On the Interference of Ultra Wide Band Systems on Point to Point Links and Fixed Wireless Access Systems

Romeo Giuliano, Gianluca Guidoni, and Franco Mazzenga

Abstract: **Ultra Wide Bandwidth (UWB) spread-spectrum techniques will play a key role in short range wireless connectivity supporting high bit rates availability and low power consumption. UWB can be used in the design of wireless local and personal area networks providing advanced integrated multimedia services to nomadic users within hot-spot areas. Thus the assessment of the possible interference caused by UWB devices on already existing narrowband and wideband systems is fundamental to ensure non-conflicting coexistence and, therefore, to guarantee acceptance of UWB technology worldwide. In this paper, we study the coexistence issues between an indoor UWB-based system (hot-spot) and outdoor point to point (PP) links and Fixed Wireless Access (FWA) systems operating in the $3.5 - 5.0$ GHz frequency range. We consider a realistic UWB master/slave system architecture and we show through computer simulation, that in all practical cases UWB system can coexist with PP and FWA without causing any dangerous interference.**

Index Terms: **4G communication systems, spread spectrum, ultra wide band.**

I. INTRODUCTION

The ultra wide bandwidth (UWB) technology is one viable candidate for short-range indoor radio communication systems supporting very high bit rates services and low power consumption [1], [2]. It is widely recognized that UWB enables the implementation of innovative wireless local and personal area networks providing advanced multimedia services to nomadic users over hot-spot areas. UWB signal bandwidth overlaps with the bands of many narrowband services, thus the requirement of guaranteeing existing systems from UWB emissions was evident. To this aim the Federal Communications Commission (FCC) in the United States restricted the UWB operating bands in the $3.1 - 10.6$ GHz frequency range and regulated UWB power emission by defining frequency-power masks for each specific UWB application/device [3]. In general the assessment of interference caused by UWB devices is of fundamental importance to guarantee non-conflicting coexistence and to gain acceptance of UWB technology worldwide. The existing narrowband systems that could be impaired by UWB operating at $3.1 - 10.6$ GHz are the fixed wireless access (FWA) systems and the point-to-point (PP) links commonly deployed to build flexible radio transport networks[1]. Some results on the coexistence of UWB with fixed systems have been already presented in the literature and in regulatory forums [4]–[7]. The preliminary results in [4] were based on many pessimistic assumptions thus leading to misleading conclusions on the impact of UWB on fixed wireless systems. In particular the assessment of UWB interference on FWA and PP was carried out considering UWB terminals as uncontrolled electromagnetic radiators always transmitting at their maximum allowable power and, most importantly, no realistic communication system architecture was assumed for the UWB system. Many of the assumptions in [4] were relaxed in [5]–[7] which lead to achieving different and optimistic conclusions. In this paper, we analyze the coexistence issues between an indoor UWB system (hot spot) and the outdoor fixed wireless systems (FWA and PP). To render our results comparable with those presented in the current literature, we keep many of the assumptions made in [4]. However, in this paper we account for additional UWB system parameters such as the system architecture (a master/slave UWB system), the propagation models, and the UWB usage statistics such as the UWB device activity factor. In particular we consider the interference on fixed systems due to UWB upstream (i.e., slave to master) transmissions. Analysis is carried out by considering very large UWB terminal densities and we demonstrate that through proper selection of the UWB system features, UWB hot spots can coexist with PP and FWA without causing any dangerous interference in all practical operating conditions. The importance of power control in the UWB terminals is also investigated.

The paper is organized as follows. In Section II, we summarize the main characteristics of the considered fixed wireless systems and, starting from the ITU recommendations, we assess their interference requirements. In Section III, we describe the selected scenarios and we define the UWB system features considered in the simulation. In Section IV, we detail the assessment methodology introduced in this work. The derivation of the UWB intra-system interference is illustrated in Section V. Simulation results on the fixed systems due to UWB are discussed in Section VI. In Section VII, we analyze the dependence of UWB interference calculation on the channel model parameters. In Section VIII, we analyze the beneficial effects of UWB power control on the interference experienced by the fixed systems. Finally conclusions are given in Section IX.

II. INTERFERENCE LIMITS REQUIREMENTS

To assess the UWB interference limits on the existing fixed wireless systems, we refer to the ITU-R requirements in [8] about the interference power I due to unwanted emissions from sources other than fixed service or services sharing the same band on primary bases. As indicated in [8], the total interfer-

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R. Giuliano and G. Guidoni are with the Consorzio Università Industria Laboratori di Radiocomunicazioni, RadioLabs, email: {romeo.giuliano, gianluca.guidoni }@radiolabs.it.

F. Mazzenga is with the Dipartimento di Ingegneria Elettronica, University of Rome Tor Vergata, email: franco.mazzenga@radiolabs.it.

[1]Fixed point to point links are commonly deployed in the transport network infrastructure of many cellular mobile networks operators.

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ence to a fixed service link can be partitioned as:

- 89% for the intra service interference;
- 10% for the co-primary services interference;
- 1% for the aggregation of the following interference sources:
  - Emissions from radio services which share frequency allocations on a non-primary basis;
  - unwanted emissions (i.e., out-of-band and spurious emissions such as energy spread from radio systems, etc.) in non-shared bands;
  - unwanted radiations (e.g., industrial scientific medical (ISM) applications).

The previous percentages apply to the performance objectives [9], [10] and degradation allowance refers to the aggregation of the whole secondary services transmitters and unwanted signals. UWB systems are commonly classified as secondary services and for this reason, this criterion is applied. ITU-R has defined the following long and short term interference criteria in order to ensure non-conflicting coexistence:

Long term criteria (20% of the time):

- For co-primary sharing a margin degradation of 0.5 dB, equivalent to an $I/N = -10$ dB with N the thermal noise power, lead to a performance degradation of 10%.
- For secondary service interference and unwanted emissions, the performance degradation shall not exceed 1%. For these services, it was concluded that $I/N = -20$ dB is the right choice since it provides a margin degradation well below 0.1 dB.

The previous values represent generic objectives and implicitly assume that interference signals have spectral characteristics similar to white noise (i.e., flat spectrum). In this paper, we assume the UWB spectrum as practically flat. This approximation may not hold especially considering the time-hopping based UWB signals having discrete spectral components [11]. In this paper, we consider average interference analysis. However, due to UWB pulsed characteristics, separate considerations would be needed for both average and peak interference objectives within the fixed service receiver bandwidth. Finally it should be noted that the allocation of 99% of the interference margin to intra-service and/or co-primary services $(89\%+10\%)$ might also be too pessimistic with today's technology since in more realistic conditions, higher margins than 1%, in particular I/N much closer to 0 dB, could be tolerated by fixed links for secondary services. Values of I/N of -10 dB have been proposed in [6] and [7] as more realistic estimates of interference margins necessary for today's FWA and PP technologies.

