Performance of Overlay Bluetooth–WiFi Networks with QoS-oriented Vertical Handover

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***Abstract*— The performance of an overlay Bluetooth and IEEE 802.11b (WiFi) network is considered in terms of packet latency, packet error rate and throughput, in the presence of a vertical handover procedure. The objective of the overlay network is to maximize the quality of service (QoS), giving to a mobile user the possibility to switch from a network to the other, with the so-called vertical handover. The vertical handover is activated by the crossing of thresholds determined according to the user's profile, which comprises objective values for the main QoS parameters, such as the packet error rate and the packet delay. The performance of the network is evaluated taking into account the mutual Bluetooth–WiFi interference and showing the influence of the main parameters of the network and of the handover procedure.**

***Keywords*— Vertical handover (vertical handoff), overlay networks, Bluetooth, WiFi.**

I. INTRODUCTION

Bluetooth and IEEE 802.11b (WiFi) are experiencing a great attention for their capability to provide wireless connectivity and access to multimedia contents to mobile users. In particular Bluetooth is a low-cost technology initially designed for cable replacement [1] but more generally intended for all kinds of Personal Area Networks (PAN) [2] and it is very probable that in a very near future will be embedded in almost every mobile device. On the other hand, WiFi is designed as a solution for higher bandwidth, originally for private applications, but deployed also for public access to create *hotspots* [3]. Although the two networks are conceived for different kind of applications, a possible solution towards the 4th generation, where the goal is to integrate different platforms [4], requires the possibility to transfer the connection between different networks, with the so-called *vertical handover*. Handover is one of the main procedures in almost every wireless network and a lot of studies (see [5], [6] and reference therein) have been presented, especially aiming to determine the right moment to change the serving base station, to define fast procedures and to minimize the probability of call blocking. For example, in [7] the statistical characterization of the dwell time is obtained, in [8] and [9] the call block probability is evaluated. Handover in Bluetooth and WiFi is not fully specified by the standards although the basic building blocks, in terms of procedures, are defined to allow the development of the handover functionalities. In two-tier networks the handover is considered in [9] within the same technology, while the actual vertical handover between different networks is described in [10], showing implementation issues, especially for 2G/3G networks and WLAN/PAN. The vertical handover in overlay networks is considered also in [11] where an RF over infra-red network is considered and experimental results for the handover latency are presented.

Coexistence of Bluetooth and WiFi is a hot topic [12]–[14], due to the fact that they share the same bandwidth. In [12] experimental results are presented, showing that the throughput of both the systems can be reduced approximately to half the value obtained in the absence of interference if the distance between the devices is small (around 1 m). In [13] an a analytical method is developed to determine the probability of collision in the interference scenario, with empirical results to substantiate the analytical model and in [14] the packet error probability is derived.

Here the overlay network performance is considered in the presence of a vertical handover to achieve better QoS objectives. In particular, results on the available bandwidth, the packet delay and error rate will be presented for the overlay network, considering the mutual interference between the two transmission systems. The novelty introduced here is to study the performance of a vertical handover activated on the basis of a user profile comprising a mix of QoS parameters, such as the packet error rate and the packet delay, with weights reflecting the relative importance, determined by the kind of service that has to be provided by the network.

II. BLUETOOTH AND WIFI BASICS

A. Bluetooth

Bluetooth is proposed for ad-hoc networks in the unlicensed band around 2.4 GHz and uses frequency hopping to combat interference. The network architecture of Bluetooth is based on the *piconet* where a master-slave policy is employed, with a master connected up to seven active slaves and up to 256 parked slaves. Each piconet uses a different frequency hopping sequence determined by the address and the clock of the master. The transmission is organized in time-slots (of duration 625 μs), with a gross bit-rate on the channel of 1 Mbit/s and time-division duplex. The access to the medium is controlled by the master, by means of a polling scheme. Although several polling strategies could be employed, in the following a round-robin scheme will be considered. The interconnection of several piconets to create a *scatternet* is made possible by the use of gateways, devices which belong to more than one piconet at different times.

