for each priority r and for each type i, the modified system composed by the tow following classes of burst [8]:

- $C_{g,rk}^+$: the class of bursts that arrive before the considered burst g of priority r and type k and that will be served before it. These bursts are called priority bursts.
- $C_{g,rk}^-$: the class of bursts that arrive before the considered burst g of priority r and type k and that will be served after it. These bursts are called ordinary bursts.

Arrival rate of priority bursts

- All bursts of priority s<r arrived before g of priority r and type k, will be served before it. The arrival rate of these bursts is: $\sum_{s=1}^{r-1}\sum_{i=1}^{K}\lambda_{s,i}$
- All burst of priority r and type i ≤ k arrived before g will be served before it (because i ≤ k ➔ dr,I ≤ dr,k). The arrival rate of these bursts is : $\sum_{i=1}^{k}\lambda_{r,i}$
- For bursts of priority r and type i > k arrived before g, only those witch arrived before it by at least δr,i,k = dr,i - dr,k will be served before g. The arrival rate of these bursts is: $\sum_{i=k+1}^{K}\lambda_{r,i}\ \Pr[ri \quad precede \quad rk]$

Where Pr[ri precede rk] is the probability that a burst of priority r and type i, arrives to the queue at least δr,i,k units of time before the considered burst g.

Then, the arrival rate of priority bursts (bursts belonging to the class $C^{+}_{g,rk}$) is given by :

$$\lambda^{+}_{g,rk}=\sum_{s=1}^{r-1}\sum_{i=1}^{K}\lambda_{s,i}+\sum_{i=1}^{k}\lambda_{r,i}+\sum_{i=k+1}^{K}\lambda_{r,i}\ \Pr[\,ri \quad precede \quad rk\,]$$

Computing Pr[ri precede rk]

Let:

- $\tilde{t}_{r,k}$: The random variable associated to the arrival time of bursts of priority r and type k to the queue.
- $\tilde{t}_{r,i}$: The random variable associated to the arrival time of bursts of priority r and type i to the queue.

$$\Pr[ri \quad precede\ rk]=$$

$$\int_{0}^{+\infty}\Pr\left[ri \quad precede \quad rk \Big/ t\le\tilde{t}_{r,k}\prec t+dt\right]f_{t_{r,k}}(t)dt$$

Where $f_{t_{r,k}}(t) = \lambda_{r,k}e^{-\lambda_{r,k}t}$ is the probability density function of $\tilde{t}_{r,k}$.

So:

$$\Pr\left[ri \quad precede \quad rk \Big/ t\le\tilde{t}_{r,k}\prec t+dt\right]=$$

$$\Pr\left[\tilde{t}_{r,i}\prec t+d_{r,k}-d_{r,i} \Big/ t\le\tilde{t}_{r,k}\prec dt\right]=\Pr\left[\tilde{t}_{r,i}\prec t-\delta_{r,i,k} \Big/ t\le\tilde{t}_{r,k}\prec dt\right]$$

We will consider the interval of time [0,t] as shown in figure 3, where t is the arrival time of the considered burst g of priority r and type k. after t, a burst of priority r and type i > k can't be served before g.

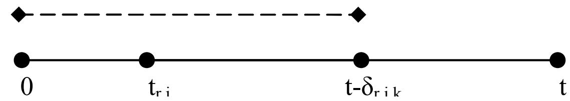

Fig. 3 Considered interval.

The bursts of priority r and type i that can be served before the considered burst g, are these which arrived in the interval of time [0, t- δr,i,k], with the condition t-δr,i,k >0. These arrival moment are uniformly distributed in [0,t]. Then, we have:

$$\Pr\left[\tilde{t}_{r,i}\prec t-\delta_{r,i,k} \Big/ t\le\tilde{t}_{r,k}\prec dt\right] = \int_{t_{r,i}=0}^{\max(0,t-\delta_{r,i,k})}\frac{dt_{r,i}}{t}$$

