Radio Resource Sharing for Ad Hoc Networking With UWB

Francesca Cuomo, Cristina Martello, Andrea Baiocchi, *Member, IEEE*, and Fabrizio Capriotti

***Abstract*—Ultra-wideband (UWB) radio is becoming a promising field for new generation's digital communication systems. This technique, based mainly on the impulse radio paradigm, offers great flexibility and shows enormous potential in view of a future broadband wireless access. In this paper, we aim at presenting the main principles to design a multiaccess scheme based on UWB. The potential of UWB is exploited within a distributed ad hoc wireless system, where we describe the principles for the definition of a medium-access control (MAC) for mobile computing applications and we analyze the main performance results derived from simulations. A general framework for radio resource sharing is outlined for classes of traffic requiring both elastic-dynamic and guaranteed-reserved bandwidth. Then, we discuss the issue of supporting the proposed radio resource sharing scheme by means of a distributed MAC protocol.**

***Index Terms*—Ad hoc networks, medium access control (MAC) protocols, power control, radio resource sharing.**

I. Introduction

Ultra-wideband (UWB) technology is an emerging paradigm both in the field of radar applications and digital communications. UWB systems are mostly based on impulse radio (IR) technology, which has recently reached an appreciable degree of development so as to be able to support high data rates with low power consumption and low complexity in terms of transmission/reception operations [1], [2]. By combining a transmission over a wide radio spectrum band with lower power and pulsed data, UWB causes less interference than conventional narrowband radio and offers potential to hit the market in unlicensed bandwidths.

Today it is clear that UWB is a promising field to create small, high bit rate transceivers that could be used for a wide set of applications, from wireless local area networks (LANs) to ad hoc networks, from IP mobile-computing to multimedia-centric applications. In this context, a consistent amount of literature has been dedicated to the analysis of UWB transmission/reception principles and of its relevant performance [3]–[7]. Besides these key issues, the challenge in using UWB technology in wireless communication systems lies in the development of multiple access techniques and radio resource sharing schemes.

The aim of this paper is to outline a framework for the adoption of UWB in a wireless ad hoc system, where the main potential of this technique can be exploited. We concentrate on the definition of radio resource sharing principles that could be applied to support IP pure "best effort" traffic (e-mail, WEB browsing, file transfer, etc.) or data services with specific quality-of-service (QoS) requirements. The paper is organized as follows. Section II describes the reference architectural scenario. Section III introduces the model considered for the definition of the radio resource sharing scheme. The joint power and rate assignment paradigm for radio resource sharing is given in Section IV, whereas Section V presents simple, suboptimal algorithms and procedures that apply the resource sharing principles identified in Section IV. In Section VI, we illustrate performance results while supporting elastic-dynamic bandwidth class of traffic. Finally, Section VII concludes the paper and discusses lines for future work.

II. Reference Architectural Scenario

A. UWB Multiple Access

IR transmits extremely short pulses (0.1 to 1.5 ns) giving rise to wide spectral occupation in the frequency domain (bandwidth from near dc to a few gigahertz). The typical pulse, named "monocycle," is the building block for data transfer that is commonly obtained by using the pulse position modulation (PPM). In a binary context, a logical "zero" is transmitted by one monocycle centered at time $t_{0,}$ whereas a logical "one" is transmitted by the monocycle shifted by δ seconds (centered at $t_0+\delta$). In order to allow several users to share the same radio resource simultaneously, the time-hopping (TH) code is added [2]. Below, we consider the use of pseudorandom TH codes.

Fig. 1 reports an example of transmission by two users, each characterized by a TH code word. Whereas the first user uses the TH code $\{1,3,0,2,\ldots\}$, the second uses the word $\{3,2,5,4,\ldots\}$. Each code word element corresponds to one of the possible N_h time shifts in the T_f period, that is, the pulse repetition time (typically a hundred or a thousand times the monocycle width). Each T_f is divided into N_h time bins of period T_c. N_s consecutive pulses transmitted at the pulse repetition time are dedicated to the transmission of 1-b (symbol). The bit rate associated to one code word is then $R=1/(N_s \cdot T_f)$. The period of a code word is denoted as N_p and generally $N_p > N_s$.

In Fig. 1, we assumed the two users were synchronous both with the T_f and with each other: whereas the first assumption can be easily satisfied, the second one is more unrealistic. However, though the users are not synchronized with each other and the TH codes are chosen in a pseudorandom way, catastrophic

Manuscript received December 14, 2001; revised June 24, 2002. This work was supported in part by the European IST Programme within the framework of the WHYLESS.COM project IST-2000-25197.

The authors are with the University of Rome "La Sapienza," Infocom Department, 00184 Rome, Italy (e-mail: cuomo@infocom.uniroma1.it; martello@infocom.uniroma1.it; baiocchi@infocom.uniroma1.it; fcapriotti@libero.it)

Digital Object Identifier 10.1109/JSAC.2002.805309

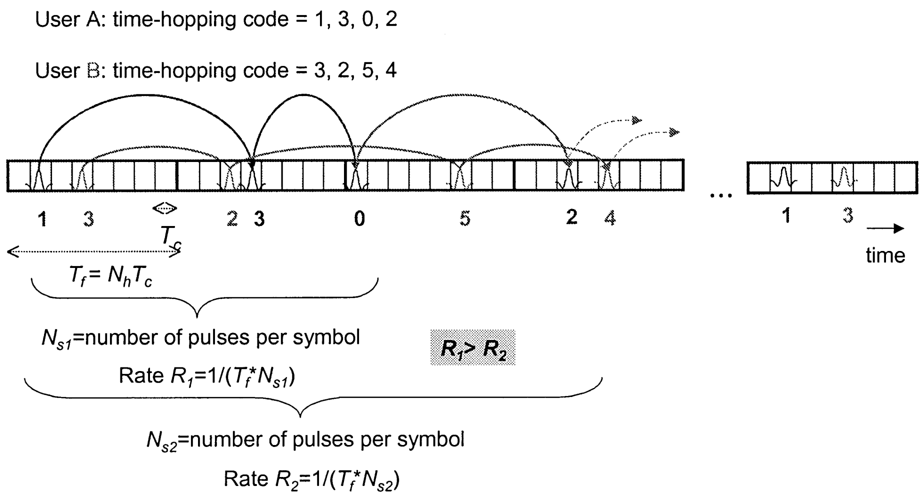


Fig. 1. UWB multiple access scheme.

collisions are not very likely to occur while just mutual interference arises and can be compensated by transmitting several monocycles for the same bit [2].

