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Radio resource management in infrastructure-based and ad hoc UWB networks

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Summary

Modeling the resource manager of an ultra wide band (UWB) network is the main object of this paper. The model is tested in two different application scenarios: (i) a UWB WLAN access network to a backbone where the resource management module is implemented at the access points (APs); (ii) a UWB ad hoc network for either local communications or data exchange among sensors, with peer-to-peer links with distributed management.

The design must include a quality of service (QoS)-aware strategy and must take into account coexistence issues raised by the use of UWB at the physical layer. Link quality is represented by the maximum end-to-end delay and minimum percentage of correct packets. From these parameters, the resource manager jointly selects the values of power and rate which must be adopted at the physical layer. In the model, radiated power by each device is supposed to be limited by an upper bound, reflecting thus the limitation imposed by regulation. QoS awareness and power constraints are satisfied, thanks to the implementation of an admission control function, which is centralized in the AP in the WLAN case and distributed in the ad hoc case. Major innovative aspects include: (i) taking into account UWB specific features; (ii) introducing QoS awareness based on network layer parameters rather than physical layer parameters; (iii) incorporating error protection functionalities for the optimization of transmission efficiency; (iv) considering both centralized and distributed resource management.

Performance of the proposed resource manager module is evaluated in the presence of different classes of traffic, that is multimedia, voice, and data traffic. For each class of traffic, performance is expressed in terms of the maximum possible number of simultaneous connections for the WLAN case, and in terms of the effective achievable throughput for the ad hoc case. Results of simulations indicate that the behavior of the proposed scheme is strongly dependent upon the class of traffic in the WLAN scenario, while it is slightly affected by changes in traffic characteristics in the ad hoc case. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: ultra wide band; resource management; MAC; QoS; WLAN; ad hoc network

1. Introduction

The recent success of a variety of wireless access technologies will possibly lead, in the near future, to the possibility of exchanging data as well as accessing the Internet from rather simple communication devices. Communicating through wireless has emerged as an increasingly appealing solution for local area as well as personal area networking (LAN and PAN). Wireless sensor networks (WSN) used for monitoring the environment and human behavior is another interesting area of application of wireless communications [1].

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In order to be widely adopted, however, a wireless technology must in principle be characterized by a set of basic features among which particular emphasis should be given to: (i) flexibility in providing access to different classes of traffic, (ii) simplicity of deployment, and (iii) capability of guaranteeing target performance requirements for data flows with heterogeneous characteristics of emission. As for (i) and (ii), radio paradigms capable of operating in an unlicensed way are particularly appealing, given their intrinsic flexibility in terms of system deployment and operation. The goal stated in (iii) can be translated into requiring that the system accommodates packet transmissions with variable bit rates and, in order to do so, be capable of tuning emitted power levels in a dynamic fashion based on interference noise levels and as a function of a set of required link performance measurements. As such, the ultra wide band (UWB) principle appears to very well meet the above requirements and is therefore expected to successfully turn into a widely spread technology [2].

The object of this paper is to present a comprehensive analysis of the resource manager model of an UWB network for application in different scenarios. Our study was carried out in the framework of European project, whyless.com [3], which was aimed at the design of an open and flexible access network based on UWB (e.g., see [4–10]). We analyze in particular the following two scenarios:

1. A centralized and static architecture as typical of a UWB-WLAN access network to a backbone. Based on UWB as the underlying physical transmission technique, a specifically designed resource management module is implemented in the network access point (AP) of a wireless LAN (see Figure 1(a)). In this case, medium access control (MAC) functionalities are almost entirely performed by the AP, which coordinates transmissions and allocates resource for all devices within the network.
2. A distributed and dynamic architecture as in a UWB ad hoc network for either local communications among mobile devices or data exchange among sensors (see Figure 1(b)). Here, UWB is the adopted transmission technique for communications over the set of peer-to-peer links between wireless devices.

In both scenarios, the radio resource management module must include mechanisms for serving data flows with quality of service (QoS) requirements, and for controlling interference in order to allow multiple devices to share the same frequency range. The interference control mechanism may also serve for monitoring interference provoked by UWB transmissions onto systems that coexist over a common frequency range. As well known, in fact, UWB signals spread by nature over very large bandwidths (from a few Hertz to several Gigahertz), and therefore overlap with signals originating from the operation of other wireless systems. As a consequence, UWB transmissions must occur at very low power levels in order to be perceived by other radio systems as a low-power interference noise [11].

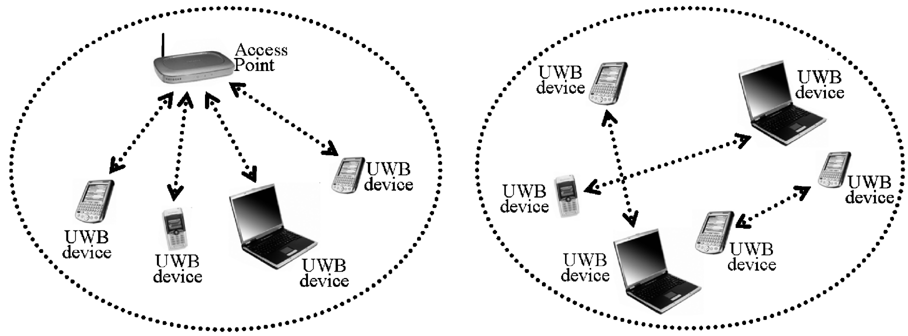
A resource allocation strategy for UWB networks was first proposed in Reference [12], where an UWB-specific admission control function is introduced in the special case of flows of traffic with no specific requirements. Recent works further extend [12] and propose advanced resource allocation procedures based on a dynamic and joint allocation of transmission rates and powers for both best-effort and QoS-guaranteed traffic [13–15]. The analysis presented in this paper is based on a similar approach, but with the following innovative aspects: (i) resource management is considered for both centralized and distributed networks; (ii) resource allocation is performed by a MAC module which also includes error protection functionalities for the optimization of transmission efficiency; (iii) QoS is defined at the network layer in terms of transmission delay and maximum tolerable packet loss, while current approaches are based on physical layer parameters, such as power and rate; (iv) resource allocation takes into account UWB-specific features such as the need for synchronization trailers on each transmitted packet, and the need to control transmission powers in order to meet the limitations imposed by regulation.

This paper is organized as follows. Section 2 describes the adopted system model for the two scenarios under examination. Resource management algorithms and procedures are reported in Section 3. Section 4 includes performance results derived from the application of the model. Finally, Section 5 contains the conclusions.

2. System Model

2.1. Reference Network Architectures

Figure 1 shows the application scenarios under consideration and related network architectures. Figure 1(a) represents the WLAN case: here the



(a) (b)

Fig. 1. Reference scenarios and network architecture: (a) centralized WLAN case, (b) ad hoc case.

network is composed by a set of UWB devices (e.g., laptops, mobile phones, palmtops, etc.) and one AP. The AP is characterized by a given radio coverage area and has the role of controlling the access to the resource in this area. All UWB devices exchange data with the AP, and the AP routes these data to other terminals either in the area or towards the external network. Uplinks and downlinks are assumed to operate over separate channels, that is, in case of code division multiple access based on time hopping (TH) codes, the sets of TH codes for the two channels are chosen in order to minimize the existing interference between uplink and downlink transmissions, which is neglected in this study.

Figure 1(b) displays the pure ad hoc architecture. Here, each UWB device (laptop, mobile phone or wireless sensor) establishes a wireless link with another device in an ad hoc fashion. Different communications at the same time are allowed, thanks to the control of the multi-user interference avoiding disruptive packet collisions. This model can be used when the wireless network is deployed over areas with no pre-existing communication infrastructure, as for example disaster recovery environments. This architecture is also typical of random deployment of wireless sensors over a geographical area to be monitored. In the following, we investigate an ad hoc scenario with only single-hop transmissions, as the one illustrated in Figure 1(b).