Short term criteria (0.0001% of time):

Short-term criteria in [12] give allowance for a positive (in dB) I/N ratio to happen for very short percentage of time (e.g., in the order of 0.0001% of the time). Positive I/N ratio can be related to peak interference. This criterion will not be considered in this paper.

A. Calculation of the Interference Limits

To assess the interference limits, the relevant characteristic is the FWA or PP receiver noise power N_A defined as:

$$N_A = -144 + 10\log_{10}(RX_{BW}) + N_F \quad [\text{dBW}], \qquad (1)$$

where RX_{BW} is the 3 dB receiver bandwidth expressed in MHz and N_F is the receiver noise figure. The value of N_A in (1) is subsequently used to evaluate the limits on the allowed UWB inter-system interference I_A, accounting for the ITU I/N requirements, i.e.,

$$\frac{I_A}{N_A} \le \left(\frac{I}{N}\right)_{ITU}, \qquad (2)$$

where $\left(\frac{I}{N}\right)_{ITU} = -20$ dB [9], [10]. In order to simply compare the allowed interference power with the power spectral density values indicated in the FCC masks, we assume that the UWB has a flat power spectral density and bandwidth $W_{UWB} = 3$ GHz.

In the following subsections, we summarize the main characteristics of FWA, PP, and UWB systems used to setup the simulator.

B. FWA System Characteristics

The FWA systems considered in this paper operate in the $3.5 - 4.2$ GHz and $4.4 - 5.0$ GHz bands. It includes two communicating devices: A FWA Central Station (CS) positioned on the building roof and a FWA Terminal Station (TS) in front of the building. When the FWA receiver operates at 3.5 GHz, we assume $N_F \cong 5$ dB and $RX_{BW} \cong 50$ MHz or as an alternative $RX_{BW} \cong 14$ MHz. Using (1), we obtain $N_{A50} \cong -122$ dBW for 50 MHz at 3.5 GHz and $N_{A14} \cong -127.5$ dBW for 14 MHz at 3.5 GHz. When the FWA systems operate in the $4.4 \div 5.0$ GHz band, we assume $N_F \cong 6$ dB and $RX_{BW} \cong 50$ MHz thus obtaining $N_{A50} \cong -121$ dBW for 50 MHz.

To evaluate the UWB interference on the FWA, it is necessary to account for the specific antenna radiation patterns envelopes in both horizontal and vertical planes. The characteristics of the antenna commonly deployed for the FWA-TS are indicated in [13]. A sectorial antenna with sectors of 90^o and a main lobe gain of 16 dBi is considered. Its radiation pattern envelopes are reported in [13] and have also been extrapolated and used in [4]–[7] and for brevity are not repeated.

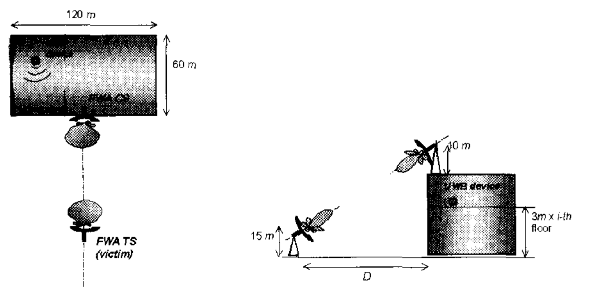
C. PP System Characteristics

To assess the UWB interference on the fixed PP link we consider a representative system with the following receiver characteristics. The PP system operates at frequency 4.0 GHz and the PP receiver has a noise figure $N_F = 6$ dB and 3 dB bandwidth of about 40 MHz [4]. Using (1), the noise figure of the PP receiver is $N_A = -122$ dBW. The typical antenna characteristics used in the evaluation of the UWB interference in the PP receiver are indicated in [14]. A parabolic approximation for the antenna main lobe is assumed with a gain of 43.6 dB and a 3 dB beam width of 1 degree.

Substituting the data of the FWA and PP receivers in (1) and using (2), we obtain the maximum allowed power spectral density (PSD) interference levels indicated in Table 1.

D. UWB System Features

We consider an UWB system with devices located inside the building and communicating in accordance to a master-slave network architecture. We assumed that any UWB device has

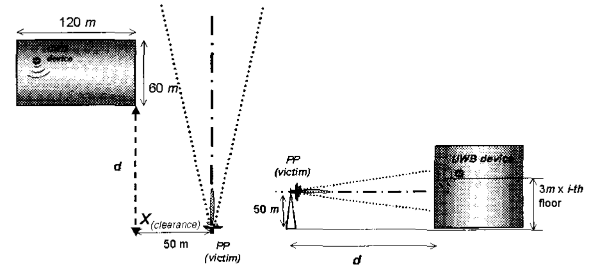


(a) (b)

Fig. 1. Hot spot scenario for FWA - UWB system coexistence: a) Building (upper view), (b) building (side view).

Table 1. UWB aggregate interference requirements for non-conflicting coexistence with fixed systems expressed in terms of the maximum allowable UWB power spectral density.

	Aggregate interference objectives
FWA TS (BW=14 MHz)	≤ -159 dBW/MHz at I/N= -20 dB
FWA TS (BW = 50 MHz)	≤ -159 dBW/MHz at I/N= -20 dB
PP (BW = 40 MHz)	≤ -157 dBW/MHz at I/N= -20 dB



(a) (b)

Fig. 2. Hot spot scenario for PP - UWB system coexistence: (a) PP scenario (upper view), (b) PP scenario (side view).

Table 2. Main parameters of the considered UWB system.

Parameter	Alternatives
Outdoor Propagation Model	Free Space, ITU-R P.1411-1, etc.
Indoor Propagation Model	Free space, Dual slope models, etc.
Power Control	Used for every UWB device
Activity Factor	1%, 5%, 8%, 10% up to 100%
Bit Rates	2, 25, 100 Mb/s

an omnidirectional antenna on the horizontal plane with gain of 0 dBi. The most important UWB parameters and channel models used for subsequent analysis are indicated in Table 2 and will be further detailed in the following sections.

The number of possible scenarios that should be explored, obtained from the combinations of several system features listed in Table 2, is quite large. However, many of them may turn out to be unrealistic. For example, it could be noted that using 100% activity factors contrasts the typical deployment scenarios envisaged for UWB devices where it is estimated that the aggregate percentage of time the single device transmits do not exceed 10% [6], [7].

III. SELECTED SCENARIOS

In this paper, we consider a hot spot scenario where the UWB system, located inside a commercial/industrial building, interferes with fixed systems such as FWA or PP located outdoor.