Then:

$$\Pr[ri \quad precede \quad rk] = \int_{0}^{+\infty}\left(\int_{0}^{\max(0,t-\delta_{r,i,k})}\frac{dt_{r,i}}{t}\right)\lambda_{r,k}e^{-\lambda_{r,k}t}dt$$

$$= \int_{t=0}^{\delta_{r,i,k}}\left(\int_{0}^{\max(0,t-\delta_{r,i,k})}\frac{dt_{r,i}}{t}\right)\lambda_{r,k}e^{-\lambda_{r,k}t}dt \ +$$

$$\int_{t=\delta_{r,i,k}}^{+\infty}\left(\int_{0}^{\max(0,t-\delta_{r,i,k})}\frac{dt_{r,i}}{t}\right)\lambda_{r,k}e^{-\lambda_{r,k}t}dt$$

$$= \int_{t=\delta_{r,i,k}}^{+\infty}\left(\int_{0}^{(t-\delta_{r,i,k})}\frac{dt_{r,i}}{t}\right)\lambda_{r,k}e^{-\lambda_{r,k}t}dt = \int_{t=\delta_{r,i,k}}^{+\infty}\frac{t-\delta_{r,i,k}}{t}\lambda_{r,k}e^{-\lambda_{r,k}t}dt$$

Arrival rate of ordinary bursts: the bursts belonging to this category are:

- The bursts of priority s > r arrived before g of priority r and type k. The arrival rate of these bursts is: $\sum_{s=r+1}^{R}\sum_{i=1}^{K}\lambda_{s,i}$
- The bursts of priority r and type i>k arrived before g verifying dr,i + t' > dr,k + t ➔ dr,i - dr,k > t-t' ➔ δr,i,k > t-t'. The arrival rate of these bursts is: $\sum_{i=k+1}^{K}\lambda_{r,i}\ \Pr[rk \quad precede\, ri]$

Where Pr[rk precede ri] is the probability that a burst of priority r and type i arrives to the queue at most δr,i,k units of time before the considered burst g. Hence, Pr[rk precede ri] = 1 - Pr[ri precede rk]

Then, the arrival rate of ordinary bursts (bursts belonging to the class $C^{-}_{g,rk}$) is given by:

$$\lambda^{-}_{g,rk}=\sum_{s=r+1}^{R}\sum_{i=1}^{K}\lambda_{s,i}+\sum_{i=k+1}^{K}\lambda_{r,i}\ (1-\Pr[ri \quad precede\ rk])$$

We try now to compute $(W^{+}_{g,rk})^{*}(s)$. The server utilization of priority bursts is given by:

$$\rho^{+}_{g,rk}=\sum_{s=1}^{r-1}\sum_{i=1}^{K}\rho_{s,i}+\sum_{i=1}^{k}\rho_{r,i}+\sum_{i=k+1}^{K}\rho_{r,i}\ \Pr[ri\quad precede\quad rk]$$

Where $\rho_{s,i}=\lambda_{s,i}\overline{B}_{s,i}\overline{X}_{c}$

The server utilization of ordinary bursts is given by:

$$\rho^{-}_{g,rk}=\sum_{s=r+1}^{R}\sum_{i=1}^{K}\rho_{s,i}+\sum_{i=k+1}^{K}\rho_{r,i}\ (1-\Pr[ri\quad precede\ rk])$$

The LST of the distribution function of service time of priority bursts is given by:

$$(G^{+}_{b,rk})^{*}(s)=\frac{1}{\lambda^{+}_{g,rk}}\Big(\sum_{s=1}^{r-1}\sum_{i=1}^{K}\lambda_{s,i}G_{b,s,i}(X^{*}_{c}(s))+\sum_{i=1}^{k}\lambda_{r,i}G_{b,r,i}(X^{*}_{c}(s))+\sum_{i=k+1}^{K}\lambda_{r,i}G_{b,r,i}(X^{*}_{c}(s))\ \Pr[ri\quad precede\ rk]\Big)$$

The LST of the distribution function of service time of ordinary bursts is given by:

$$(G^{-}_{b,rk})^{*}(s)=\frac{1}{\lambda^{-}_{g,rk}}\Big(\sum_{s=r+1}^{R}\sum_{i=1}^{K}\lambda_{s,i}G_{b,s,i}(X^{*}_{c}(s))+\sum_{i=k+1}^{K}\lambda_{r,i}G_{b,r,i}(X^{*}_{c}(s))\ (1-\Pr[ri\quad precede\ rk])\Big)$$