Access control in the first scenario is demanded to the AP. Oppositely, in the second scenario, all operations for accessing the medium as well as for controlling QoS are performed in a distributed manner by cooperative and self-organizing wireless devices. In both scenarios, each link is characterized by a required link quality expressed in terms of maximum end-to-end delay and minimum guaranteed percentage of packets which are delivered to the destination without errors. Starting from these parameters, the resource manager module allocates powers and rates by taking into account the levels of mutual interference which are generated among active devices. Radiated power by any device is supposed to be limited in compliance with regulatory recommendations [11]. Specifically, we assume that each device may transmit up to a specified maximum power, P_{bound}.

In both scenarios QoS is controlled by setting powers and rates to values which satisfy the requirements of any new link and also ensure that the establishment of the new link does not impair the QoS of already active links, which should maintain QoS thresholds negotiated when activated. This is achieved by implementing an admission control function, which is centralized in the AP in the WLAN case of Figure 1(a), and distributed in the ad hoc case of Figure 1(b).

2.2. Traffic Modeling

For both scenarios of Subsection 2.1, we adopt Dual Leaky Bucket parameters for modeling traffic activity at the network level [16]. According to this model, a traffic source that is active on a given link k is characterized by a peak rate p_k (bits/s), an average rate r_k (bits/s), a token buffer dimension b_k (bits), and a maximum packet size M_k (bits). Note that rates p_k and r_k are measured at the application level, without taking into account the overhead introduced at the lower layers, and can thus result in much lower values than the rate that must be reserved to link k at the physical layer.

Regarding QoS, each link k is characterized by a maximum tolerable end-to-end delay D_k (s), and a minimum percentage of packets F_k that must reach the destination within D_k. Note that a same set of parameters is used for both real-time and non real-time services, with no explicit need for defining classes of traffic.

2.3. Radio Access Model

For both scenarios, that is WLAN and ad hoc, a time-hopping multiple access (THMA) scheme is adopted [17] by which different users are assigned with different codes. By such coding the reference receiver is capable of isolating the reference transmitter signal from other signals, which are seen as interfering signals. The degree by which the interfering contributions can be removed mainly depends upon the characteristics of the TH codes, and on the degree of system-level synchronization. In the ideal condition of perfect system synchronization, ideal channel, and orthogonal codes associated with different data flows, the receiver is not affected by the presence of multiple transmissions. In a realistic scenario, however, where devices do not achieve ideal synchronization and codes lose orthogonality due to different propagation delays on different paths, the receiver might not be capable of completely removing the presence of the undesired signals, and as a consequence, system performance is affected by multi user interference (MUI).

In the above scenario, system capacity is mainly limited by MUI, and the basic task of the radio resource manager is thus to allocate power in order to meet the QoS over all active connections. In the WLAN case, a task that assigns TH codes and controls power levels of all devices in the network (see Subsection 3.1) is demanded to the AP. In the ad hoc case, both code selection and power allocation are performed at each device by means of a distributed algorithm (see Subsection 3.2).

In all cases, we assume that all source packets which are delivered to the radio resource management module are segmented into the so-called MAC protocol data units (MACPDUs) before being transmitted over the radio channel. We also assume that all MACPDUs have the same size L_{MAC} bits, and that each MACPDU is composed by a *header* of L_H bits and a *payload* of L_P bits. The *header* contains the information used by the module for managing the transmission of a MACPDU (e.g., addresses, flags ...), and signaling bits for receiver synchronization, channel estimation, and error detection. The *payload* conveys bits originating from the segmentation of source packets, plus redundancy bits that may be introduced for implementing forward error correction (FEC). The payload is therefore composed of two parts: a FEC field of L_{FEC} bits and an effective payload for user data of $L_{\text{eff}} = L_P - L_{\text{FEC}}$ bits.

We assume automatic repeat on request (ARQ), that is the module is capable of managing the retransmission of those MACPDUs that are received with a number of errors greater than the corrective capability of the FEC. In the following, N_R indicates the number of re-transmissions of the same MACPDU allowed by the ARQ mechanism, and RTT is the estimated round trip time of the system, that is the time which is necessary for a re-transmission request plus the time needed for the retransmission itself.

Finally, D_{sys} denotes the system delay due to a processing time of source data packets.

2.4. Transmission at the Physical Layer

Transmission at the physical layer uses impulse radio UWB signals with binary orthogonal pulse position modulation (PPM) in combination with TH coding [18]. The signal transmitted over link i writes:

$$s_i(t) = \sum_n \sqrt{P_i T_f} p_0 \left(t - nT_f - \theta_i^{(n)} - \varepsilon b_i^{\left(\lceil n/N_{S,i} \rceil\right)} \right) \quad (1)$$

where $p_0(t)$ is the energy-normalized pulse waveform (with length T_M), P_i is the average power generated by transmitter of link i, T_f is the average pulse repetition period (identical for all devices), $0 \leq \theta_i^{(n)} < T_f$ indicates the TH shift of the nth pulse for link i, $\varepsilon > T_M$ is the value of the PPM shift, $b_i^{(x)}$ is the xth bit emitted by the source over link i, and $N_{S,i}$ is the number of pulses per bit transmitted over link i. We further assume that signals propagate over a flat radio channel, and that receivers adopt a coherent correlation structure with soft decision detection [18]. Under the above assumptions, the signal at the receiver input for link i writes:

$$r_i(t) = \sqrt{g_{ii}} s_i(t - \tau_{ii}) + \sum_{\substack{j=1 \\ j \neq i}}^{N} \sqrt{g_{ji}} s_j\left(t - \tau_{ji}\right) + n(t) \quad (2)$$

where N is the total number of UWB signals that are perceived at the receiver, g_{mn} and τ_{mn} are the power gain and the transmission delay of the link between transmitter of link m and receiver of link n, and $n(t)$ is additive white Gaussian noise with single-sided power spectral density η_0. The system is asynchronous: receiver of link i has perfect knowledge of delay τ_{ii} only, while all other delays are modeled as independent random variables uniformly distributed over $[0,T_f)$. With reference to the power gain g_{mn}, the following simplified path-loss model is assumed:

$$g_{mn} = \frac{G_0}{d_{mn}^{\rho}} \tag{3}$$

where d_{mn} is the distance in meters between the mth link's transmitter and the nth link's receiver, ρ is the path-loss exponent and G_0 is a constant term such that $g_{mn} = 2.1023 \times 10^{-6}$ when $d_{mn} = 1$ m. As regards the path-loss exponent, we set $\rho = 3.5$ in order to consider a typical indoor scenario with non line of sight (NLOS) propagation [19].

As indicated above, each UWB receiver adopts a coherent correlation structure followed by an ML detector [18]. In the presence of multiple pulses per bit, soft decision detection is performed, that is, the signal formed by $N_{S,k}$ pulses is considered by the receiver as a single multi-pulse signal. The received signal is thus cross-correlated with a correlation mask that is matched with the train of pulses representing one bit. As stated in Section 2.3, each MACPDU header contains a synchronization trailer allowing the receiver to detect its presence, and then to correctly align the correlator structure. Different synchronization procedures for UWB systems have been proposed in the literature [20,21]. In all cases, performance of the synchronization procedure can be eventually expressed in terms of signal-to-interference-plus-noise ratio (SINR) on the single pulse, $\gamma_{0,i}$, which is experienced at the ith link's receiver output. For the proposed system model, $\gamma_{0,i}$ can be derived as follows [18]:

$$\gamma_{0,i} = \frac{g_{ii} P_i T_f}{\eta_0 + \sigma_m^2 \sum_{\substack{j=1 \\ j \neq i}}^{N} g_{ji} P_j} \tag{4}$$

where σ_m^2 is a term depending on the pulse shape waveform $p_0(t)$ and on the PPM shift value ε:

$$\sigma_m^2 = \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{+\infty} p_0(t+\varphi)[p_0(t) - p_0(t-\varepsilon)]\,\mathrm{d}t \right]^2 \mathrm{d}\varphi \tag{5}$$

In the following, we assume that a link can be established provided that $\gamma_{0,i}$ is greater than a specific threshold value $\gamma_{0,\min}$. In other words, we assume that two UWB devices are allowed to transmit information over link i when the devices can acquire synchronization at the physical layer.

