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Ultra Wide Band WLANs: A Self-Configuring Resource Control Scheme for Accessing UWB Hot-Spots with QoS Guarantees

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Abstract. In the framework of wireless access networks the Hot-Spot concept is attracting several operators. In a Hot-Spot near stationary terminals may reach one or more Radio Access Points (RAP) offering wireless access to the fixed network. Mobile terminals should be able to register to the network, associate to a RAP and activate a wireless communication supporting given bit rates and Quality of Service (QoS) features. Several mobile users, requiring different services, enter and exit the Hot-Spot. In this scenario network operators should have the opportunity to configure quickly radio resources to serve the mobile terminals and to handle efficiently the network resources in order to maximize the income. Among the different technologies emerging in this field, we investigate the feasibility of a wireless access based on Ultra Wide Band (UWB) radio, combined with a flexible admission control scheme based on transmission power selection. We employ UWB in unlicensed mode, i.e., we operate in accordance to the limits imposed by the regulatory bodies (e.g., US Federal Communications Commission). The flexibility of the admission control depends mainly on the capability of a mobile terminal of "measuring" the environment it is entering and thus supporting the RAP in the selection of the appropriate transmission parameters. The proposed approach provides an admission policy based on the *Maximum Extra Interference* (MEI) and selects the power level through a simple interaction among the involved mobile terminals. The information for basing the decision on is collected through measurements and signaling. In order to increase the system efficiency, transmission parameters are selected in accordance to a "balancing" criterion (thus Balanced-MEI, B-MEI). The B-MEI approach keeps quite simple the admission of new mobile terminals in a RAP's area but contemporarily satisfies the trade-off between fair resource assignment and system efficiency. This is a key trade-off in wireless access systems where interference effects determine the upper limit of the number of users that can be admitted in the network.

Keywords: Ultra Wide Band, Power Control, Wireless Access, Quality of Service

1. Introduction

At the moment the wireless network market coincides exclusively with the public cellular networks in licensed band (0.9–2.2 GHz). This market has recently achieved extremely significant results, as the billion of subscribers in the world and the overcoming of the access numbers of the fixed telephony. With such a view the scenario of the wireless access technologies both in the local (WLAN) and in the personal (WPAN) areas in the unlicensed bands (2.4 and 5 GHz) has been considered a niche in the market until the present day. However, it is a wide spread opinion that this second scenario (known also as *Hot-Spot* scenario) might change thoroughly in the very next years, especially taking into consideration the increasing interest for mobile computing applications. A substantial development of the radio access infrastructures is expected, based on technologies of the WLAN/WPAN type which will not remain restricted to the context they have been planned for but could rather become complementary or even competitive with the public cellular networks.

Technologies like IEEE 802.11, Bluetooth and Ultra Wide Band (UWB) radio are the main runners for provision of wireless access to the Internet in the Hot-Spot area [13,15]. The IEEE 802.15 working group is dedicating remarkable effort to develop consensus standards for WPAN or short distance wireless networks and UWB is considered as a candidate technology [6]. The UWB has the potential to combine reduced transceiver complexity with low power consumption, flexible configuration of the radio links and robustness with respect to multipath fading. UWB systems are based mostly on Impulse Radio (IR) which has recently reached an appreciable degree of maturity so as to be able to support high data rates [17]. By combining a transmission over a wide radio spectrum band with low power and pulsed data, UWB causes less interference than conventional narrowband radios and offers potential to hit the market in unlicensed bandwidths. In this context a considerable number of papers has been dedicated to the analysis of UWB transmission/reception principles and to the relevant performance evaluation. Detailed analysis of the potential of UWB as transmission technology is out of the scope of this paper (for the interested reader we recommend [3,5,9,14]). On the contrary, since in both WLANs and Hot-Spots a key issue is the design of a suitable radio resource control, we concentrate on networking issues related to UWB and we propose an admission control scheme, based on power control, aiming at providing an efficient and flexible radio resource sharing on one side and Quality of Service (QoS) support on the other side. The contribution of this paper is twofold: (i) we propose an admission policy based on the *Maximum Extra Interference* (MEI) a mobile terminal can sustain; (ii) we apply this approach in the UWB context.

Power control is exploited as a paradigm to accommodate in a wireless system (a Hot-Spot area in our case study)

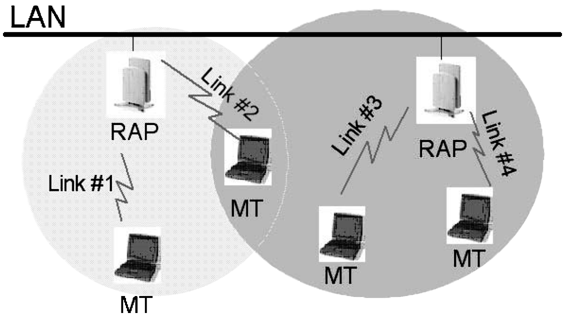

Figure 1. The overall scenario.

users heterogeneous with reference to both QoS requirements (data rate, packet error rate, etc.) and perceived quality of the wireless link (radio channel, interference conditions, etc.) [2,4,15].

In the recent literature power control is considered as a major means to adapt dynamically the transmission of concurrent users to the varying system conditions (e.g., due to channel quality or mobility) still guaranteeing the perceived QoS. We investigate how the design of a suitable power control for UWB can be used in the support of traffic requiring QoS guarantees that can be expressed, in a very general way, as a desired level of the Signal-to-Interference-Ratio (SIR). We concentrate on the Admission Control (AC) of wireless links connecting Mobile Terminals (MT) to Radio Access Points (RAP) in a Hot-Spot (see figure 1). Each MT negotiates a transmission data rate and a target level the SIR should not drop below. The AC of a new link assures that the target SIRs of the already active links are guaranteed. Contemporarily, transmission power is selected in accordance to a *balancing rule* that aims at increasing efficiency in the system resource utilization (we name our approach Balanced-MEI, B-MEI). To have high flexibility, AC is based on a distributed paradigm, i.e., each MT is able to evaluate whether the desired rate and SIR can be matched and the link can be activated. In addition, a MT might be able to select the more convenient RAP in case of multiple access points.

The remainder of this paper is organized as follows. Section 2 is dedicated to recall some literature on distributed power controlled access schemes; in this section we deal with general approaches not related to a specific transmission technology. In Section 3 we present our proposal for a distributed power regulated AC scheme for UWB; we introduce briefly the UWB technology and describe the admission control rules based on power control. Performance results are presented in Section 4. Finally, Section 5 concludes the paper.

2. Access schemes based on distributed power control mechanisms

Mechanisms for the QoS support based on suitable configuration of transmission powers allow to: (i) establish and maintain wireless links by adapting power levels to current interference; (ii) achieve differentiated QoS levels in terms of rate and target SIR (see for example [7]); (iii) mitigate interference and thus improve channel reuse.

In classical cellular systems (e.g., UMTS) power control is employed mainly as a mechanism to uniform power levels of different links concurrent to the same Base Station [12]. The use of power control could be then extended to perform the admission control of MTs requiring the activation of wireless links in a Hot-Spot area and to maintain the desired QoS during the link lifetime. Furthermore, a suitable power control can improve the overall system utilization and guarantee an efficient channel reuse; these two are key issues in networks lacking of spectrum (cell) planning.

We focus on a *distributed* AC whose goal is the activation of a wireless link between a MT and a RAP and each MT should be able to decide autonomously its own admission by collecting information regarding the Hot-Spot area it is going to enter. In particular, for each link, the receiver has typically the task of measuring the perceived interference and reporting the result to the transmitter which takes the AC decision [19]. As a consequence, for the uplink the decision is taken by the MT while for the downlink it is the RAP that decides.