A. FWA Interference Scenario

In this scenario, we assume that UWB system interferes with a FWA system located in the proximity of the building. The FWA-TS antenna is steered in order to optimally point to the FWA transmitter. We assume the building is 10 floors high and we neglect the inter-floor interference among the UWB devices. The geometrical layout of the selected reference scenario is depicted in Fig. 1. The aggregate interference due to UWB hot spot will be evaluated considering different values for the distance between the FWA-TS and the building (see Fig. 1).

B. PP Interference Scenario

We consider a sub-urban area where a PP link passes a nearby building containing the UWB hot spot. We assume that in the PP design phase the necessary clearance for the line of sight propagation, which is greater than 2 times the radius of the first Fresnel zone, has been ensured. The geometrical scheme for the PP scenario is depicted in Fig. 2. The minimum PP path offset indicated as $X_{clearance}$ in Fig. 2 is defined as the clearance of the first Fresnel ellipsoid radius and it can be calculated using standard equations as indicated in [4]. Assuming 4.0 GHz as the operation frequency of the PP system, we fix $X_{clearance} = 50$ m. The aggregate UWB interference on the PP receiver will be evaluated as a function of the distance from the building (indicated with d in Fig. 2).

IV. INTERFERENCE EVALUATION PROCEDURE

To assess the UWB system performance and to evaluate the interference generated by the UWB hot spot on the FWA and PP systems, we used the software simulator developed within the IST ULTRAWAVES European project [15]. Only UWB upstream transmissions are considered, the UWB system area is assumed to be rectangular and UWB masters (acting as network access points) are positioned on a regular grid while slaves are randomly located within each floor as shown in Fig. 3. The UWB system simulator is snapshot-based. Its operation principles are illustrated in the flowchart of Fig. 4. At the beginning of each *outer loop* iteration a new scenario is generated. Scenario generation consists of randomly placing the slaves in the area according to a uniform spatial distribution. Each slave is connected to the master with the lowest overall loss[2]. The *inner loop* is used to simulate an iterative power control procedure. In each inner iteration the power of each transmitter is increased or decreased in accordance to the comparison result between the received power-to-interference ratio C/I, calculated for each slave in the area, and the *target* C/I, i.e., $(C/I)_{Target}$. The updating procedure is halted when the power transmitted by each active UWB device is practically constant or the maximum

[2]Overall loss includes losses due to distance and also shadowing. The standard deviation of the shadowing was $\sigma_S = 4.3$ dB. No shadowing is considered for outdoor propagation.

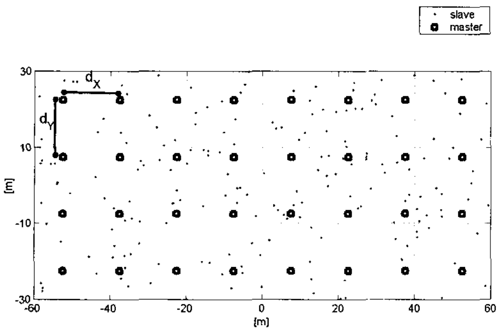


Fig. 3. Grid of UWB master devices on each floor - d_X and d_Y are the horizontal and the vertical distances between two adjacent masters.

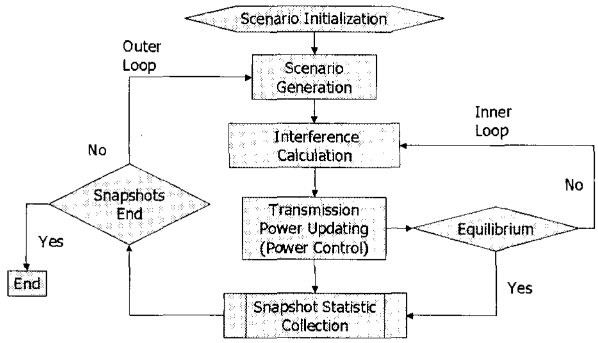


Fig. 4. Simulator flowchart - upstream simulation.

allowable transmission power has been reached[3]. At the end of the inner loop all the relevant parameters such as the power level transmitted by each user, and the number of terminals in outage etc., are collected. The power transmitted by each UWB device after reaching the system equilibrium, is subsequently used to evaluate the interference on the FWA or PP systems.

The several parameters used for UWB upstream analysis are now summarized.

- *Source traffic model*
  Different traffic sources characterized by different bit rates and activity factors have been considered in the analysis. A typical mixed population of UWB devices is expected to have many kinds of services characterized by different bit-rates. Thus some results considering a combination of source traffic models will be presented in the next sections.
- *Path loss models: Indoor propagation*
  To study the dependence of the interference results on the selected channel model, we consider two different models: The simple free space and the dual slope models, i.e.,
  - *Free space propagation model*

$$A_{fs}(d) = a_0 + a_1 \log_{10}(d) \quad [\text{dB}], \tag{3}$$

where d is expressed in m, a_0 is the path-loss at 1 m equal to $a_0 = 20\log_{10}(\frac{4\pi}{\lambda})$, and $a_1 = 20$.

  - *Dual slope propagation model*

$$A_{dual}(d) = \begin{cases} 0 & d \in [0,1] \\ c_0 \log_{10}(d) & d \in [1, d_{break}] \\ c_1 + c_2 \log_{10}\left(\frac{d}{d_{break}}\right) & d > d_{break}, \end{cases} \tag{4}$$

where d is expressed in m and c_i are constants. From recent UWB channel measurements indicated in [16] we can assume $c_0 = 17$ for line of sight (LOS) propagation and $c_0 = 37$ for non-LOS. In [16], we further observe that channel measurements were collected up to a distance of 11 m. The path loss after 11 m is not indicated in [16] while in [17] $c_2 = 74$ is assumed. However, this value is considered to be too large which perhaps may be due to the particular propagation characteristics of the environment where the measurements were originally collected.

To account for both indoor and outdoor propagation, the overall propagation channel model used to evaluate the UWB interference on fixed systems is the merge of two channel models. In particular, to account for indoor propagation, we use the free space or the dual slope model(s). Outdoor propagation is always modeled using the free space model.

- *Other UWB system features*
  Call admission control (CAC) strategies allow the reduction of interference in both UWB (intra-system interference) and external narrow band systems, and therefore, enhancing the performance of both. For example, a UWB slave transmitter could be stopped when its power requirements are deemed to be too large by the master. Assuming that masters are interconnected to form a network, when the number of masters in the area increases, a slave can be simultaneously served by more than one master. In this case, we could exploit diversity to reduce the power to be transmitted by the slave thus reducing interference. The beneficial effects of CAC strategies and diversity were not considered in this paper and will be the subject of future investigations where more complex UWB network architectures and MAC protocols will be considered.