B. Ad Hoc Concept Based on UWB

Recent research efforts have been dedicated to ad hoc networks. Until recent years, these radio networks were considered mainly for military applications, as their distributed architecture offered a fundamental, operative advantage. As regards the commercial sector, ad hoc networks are expected to enhance the networking world, by providing access where no infrastructure is available, or by quickly and cheaply extending existing coverage areas [8], [9].

Several technologies are emerging for ad hoc networking [10], [11]. UWB appears competitive in this field and could be exploited as a promising and flexible transmission technology that brings some specifically suitable advantages, thanks to a few UWB features matching exactly the requirements needed to design an ad hoc network.

First of all, UWB can provide high data rates in indoor, dense multipath environments [12], [13], as is expected of the technologies of future generation radio systems. An additional feature of UWB is its flexibility in the reconfiguration process of data rate and power, due to the availability of a number of transmission parameters, which can be tuned to better match the requirements of a data flow. As far as radio-terminal equipment is concerned, this is generally cheaper than the equipment for traditional technologies, as the structure of the receiver is extremely simple due also to the absence of a carrier.

Moreover, IR calls for the synchronization of transmitting-receiving pairs (communicating through a *link*), but works efficiently even though different links in the network are asynchronous; this feature is particularly suitable in an ad hoc network, where the absence of an infrastructure implies a highly complex synchronization of all the network terminals.

In our work, we aim at defining a multiple access control protocol that can be applied in different architectural scenarios (a wireless, local area access or a pure ad hoc network) to support mobile computing applications [14].

C. Reference Architectural Model

The reference architectural model is reported in Fig. 2. The model includes radio terminals (RT) and access points (AP). We selected a distributed mechanism to handle radio resource sharing that could be used both in an infrastructure network, (where APs interconnect the RTs to the fixed network) and in a pure ad hoc network, supporting peer-to-peer communications between RTs. Fig. 2 highlights the presence of an medium-access control (MAC) domain, where access to the radio resource is controlled. Every MAC domain refers to the area where transmission of an RT (or AP) has an impact on the transmission/reception of other RTs (or APs). As a consequence, the multiple access control function will operate in every MAC domain, in order to share the capacity among the RTs/APs belonging to that domain. Mutual interference among competing RTs/APs plays a fundamental role in the control of access to the radio part and power control is seen as a mechanism to be used jointly within MAC procedures in order to increase use of the radio trunk [15], [16].

The radio resource sharing mechanism we are going to propose jointly manages both powers and data-rates in order to support two different classes of traffic. A first class of traffic named reserved bandwidth (RB), requires a QoS expressed as a given amount of bandwidth negotiated at the beginning of a session; this class typically accommodates time-constrained data flows. A second class of traffic named dynamic bandwidth (DB), can elastically adapt the bandwidth to the varying system conditions; this class can be used to map the classic "best effort" service of the IP networks. The name DB refers to the fact that the MAC can dynamically reconfigure the amount of bandwidth into a time scale of the packet duration. This reconfiguration is needed in order to counteract changes in interference conditions and to use the radio resource efficiently.

III. Radio Resource Sharing Model

UWB transmission was analyzed in [1] and [2] according to the standard, additive white Gaussian noise (AWGN) hypothesis, with independent users exploiting pseudorandom codes.

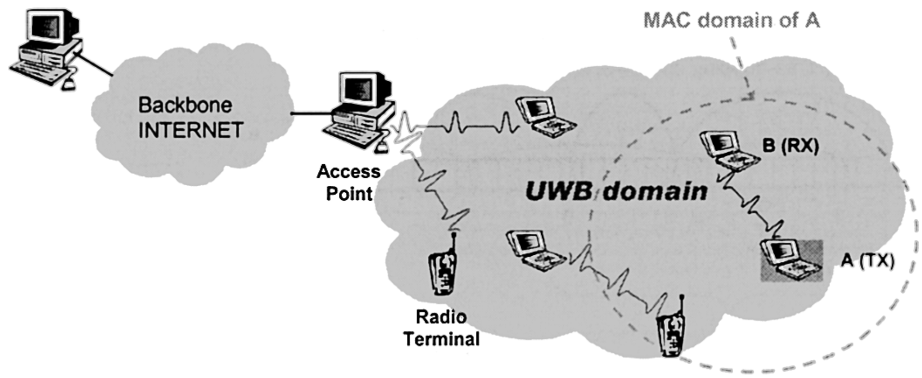


Fig. 2. Reference architectural scenario and MAC domains.

The receiver is assumed to be synchronized exactly on the intended pulse stream. The bit error probability is evaluated by assuming that the background, noise and UWB self interference are both gaussian and are, therefore, a function of the signal-to-noise ratio (SNR).

We consider N pairs of communicating UWB terminals, each pair consisting of one transmitter and one receiver and using one pseudorandom code. In the following, we refer only to RTs even if the model applies also to communications involving also APs. Then, N links are active and the SNR at the ith link's receiver is

$$\mathrm{SNR}_i = \frac{P_i g_{ii}}{R_i\left(\eta_i + T_f \sigma^2 \sum_{k=1, k\neq i}^{N} P_k g_{ki}\right)} \quad i = 1, \ldots, N \tag{1}$$

where we use the following definitions:

- R_i binary bit rate of the ith link;
- P_i average power emitted by the ith link's transmitter;
- g_{ij} path gain from the ith link's transmitter to the jth link's receiver;
- η_i background noise energy plus interference from other non-UWB systems;
- σ^2 an adimensional parameter depending on the shape of the monocycle.

