QoS Analysis in Overlay Bluetooth-WiFi Networks with Profile-Based Vertical Handover

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Abstract—The performance of an overlay Bluetooth and IEEE 802.11b (WiFi) network is considered in terms of quality of service parameters such as the packet latency, the packet error rate, and the throughput, in the presence of a vertical handover procedure, taking into account the mutual Bluetooth-WiFi interference and showing the influence of the main system parameters. The objective is to maximize the user QoS allowing the mobile to switch from a network to the other, with the so-called vertical handover. The basic idea is to activate the vertical handover, not on the basis of the received power level, but by the crossing of thresholds defined by the user profile, which comprises objective values for parameters such as the packet error rate and the packet delay. The results show that the use of the vertical handover procedure can lead to an improvement in the QoS parameters.

Index Terms—Vertical handover (vertical handoff), overlay networks, QoS, Bluetooth, WiFi.

1 Introduction

Bluetooth and IEEE 802.11b (WiFi) are experiencing a great attention for their capability to provide wireless connectivity. In particular, Bluetooth is a low-cost technology initially designed for cable replacement [1] but more generally intended for all kinds of Personal Area Network (PAN) applications [2]. It is probable that, in the very near future, Bluetooth will be embedded in almost every mobile device. On the other hand, WiFi is designed as a solution for high transmission rate, originally for private applications in wireless local area networks (WLANs), but deployed also for public access to create *hotspots* [3]. Although the two networks are conceived for different kinds of applications, a possible solution toward the fourth generation, where the goal is to integrate different standards [4], requires the possibility to transfer the connection among different networks with the so-called *vertical handover*.

Handover is one of the main procedures in almost all wireless networks and quite a lot of studies (see [5], [6], and references therein) have been presented to determine the right moment to change the serving base station or to define fast procedures and to minimize the probability of call blocking. In [7], the statistical characterization of the dwell time, that is, the allowed queuing time, is obtained in terms of the main propagation and mobility parameters. In [8] and [9], the call block probability is evaluated resorting to a Modulated Markov Process to model the cell crossing and the new calls. All these studies refer to a generic mobile network. Handover in Bluetooth or WiFi is not fully specified by the standards, although the basic building blocks are defined to allow the development of the handover functionalities. In two-tier networks, the handover procedure is considered in [9], where the two networks share the same technology, while the vertical handover between different networks is described in [10], showing implementation issues at the network protocol level, especially for 2G/3G networks and for WLAN/PAN. The vertical handover with different networks is also considered in [11], where a radio network over an infrared one is analyzed and experimental results for the handover latency are presented.

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

Herein, the performance is considered with the vertical handover used to achieve better QoS objectives. In particular, results on the available bandwidth and on the packet delay will be presented for the overlay network, considering the advantages of the vertical handover. Note that, although the two systems have a huge capacity difference, there can also be an advantage in the switch from WiFi to Bluetooth for better interference conditions. The novel approach proposed here is to activate the vertical handover on the basis of a user profile comprising a set of QoS parameters, such as the packet error rate (PER) and the packet delay D. Each parameter is weighted, reflecting the relative importance, determined by the kind of service that has to be provided by the network. The definition of a set of parameters to evaluate the quality of a communication is an approach already introduced by the 3G systems; for example, by the UMTS standard [15]. This principle is flexible enough to define a profile that could also include

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parameters, such as the cost of the communication, as it will be considered in the last part of the paper or others.

The paper is organized as follows: In Section 2, the basic principles of the two technologies constituting the overlay network are summarized; then, the model and the main characteristics of the overlay network are presented in Section 3. The vertical handover procedure is presented in Section 4. Finally, in Section 5, the numerical results for the performance parameters are presented and discussed.

2 Bluetooth and WiFi Basics

2.1 Bluetooth

Bluetooth is proposed for ad hoc networks in the unlicensed band around 2.4 GHz and uses frequency hopping to combat interference and selective fading. The network architecture of Bluetooth is based on the *piconet*, where a master-slave policy is employed with a master connected to up to seven active slaves and up to 256 parked ones. Each piconet uses a different frequency hopping sequence. The transmission is organized in time-slots (of duration 625 μs) with a gross bit-rate on the physical channel of 1 Mbit/s. The packets can occupy one, three, or five slots. The access to the medium is controlled by the master by means of a polling scheme. The interconnection of several piconets to create a *scatternet* is made possible by the use of gateways, which belong to more than one piconet, or by a wired connection among the masters [1].

2.2 WiFi

WiFi is the name adopted by the Wireless Ethernet Compatibility Alliance (WECA) for the IEEE 802.11b standard and is designed for WLANs. It allows a maximum data rate of 11 Mbit/s with dynamic rate functionalities. The transmission is organized in slots, with a slot duration of 20 μs. The network is composed of Basic Service Sets (BSSs), each corresponding to the area controlled by an access point. Several BSSs can be connected to form an Extended Service Set (ESS). Also, the possibility to create ad hoc networks is considered by the standard, by means of the Independent Service Set (ISS) [16]. The multiple access scheme is based on the carrier sense technique with collision avoidance (CSMA/CA) using a binary exponential backoff time and the Request To Send/Clear To Send (RTS/CTS) service primitive.

3 System Model

The scenario consists of one Bluetooth and one WiFi network, both covering the same service area, considered as an $R_{max} \times R_{max}$ square. It is assumed that each mobile terminal is equipped with both radio interfaces and can connect to each network but not simultaneously to both. Together with the physical layer and access scheme of the standards considered, other aspects have an impact on the network performance: mainly, the propagation model, determining the conditions on the PER, and the traffic model, which influences the packet delay. However, to derive the actual values of PER and delay, the relative distances among the users play a fundamental role. Hence, also the mobility model within the coverage area has to be presented.

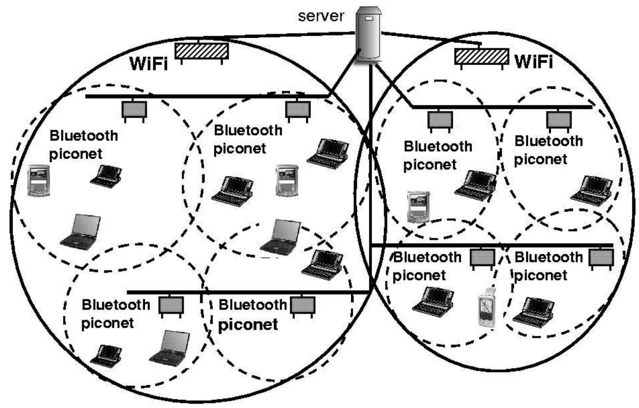

Fig. 1. Schematic of the overlay WiFi-Bluetooth network: Example with two WiFi BSSs, each covering four Bluetooth piconets.

3.1 Network Architecture

We assume that, in the overlay network, each WiFi BSS is covering several Bluetooth piconets with a topology similar to that depicted in Fig. 1. We suppose that a wired connection is available to connect the access points and the masters to the server providing the delivery of multimedia contents. The term *base station* will be used in the following to denote an access point or the master whenever it is not necessary to discriminate if WiFi or Bluetooth is considered. Since the communication is intended primarily between the mobile terminal and the server, connections among mobiles are not considered. This assumption implies that the packet delay is mainly determined by the wireless link between the mobile and the base station, rather than by the wired link, and the delay between the base station and the server will be neglected.