V. CALCULATION OF UWB INTRA-SYSTEM INTERFERENCE

In this section, we describe in greater detail the procedure and the assumptions used to evaluate the UWB intra-system interference. This is a basic step in the simulated power control procedure which is used to reach the UWB system equilibrium condition.

The total interference $I_{n,m}$ as measured in the n-th UWB master receiver for the slave number m connected to it is:

$$I_{n,m} = I_{Intra}^{(n,m)} + I_{FS \to UWB} + \eta, \tag{5}$$

where η is the thermal noise power[4] and $I_{FS \to UWB}$ is the inter-system interference due to fixed systems on the UWB receivers.

[3]The maximum UWB transmitting power considered in this paper is -6.2 dBm and can be easily calculated starting from the maximum allowable power spectral density proposed by FCC (i.e., -41 dBm/MHz), assuming an UWB signal bandwidth of 3 GHz and a flat UWB spectrum.

[4]A noise figure of $N_F = 5$ dB was assumed.

The $I_{FS \to UWB}$ could be accounted for by increasing the noise figure in the UWB receiver but this effect is neglected in this paper[5].

The term $I_{Intra}^{(n,m)}$ in (5) represents the UWB intra-system interference caused by the UWB slave devices in the area. In the upstream case $I_{Intra}^{(n,m)}$ can be written as:

$$I_{intra}^{(n,m)} = \sum_{k, k \neq m} P_{T_k} L_{Ind}(d_{nk}), \tag{6}$$

where P_{T_k} is the power transmitted by the kth *active* slave device and $L_{Ind}(d_{nk})$ is the indoor propagation loss accounting for both distance between the nth master, $n = 1, 2, \cdots, N_{mast}$ and the kth active slave, d_{nk}, and shadowing effects[6].

The interference term $I_{n,m}$ is used to evaluate the carrier to noise plus interference ratio of the slave number m connected to the nth master, $C^{(n,m)}/I^{(m,n)}$.

The ratio $C^{(n,m)}/I^{(m,n)}$ is compared with $(C/I)_{Target}$ in order to increase or decrease the mth slave transmission power. The $(C/I)_{Target}$ used in the simulated power control procedure was evaluated as:

$$\left(\frac{C}{I}\right)_{\text{Target}} = \left(\frac{E_b}{N_0}\right)_{\text{Target}} - PG, \tag{7}$$

where $PG = W_{UWB}/R_b$ and R_b is the source bit rate depending on the characteristics of the considered service. The UWB reference $(E_b/N_0)_{Target}$ was always set to 4 dB in each scenario and for each bit rate.

A. Calculation of UWB Interference on FWA and PP Receivers

To assess the interference of UWB hot spot on the FWA and PP systems, we evaluate the power of the UWB aggregate interference $I_{UWB \to FS}$ at the FWA and PP receivers and we compare the results with the values in Table 1 assuming $W_{UWB} = 3$ GHz. The $I_{UWB \to FS}$ is evaluated as:

$$I_{UWB \to FS} = \sum_{m} P_{T_m} L_{IndOut}(d_m), \tag{8}$$

where P_{T_m} is the power transmitted by the mth UWB active slave and $L_{IndOut}(d_m)$ is the overall path loss between the mth UWB device and the FWA-TS or PP receivers located at relative distance d_m. The overall path loss $L_{IndOut}(d)$ in (8) accounts for both indoor and outdoor propagation and it is obtained as a combination of two propagation models.

VI. SIMULATIONS RESULTS

Simulation results were obtained considering different combinations of the system features in Table 2. We considered variable UWB device densities and a building floor with dimensions 120×60 m^2. The vertical distance between floors is 3 m (see also Figs. 1 and 2). Unless otherwise stated, the dual slope channel model in (4) with $c_0 = 17$ and $c_2 = 40$ is adopted in the simulation.

[5] This assumption can be justified observing that in the FWA case the transmitter is located above the building. Therefore, in this case, the FWA interference on the UWB system is only due to secondary lobes of the FWA antenna and can be considered as negligible. In the PP case, we can assume that the PP transmitter is far so that the interference power received by the UWB devices is practically negligible.

[6] The generic slave is always connected to the master seen with the lowest loss $L_{Ind}(d_{ij})$ and $i = 1, 2, \cdots, N_{mast}$, $j = 1, \cdots, N_{slave}$ and N_{mast} and N_{slave} are the number of masters and slaves in the area, respectively.

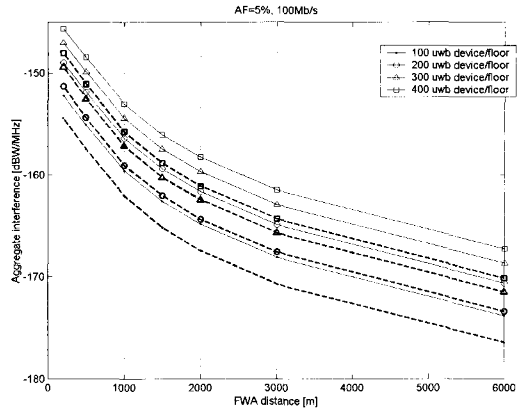


Fig. 5. UWB aggregate interference (dBW/MHz) vs. FWA distance; single service case; free space model (continuous lines) and dual slope (dashed lines); 32 masters per floor; activity factor 5%; variable number of UWB terminals per floor transmitting at 100 Mb/s.

Results on FWA and PP system are discussed separately in the following two subsections.

A. FWA Results

A.1 Single Service Cases

We assume that UWB terminals transmit with the same bit rate: 2 Mb/s, 25 Mb/s, or 100 Mb/s. The building penetration loss is included by increasing the interference reference levels in Table 1 by 10 up to 12 dB, i.e., considering 10 dB of building penetration loss the target aggregate interference is -149 dBW/MHz at $I/N = -20$ dB for FWA or -147 dBW/MHz at $I/N = -20$ dB for PP.