Depending on the adopted multiple access technique, power control schemes can be applied in systems sharing a single channel (as IEEE 802.11) and in multi-channel environments (as ones based on CDMA). However, it can be shown that in both cases the problem of power controlled access can be formalized in very similar terms [1]. In general, what shall be controlled is the interference among different communications that access the system in a distributed way, i.e., without the supervision of a centralized entity. This interference can be controlled by means of a suitable power selection strategy. In case of multi-channel systems, interference is mitigated by a processing gain and thus resource reuse is higher. Power is regulated with two different aims: (i) to achieve the desired rate and SIR on the link; (ii) to avoid a destructive interference on the other neighbor communications. Moreover, power control can be employed suitably to sustain links with heterogeneous QoS requests (e.g., different classes of services in terms of data and bit error rates); each link can set its transmission power level in accordance to its specific QoS requirement.

In [10] it has been investigated how the introduction of power control in the access procedure can enhance the system performance in terms of efficiency in the radio spectrum utilization; different strategies have been described and compared in order to discuss their advantages and drawbacks.

Generally speaking, when considering distributed solutions, an interesting classification focuses on the employment or not of explicit signaling among the different links. In this context, two main classes of distributed power controlled access schemes can be identified:

(1) access schemes based exclusively on measurements;
(2) access schemes based on both measurements and signaling among different links.

Table 1
Comparison of different distributed power control schemes.

Strategies	Interaction among different links	System efficiency	Access decision time	Capability to support heterogeneous QoS levels	Overall complexity
Based exclusively on measurements with a continuous power reconfiguration [1,19,20]	Not required	Aim at converging or at approaching an optimal power assignment	Depends on the convergence speed	Yes	High
Based on measurements and signaling with power selection performed at the access of a new link [8,11,18] [this proposal]	Required (via signaling)	The overall power assignment results in a sub-optimal configuration	Depends on the signaling phase duration	Yes	Low

Proposals belonging to the first class are [1,19,20]. These works assume that a link extracts information on the system just by performing measurements. In particular, in [20] a local (hence distributed) probing scheme is developed aiming at discovering admissibility of the new link just by comparing interference measurement results before and after activating the transmission on the link itself: a link evaluates the impact of its entrance on the others (which will have adapted to the increased interference) and decides whether it is admissible or not. In [1] a distributed power control algorithm is proposed which protects active links with respect to the interference brought by new access attempts. Each link just applies a rule for power updating on the basis of the current SIR measure: the algorithm guarantees maintenance of a target SIR during updating. However, a weakness of [1] is that no bounds on the maximum power a device can emit are taken into account. This latter issue, that is not to neglect, can not be solved when links operate only on the basis of measurements. In fact, in this case a link evaluates the possibility to enter the system on the basis of the reaction that other links have when it starts transmitting. However, this reaction could be feebler since some links might have saturated their maximum power value and thus they would react only in a limited way. As a consequence, a positive admission decision could cause the dropping of power saturated links. Finally, the work in [16] discusses non cooperative power control games and shows benefits introduced by using pricing functions.

Other approaches face and overcome the problem related to the maximum power constraint by means of explicit *interlink signaling*. Proposals in this context can be found in [8,11,18]. The adopted solution consists in protecting links by maintaining margins on the target SIR and by broadcasting in the network the information of their values. Thus margins are signaled explicitly in the system and are used for the admission of new links. These strategies result more robust and suitable for a distributed framework since they avoid both global reconfiguration of power levels at the entrance of each new link and links dropping due to maximum power saturation. Maintenance of a margin implies that each link can tolerate positive extra interference introduced by new accesses and also absorb link quality variations due to unpredictable phenomena (e.g., radio channel impairments and terminal mobility). Obviously, a tradeoff exists between setting large margins, thus accommodating a high number of QoS links but contemporarily transmitting elevated power values, or fixing the margins at very low values thus reducing system flexibility and number of contemporary active links. Margins are advertised by means of common broadcast channel and can by signaled by a data packet or by a suitable tone (see [11]); moreover, margin exchange can be done periodically (like in [11]) or on demand (like in [8]).

Finally, a further classification concerns the way powers are managed each time a new link tries to be established: the power management can be either *global* or *incremental* [8]. A global management implies that the whole set of power levels employed by the active links are reconfigured each time a new link enters the system or leaves it. On the contrary, an incremental scheme does not reconfigure previously assigned power levels but proceeds incrementally: the decision whether a new link can be established is based only on the current system situation that is not reconfigured globally. An incremental strategy can be much simpler to be implemented; on the other hand, in principle, it could lead to a less efficient system utilization. Typically, schemes based only on measurements fall into the class of global power management, since all powers are continuously adapted to current interference; anyway, not all the proposals can guarantee maintenance of negotiated SIR levels during the updating phase (like in [20]). Instead, schemes based on both measurements and interlink signaling can be either global or incremental, although proposals found in literature do not introduce the possibility to reconfigure transmission powers after access and are thus to be considered incremental approaches. Table 1 summarizes the main characteristics of the discussed strategies.

In this paper we propose a strategy for distributed AC based on both measurements and inter-link signaling. In order to privilege the robustness of the AC and the simplicity of the relevant implementation, still aiming at a flexible and efficient system, we pursue an incremental-like approach. The innovative aspects are two: (i) the selection of powers and thus margins during the AC phase is performed with the aim of balancing their values with respect to the ones of the active links in the system; (ii) this self-reconfigurable approach is proposed for UWB systems. Balancing of the transmission parameters goes in the direction of increasing the system efficiency by reducing the link block probability; this latter is defined as the probability that the system can not accept an incoming link due to saturation of margins of already active links. The possibility to apply the self-reconfigurable approach to UWB goes in the direction of employing this radio technique in Hot-Spots and WLANs that do not require cell planning, that operate in unlicensed mode and that aim at maximizing the spectrum resource usage.

3. Joint admission control and power regulation in UWB

We consider UWB based on IR, according to which extremely short pulses (of duration 0.1–1.5 ns), named monocycles, are transmitted on a time axis structured in time frames of duration T_f (typically about 100 ns). A monocycle is characterized by an energy level denoted by E_m. Each time frame is divided in N_h short time periods of duration T_c. A symbol is transmitted by N_s pulses according to a Pulse Position Modulation scheme. The multiple access is based on the adoption of pseudo-random Time Hopping (TH) codes whose elements are chosen among N_h possible T_c-shifts within the period T_f. The SIR value, denoted by γ, for an UWB multiple access scheme based on TH can be computed under the hypothesis of gaussian approximation of the multi-user interference [17]. For the ith link it is determined according to the following formula:

$$\gamma_i = \frac{P_i \cdot g_{ii}}{R_i \cdot \left(\eta_i + \sigma^2 T_f \sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij}\right)} \tag{1}$$

where

- N is the number of the active links in the system;
- P_i is the average power emitted by the ith link's transmitter ($P_i = E_{m,i}/\{T_c \cdot N_h\}$);
- g_{ij} the path gain from the jth link's transmitter to the ith link's receiver;
- R_i denotes the transmission rate of the ith link;
- η_i is the noise spectral density power at the ith link's receiver;
- σ^2 is an adimensional parameter depending on the pulse shape.

As it can be noticed, different UWB parameters have an impact on the SIR: in fact, its value—besides increasing with power as in a generic wireless system—depends on the pulse shape via σ, on the TH period via T_f and on the number of pulses per symbol via R (in a TH scheme transmitting one bit per symbol, the transmission rate is $R = 1/\{T_f \cdot N_s\} = 1/\{T_c \cdot N_h \cdot N_s\}$).

In the following we assume that the link's QoS requirements are expressed in terms of transmission rate, R, and target SIR, γ^T.