Even in the presence of perfect synchronization between transmitter and receiver, transmission over the physical layer is still affected by errors due to the presence of both thermal noise and MUI at the receiver input. We assume to measure system performance at the physical layer based on the standard Gaussian approximation (SGA), which models the cumulative effect of all noises at the receiver as an additive white Gaussian noise with uniform power spectral density over the range of frequencies of interest. The SGA derives from the central limit theorem by which the cumulative effect of a large number of independent random variables tends to have a Gaussian behavior. The SGA is thus valid only asymptotically, and was demonstrated in fact to provide good estimations of BER for PPM-TH-UWB systems when high values of the transmission rate [22] and dense topologies [23] are taken into account. Under the SGA hypothesis, the average bit error rate (BER) for link i writes as follows [18]:

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{\gamma_i}{2}}\right) \tag{6}$$

where $\mathrm{erfc}(\cdot)$ is the complementary error function, and γ_i is the SINR at the output of receiver $i.\gamma i$ can be expressed as follows:

$$\gamma_i = \frac{g_{ii} P_i N_{S,i} T_f}{\eta_0 + \sigma_m^2 \sum_{\substack{j=1 \\ j \neq i}}^{N} g_{ji} P_j} = \frac{g_{ii} P_i}{R_i \left(\eta_0 + \sigma_m^2 \sum_{\substack{j=1 \\ j \neq i}}^{N} g_{ji} P_j \right)} \tag{7}$$

where $R_i = 1/N_{S,i}\,T_f$ is the transmission rate in bits/s at the physical layer.

3. Design of the Resource Manager Module

3.1. Resource Management for Centralized UWB Access Networks

As stated in Section 2, access control in the WLAN scenario is demanded to the AP, which assigns TH codes and controls power levels for all UWB devices within the network. The power allocation procedure which is performed by the AP consists of four steps. First, the AP evaluates the minimum power which is required for all UWB devices in order to achieve synchronization at the physical layer. Secondly, the AP determines for all sources the average packet error rate when all devices are assigned the minimum power. Third, error protection at the MAC is considered for those sources which do not fulfill QoS requirements. Fourthly, power levels are adjusted in order to take into account the increase of transmission rate for introducing error protection.

The proposed procedure is based on the assumption that the AP is always capable to estimate the level of the interference which is suffered by all receivers within the network. This assumption is realistic because of the privileged role of the AP in the centralized network architecture, that is all links either start from or finish into the AP. Accordingly, transmission powers and rates can be allocated with one single run of the procedure, with no need of incremental executions.

Moreover, the procedure requires the AP to have the knowledge of the path gains for all the connections within the network. In the following, we assume that such an information is available to the AP, thanks to the possibility to operate channel estimation with specific signaling bits within the MACPDU *header*.

3.1.1. Step one

As indicated in Subsection 2.4, each MACPDU *header* is provided with a synchronization trailer which allows the receiver to detect its presence, and then to correctly align the correlator structure. In particular, we assume that a link can be established provided that the signal to noise ratio on the single pulse $\gamma_{0,i}$ is greater than a specific threshold value $\gamma_{0,\min}$. With reference to the *uplink*, we assume complete asynchronism among the $N_{\mathrm{up}} \leq N$ transmitters but power control at the AP, that is each transmitted signal is received by the AP with same power P_{RX}. In order to guarantee the constraint imposed by $\gamma_{0,\min}$, we easily derive from Equation (4) that the P_{RX} value *uplink* must verify:

$$P_{RX} \geq \frac{\eta_0}{T_f}\left(\frac{1}{\gamma_{0,\min}} - \frac{\sigma_m^2}{T_f}\left(N_{\mathrm{up}} - 1\right)\right)^{-1} \tag{8}$$

which leads to the following minimum power allocation for the generic transmitter k:

$$P_{k,\min}^{(\mathrm{up})} = \frac{\eta_0}{g_{\mathrm{AP}k} T_f}\left(\frac{1}{\gamma_{0,\min}} - \frac{\sigma_m^2}{T_f}\left(N_{\mathrm{up}} - 1\right)\right)^{-1} \tag{9}$$

where $g_{\mathrm{AP}k}$ is the power gain of the link between transmitter k and the AP.

In the *downlink* case, MUI can be neglected because of the orthogonality of TH codes at each receiver input. In order to guarantee the synchronization with a generic device k, the AP must therefore transmit with the following minimum power:

$$P_{k,\min}^{(\mathrm{down})} = \frac{\eta_0}{g_{k\mathrm{AP}} T_f}\gamma_{0,\min} \tag{10}$$

where $g_{k\mathrm{AP}}$ is the power gain of the link between the AP and receiver k.

3.1.2. Step two

In order to evaluate whether the minimum power allocation evaluated after step one is sufficient or not for guaranteeing the QoS, the AP has to estimate the BER on all active links, when the power levels in Equations (9) and (10) are assigned for the kth *uplink* and the kth *downlink*, respectively. According to Equations (6) and (7), one has:

$$\mathrm{BER}_k = \begin{cases} \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{1}{2}\frac{g_{\mathrm{AP}k} P_{k,\min}^{(\mathrm{up})}}{R_k\left(\eta_0 + \sigma_m^2\left(N_{\mathrm{up}} - 1\right) g_{\mathrm{AP}k} P_{k,\min}^{(\mathrm{up})}\right)}}\right), & \textit{uplink} \\ \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{1}{2}\frac{g_{k\mathrm{AP}} P_{k,\min}^{(\mathrm{down})}}{R_k \eta_0}}\right), & \textit{downlink} \end{cases} \tag{11}$$

where R_k is the transmission rate in bits/s at the physical layer for the link k. In absence of error protection, R_k can be evaluated according to the analytical rule presented in Reference [24], that is:

$$R_k = \frac{L_{\mathrm{MAC}}}{L_P}\mathrm{X}_k\left(\hat{D}\right) \tag{12}$$

where $\mathrm{X}_k(\cdot)$ is defined as follows:

$$\mathrm{X}_i(d) = \begin{cases} \frac{p_i b_i - r_i M_i}{(d - D_{\mathrm{sys}})(p_i - r_i) + b_i - M_i}, & \text{if} \quad p_i > r_i \\ \frac{M}{(d - D_{\mathrm{sys}})}, & \text{if} \quad p_i = r_i \end{cases} \tag{13}$$

and where:

$$\hat{D} = \min\{D_i, \Delta_i(r_i)\} \tag{14}$$

with:

$$\Delta_i(c) = \begin{cases} \left[\frac{p_i - c}{p_i - r_i}(b_i - M_i) + M_i\right]\frac{1}{c} + D_{\text{sys}}, & \text{if} \quad p_i > r_i \\ \frac{M_i}{c} + D_{\text{sys}}, & \text{if} \quad p_i = r_i \end{cases} \tag{15}$$

Given the BER expressions in Equation (11), the AP is capable to compute the average MACPDU packet loss probability PL_k which is experienced on the kth link:

$$\text{PL}_k = 1 - (1 - \text{BER}_k)^{L_P} \tag{16}$$

which leads to the following percentages Φ_k of source packets, which are correctly delivered to the destination within the maximum tolerable end-to-end delay D_k:

$$\Phi_k = 100(1 - \text{PL}_k)^{\lceil M_k/L_P \rceil} \tag{17}$$

3.1.3. Step three

Power allocation of step one is QoS-compliant if $\Phi_k \geq F_k$ is verified for all links, on both *downlink* and *uplink*. If at least one link does not verify $\Phi_k \geq F_k$, power allocation should be re-considered for all UWB devices. In particular, the AP could try to increase all P_k values until QoS is satisfied for all devices. It has been demonstrated, however, that such an increase of power can be minimized if error protection mechanism is introduced at the MAC level [25]. An analytical method for optimizing error protection at the MAC was proposed in Reference [24]. This method is based on the combination of error correction, FEC, with packet re-transmission, ARQ, and provides the minimum amount of additional capacity which is required for guaranteeing the requested QoS when the channel has a given BER. With respect to error correction, the analytical method in Reference [24] is based on the assumption that both the size of the FEC field, L_{FEC}, and the maximum number of ARQ re-transmissions, N_{R}, can change dynamically according to the current status of the channel. In the proposed MAC, the AP applies the method in Reference [24] by considering the values in Equation (11) as a measure of channel BER for all active links within the network. For the kth link, the AP can thus determine the optimal scheme for error protection and therefore the effective rate $R_{\text{b}k} = R_k \Delta_{R_k}$ which is required at the physical layer, where Δ_{R_k} indicates the increase in transmission rate due to error protection. Note that $\Delta_{R_k} > 1$ only if $\Phi_k < F_k$, because error protection is not required for link k when $\Phi_k \geq F_k$.