Typical values of the above parameters are as follows [2] : the pulse duration is 0.75 ns and $T_f = 100$ ns; $\sigma^2 = 1.9966\ 10^{-3}$; $\eta = 2.568\ 10^{-21}\ \mathrm{V}^2\mathrm{s}$.

Equation (1) is structurally the same as the one found for asynchronous wideband code-division multiple access (WCDMA). Apart from the value of key parameters (e.g., the mutual interference "weight" σ^2), the major points that are specific to IR UWB are those showing how power and rate can be adjusted.

The rate is $R = 1/(N_s N_h T_c)$, so that it can be modified by changing either the basic chip time T_c (that appears to be quite a technological challenge), or the number N_h of chip times per pulse repetition frame, or the number N_s of pulses corresponding to an information bit. The latter is also the easiest way: it is similar to the WCDMA variable spreading factor, but differs mainly in its fine adjustment, which, in the case of WCDMA, is geometric. Furthermore, as opposed to WCDMA, to adjust N_s does not imply a change in code, since it can be varied by keeping the code length N_p constant, instead simply the number of pulses to be integrated at the receiver changes.

As regards power, this is $P = E_W/(N_h T_c)$, where E_W is the pulse energy. Hence, the power can be modified by changing either the pulse energy E_W, or N_h, or T_c; these latter two are specific in the case of UWB IR. Adjusting N_h is an extremely simple way of adapting the power level, even though it translates into quantized variations because N_h is an integer. In the remainder of this paper, we deal with R and P as though they were continuous variables. This is justified by the typical values of N_h and N_s that imply a negligible quantization effect on power and rate values.

Moreover, in our model we assume that path gains remain fixed; path gains do, in fact, fluctuate due to changing multipath patterns and ultimately to terminal mobility. It is a customary assumption to deal with path gains as constants, which is justified when RT mobility is significant on a time-scale which is at least one size larger than the time-scale for the MAC layer connection adaptation (e.g., the time needed for power and rate assignment, channel measurement, signaling). This is indeed a reasonable assumption in a mobile computing context. A similar modeling to the one assumed here is typical of most works dealing with ad hoc network algorithms (e.g., routing) [17] or power control schemes [18].

IV. Joint Power and Rate Assignment as an Optimization Problem

A basic requirement of the physical layer is to offer bit transmission with an error probability no greater than a given threshold value. That in turn means that the SNR of the ith link must not be maintained below a specified threshold γ_i. Moreover, an upper constraint is enforced on the average value of the transmission power level; this value is referred to as $P_{\max}$. Therefore, from (1), we infer that the power levels and bit rates should meet the following constraints:

$$\begin{cases} P_i g_{ii} - R_i \gamma_i T_f \sigma^2 \sum_{k=1, k\neq i}^{N} P_k g_{ki} \geq \eta_i R_i \gamma_i, & i = 1, \ldots, N \\ 0 < P_i \leq P_{\max}, & R_i > 0. \end{cases} \tag{2}$$

It is natural to pose the power and rate assignment as an optimization problem, and to aim at optimizing some throughput, delay or energy consumption metric under the constraints in (2)

[18]–[20]. The assignment problem splits into two subproblems, depending on the required service guarantees.

In the case of RB flows, the target value of R_i comes as a requirement from the network layer; hence, the point is to check whether feasible power levels can be set in all transmitters, so that the required bit rates are supported. That in turn is equivalent to the problem of the existence of a solution for the inequalities system (2) with a given set of values for bit rates. In addition, the minimal power values are searched for.

The RB traffic problem can be specifically stated as follows as shown in (3), at the bottom of this page, where $\mathbf{r}$ and $\mathbf{p}$ are the N-dimensional vectors of rates and powers, respectively.

$$\text{given } \mathbf{r} > \mathbf{0} \text{ find the minimum } \mathbf{p} \text{ such that } \begin{cases} P_i g_{ii} - R_i \gamma_i T_f \sigma^2 \sum\limits_{k=1, k\neq i}^{N} P_k g_{ki} \geq \eta_i R_i \gamma_i & i = 1, \dots, N \\ 0 < P_i \leq P_{\max} \end{cases} \quad (3)$$

The first N inequalities can be compactly stated in matrix form as $\mathbf{pM} \geq \mathbf{h}$, where $\mathbf{M} = \mathbf{D} - \mathbf{B}$, $\mathbf{D}$ is a diagonal matrix whose ith diagonal element is $g_{ii} N_{s,i}/(\gamma_i \sigma^2)$, $\mathbf{B}$ is a nonnegative matrix with nil diagonal elements and off-diagonal elements equal to g_{ij} and $\mathbf{h}$ is an N-dimensional vector with elements equal to $\eta_i / T_f \sigma^2$. A positive vector $\mathbf{p}$, satisfying the first N inequalities of (3), exists if the matrix $\mathbf{M}$ is such that the spectral radius of $\mathbf{BD}^{-1}$ is less than one. Remember that the spectral radius of a matrix is the maximum of the modulus of its eigenvalues. A sufficient condition for this and for $\mathbf{M}^{-1}$ to exist and to be a nonnegative matrix, is that the matrix $\mathbf{M}$ is strictly (or irreducibly) dominant diagonally. In that case, the power assignment $\mathbf{p}^* = \mathbf{hM}^{-1}$ is Pareto optimal, in the sense that any other power assignment $\mathbf{p}$ satisfying (3) is such that $\mathbf{p} \geq \mathbf{p}^*$. This power assignment is optimal both from the point of view of energy consumption and because—according to the hypothesis of the reconfigurability of powers—it minimizes the blocking probability of new links (i.e., the probability of the event that a new link request is offered and cannot be assigned a feasible power level according to (2), given a set of already established links).