3.1. Problem formalization

The evaluation of admissibility of a configuration of N links consists in finding out, if there exists, a proper set of transmission powers P_i, $i = 1, \ldots, N$, which—for each link $i \in N$—satisfies the requirement on the rate R_i and assures $\gamma_i \geq \gamma_i^T$.

More precisely, this problem can be formalized according to the following matrix form which identifies a well-known condition for the existence of a feasible solution:

$$\begin{cases} (\mathbf{I} - \mathbf{F}) \cdot \mathbf{P} \geq \mathbf{u} \\ \mathbf{P} \geq \mathbf{0} \end{cases} \tag{2}$$

where

- $\mathbf{I}$ is the $N \times N$ identity matrix;
- $\mathbf{P}$ is the column vector of the N transmission powers;
- $\mathbf{F}$ is an $N \times N$ matrix whose elements depend on the system topology (e.g., MTs reciprocal distances and MTs distances from the RAP); in particular $F_{ii} = 0$ and $F_{ij} = \frac{\gamma_i^T \cdot R_i \cdot \sigma^2 T_f \cdot g_{ij}}{g_{ii}}$ with $i \neq j$;
- $\mathbf{u}$ is an N-dimensional column vector related essentially to noise powers ($u_i = \frac{\gamma_i^T \cdot R_i \cdot \eta_i}{g_{ii}}$).

Both $\mathbf{F}$ and $\mathbf{u}$ depend on the the desired transmission rates and target SIRs. In equation (2) the inequalities between vectors have to be taken as inequalities component by component.

The condition of existence of a feasible solution of the problem (2) consists in a constraint for the maximum modulus eigenvalue of $\mathbf{F}$, ρ_F, and is $\rho_F < 1$. If a solution of the problem (2) exists, then the minimum power configuration is called *Pareto-optimal* solution and is provided by the following expression:

$$\mathbf{P}^* = (\mathbf{I} - \mathbf{F})^{-1} \cdot \mathbf{u} \tag{3}$$

which has the property that every other power configuration sets transmission powers at values that are not lower than their corresponding Pareto-optimal ones. In other words, any other solution $\mathbf{P}$ can be expressed as $\mathbf{P} = (\mathbf{I} - \mathbf{F})^{-1} \cdot (\mathbf{u} + \Delta\mathbf{u})$ where $\Delta\mathbf{u}$ is a column vector of N real positive values.

We name $\mathcal{D}$ the domain of the feasible solutions $\mathbf{P} \geq \mathbf{P}^*$. Since, as observed before, a typical real scenario is power constrained, we aim at selecting solutions not exceeding the maximum level of transmission power, $P_{\max}^{dv}$, that radio devices can emit. Therefore an admissible topology is characterized by a non-empty domain $\mathcal{D}$ of solutions which is composed by: (i) the Pareto-optimal solution $\mathbf{P}^*$ allowing to match exactly the desired SIR levels at the minimum transmission powers; (ii) the set of solutions $\mathbf{P}^-$ such that $\mathbf{P}^* < \mathbf{P}^- \leq \mathbf{P}_{\max}^{dv}$ (denoted by $\mathcal{D}^-$); these solutions do not exceed the maximum powers and assure SIR levels greater than the target, (iii) the set of solutions $\mathbf{P}^+$ (denoted by $\mathcal{D}^+$) such that $P_i^+ > P_{\max}^{dv}$ for some $i \in N$; in this case the bound on the maximum power is exceeded.

When the topology is admissible but the activation of all links requires to set some transmission power above the maximum $P_{\max}^{dv}$, it happens that the set $\mathcal{D}^-$ is empty and the set $\mathcal{D}^+$ includes the Pareto-optimal solution $\mathbf{P}^*$.

A scheme based on the Pareto-optimal solution can be implemented by either a centralized or a distributed procedure. In the centralized case a RAP should act a central controller (i) collecting all information required to build the matrix $\mathbf{F}$ and the noise vector $\mathbf{u}$; (ii) computing the Pareto-optimal solution $\mathbf{P}^*$ according to equation (3); (iii) signaling to the involved MTs the transmission powers to be used. While steps (ii) and (iii) are quite simple to be implemented, the first one presents some crucial issues since the knowledge of the matrix $\mathbf{F}$ and of the noise vector $\mathbf{u}$ in turn requires the knowledge of the reciprocal path gains among all the MTs. As a consequence, either a localization procedure or a distributed one of estimation of the reciprocal distances among all the MTs is needed. For these reasons, a centralized approach seems hardly feasible in a real scenario, especially if we consider that tasks (i), (ii), (iii) should be frequently performed in relation with the arrival/departure/movement of MTs.

Some works (e.g., [1]) address distributed implementations of the Pareto-optimal solution; also in this case there are several aspects that introduce high complexity in the system making these approaches unsuitable for distributed self-configuring systems, as discussed in the previous Section 2.

3.2. A distributed power regulated admission control scheme for UWB

One of the appealing features of UWB based on IR regards the possibility to support distributed flexible radio resource management schemes. System efficiency is achievable also when different wireless links are mutually asynchronous. In accordance to the multiple access scheme considered in this paper for an UWB Hot-Spot, different transmissions use different TH codes. Power is configured by tuning the monocycle energy E_m or by changing the parameters T_c or N_h. Transmission rates are varied by controlling suitably the parameters T_c, N_h or N_s.

The AC decisions are taken at MTs in a distributed manner, on the basis of information regarding neighboring wireless links and obtained by measurements and signaling. The distributed nature of these operations assures that transmission parameters of a link are adapted to the status of the neighboring links and to the conditions of the system. It is worth noting that in this latter aspect resides one of the key potentials of UWB transmission. As indicated in [13], "*the novel and unconventional approach underlying the use of UWB is based on sharing optimally the existing radio spectrum resources rather than looking for still available but possibly unsuitable new bands*". This is the reason why an UWB radio resource control should take care of the environment in terms of *introduced* interference on one side and of *perceived* interference on the other side. To guarantee that UWB devices can operate in unlicensed mode, we take into consideration the maximum power value imposed by the regulatory bodies (e.g., the average EIRP value of 0.56 mW derived from a power spectral density of −41.3 dBm/MHz indicated by the FCC). Moreover, we also consider technological power bounds of the involved devices (i.e., the aforementioned $P_{\max}^{dv}$ value). These two values limit the power a device can employ. We relay on a control of the saturation of these limits performed independently by each MT or by the RAP. We name P_{bound} the maximum power a device can use, accounting for both the device's capabilities related to technological issues ($P_{\max}^{dv}$) and upper bounds imposed by the regulatory bodies ($P_{\max}^{reg}$):

$$P_{\text{bound}} = \min\left\{P_{\max}^{dv}, P_{\max}^{reg}\right\}. \tag{4}$$

To support QoS in terms of the bit rate and target SIR, we introduce the so-called *Maximum Extra Interference* (MEI) [5], that is the amount of interference that can be tolerated by a link without endangering the negotiated QoS level. When a link has its MEI equal to zero no other interfering emissions can be tolerated; when the MEI is positive, other links can be activated, provided that the overall interference they produce does not make MEIs go below zero. The aim of our AC mechanism is primarily to guarantee that the MEIs of all active links in a Hot-Spot area are never negative. In addition, for efficiency reasons, our AC procedure tends to balance all MEIs within a Hot-Spot, so as to avoid bottleneck regions and regions where high MEIs are available. It is to be noticed that the link block probability is related to the MEI values. This probability is high if just a single MEI is low and, conversely, the probability is low if the MEIs are all high.

The MEI level perceived by the ith link, denoted by M_i, depends on the QoS parameters, the transmission power and the current interference conditions according to the following expression:

$$\gamma_i^T = \frac{P_i \cdot g_{ii}}{R_i \cdot \left(\eta_i + \sigma^2 T_f \sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij} + \sigma^2 T_f M_i\right)} \tag{5}$$

where γ_i^T and R_i denote the desired SIR and rate respectively.