3.1.4. Step four

According to Equation (7), any increase of transmission rate, which is not compensated by an increase of transmitted power, has the effect of decreasing receiver performance. Such a problem requires the AP to adjust power levels in order to compensate the increase in transmission rate due to error protection.

For each device transmitting in *uplink*, the increase of transmission power ΔP_k which compensate the increase of transmission rate ΔR_k can be computed as follows:

$$\Delta P_k = \frac{\Delta R_k}{1 - (\Delta R_k - 1)\frac{\sigma_m^2}{\eta_0}(N_{\text{up}} - 1)P_{RX,\min}^{(\text{up})}} \tag{18}$$

where:

$$P_{RX,\min}^{(\text{up})} = \frac{\eta_0}{T_f}\left(\frac{1}{\gamma_{0,\min}} - \frac{\sigma_m^2}{T_f}(N_{\text{up}} - 1)\right)^{-1} \tag{19}$$

The expression in Equation (18) was derived under the hypothesis of power control at the AP. In order to verify the above hypothesis, all the N_u connections which are active over the *uplink* should be assigned the same increase of power with respect to the minimum power allocation in Equations (9) and (10). We have thus:

$$P_k^{(\text{up})} = \Delta P \frac{P_{RX,\min}^{(\text{up})}}{g_{\text{AP}k}} \tag{20}$$

where:

$$\Delta P = \max_{k \in [1, N_{\text{up}}]} \{\Delta P_k\} \tag{21}$$

The above problem is not present in *downlink* because of the absence of MUI, and we simply have:

$$P_k^{(\text{down})} = \Delta R_k P_{k,\min}^{(\text{down})} = \Delta R_k \frac{\eta_0}{g_{k\text{AP}} T_f}\gamma_{0,\min} \tag{22}$$

At the end of the presented procedure, the AP has determined transmission powers and rates to be allocated for all the active links within the network. Such an allocation is compliant with regulation constraints provided that allocated power for each device is below the P_{bound} value.

Note that power levels in Equations (20) and (22) should be re-calculated only when the AP observes a change in network configuration, that is, when a new link must be established between a UWB device and the AP, or an existing link has to be removed. If the number of active links does not change, the AP can manage variations in the path gains by simply updating the $g_{\text{AP}k}$ values in Equation (20) and the $g_{k\text{AP}}$ values in Equation (22).

3.2. Resource Management for Distributed UWB Networks

In the single-hop ad hoc scenario, we exploit the feature of UWB-IR to support distributed flexible radio resource management schemes. Specifically, we consider that UWB transmissions use different TH codes and are mutually asynchronous. The TH-code employed by two UWB devices to communicate is selected locally by the two devices themselves and thus is not known to the other ones. Devices themselves are in charge of the full control of UWB access acting 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. We relay on a control of the saturation of the maximum transmission power, P_{bound}, performed independently by each UWB device.

In order to privilege simplicity of the MAC design in a distributed system, we select a plain mechanism of QoS support. In particular, QoS parameters (i.e., maximum tolerable transmission delay, D_i, and maximum tolerable packet loss rate, PL_i, for link i) are translated in only two transmission parameters, namely the SINR to guarantee at the ith link's receiver (target SINR, γ_i^T) and the bit rate to be used by the ith link's transmitter (R_i).

In the following, we will present an analytical method which allows to determine both γ_i^T and R_i for the generic link i of the ad hoc network. Differently from the WLAN case, transmitters cannot predict the effective level of noise at the receiver side; as a consequence, the possibility to adapt the corrective capability as a function of the perceived BER at the receiver is not effective. Thus, in the proposed procedure the optimization of the error protection is restricted to the adaptation of the maximum number of re-transmissions, N_R, which are allowed by the ARQ mechanism. Such an adaptation takes only into account delay requirements and can be thus performed locally at each transmitter. We assume that the MACPDU structure is fixed for all UWB devices, that is, the size of the effective payload L_{eff} for all MACPDUs is fixed at network start-up and is the same for all transmitters.

In order to determine the γ_i^T value, we start by evaluating the maximum MACPDU packet loss rate, PL_i, which can be tolerated at the receiver. As shown in Reference [24], we have:

$$\text{PL}_i(N_R) = \left(1 - \left(\frac{F_i}{100}\right)^{\frac{1}{\lceil M/L_{\text{eff}} \rceil}}\right)^{\frac{1}{1+N_R}} \tag{23}$$

where F_i denotes the minimum percentage of packets that must reach destination within the maximum tolerable end-to-end delay D_i.

Given the $\text{PL}_i(N_R)$ value in Equation (23), we obtain the following expression for the maximum BER which can be tolerated at the output of the receiver for link i:

$$\text{BER}_i(N_R) = (1 - \text{PL}_i(N_R))^{\frac{1}{L_P - (L_{\text{FEC}}/2)}} \tag{24}$$

In order to guarantee the BER in Equation (24), the following γ_i^T value should be achieved at the input of the receiver:

$$\gamma_i^T(N_R) = 2\left(\text{erfc}^{-1}(2\text{BER}_i(N_R))\right)^2 \tag{25}$$

Given the result in Equation (25), each transmitter can easily select the N_R value which minimizes the target SINR at the receiver. Such a value, in fact, is the one which reduces the amount of power to be transmitted over the ith link. Note that the above selection can be performed by simply computing γ_i^T for all the possible values of N_R in the range between 0 (i.e., no ARQ) and the maximum value $\lfloor (D_i - D_{\text{sys}})/\text{RTT} \rfloor$. Once the N_R value is selected, the transmission rate R_i does only depends on the maximum tolerable end-to-end delay D_i which must be guaranteed for the link under examination.

Similar to the WLAN case in Subsection 3.1, R_i can be evaluated as follows:

$$R_i = \frac{L_{\text{MAC}}}{L_{\text{eff}} \text{X}_i(\hat{D})} \tag{26}$$

where $\text{X}_k(\cdot)$ is the function defined in Equation (13).

In order to support QoS in terms of the bit rate and target SINR, we introduce the so-called *maximum extra interference* (MEI) that is the amount of interference that can be tolerated by a link without endangering the negotiated QoS level [12]. 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 this approach is primarily to guarantee that the MEIs of all active links are never negative. In addition, for efficiency reasons, our procedure tends to balance all MEIs within an area, so as to avoid bottleneck regions and regions where high MEIs are available [13]. Note that the link block probability is related to MEI values. Such a 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 Mi, depends on the QoS parameters, the transmission power, and the current interference conditions according to the following expression:

$$\gamma_i^T = \frac{g_{ii}P_i}{R_i\left(\eta_0 + \sigma_m^2 \sum_{\substack{j=1\\ j\neq i}}^{N} P_j g_{ji} + \sigma_m^2 M_i\right)} \tag{27}$$

where γ_i^T and R_i derive from the QoS specifications of link i.