3.2 Channel Model

The channel is characterized in terms of its packet error rate. In the considered environment, the principal source of degradation is the interference deriving from the other system. Hence, the signal-to-interference ratio (SIR) is the main parameter influencing the PER. The path loss PL in the propagation between transmitter and receiver at distance d, expressed in dB, is

$$PL(d) = \begin{cases} PL_0 & d < d_0 \\ PL_0 - \beta \log_{10}\left(\frac{d_0}{d}\right) & d > d_0. \end{cases} \tag{1}$$

The above model represents a two-step law with a fixed loss for distances below d_0 and a power-law $d^{-\beta}$ for large distances, where the exponent β is commonly assumed between 2 and 4. In addition to this path loss, a log-normal shadowing S is also considered with standard deviation σ_S. The received power at distance d, in dB, is then given by $P(d) = P - PL(d) - S$, where P is the transmitted power. We remark that P can be assumed to be fixed since power control is not used in this kind of network. Then, the SIR experienced by user 0, considered the desired user, can be expressed as

$$SIR_0 = \frac{P_0(d_0)}{\sum_{i=1}^{N_u} P_i(d_{0i})}, \tag{2}$$

where N_u is the number of interfering users, that is, the users belonging to the other system. $P_0(d_0)$ and $P_i(d_{0i})$ denote the intended and the interfering power at the distance d_0 and d_{0i}, where d_0 is the transmitter-receiver distance for the intended user and d_{0i} between the ith interfering transmitter and the intended receiver. The actual value of SIR is determined not only by the power level, but also by the frequency offset Δf between the two systems that varies according to the frequency hopping sequence used by the Bluetooth transmitters. Since, in general, only a partial spectral superposition of the Bluetooth and WiFi transmissions occurs, the effect of the level of SIR on the error rate depends on the spectral overlapping. The relation between the level of SIR and the PER has been derived in [14] and the results will be applied in the sequel to relate the desired value of PER to a corresponding value of SIR.

3.3 Traffic Model

Taking into account that the main purpose of the overlay network 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 with a different packet structure at the physical level, the packet source is assumed at the IP level. The IP packet length is modeled by a truncated geometric random variable, with mean value L bytes and maximum length 1,500 bytes. In this study, the mean value of the packet length is chosen equal to 128 bytes, a value also in the range suggested for wireless applications in [17]. Then, both the offered traffic and throughput are referring to the gross (including IP headers) traffic at the IP level. The packet traffic per user is generated by an Interrupted Poisson Process (IPP) [18]; that is, a two-state (ON-OFF) process where the intensity of the Poisson arrival rate switches from 0 to a value λ. The transition probabilities between the states are set as proposed by the IEEE 802.16 working group [19]: In detail, the transition probability from ON to OFF is $c_1 = 1.445 \cdot 10^{-2}$ and from OFF to ON is $c_2 = 1.084 \cdot 10^{-2}$. The arrival rate λ depends on the mean offered traffic value R_b (expressed in bit/s) according to the relation $\lambda = \frac{R_b}{p_0 L}$, where $p_0 = c_2/(c_1 + c_2)$ represents the probability of the state ON. The packets are taken from the transmission buffer according to a FIFO queuing policy by the MAC layer to accommodate them in the physical layer packet. This packet fragmentation into the physical layer packets is performed at the L2CAP layer of the Bluetooth protocol, resulting in packets of one, three, or five slots. For the IEEE 802.11b standard, the WiFi packet payload has a variable length up to a maximum of 2,346 bytes.

Note that, in the following, the values of the mean offered traffic refer to the download stream, considering highly unbalanced connections with asymmetric traffic where uplink is almost negligible compared to the downlink due to the assumption of Web-browsing applications. For example, for Bluetooth, this means that the use of a single slot for the reverse link is sufficient, every one, three, or five downlink slots.

A buffer analysis can be conducted for the Bluetooth or WiFi case, separately, resorting to the classical queuing theory [20] since the arrival process is modeled by an IPP. The number of packets in the queue is well approximated by a geometric random variable with parameter $(1-\rho)$, where ρ is the *activity coefficient* [20] given by the ratio between the arrival rate, given by the sum of the arrival rates of the N_{active} active users in the cell and the service rate μ:

$$\rho = \frac{N_{active}\lambda}{\mu}. \tag{3}$$

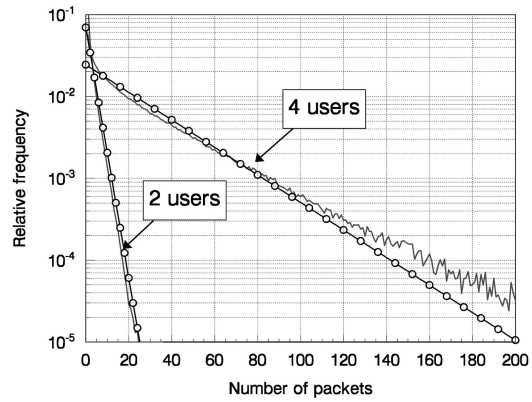

Fig. 2. Histogram of the number of packets in the queue in a Bluetooth piconet with offered traffic per user of 100 kbit/s and two or four users per piconet: The dots represent the theoretical values.

For Bluetooth, the available physical layer bit-rate, representing the piconet service rate in bit/s, depends on the type of packets used. Assuming the use of DH5 packets, the value is 723.2 kbit/s in asymmetric traffic [1]. An example of the number of packets in the buffer of a piconet running Bluetooth connections with an asymmetric offered traffic of 100 kbit/s per user is presented in Fig. 2 for two and four users and compared to the simulation results. Since the packet length is modeled by a geometric random variable with parameter $p_l = 1/(L+1)$, the characteristic function [27] of the total number of bytes b in the buffer results in

$$\begin{aligned}\psi_b(f) &= E[e^{j2\pi fb}] \\ &= \frac{(1-\rho)^2}{1 - \frac{\rho p_l}{1-(1-p_l)e^{j2\pi f}}} + \rho(1-\rho)\frac{\rho p_l}{1-(1-p_l)e^{j2\pi f}}.\end{aligned} \tag{4}$$

The numerical Fourier inversion of the characteristic function by means of the FFT then gives the probability density function, which is compared to the histogram derived from the simulations in Fig. 3 for the same conditions of Fig. 2, showing a perfect agreement. For WiFi, the same analysis can be applied, varying the service rate μ in relation to the rate employed by the device up to 11 Mbit/s. To take into account the effects of a finite buffer, a feedback is considered, blocking the incoming traffic whenever the buffer occupancy exceeds 90 percent of its capacity. In the simulations, the buffer capacity is considered at 128 kbyte.