The scheme we propose proceeds in an incremental way: given a set of active links, the two entities (transmitter and receiver) willing to establish a new link take the access decision by measuring the system. Once verified the admissibility of the new link, the links' power levels will be maintained at a power configuration included in the domain $\mathcal{D}^-$ (thus assuring that the transmission powers are within P_{bound}). Power levels are computed on the basis of the current MEI values M_i, $i = 1, \ldots, N$, according to:

$$\begin{cases} \mathbf{P}^- = (\mathbf{I} - \mathbf{F})^{-1} \cdot (\mathbf{u} + \Delta\mathbf{u}), \\ \Delta u_i = \dfrac{\gamma_i^T \cdot R_i \cdot \sigma^2 T_f M_i}{g_{ii}}, \quad i = 1, \ldots, N. \end{cases} \tag{6}$$

As stated in Section 3.1, the power configuration $\mathbf{P}^-$ provides for power levels greater than the corresponding Pareto-optimal ones and can be expressed as $\mathbf{P}^- = \mathbf{P}^* + \Delta\mathbf{P}$ where $\Delta\mathbf{P} =$

$(\mathbf{I}-\mathbf{F})^{-1}\cdot\Delta\mathbf{u}$ is a vector of positive elements. MEI levels can be expressed as functions of the additional powers ΔP_i, $i=1,\ldots,N$, employed by the N links; in particular, it is derived the following expression of the MEI of the ith link, M_i, by exploiting equation (5), substituting $P_i = P_i^* + \Delta P_i$, $i=1,\ldots,N$, and accounting for the property of the Pareto-optimal solution of providing null MEIs:

$$M_i = \frac{g_{ii}\Delta P_i}{\sigma^2 T_f \gamma_i^T R_i} - \sum_{j=1, j\neq i}^{N} g_{ij}\Delta P_j \tag{7}$$

Equation (7) highlights a tradeoff: the additional power ΔP_i used by the ith link increases the relevant MEI, M_i, while the terms ΔP_j, $j=1,\ldots,N$, $j\neq i$, of the other active links, reduce it. Furthermore, MEI is inversely proportional to the QoS parameters; as an example, the support of a higher transmission rate leads to a reduced MEI level if the transmission power is kept constant.

The AC rule for an $(N+1)$th link, given N active ones, consists in the comparison between the minimum power, $P_{\min,N+1}$, needed to satisfy the link's QoS requirements (γ_{N+1}^T and R_{N+1}) on the basis of the current interference level measured at the receiver $I_{N+1} = \sum_{j=1}^{N} P_j \cdot g_{N+1j}$, and the maximum power, $P_{\max,N+1}$, bounded by equation (4) and satisfying the constraints imposed by the MEI levels of the N active links (that should not reduce to zero when the new link is activated).

The minimum and maximum power are derived according to the two following equations:

$$P_{\min,N+1} = \frac{\gamma_{N+1}^T \cdot R_{N+1} \cdot (\sigma^2 T_f I_{N+1} + \eta_{N+1})}{g_{N+1N+1}}, \tag{8}$$

$$P_{\max,N+1} = \min\left\{P_{\text{bound}}, \min_{1\le j\le N}\left\{\frac{M_j}{g_{jN+1}}\right\}\right\}. \tag{9}$$

The access can take place if:

$$P_{\min,N+1} \le P_{\max,N+1}. \tag{10}$$

A suitable transmission power level, within the range $[P_{\min,N+1}, P_{\max,N+1}]$, is selected. As stated before, the considered criterion for power selection is to keep balanced the MEI values in the system. In fact, it is to be noticed that the access probability for the $(N+1)$th link, defined as $Prob\{P_{\min,N+1} \le P_{\max,N+1}\}$, is as higher as greater the MEI values M_i, $i=1,\ldots,N$, are. In equation (9) the lowest MEI constitutes a bottleneck for further accesses.

In our incremental approach, at the access of the $(N+1)$th link, the optimal working point $\mathbf{P}^-$ (see equation (6)) can be tracked by choosing suitably P_{N+1}. In particular, the optimal power $P_{opt,N+1}$ for the new link will be the one that maximizes the minimum MEI. On one side we consider the impact of the $(N+1)$th link on the active ones in terms of MEI reduction and, on the other side, we consider the MEI level acquired by the new link as functions of the transmission power P_{N+1}:

$$M_i^+ = M_i^- - P_{N+1}\cdot g_{iN+1}, \quad 1\le i\le N, \tag{11}$$

$$M_{N+1} = \frac{P_{N+1}\cdot g_{N+1N+1}}{\sigma^2 T_f \gamma_{N+1}^T R_{N+1}} - I_{N+1} - \frac{\eta_{N+1}}{\sigma^2 T_f}. \tag{12}$$

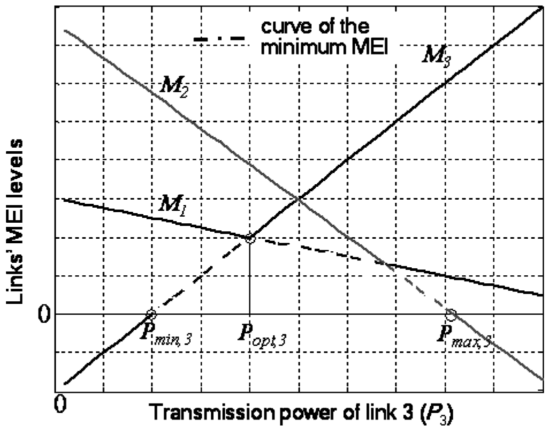

Figure 2. Case of three links: MEI levels as a function of the entering link's transmission power.

where in equation (11) M_i^- and M_i^+ denote the value of the MEI for the generic i-th link respectively before and after the $(N+1)$th link's access at power P_{N+1}. An example of the potential impact of a new link's transmission in terms of MEIs is shown in figure 2 for the case $N=2$ where also the optimal power $P_{opt,N+1}$ is indicated (in the example $P_{opt,3}$).

The optimal power value is computed according to the following equation which provides the minimum value among the intersection abscissas of equations (11) and (12):

$$P_{opt,N+1} = \min_{1\le i\le N}\left\{\frac{M_i^- + I_{N+1} + \frac{\eta_{N+1}}{\sigma^2 T_f}}{g_{iN+1} + \frac{g_{N+1N+1}}{\sigma^2 T_f \gamma_{N+1}^T R_{N+1}}}\right\}. \tag{13}$$

The selected power $P_{opt,N+1}$ actually represents just a sub-optimal choice with respect to the Pareto-optimal solution since the access is managed in an incremental way, that is without reconfiguring transmission powers of the active links. Although such a strategy is less efficient than a global one—as pointed out in Section 2—it results quite simple to be implemented since it is based only on the computation of a single power level within the range limited by the two values in equations (8) and (9) respectively. Furthermore, it is to be noticed that, if a link verifies the non-admissibility at the given QoS level, it can try to relax its QoS request reducing the transmission rate, R, or the target SIR, γ^T, in order to satisfy equation (10).

3.3. Steps of the access scheme

In the following we aim at presenting a possible implementation scheme of the proposed AC strategy. With this purpose, we highlight the operations performed at the transmitter (TX) and the receiver (RX) of a link that should be activated. These operations are reported in the flow charts of figure 3.