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. Without any loss in generality, we will consider the case where N links are already active with non-negative MEIs, and an $(N+1)$th link has to be activated. In the following, we will present the procedural steps which are performed at the transmitter (TX) and the receiver (RX) of this $(N+1)$th link in order to set up the connection. These steps are also summarized in Figure 2.

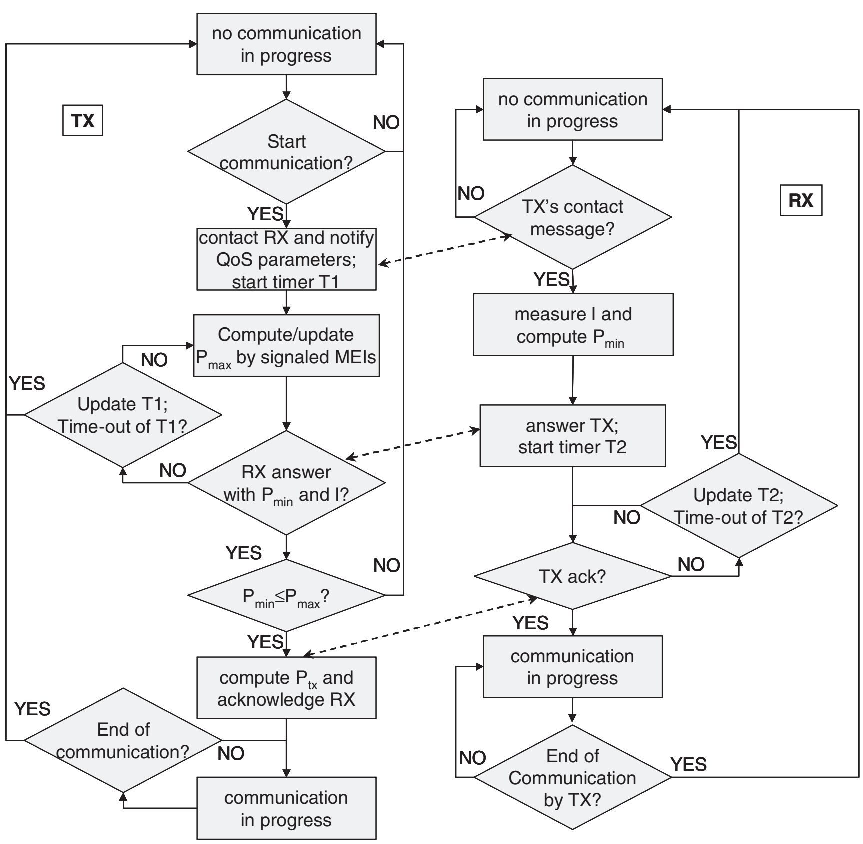


Fig. 2. Flowcharts of the distributed MAC.

A fundamental assumption is that the transmitter, which is going to initiate a communication, acquires the current MEI values of its neighboring receivers (n_RXs in the following). The acquisition of MEIs allows TX to compute the maximum transmission power, which guarantees that n_RXs still maintain their negotiated QoS. The above assumption requires that an explicit inter-link signaling must be implemented among devices for communicating their MEI values. We thus introduce a common broadcast channel where MEI levels are communicated through an *MEI Message*. The broadcast channel could be constituted by a common TH-code shared by all devices. We assume that a device has the capability of listening to a multiplicity of signaling packets transmitted on the same TH-code.

Once the current MEIs of the neighboring devices are acquired, the maximum power allowed to TX is:

$$P_{\max,N+1} = \min\left\{P_{\text{bound}}, \min_{j=1,\ldots,N}\left\{\frac{M_j}{g_{N+1j}}\right\}\right\} \tag{28}$$

where P_{bound} is a system parameter (hence known). As for the estimation of the path gains in Equation (28), TX is not supposed to know the locations of the neighbor receivers. Instead, the path gain g_{N+1j} between the receiver of link j and TX (belonging to the link $N+1$) is derived as the ratio between the transmitted and the received power of the relevant *MEI Message*.

Although in Equation (28) all the N links in the systems are considered for the computation of $P_{\max,N+1}$, only MEIs of the n_RXs neighboring devices are actually acquired. This leads to a consistent value of $P_{\max,N+1}$ since the impact that the transmission could have on a generic device is inversely proportional to the distance of this device from the TX.

Besides the MEI advertisements, the activation of the new link requires a handshake 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 2, the dotted lines between the two flowcharts indicate signaling exchange between the TX and the RX involved in the link activation. The *Contact Message* also contains the desired QoS parameters, and its reception at the RX triggers the measurement of the perceived interference and the computing of the minimum transmission power on the basis of the desired SINR, γ_{N+1}^T, and of the transmission rate, R_{N+1}, according to the following formula:

$$P_{\min,N+1} = \frac{\gamma_{N+1}^T R_{N+1}}{g_{N+1N+1}}\left(\sigma_m^2 I_{N+1} + \eta_0\right) \tag{29}$$

In Equation (29), the term of disturb ($\sigma_m^2 I_{N+1} + \eta_0$) is obtained by measurements while the path gain g_{N+1N+1} of the $(N+1)$th link is estimated by RX on the basis of the transmitted and received power levels of the *Contact Message*.

RX answers to TX by communicating the values of the minimum transmission power and of the measured interference. Then, TX autonomously decides to set-up the link toward RX if the following condition is fulfilled:

$$P_{\min,N+1} \leq P_{\max,N+1} \tag{30}$$

In Equation (30), the minimum power which is required to satisfy QoS requirements is compared with the maximum power computed in Equation (28).

If the access of the $(N+1)$th link can take place, TX acknowledges RX about the access decision. A suitable transmission power level is selected within the range $[P_{\min,N+1}, P_{\max,N+1}]$. The considered criterion for power selection is the maximization of the minimum MEI resulting from the new access [13]. The $P_{\max,N+1}$ value in Equation (28) is in fact limited by the lowest MEI, which thus constitutes a bottleneck for further accesses. The computation of the transmission power is performed by the TX in accordance to the following equation:

$$P_{\text{tx},N+1} = \min\left\{\frac{M_i + I_{N+1} + (\eta_0/\sigma_m^2)}{g_{N+1i} + g_{N+1N+1}/\left(\sigma_m^2 \gamma_{N+1}^T R_{N+1}\right)}\right\}_{i=1,\ldots,N} \tag{31}$$

When the link can be activated, a last signaling exchange takes place through an *Activation Message*, which contains all the transmission parameters as well as the selected TH code.

Finally, in Figure 2 we indicated the adoption of two timers, T1 at TX and T2 at RX. T1 is used by TX while it is waiting for the RX answer to its *Contact Message*; if the answer does not arrive until the time-out of T1, TX argues that the contact attempt failed; the procedure of the link activation is ended coming back to the status of 'no communication in progress.' As regards T2, it is started by RX after its answer to

Table I. DLB and QoS parameters for the three considered classes of traffic.

Parameter	Symbol	Value		
		Multimedia	Voice	Data
DLB parameters				
Peak rate	p	1 Mbits/s	256 kbits/s	5 Mbits/s
Average rate	r	500 kbits/s	128 kbits/s	2 Mbits/s
Token buffer dimension	b	2560 bits	1280 bits	10 240 bits
Maximum packet size	M	512 bits	256 bits	512 bits
QoS parameters				
Maximum tolerable end-to-end delay	D	10 ms	5 ms	150 ms
Minimum percentage of packets that must reach destination within D	F	99%	97.5%	99.9999%

the TX and specifically when it begins waiting for the TX acknowledgment 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.'

4. Simulation Results

This section is devoted to present quantitative results derived by simulations relevant to the two MAC schemes proposed in Section 3.

As for traffic, in both scenarios—WLAN and ad hoc network—we consider three classes of traffic, namely: multimedia, voice, and data exchange. We simulated only homogeneous scenarios, that is scenarios with traffic flows all belonging to the same traffic class. In Table I, the values used for the DLB parameters and for the QoS requirement parameters (see Subsection 2.2) are reported for the three considered traffic of classes.