3.4 Users Mobility

Users are supposed to move in the depicted scenario following a random way-point process [21]. In such a case, each user chooses a random destination in the coverage area

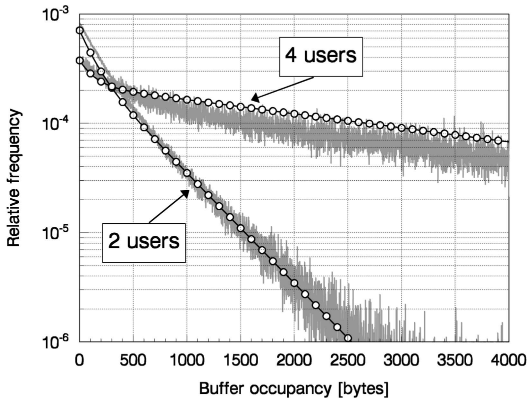

Fig. 3. Histogram of the buffer occupancy (in bytes) for a Bluetooth piconet with offered traffic per user of 100 kbit/s and two or four users per piconet: The dots represent the theoretical values.

and moves along a straight line to reach it, independently of the others, at a fixed speed. At the end of the random interval, the user chooses another destination which will be followed for the next time. The piconets and the BSSs will be modeled as square areas to derive the probability density function of the distance between user and base station connected to the wired net. The evaluation is carried out in Appendix A and is used to obtain the statistics of the received power and SIR on the basis of the stationary probability density function $f_{(x,y)}(a,b)$ of the user location (x,y) [22]. It should be noted that the probability density function $f_{(x,y)}(a,b)$ corresponding to a random waypoint model is not uniform [22], [23], but it shows a higher probability for the locations at the center of the area, while the probability is going to zero for the positions at the borders. Also, the circular symmetry of the density function is lost approaching the borders of the area. On the other hand, for a limited portion of the coverage area, as the piconet can be considered with respect to the overall area, the probability density could be approximated as a constant.

3.5 Horizontal Handover

Due to mobility, users need to change the base station to get a better link, therefore performing the *handover*. First of all, it should be pointed out that *horizontal* refers to the handover within the same network; that is, from a piconet to another in Bluetooth or from a BSS to another in WiFi. In Bluetooth, the procedures to perform the handover are not fully defined by the standard. However, the paging procedure, designed to synchronize to a newly discovered master, could be employed also to perform the handover [24]. Also, for WiFi, efficient procedures to perform the handover are being investigated. The handover procedure is based on the beacon signal transmitted by the access points every 100 ms. The mobile terminal keeps track of the received signal strength indicator (RSSI) from the beacon and, when weak, it scans the beacon signals from others access points and a reassociation procedure to the new access point takes place. The aspects to be considered are:

- the conditions which trigger the handover,
- the admission strategy, and
- the execution of the handover, characterized in terms of its duration.

As it happens for WiFi in this study, in Bluetooth, the horizontal handover is also performed on the basis of the received power by a comparison among the powers received from different base stations. The horizontal handover is then activated when the power received from another base station exceeds the power of the actual connection by a suitable threshold ΔP, which represents one of the design parameters of this procedure.

The admission control is not usually implemented in WiFi by the BSS since low mobility is normally considered, so that when a user enters the network, it is assumed that the resources are available and the probability that the reassociation procedure fails is negligible. Therefore, with respect to the horizontal handover, the admission is limited to Bluetooth; that is, a new user, after attempting the handover, is always accepted in a WiFi BSS, while it can be refused by the master of a Bluetooth piconet if the number of the active users is already equal to seven. For the vertical handover procedure, a simple admission control will be considered and a new user coming from Bluetooth to WiFi can be refused.

The handover execution involves different network components, but, to this study, the relevant aspect is the time needed to exchange the signaling information; that is, the handover duration, during which the link is not available for the traffic transmission. In particular, the delay can be divided into

- a signaling to the current base station,
- a signaling among base stations, and
- the confirmation of the new base station; that is, a signaling from the new base station to the mobile terminal.

In Bluetooth, the discovery phase is generally very long, but, as shown in a previous study [24], the handover duration can be reduced to the order of tenths of milliseconds also in the case of a pure ad hoc network, by using the paging procedure. Also, in WiFi, experimental results [25] give short values for the handover delay of the order of some tenths of milliseconds. Herein, the horizontal handover duration is modeled by a Gaussian random variable with mean value 100 ms and "minimum" value (three times the standard deviation away from the mean value) of 10 ms; in other words, the standard deviation is 30 ms.

3.5.1 Horizontal Handover Attempt Probability Due to Shadowing

A horizontal handover is attempted whenever the received power from another base station exceeds, by an amount of ΔP dB, the received power from the base to which the mobile is currently connected. This probability due to the shadowing effect, once connected to the closest base station, is quite low. In fact, it can be derived by conditioning with respect to the position (x,y) of the user. For each position, the distances from all the base stations can be evaluated. The received power $P_0(d_0(x,y))$ from the serving base station has average value $m_{P_0}(x,y)$ determined by the path loss model with distance $d_0(x,y)$ and the same holds for the N_b powers $P_i(d_{0i}(x,y))$ received from the other base stations at distances $d_{0i}(x,y)$ with mean values $m_{P_i}(x,y)$. Therefore, the horizontal handover attempt probability, $P^H_{att|(x,y)}$, conditioned by the user position, is given by

$$P^H_{att|(x,y)} = 1 - \prod_{i=1}^{N_b} P[P_i(d_{0i}(x,y)) - P_0(d_0(x,y)) < \Delta P]. \quad (5)$$

Considering the log-normal shadowing superimposed to the path loss, the probabilities in the above product can be expressed in terms of the Gaussian distribution function. Averaging with respect to the probability density function $f_{(x,y)}(a,b)$ of the user position, reported in Appendix A for the random waypoint model, the attempt probability then results in

$$P^H_{att} = 1 + - \int_0^{R_{max}} \int_0^{R_{max}} \prod_{i=1}^{N_b} Q\left(\frac{\Delta P - m_{P_i}(a,b) + m_{P_0}(a,b)}{\sqrt{2}\sigma_S}\right) \times f_{(x,y)}(a,b)\, dadb \quad (6)$$

with R_{max} representing the length of the square coverage area. The probability has been evaluated numerically, averaging the probabilities for Bluetooth and IEEE802.11b users, and it is quite low for values of the shadowing standard deviation in the typical range up to about 6 dB.

3.6 Simulation Settings

To validate the approximate analysis and to obtain the performance of the network in terms of available throughput, packet delay, and PER, a simulation has been developed, where the position of the users is randomly generated, to determine the SIR conditions. The positions are initialized by the stationary node distribution of the waypoint model and updated along the simulation according to the mobility model. For each user, the packets are generated by the traffic model outlined before and the traffic statistics collected.

To limit the degrees of freedom, some system parameters have been set:

- square coverage area $40\text{m} \times 40\text{m}$, with four BSSs, each covering four piconets,
- Bluetooth transmit power 0 dBm,
- WiFi transmit power 20 dBm,
- propagation loss coefficient $\beta = 3$,
- path loss parameters in (1): $d_0 = 1$ m and $PL_0 = 10$ dB,
- propagation shadowing standard deviation $\sigma_S = 3$ dB, and
- user speed 1 m/s.