In the case of DB traffic, a strict requirement on the bit rate does not exist; as a consequence, it is clear from the form of (2) that a feasible solution for power levels always exists, provided that the bit rates are sufficiently small. The DB traffic optimization problem for joint power and rate assignment is defined in this work by the following target function representing the overall system net throughput:

$$H(\mathbf{r}, \mathbf{p}) = \sum_{i=1}^{N} R_i(\mathbf{p}). \quad (4)$$

Due to the constraints (2), it can be verified that for any fixed $\mathbf{p}$, we have $H(\mathbf{r}, \mathbf{p}) \leq H(\mathbf{p})$ for all feasible $\mathbf{r}$ with

$$H(\mathbf{p}) = \sum_{i=1}^{N} \frac{1}{\gamma_i} \frac{P_i g_{ii}}{\eta_i + T_f \sigma^2 \sum\limits_{k=1, k\neq i}^{N} P_k g_{ki}}, \quad 0 \leq P_i \leq P_{\max}. \quad (5)$$

Moreover, we have $H(\mathbf{r}, \mathbf{p}) = H(\mathbf{p})$ when $\mathbf{r}$ coincides with the set of the maximum rates satisfying (2). Hence, the optimization (i.e., maximization) of $H(\mathbf{r}, \mathbf{p})$ agrees with that of $H(\mathbf{p})$ in the hypercube $[0, P_{\max}]^N$. The main result for DB traffic is that a dyadic form turns out to be the optimum solution, i.e., either the new link is shut off, or it is admitted and then transmission is performed at peak power. In other words, all active DB traffic links have to use peak power to optimize the overall throughput according to (5). In fact, $H(\mathbf{p})$ can be demonstrated to be convex with respect to each variable P_i in the hypercube $[0, P_{\max}]^N$. Thus, we can write

$$\begin{aligned} H(\mathbf{p}) &= H(P_1, P_2, \dots, P_N) \\ &\leq \max\{H(0, P_2, \dots, P_N), H(P_{\max}, P_2, \dots, P_N)\} \\ &\leq \max_{\varepsilon \in \{0,1\}^N} \{H(\varepsilon_1 P_{\max}, \varepsilon_2 P_{\max}, \dots, \varepsilon_N P_{\max})\} \end{aligned} \quad (6)$$

where the last max operator is carried over the entire permutation of N binary values belonging to $\{0, 1\}$. According to (6), the maximum of $H(\mathbf{p})$ is achieved in one of the vertices of the hypercube $[0, P_{\max}]^N$. This corresponds to the extreme choice of either zero or maximum power level transmission of the N pairs of RTs.

We shall show that this dyadic optimum solution entails an essential unfairness in resource sharing, which can be mitigated by a possible change in radio channel path gains (e.g., because of mobility), if mobility is on a smaller time scale than connection/session lifetime. However, there is a basic conflict between system efficiency [optimization of (4)] and fairness.

In Section V, we present a practically feasible, distributed, (sub)optimal solution of the optimization problem mentioned in this section for RB traffic (power minimization) and for DB traffic (throughput maximization). Furthermore, we discuss the fairness issue for DB traffic.

V. A Protocol for Radio Resource Sharing

This section exploits the models defined in Sections III and IV in the context outlined in Section II, i.e., UWB ad hoc networking. Section V-A outlines an MAC protocol for the RB class with the objective of maintaining QoS requirements by simple, distributed actions of RTs. In brief, since the implementation of the minimum power solution would require a complete reconfiguration of powers to adapt to every network change due to new accesses or releases, a different, suboptimal, solution is proposed, which requires the acquisition of a margin with respect to the minimum power, and which aims at avoiding reconfigurations, in order to be easier implemented in the distributed environment under consideration. Section V-B approaches the issue of defining a practical solution for the optimization problem for the DB class, that lends itself to a distributed implementation in the ad hoc environment; here "practical" refers essentially to computational simplicity and low signaling and measurement complexity. Moreover, an extension is proposed to mitigate the potential unfairness of the optimization approach for DB traffic.

In the case of both DB and RB traffic, the proposed suboptimal solutions are based on local measurements and signaling, achieving a tradeoff between signaling load and accuracy of the optimization. In this work in particular, we adopt a step-by-step approach: we assume N links are active and a new link requests to join in. Then, the aforementioned problems are solved in order to decide whether the new link is admissible and which is the (best) bit rate and/or power level for it.

A. A Simple Suboptimal Distributed Algorithm for Power and Rate Assignment: RB Case

We discuss the case of a UWB terminal pair wishing to start a new RB link. Let this pair be labeled zero. We assume that the constraints (2) are met for on-going N RB traffic links. The rate R_0 associated to the new link is constrained by QoS requirements (e.g., limited transfer delay for real time services, time deadlines for given blocks of data, a target SNR γ_0).

The power level P_0 is chosen so that a margin is acquired over the minimum required SNR γ_0. The margin, denoted as maximum sustainable interference (MSI), represents the amount of additional UWB interference that can be tolerated while maintaining SNR to below γ_0. Formally, the ith link can be characterized by a margin derived as

$$\frac{P_i g_{ii}}{R_i(\eta_i + U_i + \mathrm{MSI}_i)} = \gamma_i \Rightarrow \mathrm{MSI}_i = \frac{P_i g_{ii}}{\gamma_i R_i} - \eta_i - U_i \quad (7)$$

where $U_i = T_f \sigma^2 \sum_{k=1}^{N} P_k g_{ki}$.

A number of constraints must be met: i) the MSI value must be nonnegative; ii) the interference due to the new RB link on the on-going RB links must be limited within their MSIs; iii) the power level P_0 cannot exceed $P_{\max}$.

The constraints listed above are all met iff

$$\frac{\min\{P_{\max}, P_{\mathrm{allowed}0}\}\, g_{00}}{\gamma_0 R_0} - \eta_0 - U_0 \geq 0$$
$$\text{with } P_{\mathrm{allowed}0} = \min_{l \leq i \leq N} \left\{ \frac{\mathrm{MSI}_i}{T_f \sigma^2 g_{0i}} \right\}. \quad (8)$$

The larger the acquired margin, the more probable the accommodating new links without having to rearrange the power levels, as assumed here. On the other hand, large margins also imply an inefficient use of the spectrum and of RT energy. A tradeoff exists between the minimum power solution defined in Section IV, that implies power level rearrangements at any change in the air interface, and a high margin approach with static power levels, chosen once and for all on activation of the RB link and kept constant throughout the link lifetime.