Furthermore, we define $a^{+}_{g,rk}(j)$ as the probability that j priority bursts arrive during the service time of a priority burst, and $a^{-}_{g,rk}(j)$ as the probability that j priority bursts arrive during the service time of an ordinary burst. Then we have:

$$a^{+}_{g,rk}(j)=\int_{0}^{\infty}\frac{(\lambda^{+}_{g,rk}x)^{j}}{j!}e^{-\lambda^{+}_{g,rk}x}dG^{+}_{b,rk}(x)$$

$$a^{-}_{g,rk}(j)=\int_{0}^{\infty}\frac{(\lambda^{+}_{g,rk}x)^{j}}{j!}e^{-\lambda^{+}_{g,rk}x}dG^{-}_{b,rk}(x)$$

$$A^{+}_{g,rk}(z)=\sum_{j=0}^{\infty}a^{+}_{g,rk}(j)z^{j}=G^{+}_{b,rk}(\lambda^{+}_{g,rk}-\lambda^{+}_{g,rk}z)$$

$$A^{-}_{g,rk}(z)=\sum_{j=0}^{\infty}a^{-}_{g,rk}(j)z^{j}=G^{-}_{b,rk}(\lambda^{+}_{g,rk}-\lambda^{+}_{g,rk}z)$$

While following an approach similar to that of [8] by using an embedded Markov Chain, $(W^{+}_{g,rk})^{*}(s)$, the LST of the probability density distribution of the waiting time generated by all bursts founded in the queue when g arrives and which will be served before it is given by:

$$(W^{+}_{g,rk})^{*}(s)=\frac{(1-\rho)s+\lambda^{-}_{g,rk}(1-G^{-}_{b,rk}(s))}{s-\lambda^{+}_{g,rk}+\lambda^{+}_{g,rk}G^{+}_{b,rk}(s)}$$

The total waiting time $(W_{g,rk})^{*}(s)$ of a burst of priority r and type k consists of $W^{+}_{g,rk}$ and the sum of the service times for priority bursts that arrive during the delay busy period initiated by $W^{+}_{g,rk}$.

We noted by $C^{++}_{g,rk}$, the class of priority bursts that arrive after the considered burst g and witch will be served before it.

The bursts belonging to the class $C^{++}_{g,rk}$ are:

- The bursts of priority s<r arrived after g of priority r and type k. The arrival rate of these bursts is: $\sum_{s=1}^{r-1}\sum_{i=1}^{K}\lambda_{s,i}$
- The bursts g' of priority r and type i<k arrived at moments t' verifying dr,i + t' < dr,k + t. It means that g' arrives to the queue at most δr,k,i units of time after the considered burst g. The arrival rate of these bursts is: $\sum_{i=1}^{k-1}\lambda_{r,i}\ \Pr[ri\quad precede rk]$

Where Pr[ri precede rk] is the probability that a burst of priority r and type i arrives to the queue at most δr,k,i units of time after the considered burst g of priority r and type k. Then, the arrival rate of bursts of class $C^{++}_{g,rk}$ is given by:

$$\lambda^{++}_{g,rk}=\sum_{s=1}^{r-1}\sum_{i=1}^{K}\lambda_{s,i}+\sum_{i=1}^{k-1}\lambda_{r,i}\ \Pr[ri\quad precede\quad rk]$$

Computing Pr[ri precede rk]

Let:

- $\widetilde{t}_{r,k}$: The random variable associated to the arrival time of bursts of priority r and type k to the queue.
- $\widetilde{t}_{r,i}$: The random variable associated to the arrival time of bursts of priority r and type i to the queue.

$$\Pr[ri\quad precede\quad rk]=\int_{0}^{+\infty}\Pr\left[ri\quad precede\quad rk \Big/ t\le\widetilde{t}_{r,k}\prec t+dt\right]f_{t_{r,k}}(t)dt$$

Where $f_{t_{r,k}}(t)=\lambda_{r,k}e^{-\lambda_{r,k}t}$ is the probability density function of $\widetilde{t}_{r,k}$

Since $C^{++}_{g,rk}$ represents the priority bursts that arrive after g (arrived at t)and witch will be served before it, then we will considered only arrival moments > t to compute Pr[ri precede rk]. Then,

$$\Pr[ri \quad precede \quad rk]$$

$$= \int_0^{+\infty} \Pr\left[\tilde{t}_{r,i} \prec t + d_{r,k} - d_{r,i} \Big/ t \le \tilde{t}_{r,k} \prec t + dt, \tilde{t}_{r,i} \succ t\right] f_{t_{r,k}}(t)dt$$

$$= \int_0^{+\infty} \Pr\left[t \prec \tilde{t}_{r,i} \prec t + \delta_{r,k,i} \Big/ t \le \tilde{t}_{r,k} \prec t + dt\right] f_{t_{r,k}}(t)dt$$

We will consider the interval of time [t, t+drk] as shown in figure 4, because the burst g must be scheduled before t+drk.