4 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 attempts to move to the other network. The vertical handover is allowed from both Bluetooth and WiFi. The idea is to activate the vertical handover on the basis of a profile, which takes into account the service requirements. In this study, the set of parameters of the profile is composed by the PER and the packet delay D, that can be practically estimated by the upper protocol layers. The procedure is controlled by assigning objective values PER_{th} and D_{th} and weights $[w_{PER}, w_D]$, with $w_{PER} + w_D = 1$, to the parameters of the profile. The weights reflect the relative importance of each objective, according to the type of service. The objective values are used as threshold to determine a QoS-dissatisfaction value U on the basis of the weights assigned to the profile parameters

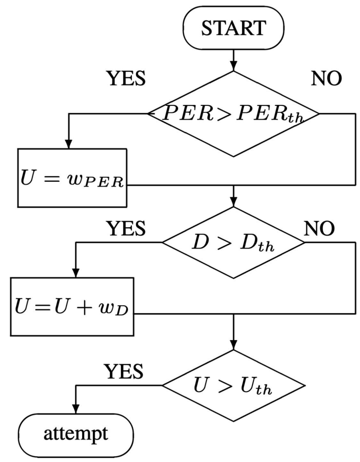

Fig. 4. Procedure to attempt the vertical handover.

$$U = w_{PER}\, \mathcal{I}[PER > PER_{th}] + w_D\, \mathcal{I}[D > D_{th}], \quad (7)$$

where $\mathcal{I}[X]$ denotes the indicator function of the event X. The scheme is presented in Fig. 4. When U crosses the threshold U_{th}, which is one of the handover parameters, the vertical handover is activated. Also, note that other elements could be included in the profile, even very different from transmission parameters; for example, a cost could be assigned to each of the networks. This will be considered in the last part of the paper. Also, note that this approach gives the possibility to summarize the performance in a single parameter, defining the *QoS satisfaction* as the percentage of time during which the objective values are achieved. This parameter allows us to compare the different networks (pure Bluetooth, WiFi, or overlay).

4.1 Vertical Handover Attempt Probability

The vertical handover is attempted when a mix of conditions occurs on the PER, which is directly related to the SIR, and on the queuing delay, which is more directly related to the number of users and to the offered traffic. The two cases are considered separately to derive an approximation to the handover attempt probability that will be compared to the simulation results.

4.1.1 PER

The condition on the PER is reconduced to a condition on the SIR, according to the results presented in [14], so that the vertical handover attempt probability due to the PER condition, $P^V_{att,PER}$, is given by

$$P^V_{att,PER} = P[PER < PER_{th}] = P[SIR < SIR_{th}]. \quad (8)$$

Since the average received power is a function of the distance, the position of all the users would be required to determine the value of SIR. If the number of users of the network increases, conditioning on the position of all the users and then averaging over the multidimensional joint probability density function of their position would be almost impossible if the number of users is high, so that the probability is evaluated by considering only the nearest interfering user. Considering the uplink, $f_{d_0}(a)$ denotes the probability density function of the distance d_0 between the serving base and the desired user and $f_{d_{min}}(a)$ of the distance d_{min} between the closest interfering user and the serving base station. The stationary probability density function $f_d(a)$ of the distance from the center of a square region $R \times R$, for a user following a way-point model, is obtained in Appendix A. Then, the density of the distance d_0 is given by (21) for $R = R_c$, where R_c is the dimension of the coverage area for the intended user, which corresponds to a piconet or to a BSS,

$$f_{d_0}(a) = f_d(a, R_c) = \frac{3\pi}{2}\left[\frac{3a}{R_c^2} + 6\frac{a^5}{R_c^6} - 12\frac{a^3}{R_c^4}\right], 0 \leq a \leq \frac{R_c}{2}. \tag{9}$$

On the other hand, the minimum distance d_{min} varies in a wider range since the interfering user can be located over all the coverage area, not only in the piconet or in the BSS of the desired user. The probability density function of d_{min} results in

$$f_{d_{min}}(a) = N_u[1 - F_d(a, R_{max})]^{N_u - 1} f_d(a, R_{max}), \tag{10}$$

where $f_d(a, R_{max})$ is given by (21) for $R = R_{max}$ and $F_d(a, R_{max})$ is the corresponding probability distribution function given by (20). Then, the probability that the SIR is lower than the target value SIR_{th} is expressed conditioning on these distances as

$$P^V_{att,PER} = \int_0^{R_{max}} \int_0^{R_c} Q\left(\frac{SIR_{th} - m_{P_{min}(b)} + m_{P_0}(a)}{\sqrt{2}\sigma_S}\right) \times f_{d_0}(a) f_{d_{min}}(b) da db, \tag{11}$$

where, again, $m_{P_0}(a)$ denotes the mean of the received power for the desired user and $m_{P_{min}}(b)$ the mean power received from the nearest interfering user at distances a and b.

The sensitivity to the PER threshold is shown in Fig. 5, where the vertical handover attempt probability $P^V_{att,PER}$ is shown as a function of PER_{th} with different numbers of users. It can be seen that the attempt probability changes almost unnoticeably with the PER threshold up to a very high value, where the handover probability drops to negligible values. Note that, for such a high PER, the network would become unreliable. The approximate theoretical value gives a close upper bound to this probability.

4.1.2 Delay

The evaluation of the probability of the queuing delay exceeding a threshold D_{th} starts from the expression of the delay

$$D = \sum_{i=0}^{p_q} \sum_{j=0}^{N_{active}(i)-1} l_{i,j}, \tag{12}$$

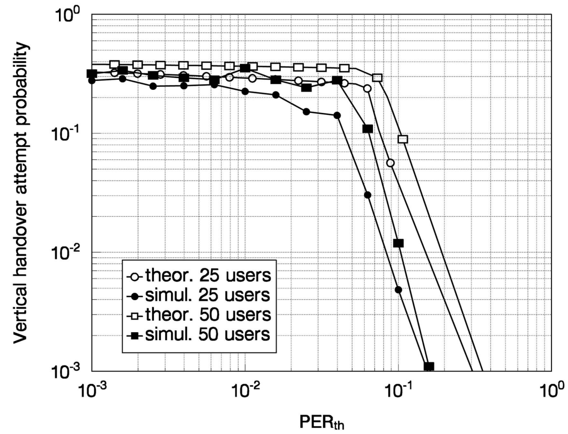

Fig. 5. Vertical handover attempt probability $P^V_{att,PER}$ as a function of the PER objective PEr_{th} and different values of the number of users in the network.

where p_q denotes the number of packets in the queue of the desired user, $N_{active}(i)$ is the number of active users during the transmission of packet i, and $l_{i,j}$ is the length of the packet transmitted by user j during the ith round. Then, the vertical handover attempt probability determined only by the condition on the delay is

$$P^V_{att,D} = P[D > D_{th}]. \tag{13}$$

The derivation of a bound on the probability is performed in Appendix B and is obtained by conditioning on the number of active users and on the number of packets in the queue,

$$P^V_{att,D} = \sum_n \sum_m P^V_{att,D}[D > D_{th} | N_{active} = m, p_q = n] \times P[N_{active} = m] P[p_q = n]. \tag{14}$$

Once the probabilities are evaluated, the dissatisfaction U can be modeled as a discrete random variable that assumes the values $\{0, w_{PER}, w_D, 1\}$. The vertical handover attempt probability depends on the relation between the QoS dissatisfaction threshold U_{th} and the weights of the profile.

$$P^V_{att} = P[U > U_{th}] = \begin{cases} P^V_{att,PER} + P^V_{att,D} - P^V_{att,PER}P^V_{att,D} & \text{if } U_{th} < w_{PER}, U_{th} < w_D \\ P^V_{att,PER} & \text{if } w_D < U_{th} < w_{PER} \\ P^V_{att,D} & \text{if } w_{PER} < U_{th} < w_D \\ P^V_{att,PER}P^V_{att,D} & \text{if } U_{th} > w_D, U_{th} > w_{PER}. \end{cases} \tag{15}$$

In Fig. 6, the vertical handover attempt probability $P^V_{att,D}$ is shown as a function of the threshold D_{th} for different values of the global number of users in the overlay network, assuming $PER_{th} = 10^{-3}$ and offered traffic per user of 200 kbit/s. The attempt probability drops to a very low value as soon as the requirements on the delay D_{th} are quite relaxed. On the other hand, it keeps to a quite constant value for lower objective values. Note that the theoretical analysis gives an approximation to this probability which is valid for values of D_{th} up to approximately 10 ms, where it