1) MAC Procedures and Implementation Issues in the RB Case: In this section, we give a description of a distributed protocol applying the defined algorithm for the access of RB flows. We assume that RTs wishing to communicate with QoS requirements must initiate an access procedure at the beginning of the data session to establish a link.

As said previously, the access procedure includes both measurements and signaling operations in order to achieve a good tradeoff between slight signaling and sufficient network knowledge. More in detail, the access rule expressed by (8) can be evaluated on the basis of quantities which can be discovered by means of local measurements (e.g., U), with the exception of P_{allowed}, which requires explicit signaling of the N receiving RTs. To be more precise, every receiver must signal its amount of MSI, whose value cannot be captured by means of measurements, and at the same time, every new transmitter must listen to this signaling in order to compute P_{allowed}.

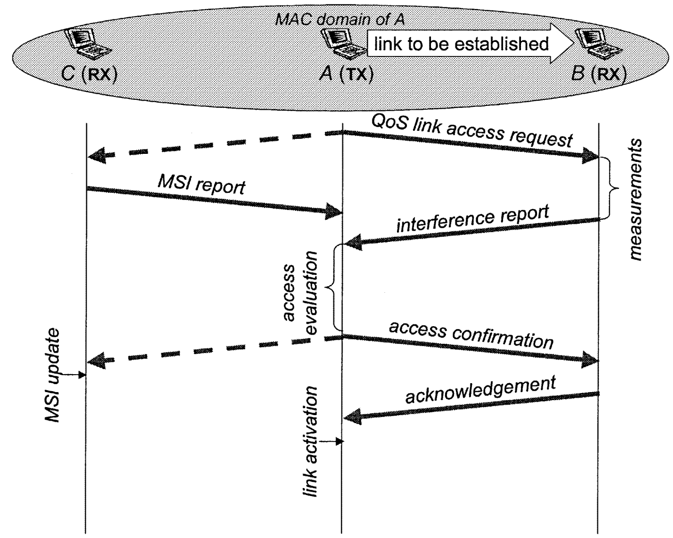


Fig. 3. Signaling procedure for the access of an RB flow.

A scheme describing the complete procedure is shown in Fig. 3. The procedure involves the transmitter for the new link (the RT A) and receiver (the RT B), as well as A's neighboring receivers (e.g., the RT C), and consists of the following steps.

- Step 1) RT A contacts B to notify its intention to start a communication at a given rate, this signaling is also heard by A's neighboring receiver (C) which in turn is triggered to signal its MSI; this represents the signaling phase. Obviously, if other receivers are in A's MAC domain, they are also requested to answer giving their MSI.
- Step 2) RT B measures the perceived interference and notifies the relevant result to A; this is a measurement phase.
- Step 3) RT A has now acquired all the information needed to check the access rule given by (8), and can, thus, perform the access check phase. In short, A computes P_{allowed} on the basis of the MSI values and of the interference. The fulfillment of condition (8) means that a transmission power exists which is compliant with the requirements of the other links (i.e., with their MSIs) and simultaneously allows the new link to acquire a positive MSI, given the required rate and the target SNR.
- Step 4) The final phase is the link activation, during which a confirmation handshake is performed by A and B. This acknowledgment implies also the update of the MSIs of the already active links; this is performed on the basis of new measurements. As the transmission from A to B starts, B, as a new receiver, also computes the amount of its MSI.

With reference to the access procedure, a specific implementation issue is concerned with the channels supporting signaling. First of all, the signaling procedure considers multichannel air interface to be a fact, since it must support concurrent active links which will interfere each other.

A broadcast channel must be provided that will carry the access signaling exchange (see the access request). In our specific context, this implies devoting an a-priori known TH code heard by everybody. Of course, multiple, concurrent accesses are possible and, thus, this broadcast channel could be used simultaneously by several RTs; however, the asynchronism among different transmissions ensures that, even though reciprocal time shifts are very short (in the order of ns), no catastrophic collisions occur, but just multiuser interference arises.

Furthermore, a critical point concerns the signaling of MSIs by several RTs, which are all triggered by the same event, i.e., the access request; the relevant messages must also be collected by one RT (A in the example). The adoption of UWB facilitates the solution of this problem, since all MSI report messages could be brought onto the same channel, i.e., the same TH code; the various transmissions—starting with different delays—partially overlap in time, but can still be separated if a number of receivers are provided, each of which is trying to capture one transmission.

B. A Simple Suboptimal Distributed Algorithm for Power and Rate Assignment: DB Case

Let us assume that N DB links are active and a new link wishes to join in. The SNR and peak power constraints are met for the already established links. Then

$$H(\mathbf{p}) = \sum_{i=1}^{N} R_i(\mathbf{p}) = \sum_{i=1}^{N} \frac{1}{\gamma_i}\frac{P_i g_{ii}}{\eta_i + U_i}. \tag{9}$$

If a new link joins in, the rate of the other DB links are adjusted so as to achieve the maximum throughput under the SNR constraint, that is

$$\begin{aligned} \mathrm{SNR}_0 =& \frac{P_0 g_{00}}{R_0\left[\eta_0 + U_0\right]} = \frac{P_0 g_{00}}{R_0 I_0} = \gamma_0 \\ \mathrm{SNR}_i =& \frac{P_i g_{ii}}{R_{i,\mathrm{new}}\left[\eta_i + U_i + T_f \sigma^2 P_0 g_{0i}\right]} \\ =& \frac{P_i g_{ii}}{R_{i,\mathrm{new}}\left(\eta_i + U_i + c_i R_0\right)} = \gamma_i \quad i = 1,\ldots,N \\ 0 \le& P_i \le P_{\max} \;\; i = 0,1,\ldots,N \end{aligned} \tag{10}$$

where $c_i = T_f \sigma^2 I_0 \gamma_0 g_{0i}/g_{00}$. As a result of (9) and (10), it follows that:

$$\begin{aligned} H =& R_0 + \sum_{i=1}^{N} R_{i,\mathrm{new}} \\ =& R_0 + \sum_{i=1}^{N} R_i \frac{\eta_i + U_i}{\eta_i + U_i + c_i R_0} \\ 0 \le& R_0 \le \frac{P_{\max} g_{00}}{I_0 \gamma_0} \equiv R_{0\,\max}. \end{aligned} \tag{11}$$