We remark that the proposed scheme is based on the assumption that each device that should initiate a communication as the TX—either MT or RAP—acquires the current MEI

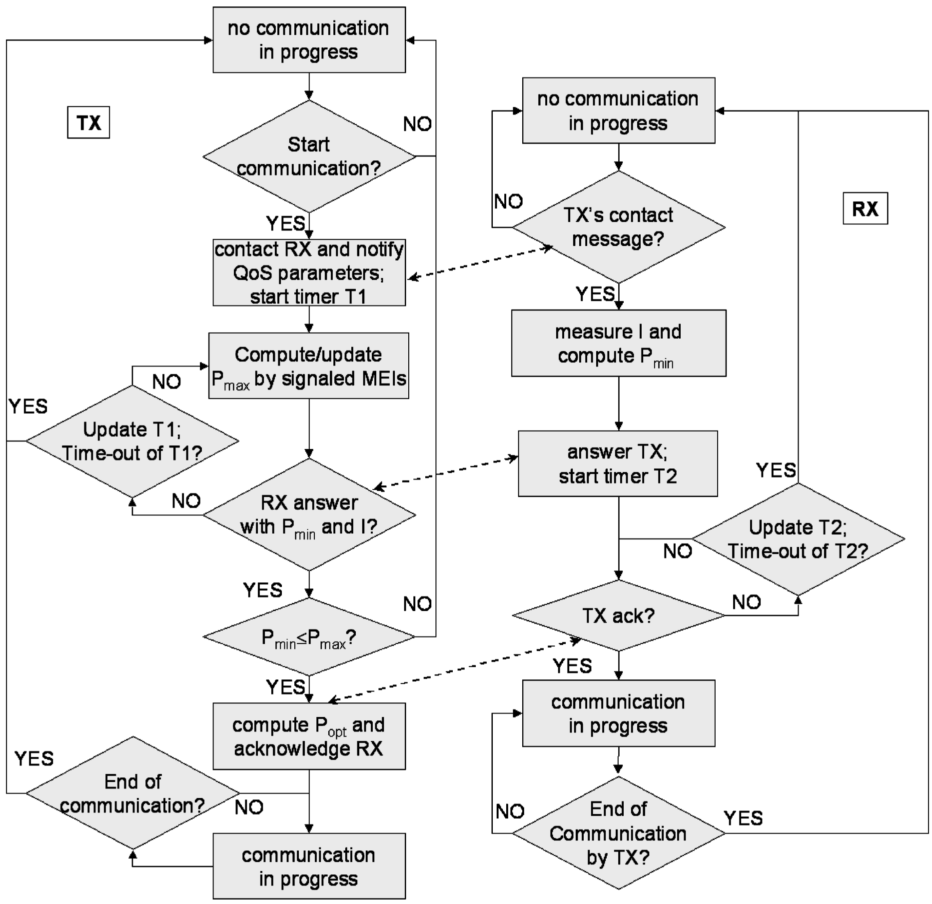

Figure 3. Flow charts of the operations performed at the Transmitter (TX) and the Receiver (RX).

values of its neighboring receivers (named in the following n_RXs in order to be not confused with the candidate device receiver, RX, of the link to setup). The acquisition of MEIs allows the TX to compute the maximum power it can emit so that the n_RXs still maintain their negotiated QoS, even if further interference will be introduced in the system by the new transmission. As a consequence, the implementation of the access scheme requires an explicit inter-link signaling: each device advertises on a broadcast channel its current MEI level. The broadcast channel could be constituted by a common TH-code shared by all mobile devices. We assume that a device has the capability of listening to a multiplicity of signaling packets transmitted on the same TH-code. It is to be noticed that in equation (9) we indicated that MEIs are acquired for all the N links in the systems. However, since the impact that the transmission could have on a generic device is inversely proportional to the distance of this device from the TX, it is sufficient that only MEIs of the neighboring devices, n_RXs—which are less than or equal to N—are acquired.

Besides the MEI advertisements, the AC of the new link requires a signaling exchange between the TX and the RX. This is obtained by the exchange of a `Contact Message` in the TX → RX direction and a `Contact Reply` in the RX → TX direction. In figure 3, the dotted lines between the two flow charts indicate signaling exchange between the TX and the RX involved in the link activation. The TX has the task of computing the maximum power on the basis of the current MEI values acquired by the broadcast signaling. Since the TX can listen just to the MEIs signaled by its n_RXs, the maximum power computation at the TX assures that the considered MEIs concern only those links which actually could be disturbed. Moreover, the TX estimates the reciprocal path gains between itself and the n_RXs; this estimation is derived by the signaling messages transporting MEIs by comparing the relevant transmitted and received powers: the first one can be a-priori known while the second one can be measured. The reception of a `Contact Message` at the RX triggers the measurement of the perceived interference, I, and the computation of the minimum transmission power on the basis of the desired SIR and of the transmission rate. The `Contact Message` also contains the desired QoS parameters. The RX answers to the TX communicating the values of the minimum transmission power and of the measured interference. The admission rule—expressed by equation (10)—is checked by the TX which acknowledges to the RX the access decision. If the access is denied (since it results $P_{\min} > P_{\max}$), it may be possible to reconfigure the QoS request by reducing, for example, the desired rate R (see equation (8)). On the contrary, if the access is possible, the computation of the optimal power is performed by the TX in accordance to equation (13). At the end of the process the TX sends the AC result to the RX. If the link can be activated, in this last signaling exchange all the transmission parameters as well as the selected TH code are announced.

Finally, in figure 3 we indicated the adoption of two timers, T1 at the TX and T2 at the RX. T1 is used by the TX while it is waiting for the RX's answer to its `Contact Message`; if the answer does not arrive by the time-out of T1, the TX argues that the contact attempt failed and the procedure of the link activation is ended coming back to the status of "no communication in progress". As for T2, this timer is started by the RX after its answer to the TX and specifically when it begins waiting for the TX's acknowledgement of the activation success. If the timer T2 expires, the RX assumes that the activation attempt failed and enters the status of "no communication in progress".

According to the procedure described in figure 3, a MT entering a Hot-Spot and willing to establish an uplink with a discovered RAP initiates the activation procedure by contacting the RAP in order to signal the desired QoS parameters. Then, the MT starts listening to the broadcast channel in order to acquire the current MEI values of MTs and possible other RAPs in its neighboring. The MT computes the maximum transmission power on the basis of these acquired MEIs. Let us notice that RAPs and MTs operate in the same way according to a peer-to-peer communication paradigm. Since the MT is the transmitter part of the uplink, the admission control is performed autonomously by the MT itself. The RAP cooperates by computing and signaling the minimum required power which depends on its perceived interference. Thus the distributed nature of the scheme stands in the fact that MTs are involved actively in the admission control; besides, also the collection of the information needed to perform the admission control requires a distributed cooperation of each MT. It is evident the difference between this approach and typical cellular radio systems where admission control functions are fully centralized in the Base Stations.

When the setup of a downlink is attempted, the RAP operates as TX. In this case the computation of the maximum power the RAP can emit depends also on the number of the already active downlinks.

4. Performance analysis

In this section we evaluate the performance of our distributed AC scheme based on MEIs. First we compare our B-MEI approach and a similar approach appeared in literature; this comparison is quite general and does not depend on the adoption of UWB as transmission scheme. In this case the analysis shows the advantages, in terms of link access probability, of balancing the system's MEIs. Then, we analyze the behavior of our AC in a typical Hot-Spot scenario and we discuss the impact of some UWB parameters on the perceived performance. The design parameters of the system at hand are reported in Table 2. We referred to a path loss increasing as the power 2.4 of distance and equal to 1259 at 1 m. We assume an ideal signaling scheme: no collisions occur on the broadcast channel among signaling messages of MEIs.

Table 2
List of parameters for the UWB hot-spot used in the experiments.