B. WiFi

WiFi is the name adopted by the Wireless Ethernet Compatibility Alliance (WECA) for the IEEE 802.11b standard, and is designed for wireless LAN applications, allows a maximum data rate of 11 Mbit/s, with dynamic rate functionalities. The slot time is 20 μs. The network is organized in Basic Service Set (BSS) which can be connected to form an Extended Service Set (ESS). Also Independent Service Set (ISS) can be considered for ad-hoc networks. The access scheme is based on carrier sense, with the CSMA/CA protocol using a binary exponential backoff and the Request To Send/Clear To Send (RTS/CTS) procedure.

III. SYSTEM MODEL

We consider a scenario where both a Bluetooth and a WiFi network are covering a certain area and the mobile terminal has both the radio interfaces and can connect to one of the networks according to the QoS that it achieves.

A. Network architecture

We assume an overlay network with WiFi BSSs covering N Bluetooth piconets, with a topology similar to that depicted in Fig. 1 for $N = 4$.

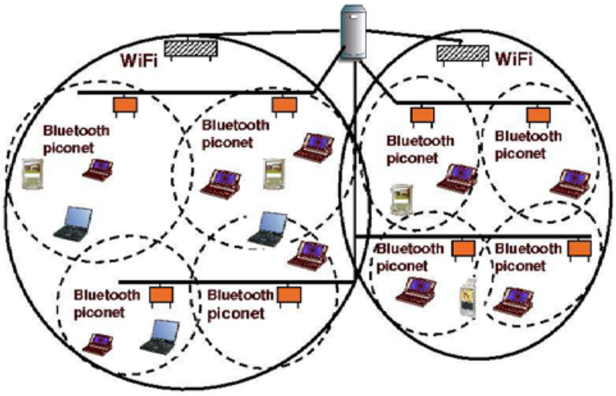

Fig. 1. Schematic of an example of overlay WiFi–Bluetooth network with two WiFi BSSs, each covering four Bluetooth piconets.

The connection is intended primarily between the mobile terminal and an access point, for web-browsing applications, so that connections among mobile users are not considered. Moreover, we suppose that a wired or fixed connection is available to connect the access points (considered in both the technologies) to the server providing the delivery of multimedia contents. In this model, the packet delay is actually determined by the queuing delay to access the wireless link and the delay introduced by the fixed link can be neglected.

B. Traffic model

Taking into account the main purpose of the overlay network, that is to provide access to multimedia contents, the traffic model has to reflect the characteristics of the Internet traffic. To consider the peculiarities of the two standards, which have a completely different packet structure at the physical level, the packet source is assumed at the IP level. The IP packet length is assumed a geometric random variable with mean value L bits, truncated to the maximum length allowed by IP. The packet traffic per user is modeled by an Interrupted Poisson Process (IPP) [16], that is a two-state (ON-OFF) process where the intensity of the Poisson process representing the packet arrival rate switches from 0 to a value Λ, with transition probabilities between the states that depend on the time scale to be represented. In this work the probabilities are set accordingly to the values proposed as the traffic model by the 802.16 working group [17]: in detail, the transition probabilities from the ON state to the OFF state is denoted by c_1 and from the OFF state to the ON state by c_2, with $c_1 = 1.445 \cdot 10^{-2}$ and $c_2 = 1.084 \cdot 10^{-2}$. Then the arrival rate Λ depends on the mean offered traffic value R (expressed in bit/s), according to the relation

$$\Lambda = \frac{R}{p_0 L} \tag{1}$$

where p_0 represents the probability of the state ON, given by

$$p_0 = \frac{c_2}{c_1 + c_2} \tag{2}$$

The packets are then stored in a transmission buffer and taken from the queue according to a FIFO policy by the MAC layer, to accommodate them in the physical layer packet format which depends on the standard considered. This packet fragmentation is performed at the L2CAP layer of the Bluetooth protocol, resulting in a packet length of 1, 3, or 5 slots, while for the 802.11 standard the segmentation occupies the WiFi packet payload, which has a variable length up to the maximum value of 2346 bytes. The packet segmentation strategy used here is to split the packet in the minimum number of physical layer packets, that is to employ larger packets first, then smaller to empty the transmission buffer. This strategy is dictated by the objective to minimize the delay.