In Fig. 5, we plot the aggregate UWB interference PSD level as a function of the FWA-TS distance for different numbers of UWB terminals per floor. As expected the UWB interference level increases with the number of users in the area therefore the minimum safety distance of the FWA is influenced by the (temporary) UWB system load. As shown in Fig. 5, the interference level is always well below the limits in Table 1 in all practical cases and even for very large UWB devices' densities such as 400 UWB terminals per floor corresponding to about 560000 UWB terminals km^2, each one transmitting at 100 Mb/s. A maximum density of 100 UWB users per floor (i.e., 140000 UWB terminals km^2) allows coexistence between FWA and UWB independently of their relative distance. However, if we include the building penetration loss, the upper limit on the UWB devices density can be raised up to 400 UWB devices per floor. Obviously, the reduction of the bit rate allows to further increase the UWB devices density per floor, as also shown in Fig. 6, where the interference reduction due to a decrease in the bit rate for fixed UWB devices density is evidenced. In Fig. 7, we plot the aggregate UWB interference as a function of the number of available masters on the floor. It can be observed that

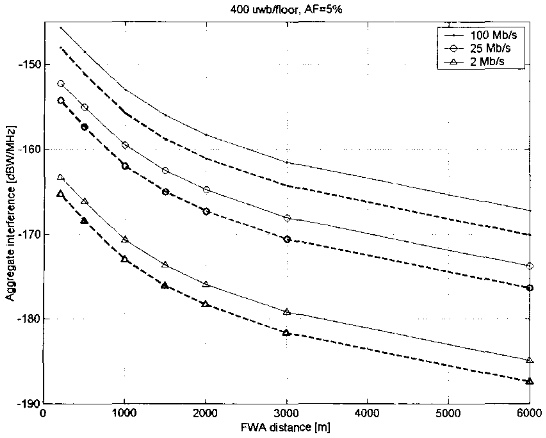


Fig. 6. UWB aggregate interference (dBW/MHz) vs. FWA distance; single service; variable bit rate; free space model (continuous lines) and dual slope (dashed lines); UWB devices at 100 Mb/s; activity factor 5%; 400 UWB devices/floor; 32 masters per floor.

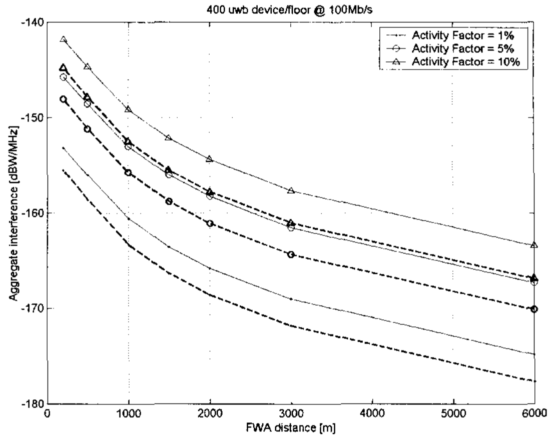


Fig. 8. UWB aggregate interference (dBW/MHz) vs. FWA distance; UWB devices at 100 Mb/s; free space model (continuous lines) and dual slope (dashed lines); variable activity factors; 400 UWB devices/floor and 32 masters per floor.

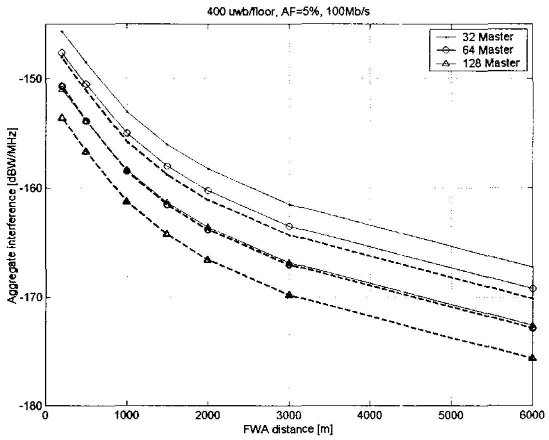


Fig. 7. UWB aggregate interference (dBW/MHz) vs. FWA distance; variable number of masters in the area; free space model (continuous lines) and dual slope (dashed lines); UWB devices at 100 Mb/s; 400 UWB devices/floor; activity factor 5%.

Table 3. Upstream: Traffic parameters for mixed bit rate simulation: 2, 25, and 100 Mb/s.

Population [percentage of the total]	Activity Factor	Data-Rate
20%	5%	100 Mb/s
30%	8%	25 Mb/s
50%	10%	2 Mb/s

increasing the number of UWB masters in the area is a practical mean to achieve a significant UWB interference reduction. In fact the shortening of the average distance between the masters and the served slaves allows to decrease the transmitting power thus reducing both intra-system interference and the external interference on FWA.

Having proved the compatibility between the UWB and the FWA systems also for very large UWB terminals' densities, we now vary the terminals' activity factors up to the maximum levels foreseeable for a UWB system, i.e., 10%. In Fig. 8, we plot the aggregate interference PSD level considering UWB transmitters at 100 Mb/s with variable activity factor (AF). The results in Fig. 8 show the expected raise in the aggregate interference levels with the increase of activity passing from 1% to 5% and then to the maximum expected of 10%. From Fig. 8, it can be further observed that even increasing the activity factor to 10%, in practice the effects of UWB on the FWA system are not harmful. The increase of the number of masters in the area can be still helpful to compensate for the larger interference due to the increase of the activity factor.

A.2 Multi-Service Case

In this section, we consider a multi-rate scenario where UWB terminals with different bit rate simultaneously operate in the area. Users with three different bit rates, 2, 25, and 100 Mb/s, were considered. The system scenario is maintained as in earlier cases and the maximum device density is of 400 UWB terminals per floor. Terminals are power controlled and are characterized by decreasing activity factors in accordance to the bit rate. In Fig. 9, we plot the aggregate interference density vs. FWA receiver distance from the building and consider different indoor propagation models. The traffic parameters used to obtain the results in Fig. 9 are summarized in Table 3. From Fig. 9, it can be observed that, including building propagation loss, full compatibility between UWB and FWA systems is practically ensured independently of the channel behavior and for practical FWA distances from the building.

In Fig. 10, we plot the histogram on the UWB transmitted power in the case of terminals operating at 2, 25, and 100 Mb/s. From Fig. 10, it is further evidenced that no UWB users are in outage and that due to power control action the UWB transmitting power is always well below than the FCC limit of -41 dBm/MHz. As expected the average power transmitted by the 100 Mb/s terminals is larger than the 2 and 25 Mb/s users. This is due to the lower coding gain available for the higher bit rate services (see (7)).

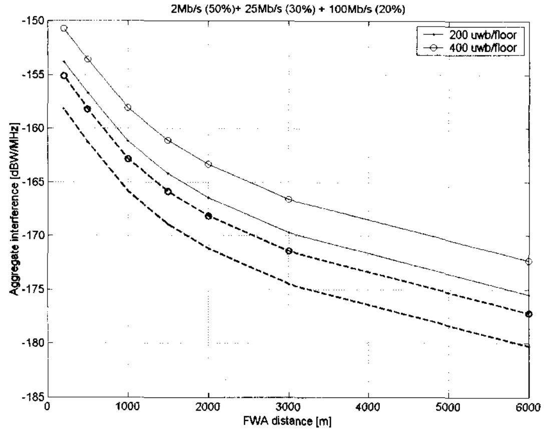


Fig. 9. UWB aggregate interference (dBW/MHz) vs. FWA distance; UWB services 100 Mb/s (20%)+ 25 Mb/s (30%) + 2 Mb/s (50%), 200-400 UWB devices/floor; free space (continuous line) and dual slope (dashed line) indoor propagation model; 32 masters per floor.