T_f, pulse frame period	100 ns
N_s, number of pulses per bit	10
R, required transmission rate	1 *M*bit/s
γ^T, target SIR	10 dB
η, noise power spectral density	$4 \cdot 10^{-21}$ W/Hz
F, receiver noise figure	10 dB
σ^2	$1.9966 \cdot 10^{-3}$
P_{bound}, maximum power per device	0.56 mW

4.1. Performance comparison with other strategies

In this section we report some results relevant to a comparison of B-MEI and the scheme proposed in [8] (here named Constant MEIs—C-MEI). The difference between the two is summarized as follows. The B-MEI balances MEIs by selecting the optimal transmission power, P_{opt}, for the new link entering the system. Conversely, C-MEI forces the new link to acquire always the same constant MEI.

We generated a number of topologies with N pairs of communicating devices located randomly in a square area of 100 m × 100 m. A first performance metric is the probability of activating successfully all the N links, at the rate R and the SIR level γ^T indicated in Table 2, as a function of N. We introduce the parameter M_0 which denotes the initial MEI acquired by the first link activated in the Hot-Spot in case of B-MEI, while represents the constant MEI in case of C-MEI.

First, we studied the impact on performance of the initial MEI, M_0. Figure 4 reports the probability of activating N links as a function of M_0 for different values of N. For both B-MEI and C-MEI the first part of the curves increases as M_0 increases. Then, the B-MEI curves saturate due to the maximum power constraint that limits also the actually achievable MEIs. Instead, as for C-MEI, the curves reach a maximum and then decrease tending to a constant value. In the C-MEI case, since M_0 represents the initial MEI of each new link, the entering links generate higher interference than in case of B-MEI. This interference has to be overcome by the new entering links with higher transmission powers, thus quickly saturating the maximum power constraint.

We included also a comparison with the theoretical curves achievable by a global scheme reconfiguring powers at the Pareto-optimal solution (indicated in the following as Minimum Power—MINPOW) [1]. We assume that MINPOW rejects access requests that would force some links to overcome

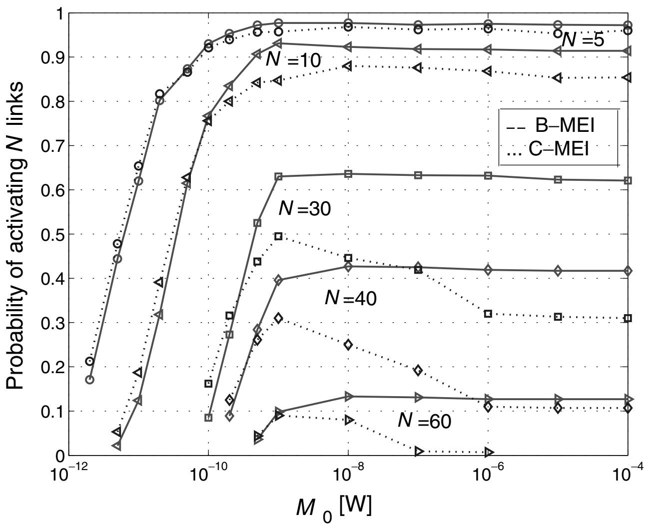

Figure 4. Probability of activating N links as a function of the initial MEI (M_0).

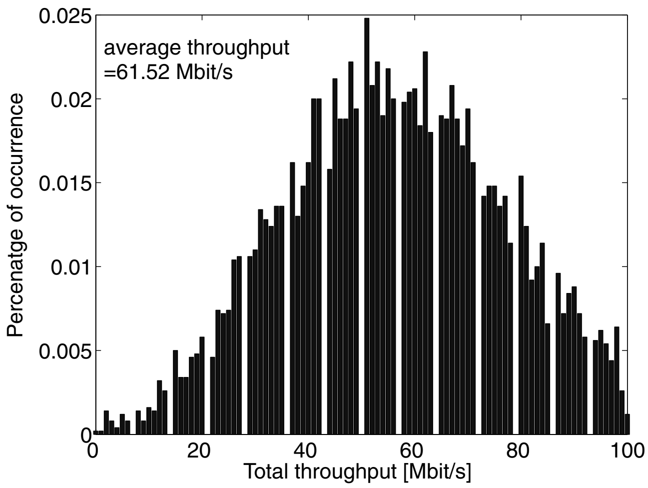

Figure 6. Percentage of occurrence of overall throughput values in case of B-MEI (number of links $N = 100$, initial MEI $M_0 = 10^{-8}$ W).

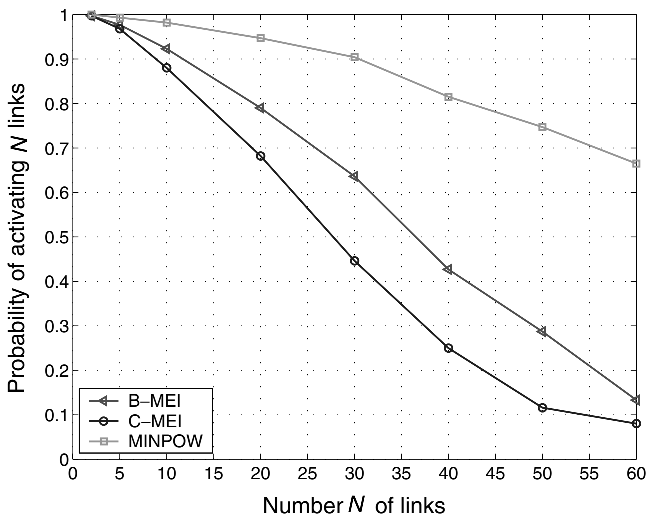

Figure 5. Probability of activating N links as a function of N (initial MEI $M_0 = 10^{-8}W$).

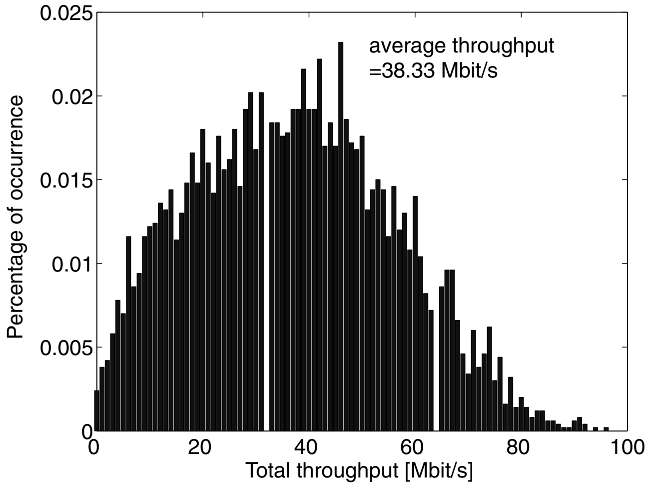

Figure 7. Percentage of occurrence of overall throughput values in case of C-MEI (number of links $N = 100$, initial MEI $M_0 = 10^{-8}$ W).

the maximum power per device. In figure 5 we plot the probability of activating N links as a function of N; for B-MEI and C-MEI we adopted an initial MEI value $M_0 = 10^{-8}W$. The curve labelled as MINPOW presents the maximum access probability. As it can be expected B-MEI outperforms C-MEI. Both strategies B-MEI and C-MEI require the signaling of MEIs. Instead, as for the distributed implementation of MINPOW, we remind that some implementations based on measurements have been proposed (e.g., see [1] and [20]); however, the bound on the device transmission power is neglected completely. This simplifying assumption affects deeply performance while it becomes essential for employing UWB in unlicensed bands respecting regulatory body's masks.

Finally, a further performance comparison between B-MEI and C-MEI has been carried out by measuring the achieved system throughput, computed as the sum of the transmission rates of all the active links. Specifically, we generated a number of topologies with $N = 100$ links located randomly in a square area of 100 m × 100 m and we measured the percentage of occurrences of possible throughput values. Each link, when activated, achieves a transmission rate of 1 Mbit/s with a SIR greater than or equal to 10 dB. Figure 6 concerns B-MEI while figure 7 represents the throughput for C-MEI. The two histograms highlight the better performance of B-MEI than C-MEI; specifically, the one of B-MEI is centered around higher values of throughput than C-MEI. The average throughput achieved by B-MEI is 61.52 Mbit/s while in case of C-MEI its value is 38.33 Mbit/s. These results are clearly in favor of a balanced MEI strategy and could be further improved by means of power reconfigurations during the links' lifetime.