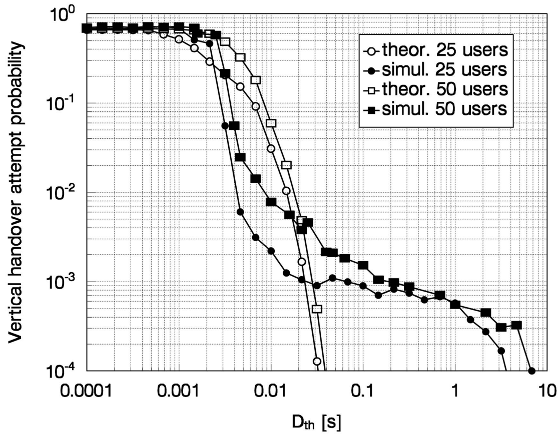

Fig. 6. Vertical handover attempt probability $P^V_{att,D}$ as a function of the delay objective D_{th} and different values of the number of users in the network.

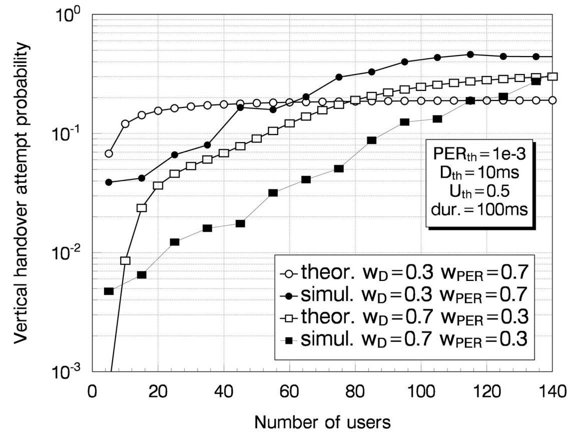

Fig. 7. Vertical handover attempt probability P^V_{att}: Comparison of simulation and theoretical values for different user profiles $[U_{th}, w_D, w_{PER}]$ with $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms, handover average duration $D_{VHO} = 100$ ms.

becomes too optimistic. This is because the analysis cannot consider the possible time spent in the handover procedures, which would increment the packet delay.

In Fig. 7, the vertical handover attempt probability is shown as a function of the number of users for the offered traffic per user of 200 kbit/s and for different settings for the weights, assuming objective values $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms and vertical handover average duration 100 ms. In this case, both the conditions on PER and delay contribute to the overall handover probability. Note, however, that having only two parameters in the profile, the range of interest for the values of the weights is the case when both are greater than U_{th}, so that the handover is triggered whenever any of the conditions is verified, a weight smaller and the other greater than U_{th}, so that handover is triggered principally by the condition corresponding to the greater weight, or both smaller, so that the handover is triggered only when both objectives are not achieved.

It can be seen that the approximate values obtained by the above analysis are in a quite good agreement with the values obtained by the simulation. It should be noted, however, that the theoretical value for the handover probability $P^V_{att,PER}$ (weights $w_D = 0.3$ and $w_{PER} = 0.7$) is too high when the number of users is low, while it is slightly underestimating the actual attempt probability when the number of users is high. This is due to the contemporary presence of the horizontal handover procedure considered in the simulations, which helps in achieving a better SIR, thus lowering the actual number of vertical handover attempts, since the user will change the serving base station if the received power from the new station is much higher than the one currently received, as explained before. On the other hand, when the number of users is high, the approximation of considering only the nearest interfering user is too optimistic since the contributions of the other users also contribute to lower the value of SIR, thus increasing the packet error rate and the attempt probability. Moreover, the assumption of independent conditions on the PER and on the delay is not fully verified. This can be explained by the fact that the activation of the vertical handover by the PER condition determines a signaling delay which also increases $P^V_{att,D}$, although this cannot be considered in the theoretical analysis. On the other hand, when the vertical handover is triggered by the delay, the theoretical analysis developed in Appendix B gives an upper bound with respect to the actual value, as it also results with respect to the simulations, apart for a very low number or total users in the network. This is justified by the fact that the approximation of considering all the users active becomes pessimistic for few users.

4.2 Vertical Handover Execution

Execution of the vertical handover requires a packet exchange between the origin and the destination network and the check of the admission conditions. Since several architectures could be developed to implement this procedure, and, in this study, the objective is to derive the performance in terms of bandwidth, PER, and delay experienced by the users, the actual details of the architecture and protocols employed by the network to manage this procedure at the upper layers are not considered: Solutions such as micromobility management methods [26] should be employed to achieve a short handover time, reducing the long delay due to the discovery process. Again, the main effect of a vertical handover on the performance parameters considered herein is the handover delay, corresponding to the time not available to the user for the transmission of traffic packets. In this study, it is modeled by an exponential random variable whose mean value is one of the parameters used to present the results.

Since the vertical handover procedure can employ many network resources for its duration, thus reducing the traffic capacity, the check of vertical handover conditions is performed only periodically with the same periodicity used to track the beacon signals. Moreover, to avoid the so-called *ping-pong effect*, that is, the fact to keep switching from network to network, a simple counter approach is used. In detail, the number of consecutive vertical handover attempts is limited to a fixed value (three in the simulation for this work): When reaching this value, the following periodic check is skipped.

A simple admission control is implemented: For Bluetooth, the limit imposed by the standard of seven active users is checked, while, in WiFi, a check on the number of

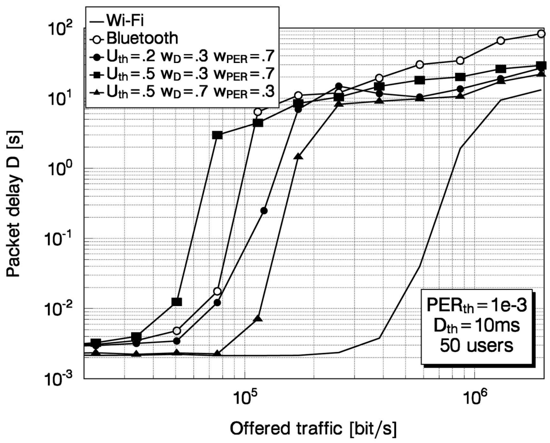

Fig. 8. Average packet delay as a function of the offered traffic, for the three systems, with different user profiles.

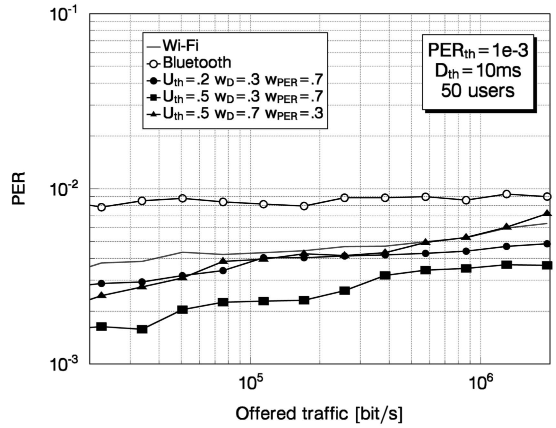

Fig. 9. Average PER as a function of the offered traffic, for the three systems, with different user profiles.

active users in the BSS is performed only if the delay weight is greater than the PER weight. If the number of active users is higher than a threshold value, the new user is refused. The threshold number has been set to 10 in the simulations. To keep the procedure fast, no check is performed if the PER weight is greater than the delay weight. In fact, PER performance depends mainly on the interference conditions, so that at least the number of interfering users should be known by the controller to determine admission conditions based on the PER requirements. When the vertical handover does not take place, the user remains in the same network.