The target function $H = H(R_0)$ is convex and, hence, it is maximized either at $R_0 = 0$ or at $R_0 = R_{0\,\max}$. The inequality $H(R_{0\,\max}) > H(0)$ is equivalent to

$$\sum_{i=1}^{N} \frac{c_i R_i}{\eta_i + U_i + c_i R_{0\,\max}} < 1. \tag{12}$$

This is effectively an admission rule for new DB links, aiming at the optimization of the overall DB throughput. The rationale behind (12) is as follows: if the new link starts transmitting, the target function H is increased by $R_{0\,\max}$ (gain), whereas each of the bit rates of the ongoing DB links will be lowered because of increased interference (cost). The balance between the gain and the costs is positive iff (12) is met. As a result, a new DB link can be stopped in the following cases: 1) ongoing RB links do not have a sufficient MSI to overcome the increased interference caused by the new DB link; and 2) the overall DB throughput would be decreased because of the new DB link entrant.

In order to highlight how the proposed suboptimal solution could be implemented in a distributed fashion, we remark that the condition $H(R_{0\,\max}) - H(0) \ge 0$ can be interpreted as the sum of a "gain" term ($R_{0\,\max}$, the bit rate of the newly admitted link, if it can be admitted) and of a "loss" term (the sum of the amount by which the bit rates of every other interfered link is decreased) which must result nonnegative. Formally:

$$\begin{aligned} H(R_{0\,\max}) - H(0) =& R_{0\,\max} - \sum_{i=1}^{N} R_i \frac{c_i R_{0\,\max}}{I_i + c_i R_{0\,\max}} \\ =& R_{0\,\max} - \sum_{i=1}^{N} \partial R_i \ge 0 \end{aligned} \tag{13}$$

where the component ∂R_i represents the decrease in the rate of the ith link, due to the new access. As a consequence, to be able to check (13) requires knowledge of the components ∂R_i, $i = 1,\ldots,N$.

1) The Fairness Issue for DB Traffic: The unfairness of DB traffic optimization depends essentially on the fact that the target function (4) under consideration aims at maximizing overall system throughput, as well as on the instantaneous character of the derived admission control rule (13). To induce a fair radio resource sharing, we require the history of each RT to be weighted into the admission control, so that RTs that have been penalized may be protected from greedy RTs that already have more than their fair share of bandwidth.

The key idea is to redefine the target function as a weighted sum of the bit rates, with time varying weights depending on the amount of average throughput obtained by each RT up until that time (we denote this weight as w). The optimal solution is again either shut-off or transmission at peak power, but a link is admitted when it improves the "weighted" sum of bit rates, i.e., it could not improve the current, overall throughput, nevertheless its throughput has sufficient "merit" (large weight) to deserve admission.

The fair admission rule is the following, instead of (13):

$$R_{0\,\max} - \sum_{i=1}^{N} w_i R_i \frac{c_i R_{0\,\max}}{I_i + c_i R_{0\,\max}} = R_{0\,\max} - \sum_{i=1}^{N} w_i \partial R_i \ge 0. \tag{14}$$

Below, we identify the weight on the basis of the amount of bits transmitted by means of a DB data *burst*. Assume $k-1$ bursts of length L_j have been transmitted by a given RT in a time T_j $(j=1,\ldots,k-1)$. The averaged time rate, obtained by an RT for the previous bursts up to the time of admission control based on (14), is named Y. The expression to compute Y after ΔT seconds, since the first request for transmission of the kth burst was issued, is

$$Y(\Delta T) = \frac{\Delta L + \sum_{j=1}^{k-1} L_j}{\Delta T + \sum_{j=1}^{k-1} T_j} \qquad (15)$$

where ΔL is the amount of bits transmitted of the kth burst within the time interval ΔT $(\Delta L \geq 0)$. The averaged rate (15) can be evaluated simply by maintaining two state variables (e.g., the averaged rate of the first $k-1$ bursts and the overall amount of time required for these bursts). In accordance with (15), the weight assigned by the entering link (zero) to the ith active link, is defined as

$$w_i = \exp\left(\alpha \frac{Y_0 - Y_i}{Y_0 + Y_i}\right), \quad \alpha > 0. \qquad (16)$$

The equations above mean that, in the case of RTs receiving a lower average bit rate than the one received by the requesting RT, the relevant penalties of their bit rate reductions are amplified by a weight greater than one and the amount of "unfairness" (i.e., the difference between the bit rates obtained in their history by the requesting RT and the disturbed one) rapidly increase. Conversely, if the requesting RT has a lower average rate than the disturbed RT, the weight is less than one and this decreases rapidly as the gap between the two enlarges.

2) MAC Procedures and Implementation Issues in the DB Case: We now give a description of a distributed protocol, relevant to the algorithm proposed for the DB class of service. Here, we assume that access is performed per burst, that is, each time an RT has a new burst ready to transmit, it carries out the access procedure. In addition, we account for both cases of access, that is to say, access based only on the optimization rule [i.e., condition (13)] and access based on throughput optimization and fairness [i.e., condition (14)].

Again, the distributed nature of the algorithm requires both local measurements (to assess interference and noise before and after the onset of the new transmission) and signaling.

Fig. 4 represents a scheme of the access procedure in the case of a DB burst. We continue to refer to A as the new transmitting RT, to B as the new receiving RT, and to C as a RT neighbor to A.

Step 1) RT A contacts B by transmitting the access request message at its maximum power $P_{\max}$; this signaling is also heard by A's neighboring receiver (C) which is triggered to adapt the rate to the new, increased interference and to signal its decrease of rate ∂R. In the case in which fairness is accounted for [see admission rule (14)], the average rate Y of C is also updated and signaled. This represents the signaling phase.