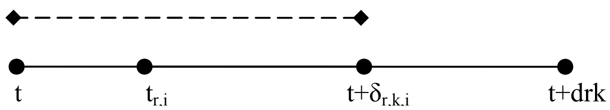

Fig. 4 Considered interval.

The bursts of priority r and type i that can be served before g, are those that arrive between t and t+ δr,k,i. these arrival moments are uniformly distributed in [t , t+drk]. Then, we have:

$$\Pr\left[t \prec \tilde{t}_{r,i} \prec t + \delta_{r,k,i} \Big/ t \le \tilde{t}_{r,k} \prec t + dt\right] = \int_{t_{r,i}=t}^{t+\delta_{r,k,i})} \frac{dt_{r,i}}{d_{r,k}} = \frac{\delta_{r,k,i}}{d_{r,k}}$$

Then, $\Pr[ri \quad precede\, rk] = \int_0^{+\infty} \frac{\delta_{r,k,i}}{d_{r,k}} \lambda_{r,k} e^{-\lambda_{r,k}t} dt = \frac{\delta_{r,k,i}}{d_{r,k}}$

Let $\tilde{V}_{g,rk}$ the random variable associated to the number of bursts of the class $C^{++}_{g,rk}$ that arrive after g and will be served before it. $\tilde{V}_{g,rk}$ is distributed according to a Poisson process with parameter $\lambda^{++}_{g,rk}$.

The LST of the distribution of the service time of bursts of the class $C^{++}_{g,rk}$ is given by:

$$(G^{++}_{b,rk})^*(s) = \frac{1}{\lambda^{++}_{g,rk}} (\sum_{s=1}^{r-1}\sum_{i=1}^{K} \lambda_{s,i} G_{b,s,i}(X^*_c(s))$$

$$+ \sum_{i=1}^{k-1} \lambda_{r,i} G_{b,r,i}(X^*_c(s)) \Pr[ri \quad precede\, rk]$$

Let $\Pr[\tilde{V}_{g,rk} = j]$ the probability that the number of bursts of the class $C^{++}_{g,rk}$ that arrive during $W^{+}_{g,rk}$, is equal to j. Then, we have:

$$\Pr[\tilde{V}_{g,rk} = j] = \frac{(\lambda^{++}_{g,rk} W^{+}_{g,rk})^j}{j!} e^{-\lambda^{++}_{g,rk} W^{+}_{g,rk}}$$

By following a busy period analyzes as in [8], $(W_{g,rk})^*(s)$ is taken by:

$$(W_{g,rk})^*(s) = (W^{+}_{g,rk})^*[s + \lambda^{++}_{g,rk} - \lambda^{++}_{g,rk}(\theta^{++}_{g,rk})^*(s)] \qquad (7)$$

Let $\sigma_{g,rk} = s + \lambda^{++}_{g,rk} - \lambda^{++}_{g,rk}(\theta^{++}_{g,rk})^*(s)$ and by using the expression of $(W^{+}_{g,rk})^*(s)$, we get:

$$(W_{g,rk})^*(s) = \frac{(1-\rho)\sigma_{g,rk} + \lambda^{-}_{g,rk}(1 - G^{-}_{b,rk}(\sigma_{g,rk}))}{s + \lambda^{++}_{g,rk} - \lambda^{++}_{g,rk} G^{++}_{b,rk}(\sigma_{g,rk}) - \lambda^{+}_{g,rk} G^{+}_{b,rk}(\sigma_{g,rk})}$$

Finally:

$$W^*_{r,k}(s) = (W_{g,rk})^*(s) * \frac{1 - G_{b,r,k}(X^*_c(s))}{\overline{B}_{r,k}(1 - X^*_c(s))} * \frac{1 - V^*(S))}{S\overline{V}}. \quad (8)$$

5. Numerical results

In this section, we provide numerical results obtained using Maple8. We assume that each node (a slave or the master) generates packet bursts with Poisson-distribution arrivals. Mean packet length is assumed to be equal to 2.4 slots (p1=0.5, p3=0.3, p5=0.2).