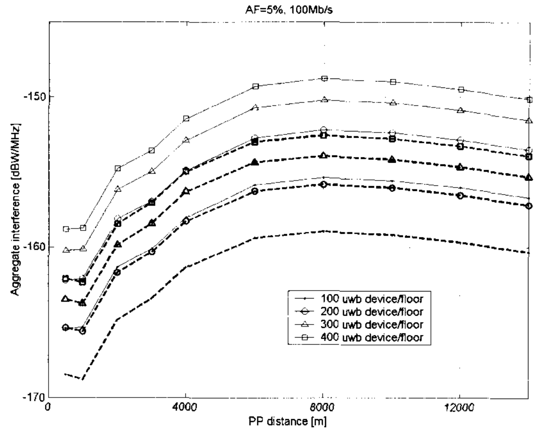


Fig. 11. UWB aggregate interference (dBW/MHz) vs. PP distance; single service case; free space model (continuous lines) and dual slope (dashed lines); 32 masters per floor, activity factor 5%, variable number of UWB terminals per floor at 100 Mb/s.

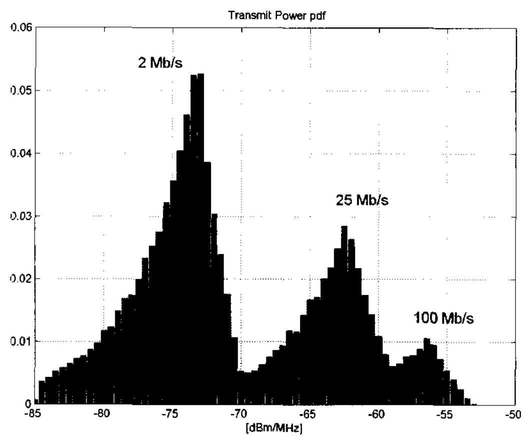


Fig. 10. Transmitted power histogram for power controlled devices operating at 2, 25, and 100 Mb/s, 400 UWB devices/floor; indoor free space channel model.

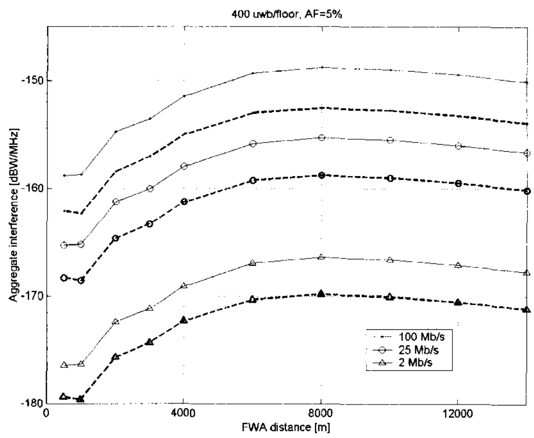


Fig. 12. UWB aggregate interference (dBW/MHz) vs. PP distance; single service case; free space model (continuous lines) and dual slope (dashed lines); activity factor 5%; 32 masters per floor; 400 UWB terminals per floor with different bit rates.

B. PP Results

In this section, we provide simulation results on the interference on the PP system due to the UWB hot spot. We consider the same UWB system features as for FWA but for brevity only the results in the single service case are provided.

In Fig. 11, we plot the aggregate UWB interference spectral density as a function of the PP distance for different number of UWB terminals per floor. As expected the UWB interference level increases with the number of users in the area therefore also the safety distance of the PP is strongly influenced by the (temporary) UWB system load. The behavior of the curves in Fig. 11 can be explained by looking at the scenario depicted in Fig. 2. It can be observed that, for a fixed clearance X by varying the distance of the PP receiver from the UWB hot spot the antenna gain under which the PP sees the hot spot increases up to the maximum (43.6 dBi). This leads to an increase in the interference power as also indicated in Fig. 11. By further increasing the PP-UWB distance, the attenuation due to propagation becomes dominant and interfering power starts to decrease. Thus, to reduce the UWB inference, unlike the FWA, it should be more convenient to locate the PP receiver in the close proximity of the UWB hot spot.

In Fig. 12, we plot the aggregate UWB interference versus the PP distance considering UWB terminals transmitting the same bit rate: 2, 25, or 100 Mb/s. In Fig. 13, we analyze the dependence of the UWB aggregate interference on the activity factors. Results in Figs. 12 and 13 still show that PP and UWB hot spot can practically coexist under all practical operating conditions and also for large UWB system loads.

Finally in Fig. 14, we analyze the dependence of the aggregate interference on the number of UWB masters per floor. Also in this case UWB interference can be conveniently controlled by varying the transmission rates but, most importantly, by increasing the density of the masters in the floor area.

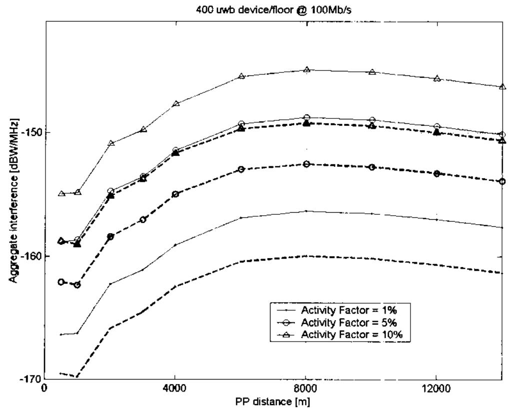


Fig. 13. UWB aggregate interference (dBW/MHz) vs. PP distance; single service case; free space model (continuous lines) and dual slope (dashed lines); 32 masters per floor; variable activity factor; UWB devices at 100 Mb/s.

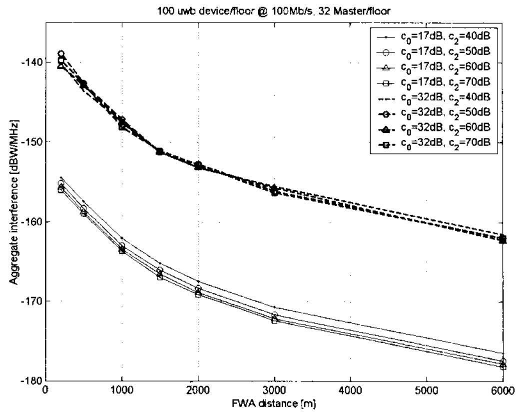


Fig. 15. UWB aggregate interference (dBW/MHz) vs. FWA distance; single service case at 100 Mb/s; dual slope channel models; 32 masters per floor, activity factor 5% and 100 UWB devices/floor.