C. Channel model

The channel is characterized in terms of its packet error rate (PER). In the environment considered, the principal source of signal degradation is the interference deriving from the other system, that is the signal-to-interference ratio (SIR) is considered as the main parameter influencing the PER.

The power loss is assumed to obey a log-distance model with a power-law $d^{-\beta}$ dependence on the distance d between transmitter and receiver, where the exponent β is assumed between 2 and 4. The power path loss PL, expressed in dB, is then given by

$$PL(d) = \begin{cases} PL_0 & d < d_0 \\ PL_0 + \beta \log_{10}\left(\frac{d_0}{d}\right) & d > d_0 \end{cases} \tag{3}$$

The above model represents a two-step law, with a fixed loss for distances below the distance denoted by d_0. In the simulations, the parameters in equation (3) are set to $d_0 = 1\,\text{m}$ and $PL_0 = 10\,\text{dB}$. Above this, a log-normal shadowing, with standard deviation σ_S, is considered.

The SIR can be expressed as

$$SIR = \frac{P_0(d_0)}{\sum_{i=1}^{U} P_i(d_{0i})} \tag{4}$$

where d_0 denotes the transmitter-receiver distance for the intended user and d_{0i} the distance between the i-th interfering user and the intended receiver, while P_0 and P_i denote the intended and the interfering power, respectively. Since the power control is not generally used in this kind of networks, P_0 and P_i are the fixed transmit powers used by Bluetooth or 802.11. The actual value of SIR is determined not only by the distances, but also by the frequency offset between the two systems Δf, that varies due to the fast frequency hopping technique used by the Bluetooth transmitters. The relation between the SIR and the PER is derived according to the results presented in [14].

D. Users mobility

Users are supposed to move in the depicted scenario following a random way-point process [19], that is for a random amount of time they move along a fixed direction at a speed that in a general model could be random, but here is assumed fixed. At the end of the random interval, the user chooses another direction which will be followed for the next random time interval.

IV. Horizontal and vertical handover

A. Horizontal handover

In Bluetooth the procedures to perform the handover are not fully defined by the standard, but the paging procedure, used to synchronize to the master of a piconet once discovered, could be employed to successfully transfer the connection from a piconet to another in a reasonable amount of time also in the case of a pure ad-hoc network, where no wired connection is assumed between the masters [15].

Also in WiFi networks, the procedures to perform the handover between different Basic Service Sets (BSS), that is the area controlled by access point, is a topic under investigation with proposals to perform it. A beacon signal is transmitted by the access points every 100 ms, that includes a time stamp for client synchronization, a traffic indication map, an indication of supported data rates, and other parameters. The mobile terminal keeps tack of the received signal strength indicator (RSSI) of the beacon and when weak, it becomes to scan the beacon signals from other access points, then a re-association procedure takes place.

In this analysis, the horizontal handover is performed as a function of the received power, by a comparison between the power received from different access points or masters. The handover is activated when the power received from another access point exceeds the power of the actual connection of a suitable amount.

Not all the handover parameters, such as the RRSI or SIR thresholds, have a large impact on the performance considered, and the handover is modeled by an amount of time needed to exchange the signaling informations, during which the link is not available for the traffic transmission.

B. Vertical handover

The possibility to perform the vertical handover has the goal to improve the quality, so that if the QoS attained in one network drops below a certain threshold, the mobile user attempt to change to the other network. In this study, the QoS parameters used to trigger the vertical handover (in both directions) are the PER and the packet delay, that can be practically estimated by the upper protocol layers. The vertical handover is modeled by a delay, corresponding to the time to transfer the signaling information between the two networks. The actual architecture employed is out of the scopes of this analysis: advanced solutions such as a micro-mobility management methods [18] should be employed to minimize the handover time.