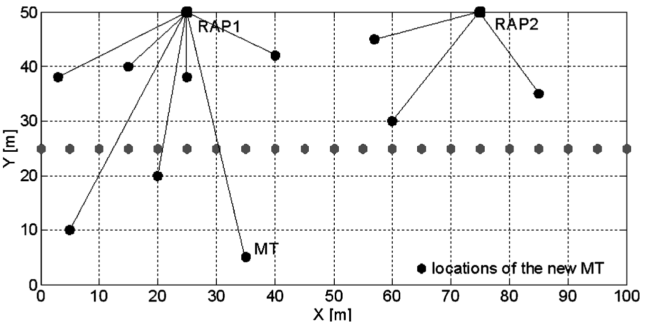

Figure 8. Considered topology (with indication of the new MT's locations).

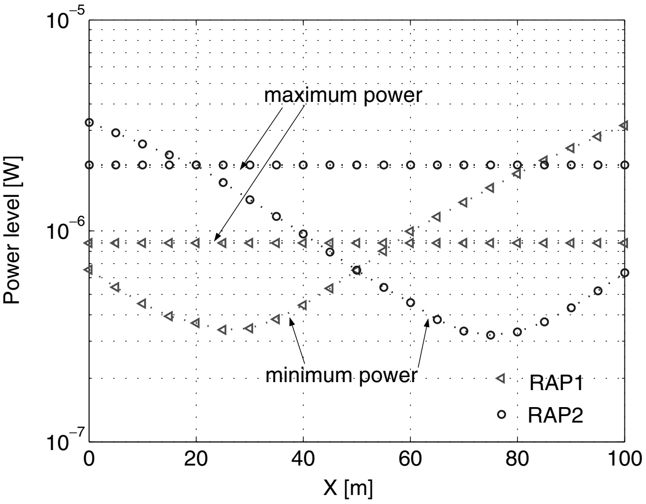

Figure 9. Downlink power levels as functions of the new MT's location.

4.2. Performance behavior in specific system topologies

Once discussed the general performance achievable by our AC scheme, we concentrate on the analysis of the B-MEI behavior in some specific network configurations. Initially, we studied the scenario represented in figure 8 where two fixed RAPs provide UWB access to a number of MTs in an area of 100 m $\times$ 50 m. The links between the MTs and their serving RAP are full-duplex and the relevant parameters are set at the values indicated in Table 2. We assume that the forward and reverse links of a radio device do not interfere each other. The initial MEI is set at $M_0 = 5 \cdot 10^{-12}$ W. Ten links are already active and a new one should be activated between a new MT entering the system and either RAP1 or RAP2.

In figure 8 gray dots indicate the considered possible locations of the new MT; these locations are distributed along a straight line at steps of 5 m. As a function of the 21 possible locations and for both RAPs, we computed analytically the minimum and maximum transmission powers in accordance to equations (8) and (9) respectively. Figure 9 plots the power values (minimum and maximum) for either RAP1 or RAP2 to sustain a downlink toward the considered MT. In figure 10 we report the maximum sustainable rate calculated for the two RAPs.

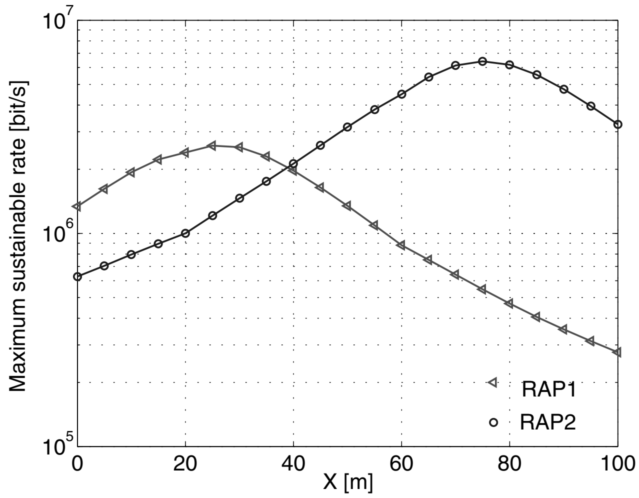

Figure 10. Downlink sustainable rates as functions of the new MT's location.

The curves in figure 9 indicate that, for both RAPs, the new link is not always admissible since for some locations of the MT the minimum power level is above the maximum one. For instance, when the new MT is placed in the locations with $X = 0 \div 20$ m the downlink can not be established at the desired QoS parameters of $R = 1$ Mbit/s and $\gamma^T = 10$ dB if the selected RAP is RAP2; nevertheless, the maximum rate sustainable by RAP2 at the given γ^T is positive and less than 1 Mbit/s, as shown in figure 10. Similarly, in figure 10 we can also observe that, when the MT is in one of the locations with $X = 55 \div 100$ m, a downlink at 1 Mbit/s is not admissible for RAP1 since the maximum rate that RAP1 can sustain is less than 1 Mbit/s.

Plots in figure 10 also indicate the most convenient RAP for each possible location of the new MT in terms of transmission rate. Let us remind that the value of the maximum sustainable rate depends on the maximum transmission power, the interference level and the path gain. In particular, in correspondence of locations with $X = 40 \div 50$ m the RAP offering the higher transmission rate is RAP2 thanks to the better overall conditions in its surrounding area, even if it is not the closest RAP to the MT. In particular RAP2 can select a higher maximum power than RAP1, as it can be observed in figure 9. This depends on the MEIs of the three links which are closest to this RAP (see figure 8).

To conclude our performance analysis, we measured the B-MEI performance in terms of SIR levels. The Hot-Spot area is the same of figure 8. We considered 20 MTs distributed in an area of 100 m $\times$ 50 m. The main difference in comparison with the previously discussed results is that each MT generates dynamically setup requests. These requests are generated in accordance to an exponential distribution; the mean frequency of setup request arrivals is equal to 0.3 s^{-1}. Each communication has duration distributed in accordance to an exponential distribution with mean value of 60 s. For each setup request the AC is performed in the network's RAPs according to the following steps: (i) each RAP

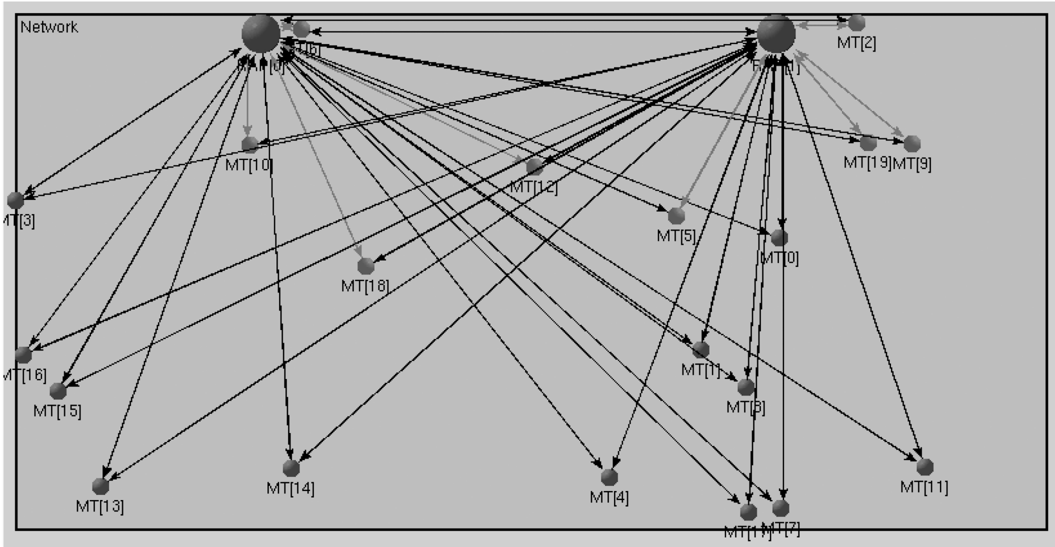

Figure 11. Snapshot of the simulated scenario.