As for the parameters characterizing the radio access (introduced in Subsection 2.3), we set the length of the MACPDU as well as the system delay and the RTT according to the values reported in Table II.

Table III summarizes the values adopted for the transmission parameters defined in Subsection 2.4.

Table II. MAC parameters.

Parameter	Symbol	Value
Length of the payload in the MACPDU	L_P	400 bit
Length of the header in the MACPD	L_H	120 bit
System delay	D_{sys}	1 ms
Round trip time	RTT	5 ms

Table III. Values adopted for the transmission parameters.

Parameter	Symbol	Value
Maximum power	P_{bound}	0.556 mW
UWB parameter depending on the pulse shape form (see equation (5)) Errore. L'origine riferimento non è stata trovata.)	σ_m^2	1.9230×10^{-10} s
Exponent of distance in the path gain expression (see equation (3)) Errore. L'origine riferimento non è stata trovata.)	ρ	3.5
Path gain at 1 m distance	$G_0/(1\text{ m})^{3.5}$	2.1023×10^{-6}
Spectral density of thermal noise	η_0	−196.0871 dBW/Hz

4.1. Scenario A: UWB Access to a Backbone

Performance of the centralized resource allocation procedure was analyzed under different network scenarios. Each scenario is characterized by N uplink links belonging to the same class of traffic. For each scenario, a set of 20 simulations were performed. On each of these simulations, the devices were randomly placed around the AP in a circular area with a radius of 15 m, having the AP in the center. Performance of the resource allocation procedure was analyzed as follows. For each simulation, the following values are recorded: the maximum transmission power allocated to a device, and the average transmission power. The performance in a given scenario is then characterized by the maximum transmission power over the entire set of simulations (peak power), the average of the maximum transmission power allocated on each simulation (average peak power), and the average transmission power over the entire set of simulations (average power).

Figures 3–5 present the result of the simulation for multimedia, voice, and data traffic, respectively. Here,

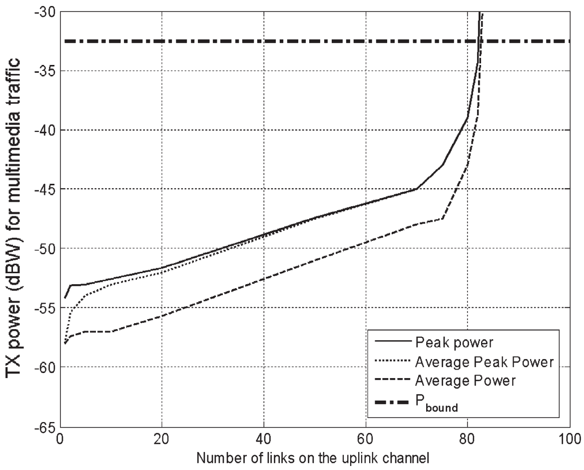


Fig. 3. Peak power (solid line), average peak power (dotted line), and average power (dashed line) as a function of the number of links for the multimedia traffic.

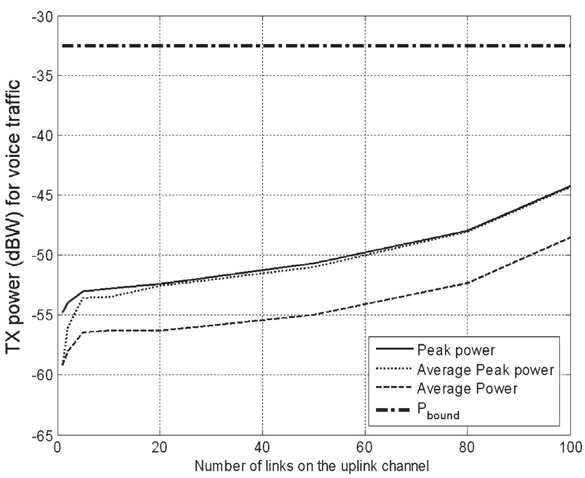


Fig. 4. Peak power (solid line), average peak power (dotted line), and average power (dashed line) as a function of the number of links for the voice traffic.

we observe that in all cases both average and peak powers increase almost exponentially with the number of active connections for small N values. For higher N values, allocated powers increase more than exponentially, and eventually overcomes P_{bound} for both multimedia and data traffic. Note that the curves in Figures 3–5 represent the theoretical transmission power that the AP would allocate without considering the constraint of P_{bound}. The procedure performed by the AP consists in fact in computing the power allocation for already active links plus the new one to activate, and then checking whether all the power levels are within P_{bound}. If at least one device

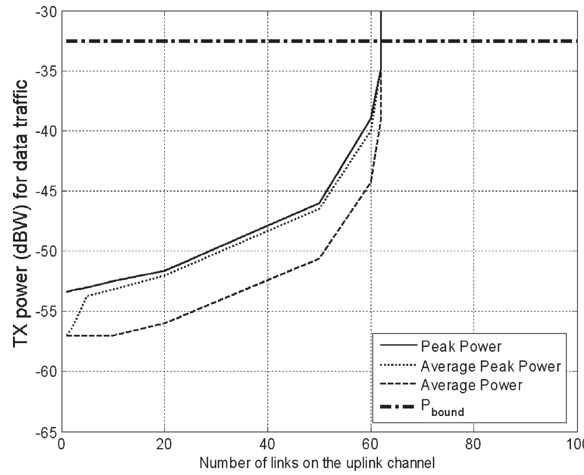


Fig. 5. Peak power (solid line), average peak power (dotted line), and average power (dashed line) as a function of the number of links for the data traffic.

requires more than P_{bound}, the AP has to reject the new link. The number of links corresponding to the cross point between the transmission power and P_{bound} represents the uplink capacity of the system, that is the maximum number $N_{\max}$ of connections that can be admitted to transmission for a given class of traffic. In particular, we can verify that $N_{\max} = 83$ for multimedia traffic, $N_{\max} = 62$ for data traffic, and $N_{\max} > 100$ for voice traffic. Note that when $N < N_{\max}$, QoS is guaranteed for all active connections.

4.2. Scenario B: Ad Hoc UWB Communications

Similarly to the WLAN case in Subsection 4.2, different simulations have been performed for the adhoc case by generating different network topologies. In the ad hoc case, UWB devices have been randomly placed within an area of 15×30 m. We recall that in the ad hoc case the payload of the MACPDU (having length $L_P = 400$ bit—see Table II) is organized in the two fixed length fields of effective payload ($L_{\text{eff}} = 256$ bit) and FEC ($L_{\text{FEC}} = 144$ bit).

Table IV. QoS parameters for the ad hoc scenario.

Class of traffic	QoS parameter	Value
Multimedia traffic	Rate	1.15 Mbit/s
	Target SINR	12.82 dB
Voice traffic	Rate	400 kbit/s
	Target SINR	14.2 dB
Data traffic	Rate	4.7 Mbit/s
	Target SINR	7.76 dB

In the ad hoc scenario, the QoS parameters have been converted in desired values for bit rate and SINR according to the values in Table IV.

In the following, we compare the results achieved by means of two different strategies:

1. The proposed scheme of admission control and resource allocation based on the admission rule in Equation (30) and on the adoption of MEIs.
2. A theoretical optimum strategy which is supposed to have the capability of re-allocating all power levels at each new entrance. With this strategy, new links are admitted when there exist suitable power allocations which fulfill the QoS, and no margins are introduced. As a consequence, allocated powers are the minimum ones [13].