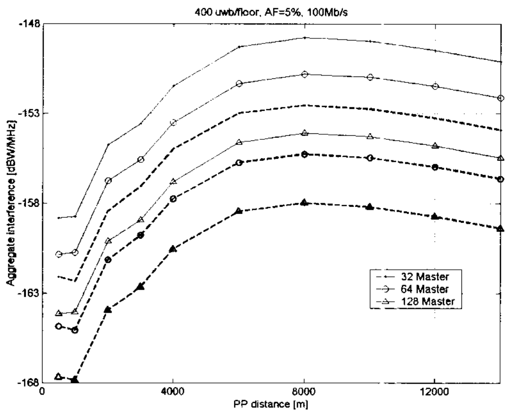


Fig. 14. UWB aggregate interference (dBW/MHz) vs. PP distance; single service case; free space model (continuous lines) and dual slope (dashed lines); variable number of masters per floor; activity factor 5%; UWB devices 100 Mb/s.

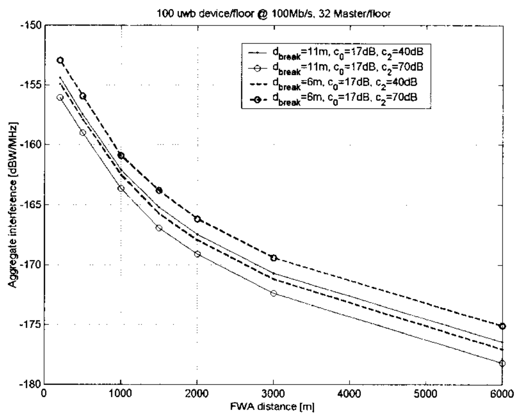


Fig. 16. UWB aggregate interference (dBW/MHz) vs. FWA distance; single service case at 100 Mb/s; dual slope channel model with variable d_{break}; 32 masters per floor, activity factor 5% and 100 UWB devices/floor.

VII. THE EFFECTS OF CHANNEL MODEL PARAMETERS ON THE UWB INTERFERENCE CALCULATION

In this section, we analyze the influence of the channel model parameters on the evaluation of the UWB aggregate interference in the attempt to evidence the critical parameters mainly influencing the results. To render simulation faster, we consider a UWB devices' density with 100 devices per floor and only FWA is considered even though the following considerations can be easily extended to PP.

In Fig. 15, we plot the UWB aggregate interference spectral density level as a function of the distance of the FWA-TS from the building. We consider the dual slope channel model for indoor propagation and we vary c_2 in (4). We assumed a $d_{break} = 11$ m and 32 masters in the area. From Fig. 15, it can be observed that interference is practically independent of c_2 in (4) and the only critical parameter is c_0 in (4) accounting for LOS or non-LOS propagation conditions for master to slave distance lower than d_{break}. As shown in Fig. 15, in the planning of the UWB system, LOS conditions should be preferred in order to reduce interference on other systems. Depending on the environment characteristics, this requirement could be achieved by increasing the density of the masters in the area.

In Fig. 16, we plot the aggregate interference vs. the FWA-TS distance considering two dual slope channel models which differ by d_{break}. From Fig. 16, it can be observed that the channel model with $d_{break} = 6$ m leads to higher interference with respect to the channel with $d_{break} = 11$ m. This fact can be explained by observing that for $N_{mast} = 32$ the distance between two adjacent masters $d_X = d_Y = 15$ m (see Fig. 3) which is greater than $2d_{break} = 12$ m. Therefore a small percentage of UWB terminals may experience a propagation channel characterized by large path loss exponents and thus they are forced to transmit higher power. The increase in the number of UWB masters in the area reverses this situation as shown in Fig. 17 where the number of masters was increased to 128. For the case in Fig. 17 the distance between two adjacent masters is

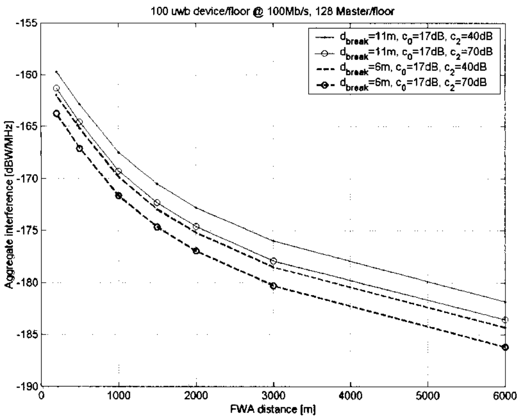


Fig. 17. UWB aggregate interference (dBW/MHz) vs. FWA distance; single service case at 100 Mb/s; dual slope channel model with variable d_{break}; 128 masters per floor, activity factor 5% and 100 UWB devices/floor.

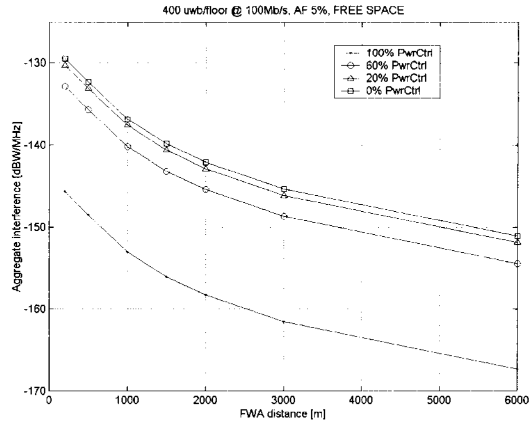


Fig. 18. UWB aggregate interference (dBW/MHz) vs. FWA distance; UWB devices at 100 Mb/s; free space indoor model; activity factor 5%; different percentages of power controlled users in the area; 400 UWB devices/floor.

reduced to 7.5 m which is comparable with $d_{break} = 6$ m. Thus the percentage of UWB slaves experiencing a bad propagation condition (i.e., path loss exponent greater than 2) is drastically reduced. Always assuming $N_{mast} = 128$ and considering a reference master, when $d_{break} = 11$ m, the percentage of interfering slaves experimenting favorable propagation conditions towards the reference master is increased with respect to the case of $d_{break} = 6$ m. This may lead to an increase in the interference as measured by the reference master receiver and slaves are required to transmit larger power leading to an increase in the interference on FWA as confirmed in Fig. 17. In the previous considerations, we implicitly assumed that each UWB slave is always connected to a single master and we did not consider diversity issues that are helpful to further reduce interference on FWA.