We show numerical results to compare the performances of using FP/FIFO or FP/EDF for the local scheduling in a Bluetooth piconet. We suppose that we have in each local queue two priorities and two real time streams by priority. The four real-time streams have the same bursts length distribution and server utilization. We assume that we have a master and two active slaves in the piconet.

Figures 5 and 6 show the response time distribution for a piconet composed of a master and two active slaves for using, respectively, FP/FIFO and FP/EDF scheduling approaches.

We observe that the response time distribution of the flows belonging to priority 1 decreases more rapidly than the one of flows belonging to priority 2. We note also that the streams of the same priority have identical curves in FP/FIFO while FP/EDF curve show a service differentiation.

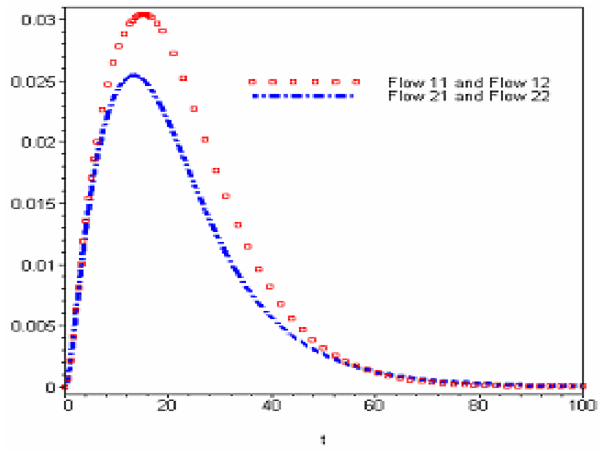

Fig. 5 Response time distribution (FP/FIFO).

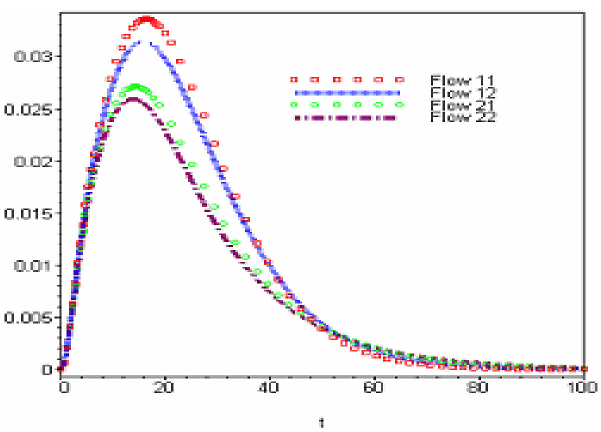

Fig. 6 Response time distribution (FP/EDF).

The response time distribution can be used to determine the missing deadline probability for a message belonging to a group of priority r and type k, having a relative deadline $d_{r,k}$ as:

$$P_{miss}(d_{r,k}) = 1 - P_{success}(d_{r,k}) = 1 - \int_0^{d_{r,k}} S_{r,k}(t)dt$$

$S_{r,k}$ is the response time distribution of a packet belonging to a group of priority r and type k obtained by inspecting its Laplace transform.

Figure 7 represents, using a semi-logarithmic scale, the missing deadline probabilities of the four considered flows scheduled using both FP/FIFO and FP/EDF.

We notice that, for each priority, the curve of FP/FIFO is between the FP/EDF's curves corresponding to the two flows of this priority. Thus, FP/EDF performs better when the group of packets belongs to the flow with low deadline. We can say that FP/EDF is better than FP/FIFO especially for low deadline classes.

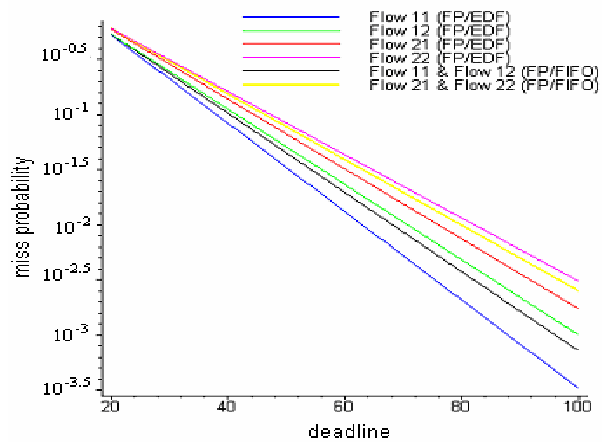

Fig. 7 Miss probability: FP/FIFO versus FP/EDF.