5 Evaluation of the Network Performance

The main parameters that can influence the performance are, basically,

- the number of users,
- the offered traffic per user,
- the vertical handover parameters such as the duration, and
- the user profile, defined by the objective parameters (thresholds) and weights.

The performance indicators considered are: the packet delay, the PER, the throughput, the QoS satisfaction, and cost aspects.

5.1 Packet Delay

The use of the overlay network with vertical handover, with respect to using a single system, has a first impact on the packet delay. Fig. 8 presents the packet latency as a function of the offered traffic per user, for Bluetooth, WiFi, and the hybrid network, where the number of users is set to 50, the objective thresholds are $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms, and the average duration of the vertical handover procedure is assumed to be 100 ms.

For low traffic and a profile where PER has higher priority, the delay can even exceed that of the Bluetooth system; otherwise, the delay lies between the performance of the two networks. When vertical handover is triggered mainly by the delay conditions ($w_D = 0.7$ and $U_{th} = 0.5$), the best control on the packet latency is achieved, but the delay increase gap is not very high if a control on the value of PER is also added ($U_{th} = 0.2$, full-dots line). The performance still has an advantage over a pure WiFi network: This is justified by the higher rate available in this network. The limiting effect to the delay, although for very high values, is determined by the control imposed to the incoming traffic when the buffer occupancy gets close to its limits.

5.2 Packet Error Rate

As far as the packet error rate is concerned, the effect of the vertical handover is shown in Fig. 9, where the PER versus the traffic is presented for the three systems, with 50 users in the network, and again objective thresholds $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms. It can be seen that the best PER is achieved by the overlay network, and it is almost independent of the offered traffic. Note also that the average PER is higher than the objective value. This is due to the fact that the average value of PER is basically determined by the worst case conditions, when PER is very high, although for a limited time. In fact, PER in bad conditions can be orders of magnitude greater than in good conditions and this situation will condition the final average. In any case, when priority is given to PER by choosing the greatest weight, the best average PER is obtained. The performance of WiFi is almost equivalent to that of the overlay network.

5.3 Throughput

In terms of throughput, in Fig. 10, the available bandwidth is shown as a function of the offered traffic per user, comparing the three systems, with $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms. Again, the number of users in the network is 50 and other parameters have the same values as in Fig. 8. Although the use of the vertical handover procedure 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 by choosing a high weight for the PER, thus forcing a control on the reliability of the transmission. On the other hand, if the focus is on the delay, the performance in terms of available throughput drops to low values in correspondence to a high offered traffic load. Moreover, note that, in this case, a control on the packet error rate and delay is performed.

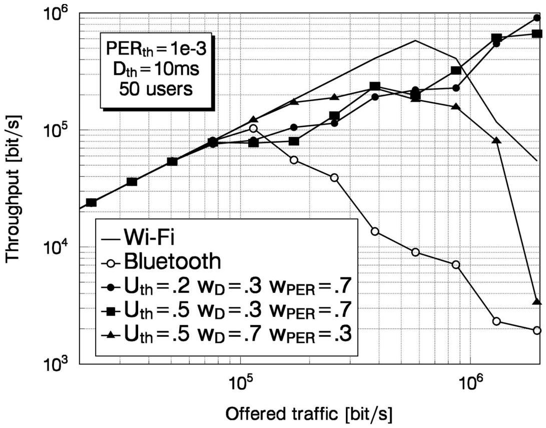

Fig. 10. Average throughput as a function of the offered traffic, for the three systems, with different user profiles.

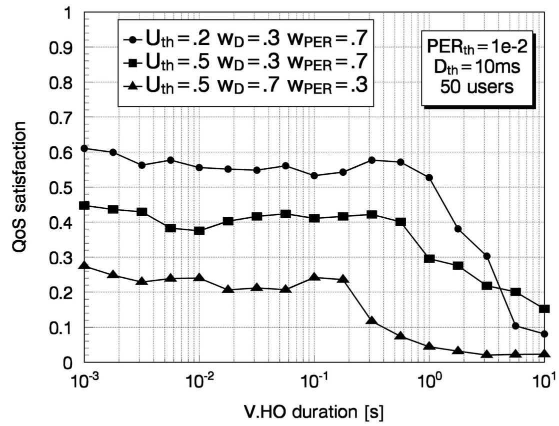

Fig. 12. QoS satisfaction as a function of the average duration of the vertical handover procedure, with different user profiles.

5.4 QoS Satisfaction

The QoS satisfaction as a function of the offered traffic, compared with the Bluetooth and the WiFi systems, is shown in Fig. 11 for 50 users, $PER_{th} = 10^{-3}$ and $D_{th} = 10$ ms. The advantage of using the overlay system can be clearly seen, although, if the priority is given to the delay, WiFi gives a better performance. The effect of the handover execution phase on the performance is considered in Fig. 12, where the QoS satisfaction is presented as a function of the average duration of the vertical handover procedure, for different users' profiles, showing that this parameter must be kept under a controlled value. Note that an average duration of the order of seconds is not so improbable if advanced solutions aiming to the reduction of the handover delay are not implemented: For example, in a pure Bluetooth network, the discovery phase, implemented by the basic inquiry procedure, would take about 10 s. Again, a suitable choice of the weight and of the dissatisfaction threshold U_{th} is needed to maximize the time when the communication objectives are achieved.

To compare the systems with different conditions on the number of users, Fig. 13 presents the values of QoS satisfaction; that is, the percentage of time when objectives are met, as a function of the total number of users in the overlay network, for $PER_{th} = 10^{-2}$, $D_{th} = 10$ ms, offered a traffic per user of 200 kbit/s and a vertical handover average duration of 100 ms. It can be seen clearly that the use of the vertical handover gives a great enhancement with respect to a pure Bluetooth network and, in most of the cases, also over the WiFi network. If the requirements on the PER are more stringent and the objective PER is lowered to $PER_{th} = 10^{-3}$, the results confirm this advantage, as shown in Fig. 14. To show the advantage of the overlay network in a wide range of PER and delay objectives, in Fig. 15, the difference in the QoS satisfaction achieved by the overlay system with respect to a pure WiFi network is presented as a function of PER_{th} and D_{th}, with an average vertical handover duration of 100 ms and $U_{th} = 0.5$, $w_D = 0.5$, and $w_{PER} = 0.5$, thus giving the same relevance to delay and PER. The total number of users in the overlay network is again 50. It can be seen that, apart for a small region where the difference is negative, that is, WiFi is performing better, the overlay network provides better QoS satisfaction almost everywhere. To better point out the regions where the overlay network gives an advantage over WiFi, the contour plot corresponding to Fig. 15 is presented in Fig. 16. Three contour levels are outlined, corresponding to the regions where the QoS satisfaction is in favor of WiFi (values lower than -5 percent). The region where the two

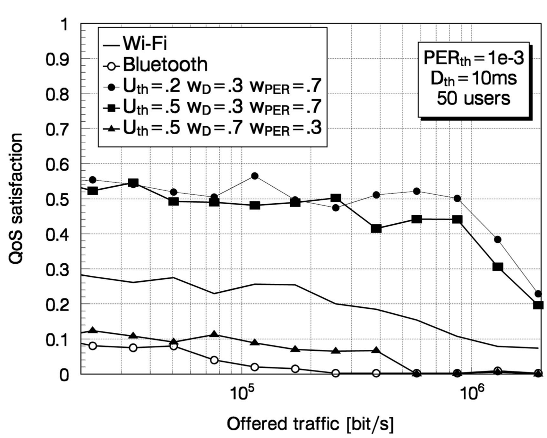

Fig. 11. QoS satisfaction as a function of the traffic, $PER_{th} = 10^{-3}$, $D_{th} = 10$ ms vertical handover duration 10 ms, with different user profiles.