verifies whether the link is admissible; (ii) the RAPs whose check of admissibility has succeeded select the appropriate transmission power; (iii) the most convenient RAP is chosen to serve the request. In order to measure the SIR levels in this dynamic scenario, we developed an Omnet simulator. Figure 11 is a snapshot of the generated scenario. Links between MTs and RAPs are activated and deactivated dynamically. In order to accomplish the FCC power bound, we imposed that both RAPs and MTs employed a maximum power value equal to $P_{\text{bound}} = 0.56/20$ mW $= 0.028$ mW. As a consequence, a RAP can sustain up to 20 MTs at the maximum power. The other transmission parameters are the ones in Table 2. We simulated 1000 s of network lifetime. In the SIR expression we introduce a factor a, the mutual interference is weighted by. A value $a = 1$ models the gaussian approximation of the mutual interference at the receiver. With values $a > 1$ we forced a performance degradation consisting in a higher weight of the mutual interference at the receiver due to non-ideal effects. Figure 12 shows the SIR level evolutions of the links of four MTs (specifically, MT1, MT9, MT13 and MT17) during the simulated time period of 1000 s and with $a = 1$. Note that variations of SIR levels are due only to variations of mutual interference since we do not simulated radio channel dynamics nor MT mobility. In case of $a = 1$ (figure 12) variations of MEIs associated with link activations/deactivations are very small due to the poor effect of mutual interference which is counteracted effectively by the high processing gain of UWB. This reflects in very slight perturbations of SIR levels during a single data session. The different segments of the SIR evolution in figure 12 correspond to different data sessions, each preceded by its admission control procedure. As new links enter the system, at the setup of a new data session the acquired MEI is lower and forced at the level of the minimum one in the network. In figure 13 we considered a case of higher impact of the mutual interference on performance (case of $a = 100$), and we show just the first 10 s of the network lifetime in order to highlight the SIR variations during a single data session. In this case we can observe larger variations of the mutual interference due to new links entering the system or old ones leaving because of the higher interference weight $a = 100$. In particular SIR decrements are associated with new links' entrance while SIR increments with old links' exit.

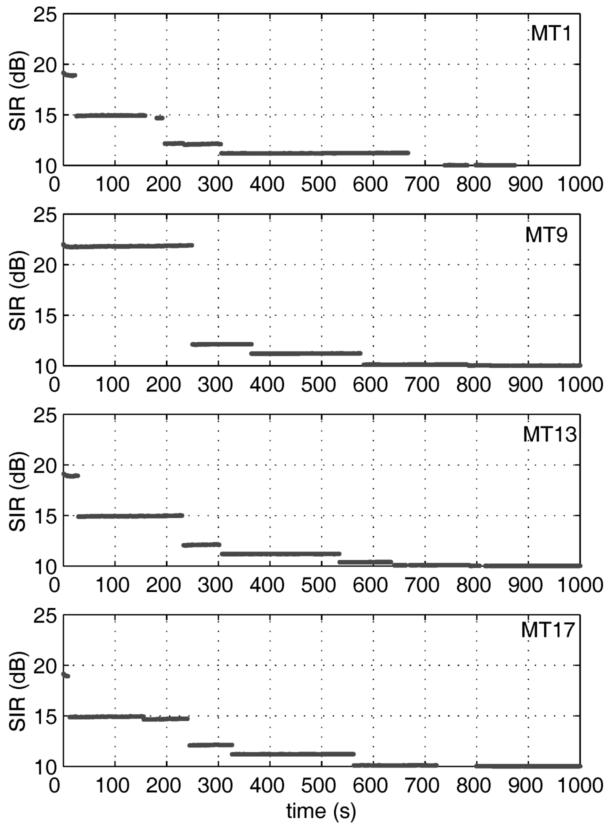

Figure 12. Time evolution of SIR levels with interference weight $a = 1$.

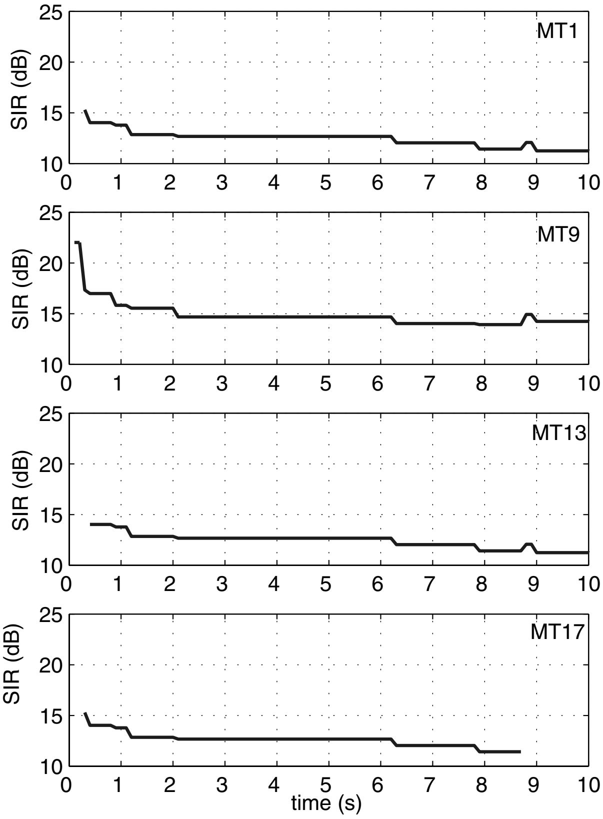

Figure 13. Time evolution of SIR levels with interference weight $a = 100$.

5. Conclusions

To facilitate and accelerate the deployment of Hot-Spot and WLAN paradigms, network operators and Internet Service Providers are directing their attention towards technologies able to operate in unlicensed bands. Among these, UWB seems one of the main candidates for providing a flexible wireless solution.

In this work we deal with an admission control scheme aiming at supporting UWB flows in a Hot-Spot area. Our solution can be classified in the category of power controlled schemes. The proposed admission control mechanism controls the current interference level in the Hot-Spot before admitting new communications that could impair the already active ones by compromising their negotiated QoS. To achieve high flexibility, the access is controlled in accordance to a distributed approach based on suitable measurements and signaling. Bounds on the UWB transmissions are also used to guarantee compliance with the regulatory body's limits. Each mobile terminal is made able to evaluate the possibility to access the Hot-Spot and to self-configure its transmission parameters. Furthermore, we investigate the possibility to select the "best" Radio Access Point when multiple points of access to the fixed network are available. We define the admission rules and derive the dependencies of these rules from the transmission parameters of the active communications as well as from technological and regulatory constraints.

The performance behavior of the proposed scheme has been analyzed both in a specific Hot-Spot scenario (to show dependencies on the network topology) and in more general scenarios. In these latter cases we showed benefits related to one of the key innovative aspects introduced in our admission control mechanism: the possibility to select, during the admission control phase, a transmission power (named P_{opt}) and a Maximum Extra Interference level balanced with respect to other communications supported within the given Hot-Spot. To single out performance dependencies related to the selection of different RAPs, we analyzed a scenario where a new MT can enter the system in 21 different locations.

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