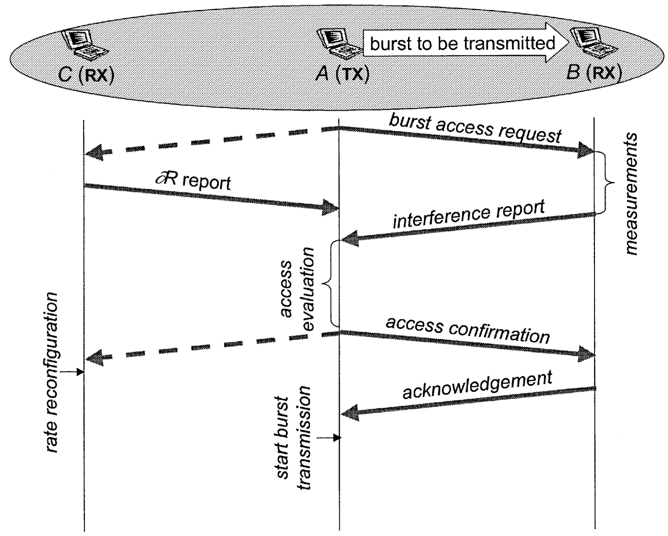


Fig. 4. Signaling procedure for the access of a DB burst.

Step 2) RT B measures the perceived interference and notifies the relevant result to A; this is the measurement phase.

Step 3) RT A has now acquired the complete set of information to check the access rule given by either (13) or (14) in order to perform the access check phase. In brief, it checks whether its transmission results in an increase or a decrease of the overall (possibly weighted) throughput.

Step 4) The burst transmission is confirmed by means of a handshake between A and B.

If the transmission set-up phase fails, a backoff procedure is begun in accordance with the various possible mechanisms presented in Section VI.

As regards implementation issues, these are similar to the ones presented for the RB case.

VI. Performance Case Study: The Dynamic Bandwidth Class of Traffic

In this section, we concentrate our analysis on the support of the DB class of traffic. We present a simulation model and the detailed performance analysis and results in order to verify the effectiveness of the optimization algorithm based on (13), as well as the fairness brought about by adopting a weighted throughput as an optimization function [see rule (14)].

A. The Simulation Model

We developed an event-based simulator. We simulated an area of 110×110 m, where 80 RTs are randomly distributed with a minimum distance of 1 m. During the simulations, the RTs are assumed immobile [21]. The propagation model consists of a deterministic geometric attenuation with distance, where the path loss exponent is four; the set of transmission parameters used in the simulation is derived from [2]. The target SNR is common to all the RTs and is equal to 14.7 dB. The ratio between the maximum power of an RT and the background noise power is $2 \cdot 10^{20}$.

As far as arrivals are concerned, new bursts arrive according to a Poisson process at rate λ burst/s and the burst size has a fixed length of 200 Kb. For each new burst, the source RT is selected randomly from among all the RTs, whereas the destination RT is chosen at random within a circular neighborhood, centered in the source RT with a 55-m radius (single hop transmission). Each RT handles a finite DB queue, able to accommodate up to 80 bursts, where upcoming data bursts line up, if enough room is available. Once a burst becomes head-of-line, the signaling and measurement phases before burst transmission are carried out in order to verify the admission criteria stated in Section V. These two phases are assumed to last approximately 15 ms. If the admission check fails, the backlogged RT schedules a new attempt; a number n of attempts takes place and, if all of them are unsuccessful, the burst is discarded. In particular, we considered five access disciplines:

— without backoff procedure (WOBP), based on (13) and with $n = 1$;
— with backoff procedure (WBP) based on (13) and with $n = 10$;
— with persistent backoff procedure (WPBP) based on (13) and with $n = \infty$;
— with fairness (WF) based on admission rule (14) and with $n = \infty$;
— without admission control (WOAC) where a burst is transmitted at maximum power without any admission check as soon as it becomes head-of-line.

Since we assume that the transmitter/receiver signaling messages are always successfully delivered and do not account for radio resources allocated to signaling, the performance results obtained represent the upper limit of achievable performance in a realistic scenario [22].

The results are calculated by averaging over 25 different network topologies with independent traffic patterns.

B. Performance Results

In this section, we report the main performance results derived in the simulation analysis. All the figures report the behavior when considering the access disciplines identified above.

In Fig. 5, the overall achievable throughput in the system is shown, whereas Fig. 6 reports the individual throughput of an RT: throughput in Fig. 6(a) is averaged during the entire transmitter lifetime (i.e., by considering the ON and OFF periods), whereas in Fig. 6(b) the time period considered coincides only with the activity period dedicated to burst emission. As the offered load increases, access mechanisms with admission control outperform WOAC: this is coherent with the fact that data bursts are transmitted only when an increase in the overall throughput is foreseen. Moreover, for a total offered load of less than 32 Mb/s with the traffic parameters used, the higher the number of attempts, the better the performance. When the total offered load is greater than 32 Mb/s, the WPBP is not the best choice because a number of RTs spend much of their time in the backoff state. In fact, in Fig. 6(b), showing the individual throughput during ON periods, we can observe that low values of the offered load lead to a decrease in throughput as the load increases, due to the growing number of active RTs. On the contrary, higher values of the offered load result in a higher number of RTs in the backoff state, depending on the number of attempts: only the RTs in the best locations can maximize their target function and transmit. Note that an RT is in a "good" position when it is going to disturb a restricted number of receivers and contemporarily the achievement of a high bit rate is envisaged thanks to the conditions of the current destination.