Figures 6–8 present the results relevant to the throughput for the three classes of traffic—multimedia, voice, and data—respectively. Specifically, the dotted line corresponds to the maximum throughput that can be theoretically achieved by means of an optimum strategy while the solid line corresponds to the throughput actually achieved with the proposed resource allocation scheme. The achieved throughput is lower than the theoretical maximum one due to the adoption of a sub-optimal access strategy. Such an effect is due to the trade-off between system performance and simplicity of the proposed access scheme, which operates in a distributed fashion based on the partial information locally gathered. An additional loss in performance is due to the necessity to protect the QoS which was negotiated with already active links. As the offered load increases, the loss in performance, measured as the of network throughput, increases. This behavior is highlighted in Figure 9, which shows the ratio between theoretical and measured throughput for the three classes of traffic under examination. In Figure 9, we observe that there are no significant differences among classes of traffic, and that the reduction of throughput is quite contained (achieved throughput equal to about 75% of theoretical throughput in the worst case of $N = 100$ links).

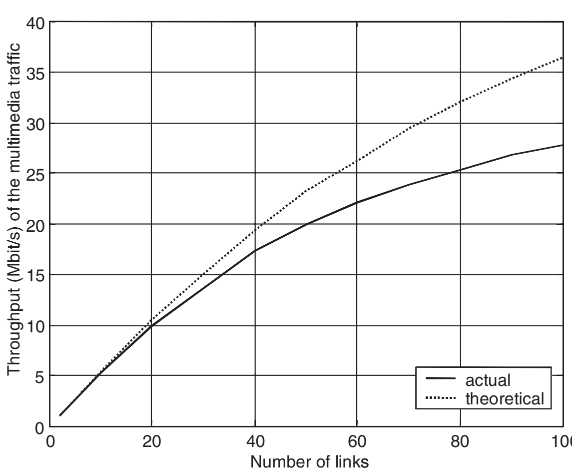


Fig. 6. Theoretical throughput and actually achieved throughput as a function of the number of links for the multimedia traffic.

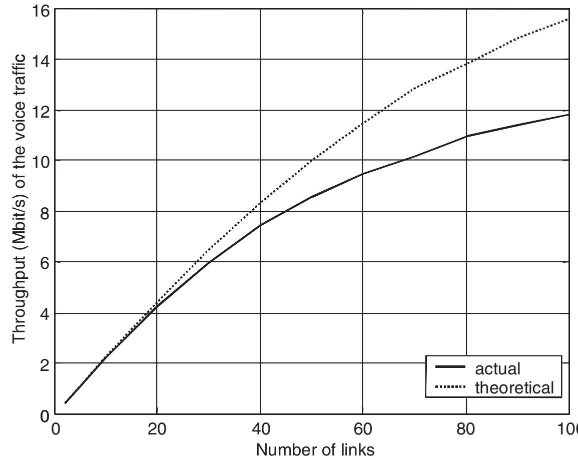


Fig. 7. Theoretical throughput and actually achieved throughput as a function of the number of links for the voice traffic.

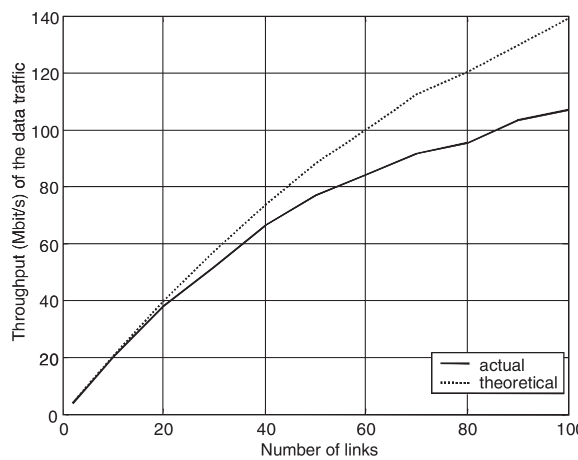


Fig. 8. Theoretical throughput and actually achieved throughput as a function of the number of links for the data traffic.

Figures 10–12 represent transmission power levels as a function of the number of links for multimedia, voice, and data traffic, respectively. In these figures, power levels obtained with the proposed resource allocation strategy are compared with both theoretical values, and the upper bound given by P_{bound}. We

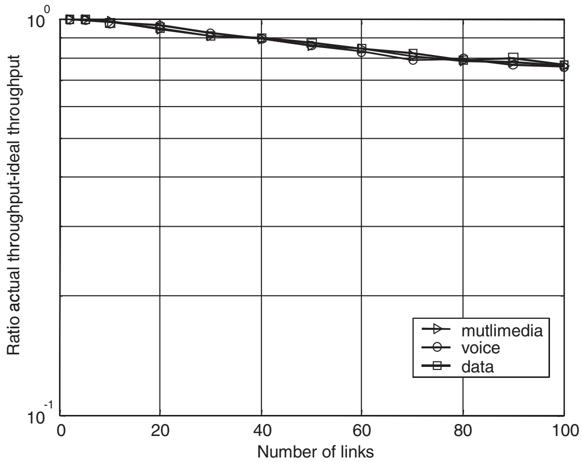


Fig. 9. Ratio between theoretical throughput and actually achieved throughput as a function of the number of links for the three classes of traffic.

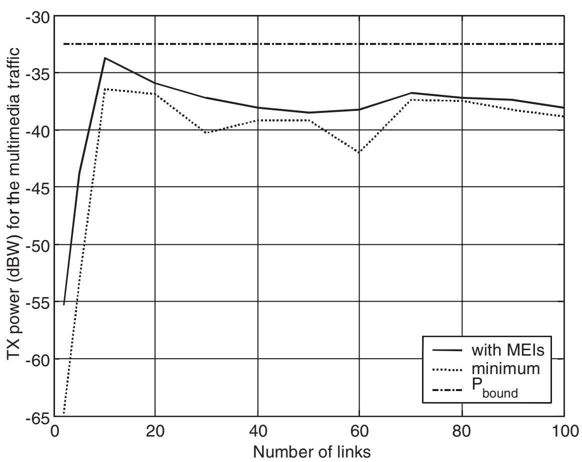


Fig. 10. Minimum transmission power and transmission power achieved with MEIs as a function of the number of links for the multimedia traffic.

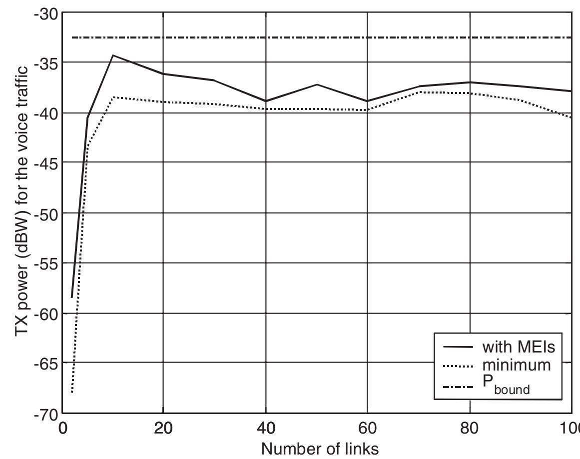


Fig. 11. Minimum transmission power and transmission power achieved with MEIs as a function of the number of links for the voice traffic.

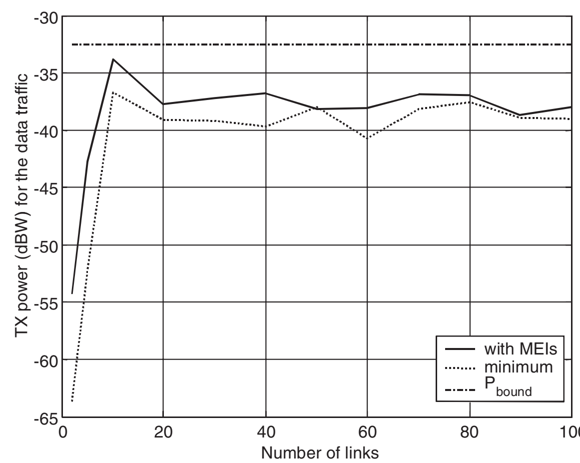


Fig. 12. Minimum transmission power and transmission power achieved with MEIs as a function of the number of links for the data traffic.

observe that transmission power levels resulting from the proposed strategy are always below P_{bound} thanks to the local check of the condition in Equation (30), during the admission control. As a consequence, curves of the transmission powers adapt to the value of P_{bound}.