The idea is to activate the vertical handover on the basis of a profile, which accounts for the requirements of the service. Herein, the profile is defined by the packet error rate PER and the delay D, setting objective values for these parameters whose importance is weighted, according to a weight vector $[w_{\text{PER}}, w_D]$. Note that also other elements could be included in the profile, even very different, for example a cost could be assigned to each of the networks. In detail, the objective values are used as thresholds PER_{th} and D_{th} to evaluate a condition, that will be called QoS-dissatisfaction, U, on the basis of the weights assigned to the parameters of the profile, namely

$$U = w_{\text{PER}}\, \mathcal{I}[PER > PER_{th}] + w_D\, \mathcal{I}[D > D_{th}] \quad , \qquad (5)$$

where $\mathcal{I}(X)$ denotes the indicator function of the event X. In other words, the weights can be seen as flags, which are set by the conditions on the delay and on the PER. When U crosses the threshold U_{th}, which is one of the handover parameters, the vertical handover is activated. To avoid the so-called *ping-pong effect*, that is the fact to keep switching from network to network, the mechanism chosen is to evaluate the conditions only in correspondence to time The alternative could be to introduce an hysteresis in the thresholds.

V. Evaluation of the network performance

The performance of the overlay network is obtained resorting to a simulation, developed in C, where the position of the users is randomly generated to determine the SIR conditions and is updated according to the mobility model. For each user the packets are generated according to the traffic model outlined before and the traffic statistics collected.

The quality indicators considered are the throughput and the packet delay and error rate. To summarize the performance in a single parameter, we define the QoS satisfaction, that is the percentage of time during which the objective values of the user profile are achieved. Indeed, this is the basic criterion used also to trigger the vertical handover and, by means of this parameter, the different networks (pure Bluetooth, WiFi or overlay) can be compared.

To limit the degrees of freedom in order to present some numerical results we set some system parameters:

- square coverage area 40 m×40 m, with 4 BSSs, each covering 4 piconets;
- Bluetooth transmit power 0 dBm;
- WiFi transmit power 20 dBm;
- propagation loss coefficient $\beta = 3$;
- propagation shadowing standard deviation $\sigma_S = 3$ dB;
- duration of the horizontal handover procedure 10 ms;
- users' speed 1 m/s.

A. Packet delay

Fig. 2 presents the packet latency as a function of the offered traffic per user, for the three systems, showing that the performance of the overlay network lies between the performance of the two networks. The number of users is set to 50, the objective thresholds are $PER_{th} = 10^{-2}$ and $D_{th} = 10$ ms and the duration of the vertical handover procedure is assumed of 10 ms. The graph legend for the curves referring to the overlay network with vertical handover denotes the values $[U_{th}, w_{\text{PER}}, w_D]$, respectively. The

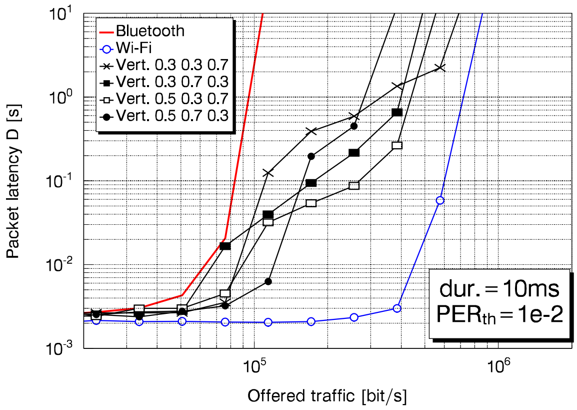

Fig. 2. Average packet delay as a function of the offered traffic, for the three systems, with different user profiles $[U_{th}, w_{PER}, w_D]$.

performance is still in advantage of a pure WiFi network: this is justified by the higher rate available in this network; note, however, that no control on the values of PER is applied.