The study developed here allows then a probabilistic QoS guarantees and permits to propose an admission control technique.

In addition, the missing deadline probability can be used to compute the schedulability criterion which is defined, in a probabilistic context, as the probability of success of the whole traffic. If we have F flows and each flow i has a relative deadline di, we obtain:

$$Schedulability = \prod_{i=1}^{F} Psuccess\ (d_i) = \prod_{i=1}^{F} (1 - Pmiss(d_i))$$

For our studied configuration, the schedulability of FP/FIFO gives 81.56% and the schedulability of FP/EDF gives 89.34%.

6. Conclusions

In this paper, we have presented analytic results regarding performance evaluation of a Bluetooth piconet, based on M/G/1 queue with batch arrivals and vacations time. We have evaluated the mean waiting time for several priorities and several types of flow by priority. We considered two application constraints: the priority of a message and its end-to-end delivery deadline in order to support QoS sensitive applications such as multimedia applications. Two new local scheduling disciplines have been introduced. The first is obtained by combining a class based priority queuing (PQ) and FIFO. The second is obtained by combining PQ and EDF. We showed that FP/EDF is an interesting scheduling that provides a clear improvement to the performances of FP/FIFO scheme. In addition, we have proposed to offer probabilistic QoS guarantee to soft real time flows by computing the waiting time distribution in order to obtain the probability that the response time doesn't exceed a given deadline. In a further work we will focus on validating the proposed model by simulations.

References

[1] IEEE 802.15, "Specification of the Bluetooth System Version 1.1", February 22 2001.

[2] J. H. KLEINSCHMIDT, M. E. PELLENZ, L. LIMA JR, An Efficient Polling Strategy for Bluetooth Piconets using Channel State Information. IEEE 6th Circuits and Systems Symposium on Emerging Technologies, 2004.

[3] A. Mercier, P. Minet, L. George, Introducing QoS support in Bluetooth Piconet with a Class-Based EDF Scheduling, INRIA Research Report 5054, December 2003.

[4] A. MERCIER, P. MINET, L. GEORGE, Accounting for message importance and deadline in Bluetooth piconet scheduling, Med Hoc Net, June 2004.

[5] M. Srinivasan, S. Niu and B. Cooper, Relating Polling Models with Zero and Nonzero Switchover Times, QUEUEING SYSTEMS 19 (1995), 149-168.

[6] J. Misic, V.B. Misic, Modeling Bluetooth Piconet Performance, IEEE Communications Letters, Vol. 7, pp.18-20, January 2003.

[7] J. Misic, K.L. Chan, V.B. Misic, On Bluetooth Piconet Traffic Performance, PIMRC 2002.

[8] H. Takagi, Queuing Analysis, vol. 1: Vacation and Priority Systems Part 1 (1991).

[9] L. Kleinrock, Queuing Systems, Volume II: Computer Applications (Wiley Interscience, 1976).

[10] K. Chen, L. Decreusefond, An Approximate Analysis of Waiting Time in Multi-Classes M/G/1/./ EDF Queues, Network Department, ENST, January 1997.

[11] H. Takagi, T. Takine, O. J. Boxma, "Distribution of the Workload in Multiclass Queueing Systels with Server Vacations", Research Report, Computer Science, 1990.

[12] C. Skianis, ?Demetres D. Kouvatsos, "A Universal me solution for an M/G/1 queue with vacation periods", supported by the Engineering and Physical Sciences Research Council (EPSRC), UK, under grant GR/K/67809

[13] J. L. Holley, "Waiting line subject to priorities", Operations Research, Vol. 2, pp. 72-742, Aout 1954.

[14] Miller, R. G., Jr., "Priority Queuing: The Annals of Mathematical statistics", Vol.31 pp. 86-103, Mars1960.

[15] K. Maalaoui, L. A. Saidane, Z. M. Faten "FP/EDF versus FP/FIFO Local Scheduling in a Bluetooth Piconet", IASTED International Conference on Communication Systems and applications (CSA 2006), Banff, Canada.