VIII. ON THE IMPORTANCE OF POWER CONTROL IN THE UWB SYSTEMS

In a typical CDMA system, power control is mainly used to avoid near-far problems. As shown in this section in UWB spread spectrum systems, power control is also a necessary mean to ensure non-conflicting coexistence with other systems. We now consider a scenario where only a (variable) percentage of users in each floor are power controlled while the others transmit at the maximum FCC allowable power. We consider slaves always transmitting at 100 Mb/s with activity factor of 5%. In Fig. 18, we plot the aggregate interference on FWA as a function of distance by considering upstream transmissions and by varying the percentage of power controlled terminals in the area. For brevity only the FWA case is analyzed but similar considerations still apply for PP. From Fig. 18, it can be observed that power control is effective in the reduction of the interference only when the percentage of power controlled users is relatively large. In the case of Fig. 18, it can be observed that when only the 20% of slaves are power controlled the beneficial effects of power control on the UWB interference on the FWA are negligible.

In Fig. 19, we plot the aggregate interference margin level above the limit of -149 dBW/MHz[7] as a function of the percentage of power controlled users on the floor. The FWA receiver is assumed to be at 1000 m from the building and slaves with different activity factors 1% and 5% are considered. It can be observed that only a limited percentage of non power controlled users can be admitted in the system without causing dangerous interference provided their activity factors are below 1%. Thus power control on UWB devices can be avoided only for those services requiring very low activity factors such as those signaling procedures requiring occasional use of the channel[8].

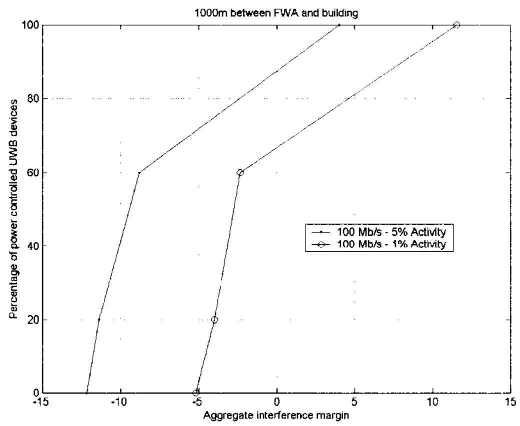


Fig. 19. UWB aggregate interference available margin (dBW/MHz) with respect to the allowable limit of -149 dBW/MHz vs. the percentage of power controlled users; FWA receiver at 1000 m and slaves transmitting at 100 Mb/s; free space indoor model; 400 UWB devices/floor and 32 masters per floor.

[7]This value was obtained including building penetration loss of 10 dB in the objective performance indicated in Table 1.

[8]A significative example of these procedure is the access to the system for the first time commonly implemented using random multiple access procedures such as ALOHA or S-ALOHA.

IX. CONCLUSIONS

The assessment of the potential interference caused by UWB devices is a fundamental research topic to guarantee non-conflicting coexistence between UWB devices and any other existing and future narrowband systems as well as to gain acceptance of UWB technology worldwide. Any study on this aspect needs to go beyond simplistic models and should adopt realistic scenario deployments. Similarly to many other wireless local area network systems, UWB terminals will be in sleep mode for the large percentage of time, will not run continuously and will not emit constantly at the maximum allowed power. Furthermore, more accurate path-loss models need to be considered to evaluate the effective aggregate interference that UWB systems might cause to any other system such as FWA and PP. In this paper, we analyzed through simulation the potential harmful interference of UWB on fixed wireless systems (FWA and PP) whose band are completely overlapped with the band of the UWB signal operating between 3.1 $\sim$ 10.6 GHz. A UWB master-slave network architecture was considered and interference on FWA and PP due to UWB upstream transmissions was considered. The results presented in this paper show that considering few simple features of the UWB system such as its system architecture, the activity factor, the power control, and more realistic propagation models, there is no practical risk for the FWA and PP operations even in the extreme densities proposed. The increase of the distance between the UWB hot spot and the FWA system leads to a reduction of the UWB interference. This is not true for PP links for which, due to the high directivity of the receiver antenna, it would be better to locate the PP in close proximity of the hot spot. Further margins not even considered in this paper still exist such as admission control techniques, deep NLOS and multiple trough-wall indoor losses. The importance of the channel model parameters in the interference evaluation and the importance of power control were also discussed. The analysis procedure introduced in this paper can be easily extended to other significative scenarios.

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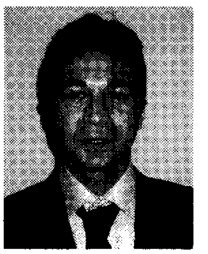
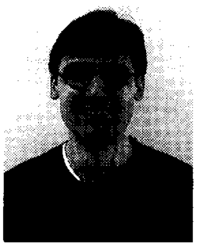


Romeo Giuliano was born in Rome, Italy, in 1974. He received the Telecommunication Engineering degree cum laude in 1999, the Master in Business Administration degree in 2001 and the Telecommunications and Microelectronic Engineering Ph.D. degree in 2004, from University of Rome Tor Vergata, Rome, Italy. From 1999 to 2001, he worked at Co.Ri.Tel, Rome, a research consortium specialized in telecommunication disciplines. Form March 2000 to 2002, he worked for CNR in the research project "5% Multimedialita" on analysis and simulations of 3^{rd}G mobile system. Since 2001, he joined RadioLabs, a research consortium specialized in wireless communication. His main research interests are on coexistence and wireless access technology as UMTS, Bluetooth, and Ultra-Wide Band systems. He is currently involved in the European ULTRAWAVES FP5 and PULSERS FP6 project. His work in the projects regards on the capacity analysis and coexistence for UWB system.



Gianluca Guidoni received the electronic engineering degree cum laude in Rome, Italy, from Tor Vergata University in 2002. Currently, he is working as researcher in the RadioLabs consortium. His main research area is call admission control and dynamic channel allocation strategies, handover techniques for UMTS, and future Ultra-Wide Band systems.

Franco Mazzenga received the Dr. Ing. degree in electronics engineering cum laude from the University of Rome Tor Vergata, Italy in 1993. From 1993 to 1994 he was with Fondazione Ugo Bordoni making research on the propagation at millimeter waves. In 1997 he obtained the Ph.D. degree in telecommunications. From 1998 to 2000 he was a researcher in Consorzio di Ricerca in Telecomunicazioni (CoRiTel). Now he is a researcher in the Electronic Engineering Department of the University of Rome Tor Vergata. From 2001 he is also the technical director of the Radiolabs consortium. He is the author of more than 40 scientific pubblications on congress and scientific international journals and he is the co-author of a book on Radar systems (in Italian). His main interests are in statistical signal processing, estimation theory, and local wireless transmission technologies.