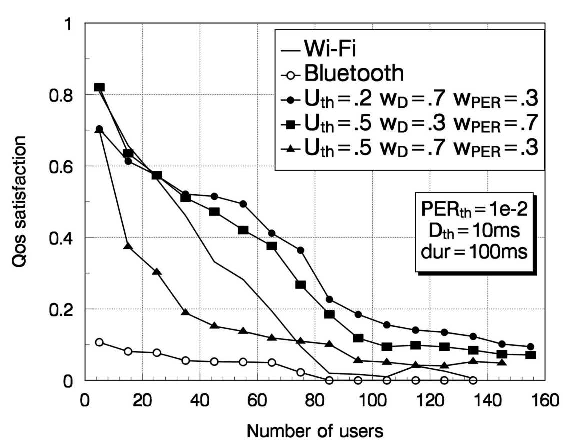

Fig. 13. QoS satisfaction as a function of the number of users for $PER_{th} = 10^{-2}$, $D_{th} = 10$ ms, with different user profiles and a vertical handover average duration of 100 ms.

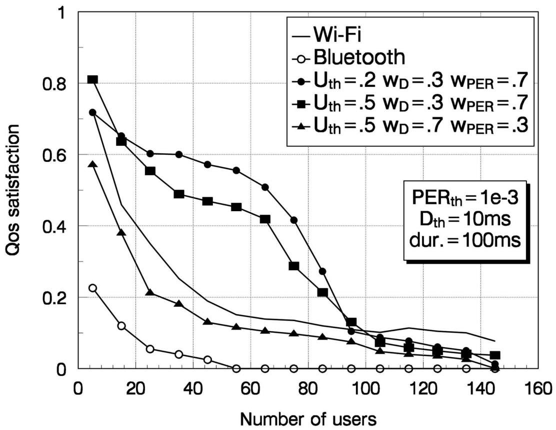

Fig. 14. QoS satisfaction as a function of the number of users for $PER_{th} = 10^{-3}$, with different user profiles and a vertical handover average duration of 100 ms.

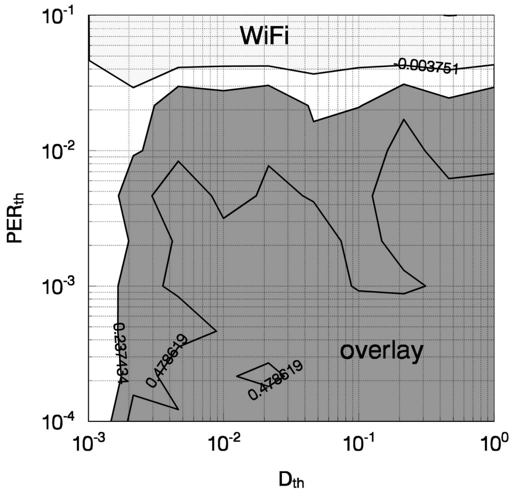

Fig. 16. Contour plot of the difference in QoS satisfactions as a function of PER_{th} and D_{th}, with user profile $U_{th} = 0.5$, $w_D = 0.5$, $w_{PER} = 0.5$, and a vertical handover average duration of 100 ms.

systems would perform almost in the same way (values from -5 percent to 5 percent) and values where the overlay network gives a better performance (difference greater than 5 percent). It can be seen that WiFi is preferable in the region where delay requirements are strict and in general if PER is not the main concern. On the other hand, for almost any other value of the objectives considered, the overlay network can provide better performance.

5.5 Cost Considerations

If cost is considered in the user profile, the vertical handover triggering procedure of Fig. 4 is modified adding a further condition. In detail, in the check of the parameters to activate the vertical handover, a cost weight w_{cost} is added to U if the user belongs to the WiFi network, with the objective to minimize the cost; therefore, the user will try to use as much as possible the lower cost network, which, in this case, is Bluetooth. This objective, however, can be in contrast with the quality objectives considered herein. First, in Fig. 17, the influence of the cost on the achieved QoS satisfaction is shown, with 50 users in the overlay network, a vertical handover average duration of 100 ms, and objectives $PER_{th} = 10^{-2}$ and $D_{th} = 10$ ms. The introduction of a cost weight determines a light worsening of the performance, especially when the network number of users is low or high, while, at a medium load, the reduction in QoS satisfaction is small. For higher values of the cost weight, the reduction is greater. To quantify the savings, in terms of the cost sustained by the user with respect to the use of WiFi only, as an example, the Bluetooth cost is assumed unitary and double for WiFi: Both time-based and traffic-based charging policies are considered. Fig. 18 shows the cost savings, together with the corresponding reduction of QoS, as a function of the weight assigned to the cost in the profile, assuming the same relevance given to PER and delay ($w_{PER} = w_D$) and, again, the same values are used in many of the results (50 users, $PER_{th} = 10^{-3}$, $D_{th} = 10$ ms, and a vertical handover average duration of 100 ms). Note that a very large savings, almost reaching the maximum value of 50 percent, can be achieved if the billing policy is time-based. On the other hand, with a traffic-based billing policy, the cost reduction deriving from the use of the overlay network is much lower due to the large capacity difference between the systems. Clearly, a trade-off appears between the available QoS satisfaction and the cost reduction.

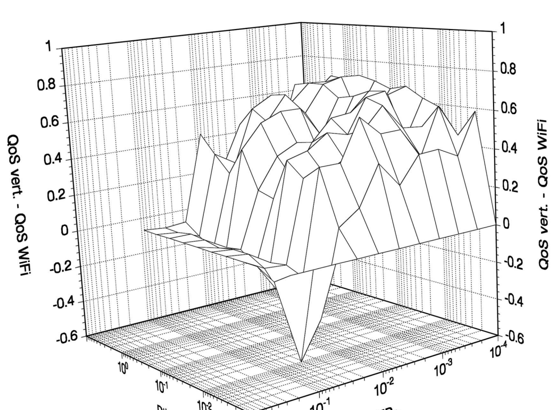

Fig. 15. Difference in QoS satisfactions as a function of PER_{th} and D_{th}, with user profile $U_{th} = 0.5$, $w_D = 0.5$, $w_{PER} = 0.5$, and a vertical handover average duration of 100 ms.