The adoption of margins (specifically, the maintenance of a positive tolerable extra interference, MEI, still satisfying the required QoS) implies that allocated powers are always higher than optimal values resulting from the application of the theoretical (optimal) allocation. Nevertheless, we can verify that such a gap is in the order of few dB (generally, about 2–3 dB). The same loss in performance, however, guarantees the possibility to handle new accesses with a smaller effort in terms of both admission control and resource allocation.

5. Conclusions

In this paper, we presented the major results of our study on a resource manager model for an UWB network in the context of two application scenarios: (i) an UWB WLAN access network to a backbone and (ii) an UWB ad hoc network with peer-to-peer links. For both the above scenarios, we propose a resource management scheme which is capable of supporting flows with different QoS requirements by adapting the selection of physical parameters (rate and power) to the specific traffic requirements, expressed in terms of network layer parameters (i.e., maximum tolerable transmission delay and maximum tolerable packet loss).

The proposed power allocation procedure is centralized in the AP in the WLAN case and distributed in the ad hoc case. Moreover, such a procedure is compliant with regulation constraints on the maximum allowed radiated power. Two important features of our design are thus the capability of supporting differentiated QoS at the network level, and the coexistence with other systems in the same unlicensed bandwidth. In addition, the proposed scheme for resource allocation includes the following innovative aspects: (i) it takes into account UWB-specific needs for synchronization trailers on each transmitted packet; (ii) it considers both centralized and distributed networks; (iii) it includes error protection functionalities (FEC and ARQ) for the optimization of transmission efficiency at the MAC layer; (iv) different from the current approaches, it is based on QoS parameters defined at network level rather than at the physical layer.

Performance results for the two scenarios under examination were derived by simulating the proposed procedure in networks with homogeneous traffic flows. Three different classes of traffic were taken into account: multimedia, voice, and data traffic, respectively. Results of simulations indicate that the maximum achievable system capacity mainly depends on the maximum allowed power for the single device (P_{bound}). Specifically, in the WLAN scenario we identified the cross-point between the curve of the allocated transmission power and P_{bound} as a measure of the maximum uplink capacity of the system. As the P_{bound} value increases system capacity increases, since an higher number of devices are allowed to access the network. A similar conclusion was derived for the ad hoc scenario. Here, we observe that as P_{bound} increases, allocated powers are steady around higher values thus leading to larger MEIs; these additional levels of tolerable interference, in turn, will allow a larger number of admitted connections corresponding to an increased system capacity.

In all the simulated scenarios, the proposed resource manager module was demonstrated to guarantee good performance for a number of devices which is compatible with typical WPAN and WLAN scenarios. In addition, simulation results indicate that the behavior of the proposed scheme is strongly dependent upon the class of traffic in the WLAN scenario, while it is slightly affected by changes in traffic characteristics in the ad hoc case.

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Authors' Biographies

Guerino Giancola received the 'Laurea' degree (magna cum laude) in Telecommunications Engineering, and the Ph.D. in Information and Communication Engineering from the University of Rome La Sapienza, in 2002 and 2005, respectively. He is currently a research affiliate at the INFOCOM Department at the University of Rome La Sapienza. He is now involved in the European projects 'UCAN—Ultra wideband Concepts for Ad hoc Networks,' and 'PULSERS—Pervasive Ultra wideband Low Spectral Energy Radio Systems.' His research interests include the analysis and modeling of multi-user interference in impulse radio ultra wide band systems, multi-carrier transmission techniques, and medium access control protocols for wireless networks. Guerino Giancola recently co-authored with Professor Maria-Gabriella Di Benedetto for a book on ultra wide band from radio to the network, titled '*Understanding Ultra Wide Band Radio Fundamentals*' and published by Prentice Hall in June 2004.

Cristina Martello received her Laurea degree in Electronic Engineering (magna cum laude) in July 2000 from Università di Roma 'La Sapienza.' She earned her Ph.D. in Information and Communications Engineering in February 2004 (Università di Roma 'La Sapienza'). Currently, she is involved in the FIRB PRIMO project (reconfigurable platforms for interoperability and mobility) on a new wireless access technology for 4G. During 2001–2003, she worked in the IST European Whyless.com project on an open mobile access network based on the ultra wide band radio technology. She collaborated with Co.Ri.Tel. (a research consortium on Telecommunications sponsored by Ericcson) as a fellowship holder in 2000/2001 for the project SWAP on the feasibility of a re-configurable software module for the dynamic radio resource control in the 3G of mobile wireless systems, and in 2002 for the project PRESTO. Her main research interests are regarding the developing of flexible and distributed radio resource control techniques for 'ad hoc like' networking paradigms.

Francesca Cuomo received her 'Laurea' degree in Electrical and Electronic Engineering in 1993, magna cum laude, from the University of Rome 'La Sapienza,' Italy. She earned her Ph.D. in Information and Communications Engineering in 1998, also from the University of Rome 'La Sapienza.' Since 1996 she is an assistant professor at the INFOCOM Department of this university. She teaches at the University of Rome 'La Sapienza' courses in Telecommunication Networks. Her main research interests focus on: modeling and control of broadband integrated networks, signaling and intelligent networks, architectures and protocol for fixed and mobile wireless networks, mobile and personal communications, quality of service guarantees, and real-time service support in the Internet and in the radio access, re-configurable radio systems and wireless ad hoc and sensor networks. She participated in: (i) the European ACTS INSIGNIA project dedicated to the definition of an Integrated IN and B-ISDN network; (ii) IST FP5 WHYLESS.COM project focusing on adoption of the ultra wide band radio technology for the definition of an open mobile access network; (iii) RAMON project, funded by the Italian Public Education Ministry, focused on the definition of a re-configurable access module for mobile computing applications. She is now participating in the European IST FP6 EPERSPACE Integrated Project focusing on the support of personalized audio/video services at home and everywhere. She is also involved in the FIRB project VIRTUAL IMMERSIVE COMMUNICATIONS (VICOM), funded by the Italian Public Education Ministry, where she is responsible for the research activities on the BAN and PAN networks. Dr Cuomo is in the editorial board of the Elsevier Computer Networks journal and has served on technical program committees and as reviewer in several international conferences and journals including *ACM Wireless Mobile Internet Workshop*, *IEEE ICC and GLOBECOM*, *IEEE Transactions on Wireless Communications*, and *IEEE Journal on Selected Areas on Communications*.

Maria-Gabriella Di Benedetto obtained her Ph.D. in Telecommunications in 1987 from the University of Rome La Sapienza, Italy. In 1991, she joined the Faculty of Engineering of University of Rome La Sapienza, where she is currently a full professor of Telecommunications at the Infocom Department. She has held visiting positions at the Massachusetts Institute of Technology, the University of California, Berkeley, and the University of Paris XI, France. In 1994, she received the Mac Kay Professorship award from the University of California, Berkeley. Her research interests include speech analysis and synthesis, and digital communication systems. From 1995 to 2000, she directed four European projects for the design of UMTS. Since 2000 she has been active in fostering the development of an ultra wide band (UWB) radio communications in Europe. Within the 5th framework, she directs for the Infocom Department two European projects (whyless.com and UCAN) aimed at the design and implementation of UWB ad hoc networks. Within the 6th EU Framework her 'Networking with UWB' research group participates in the PULSERS Integrated Project which will integrate UWB research and development in Europe for the next years, and in the LIAISON Integrated Project as regards the application of UWB to location-based services. She currently also participates in the HYCON network of excellence. Dr Di Benedetto is the co-editor for the *IEEE JSAC* Special Issue on UWB Radio in multi-access wireless communications, December 2002) and for the *Journal of Communications and Networks* special issue on ultra-wideband communications (December 2003). Maria-Gabriella Di Benedetto recently co-authored with Dr Guerino Giancola for a book on ultra wide band from radio to the network, titled '*Understanding Ultra Wide Band Radio Fundamentals*' and published by Prentice Hall in May 2004.