B. PER

As far as the packet error rate is concerned, the effect of the vertical handover is shown in Fig. 3, where the PER versus the traffic is presented for the three systems, with 50 users in the network. It can be seen that the best PER is achieved by the overlay

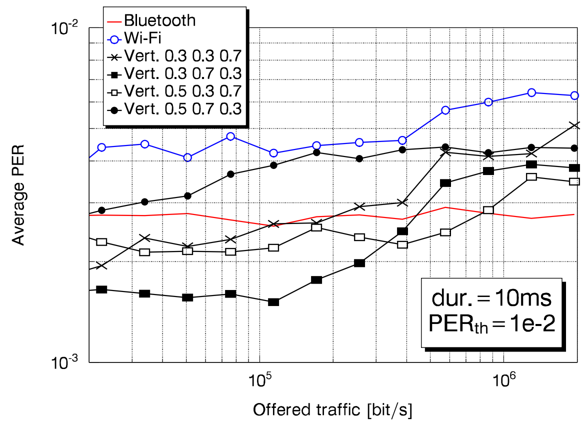

Fig. 3. Average PER as a function of the offered traffic, for the three systems.

network, with a very light dependence on the offered traffic. The fact that the PER of the Bluetooth system is better than the one of the WiFi network can be ascribed to the fact that the errors are mainly due to the interference from the users belonging to the other network and the WiF- i users are distributed over a larger area (the BSS), so that, in average, the distance from the desired receiver is higher, with a lower value of interfering power. Note that the duration of the handover procedure does not affect this performance indicator.

C. Throughput

In terms of throughput the performance is shown in Fig. 4, where the available bandwidth is shown as a function of the offered traffic per users, comparing the three systems, with PER threshold $PER_{th} = 10^{-2}$ and delay threshold $D_{th} = 10\,\text{ms}$. Again the number of users in the network is 50 and other parameters have the same values as in Fig. 2. Although the use of a vertical handover

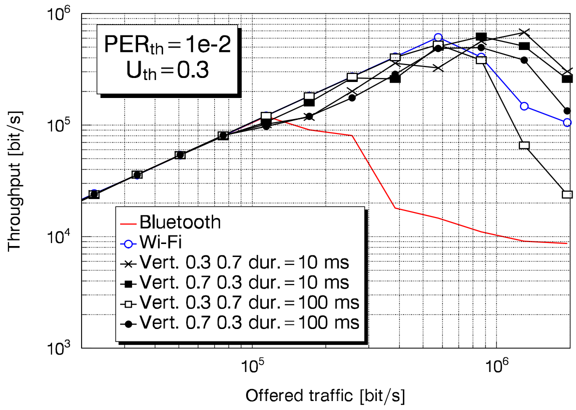

Fig. 4. Average throughput as a function of the offered traffic, for the three systems, with different user profiles $[w_{PER}, w_D]$ and vertical handover durations.

can lead to a slightly lower bandwidth with respect to a pure WiFi system at a medium load, for a high load an improvement in the throughput can be obtained. Moreover, note that in this case, a control on the packet error rate and delay is performed. The reduction of the achievable throughput with increasing values of the handover duration can be observed.

D. QoS satisfaction

We remind that the QoS satisfaction measures the percentage of time during which $D < D_{th}$ and $PER < PER_{th}$, that is the active connection is able to guarantee the objective values of delay and PER. QoS satisfaction as a function of the offered traffic, for the Bluetooth, WiFi and overlay systems, is shown in Fig. 5 for 50 users: it can be seen that if the duration of the vertical handover can be limited to 10 ms, the advantage of using a vertical handover procedure becomes apparent for heavy traffic. Note that the results of Fig. 5 refer to the objective value $PER_{th} = 10^{-2}$, which is achieved quite easily so that a pure WiFi system is almost preferable: on the other hand, if the requirements on the PER are more strict, the advantage of using both the systems appears, as shown in in Fig. 6, where the QoS satisfaction as a function of the offered traffic is presented for different users' profiles for the objective $PER_{th} = 10^{-3}$. Note that the requirement of PER envisaged by the IEEE802–2001 standard, referring to the family of 802 standards, is around 10^{-4} and even lower in the IEEE802.16.3 standard. Examples of applications requiring such objectives can be streaming services or time critical packet services: note in fact that although the delay objective of 10 ms is quite strict, quality