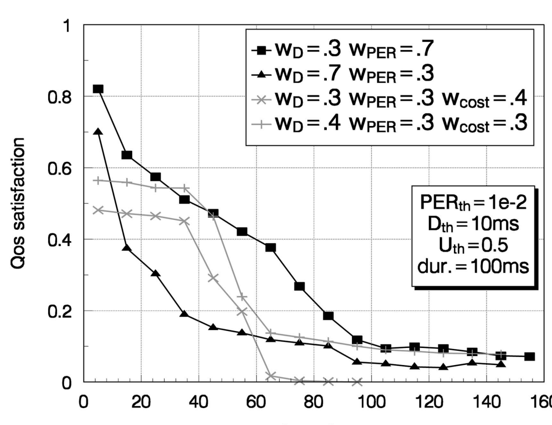

Fig. 17. QoS satisfactions as a function of the number of users for $PER_{th} = 10^{-2}$ and $D_{th} = 10$ ms, with different user profiles $[U_{th}, w_{PER}, w_D]$, and a vertical handover average duration of 100 ms.

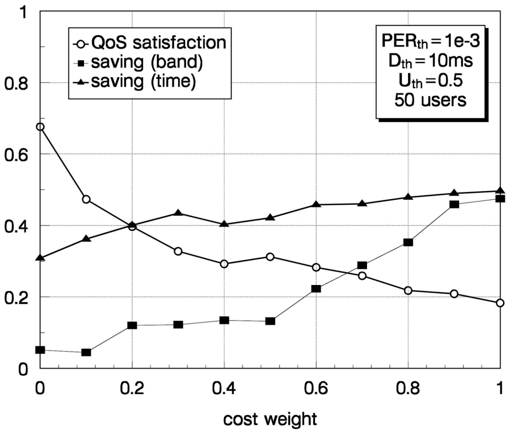

Fig. 18. Cost saving as a function of the cost weight and corresponding QoS achieved. with $PER_{th} = 10^{-3}$, $D_{th} = 10$ ms.

6 Conclusions

A novel scheme of vertical handover based on a profile of objective parameters has been considered in an overlay Bluetooth/WiFi network. An approximation for the handover probabilities has been derived and the influence of the main parameters on the network performance has been studied. It is shown that, if the requirements on the connection are demanding in terms of PER and delay, the possibility to perform the vertical handover can lead to a significant improvement. The handover parameters, such as the thresholds and the duration, should be suitably controlled to achieve an actual advantage by the use of a vertical handover procedure. A comparison for a wide range of PER and delay objectives shows the advantage of the overlay network to reduce mainly the PER due to the change in the interference conditions that gives a kind of "network diversity." On the other hand, if packet delay is the main objective, the capacity difference between the network considered leads to the choice of WiFi. However, the proposed approach gives the possibility to jointly control more objectives, which could include also the cost.

Appendix A

Derivation of the Probability Density of the Distance

From [22], the density function of the x position of a point moving on a segment is given by

$$f_x(a) = \frac{6}{R^2}a - \frac{6}{R^3}a^2, \tag{16}$$

where R denotes the length of the segment. Therefore, with respect to the center of the segment, the probability density function of the distance is

$$f_{d_x}(a, R) = \frac{6}{R^2}\left[\frac{R}{4} - \frac{a^2}{R}\right]. \tag{17}$$

The density of the location (x, y) can be approximated [22] by $f_{x,y}(a, b) \approx f_x(a)f_y(b)$. Considering the distance d from the center of the area, the distribution function is

$$\begin{aligned} F_d(c, R) &= P[d \le c] = P[d_x^2 + d_y^2 \le c^2] \\ &= \int_{\mathcal{C}(c)} f_{d_x}(a) f_{d_y}(b)\, da db \\ &= \frac{36}{R^4}\int_{\mathcal{C}(c)} \left[\frac{R}{4} - \frac{a^2}{R}\right]\left[\frac{R}{4} - \frac{b^2}{R}\right] da db, \end{aligned} \tag{18}$$

where $\mathcal{C}(c)$ denotes the circle of radius c. By a simple change of coordinates from Cartesian to polar, $a = \rho\cos\theta$ and $b = \rho\cos\theta$, we have

$$F_d(c, R) = \frac{36}{R^4}\int_0^{2\pi}\int_0^c \left[\frac{R^2}{16} + \frac{1}{R^2}\rho^4\cos^2\theta\sin^2\theta - \frac{1}{4}\rho^2\right]\rho\, d\rho d\theta, \tag{19}$$

which gives the probability distribution function

$$F_d(c, R) = \frac{3\pi}{2}\left[\frac{3}{2}\frac{c^2}{R^2} + \frac{c^6}{R^6} - 3\frac{c^4}{R^4}\right] \quad 0 \le c \le R/2 \tag{20}$$

and the corresponding probability density function

$$f_d(c, R) = \frac{3\pi}{2}\left[\frac{3c}{R^2} + 6\frac{c^5}{R^6} - 12\frac{c^3}{R^4}\right] \quad 0 \le c \le R/2. \tag{21}$$

Appendix B

Derivation of the Upper Bound on the Delay

Considering the desired user, the delay is given by

$$D = \sum_{i=1}^{p_q}\sum_{j=1}^{N_{active}(i)} l_{i,j}, \tag{22}$$

where p_q denotes the number of packets in the queue of the desired user, $N_{active}(i)$ is the active users during the transmission of the ith packet of the queue, and $l_{i,j}$ is the length of the packet transmitted by user j during the ith round. The approach followed to estimate a bound on the probability $P[D > D_{th}]$ is the following:

1. conditioning on the number of active users,
2. conditioning on the number of packets in the queue,
3. evaluating the Chernov bound on the probability, and
4. averaging the probability over the conditioning random variables.

Conditioning on the number of packets in the queue and on the number of active users in the probability of the delay exceeding the threshold is upper bounded by the Chernov bound [27]

$$P_{att,D}^V = P[D > D_{th}] \le \min_{s \ge 0} e^{-D_{th}s} H_D(s), \tag{23}$$

where $H_D(s)$ denotes the probability generating function of the random variable D, which represents the delay expressed in bits. Being the sum of independent geometric random variables, we have

$$H_D(s) = \left[\frac{p_l}{1 - (1 - p_l)e^s}\right]^K, \tag{24}$$

where $K = p_q N_{active}$ and p_l is the parameter of the geometric random variable which represents the packet length and is related to the mean packet length L by $p_l = 1/(L+1)$. Evaluation of the Chernov bound then gives

$$P^V_{att,D|K} = P[D > D_{th}|K] \leq \left\{ \frac{p_l(1-p_l)(D_{th}+K)}{D_{th}\left[1-\frac{D_{th}}{D_{th}+K}\right]} \right\}^K. \quad (25)$$

To average with respect to the conditioning random variables, their statistics are needed. The number of active users of the same type in the same cell N_{active} is approximated by the total number of users in the cell; that is, all the users are considered active. In turn, the number of users of the same type in the cell is a binomial random variable assuming values up to the total number of users in the network or up to seven for the Bluetooth piconets, which parameter (the probability of success in a single draw) is the integral of the stationary density function of the node locations over the cell.

The number of packets in the queue is the number of arrivals of the IPP which models the packet generation during an interval which is, in turn, random, since it is the transmission delay of the previous packet: To get an approximation, the mean value is considered. Therefore, the number of packets in the queue is approximated by a Poisson random variable with mean Λ, with $\Lambda = \lambda(1-p_0)N_{active}L$, where λ, p_0, and L have been defined in Section 3. Then, the probability in (25) is averaged with respect to the mass distribution of the two conditioning random variables

$$P^V_{att,D} = \sum_n \sum_m P^V_{att,D|K=mn} P[N_{active} = m] P[p_q = n]. \quad (26)$$

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