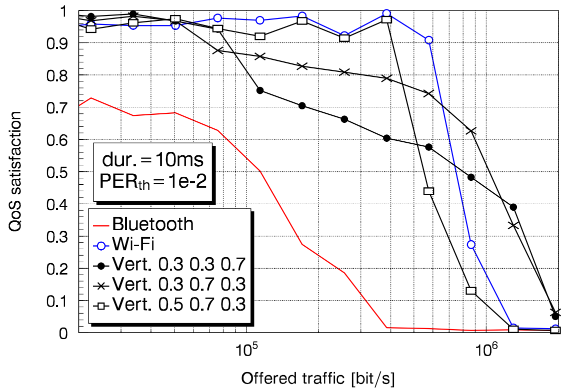

Fig. 5. QoS satisfaction as a function of the traffic, $PER_{th} = 10^{-2}$, vertical handover duration 10 ms, with different user profiles $[U_{th}, w_{PER}, w_D]$.

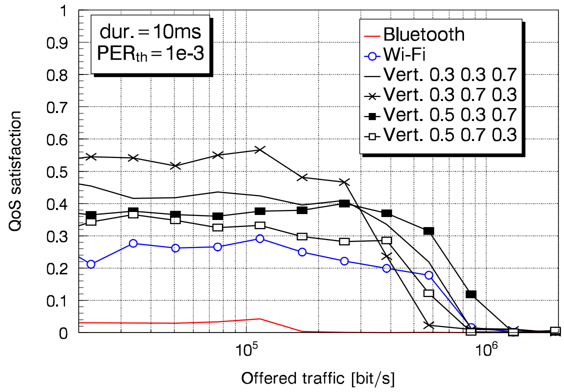

Fig. 6. QoS satisfaction as a function of the traffic, for $PER_{th} = 10^{-3}$, with different user profiles $[U_{th}, w_{PER}, w_D]$.

objectives should lay the range 20–100 ms: moreover, they refer to the overall access delay, not only to the wireless access. The effect of the handover parameters is considered in Fig. 7, where the QoS satisfaction is presented as a function of the duration of the vertical handover procedure, for different users' profiles, showing the criticality of this parameter, that must be kept under a controlled value. Note that if the QoS satisfaction of the overlay system with vertical handover as a function of the dissatisfaction threshold is shown in Fig. 8 for the objective $PER_{th} = 10^{-3}$. To compare the systems, Fig. 9 presents the values of QoS satisfaction as a function of the number of users for the objective value $PER_{th} = 10^{-2}$ and for an offered traffic per user of 200 kbit/s and a vertical handover duration of 100 ms. It can be seen clearly that the WiFi system is still giving the best performance, but the use of the vertical handover gives a great enhancement with respect to a pure Bluetooth network. On the other hand if the requirements on the PER are more stringent, that is the objective PER is lowered to $PER_{th} = 10^{-3}$, the results are quite different as shown in Fig. 10, where the QoS satisfaction of the overlay system is compared to the one obtained with Bluetooth and WiFi for two different profiles, with a vertical handover duration of 100 ms and an offered traffic per user of 200 kbit/s. In this case the advantage of using the overlay network becomes more evident.

VI. Conclusions

The vertical handover based on a profile of objective parameters has been considered in an overlay Bluetooth/WiFi network. It has

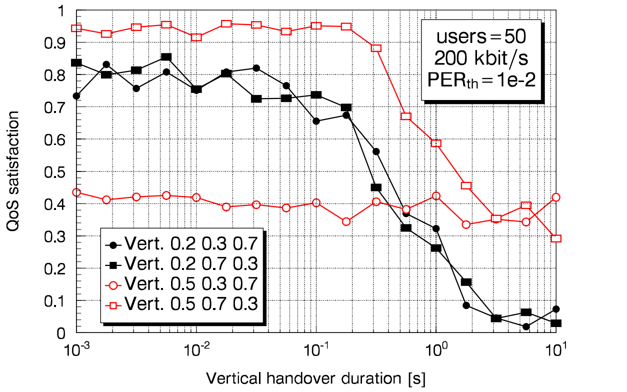

Fig. 7. QoS satisfaction as a function of the duration of the vertical handover procedure, with different user profiles $[U_{th}, w_{PER}, w_D]$.

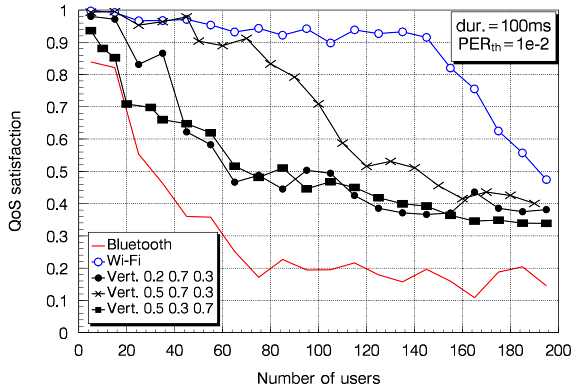

Fig. 9. QoS satisfactions as a function of the number of users for $PER_{th} = 10^{-2}$, with different user profiles $[U_{th}, w_{PER}, w_D]$.

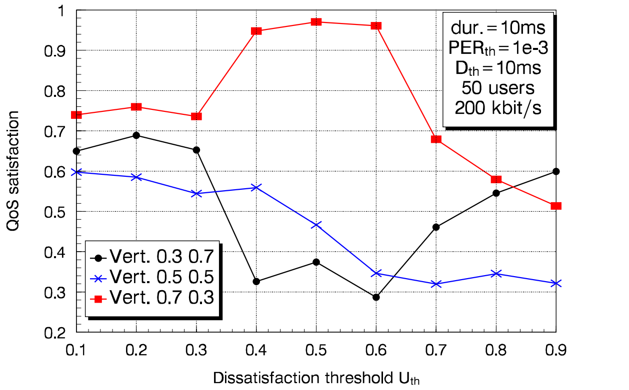

Fig. 8. QoS satisfaction as a function of the dissatisfaction threshold U_{th}, for the objective $PER_{th} = 10^{-3}$, with different user profiles $[w_{PER}, w_D]$.

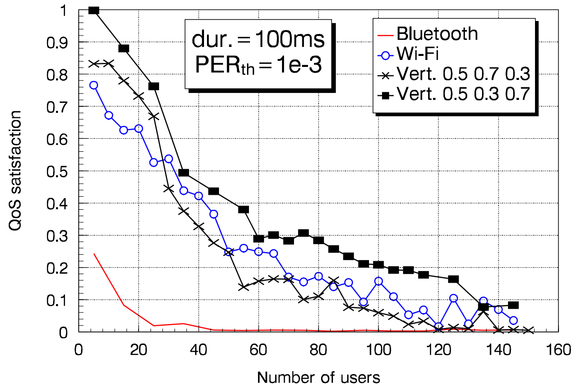

Fig. 10. QoS satisfactions as a function of the number of users for $PER_{th} = 10^{-3}$, with different user profiles $[U_{th}, w_{PER}, w_D]$.

been shown that if the requirements on the connection are demanding the possibility to perform the vertical handover can lead to a significant improvement. however, the handover parameters such as the thresholds and the duration should be suitably controlled to achieve an actual advantage by the vertical handover procedure.

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