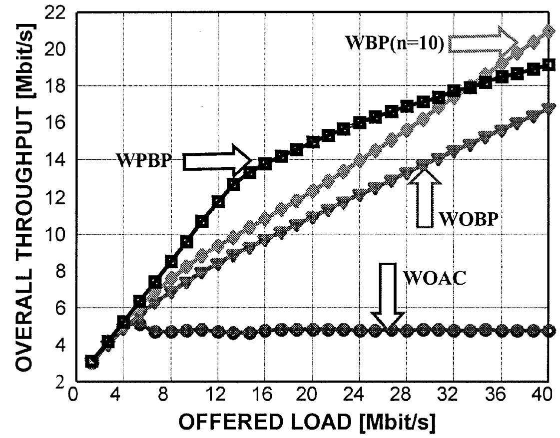
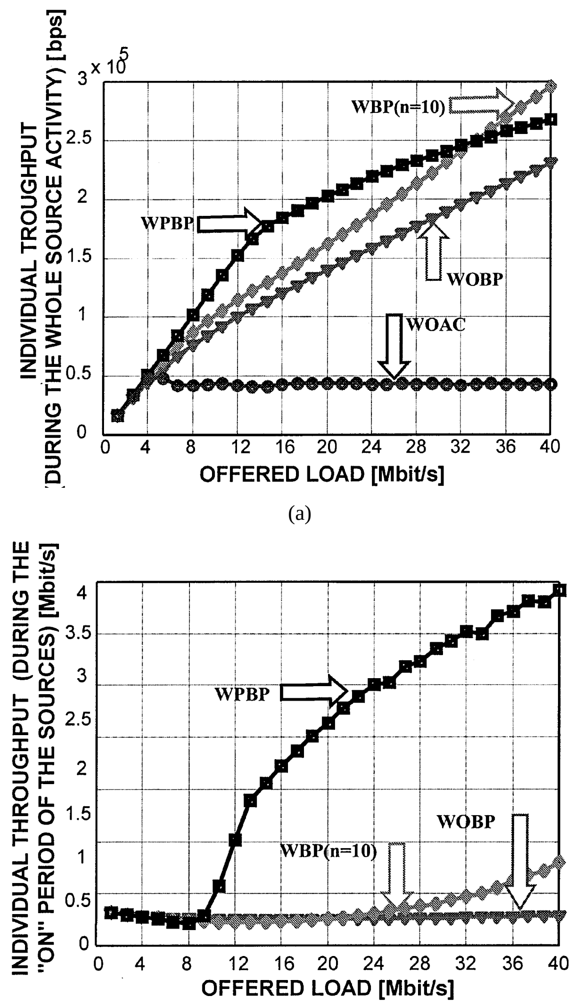


Fig. 5. Overall throughput.



(a)

(b)

Fig. 6. Individual throughput.

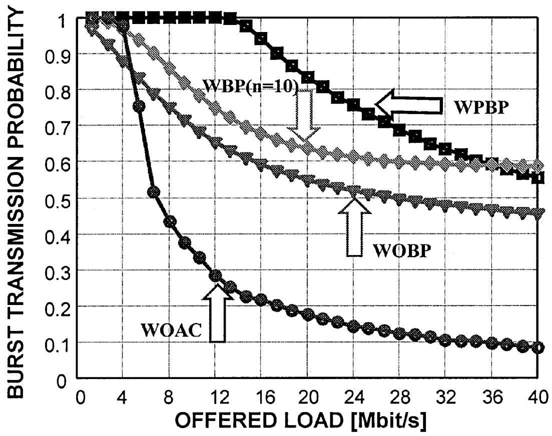


Fig. 7. Burst transmission probability.

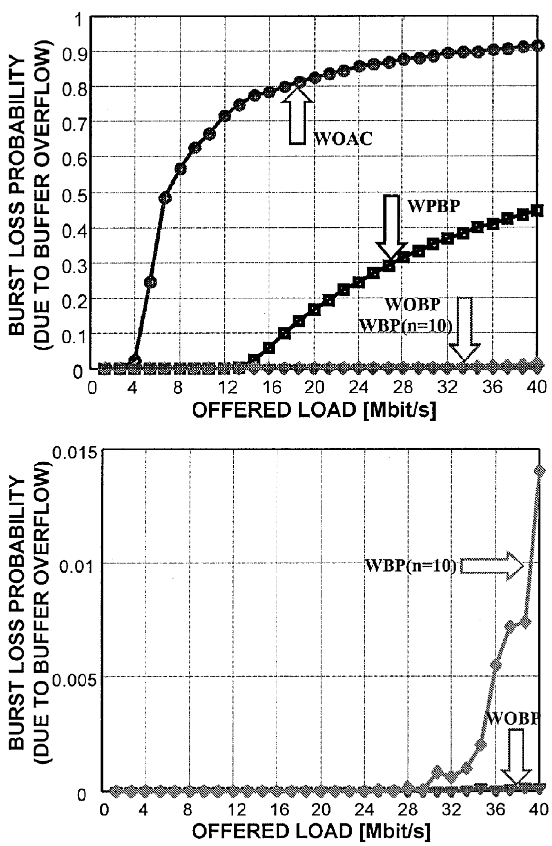


Fig. 8. Burst loss probability due to buffer overflow.

As far as WOAC is concerned, both overall and individual throughput saturate: indeed, when the offered load increases, the interference level also increases, due to the use of the maximum power $P_{\max}$ and, as a consequence, the total throughput reaches its maximum value.

Figs. 7–9 show the results concerning successful burst transmission. We observe that a burst loss occurs due to both the finite queue length assumption and the backoff mechanism (if it is not persistent). The procedures with optimization are clearly better than WOAC: in fact, although WOAC tries to transmit all the bursts that have arrived, heavy burst losses occur due to buffer overflow, since queues are heavily backlogged with respect to WPBP, WBP $(n = 10)$, and WOBP. On the contrary, in these two latter cases, burst losses due to buffer overflow are

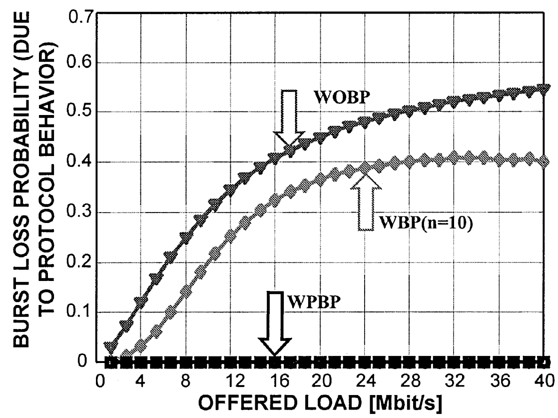


Fig. 9. Burst loss probability due to protocol behavior.

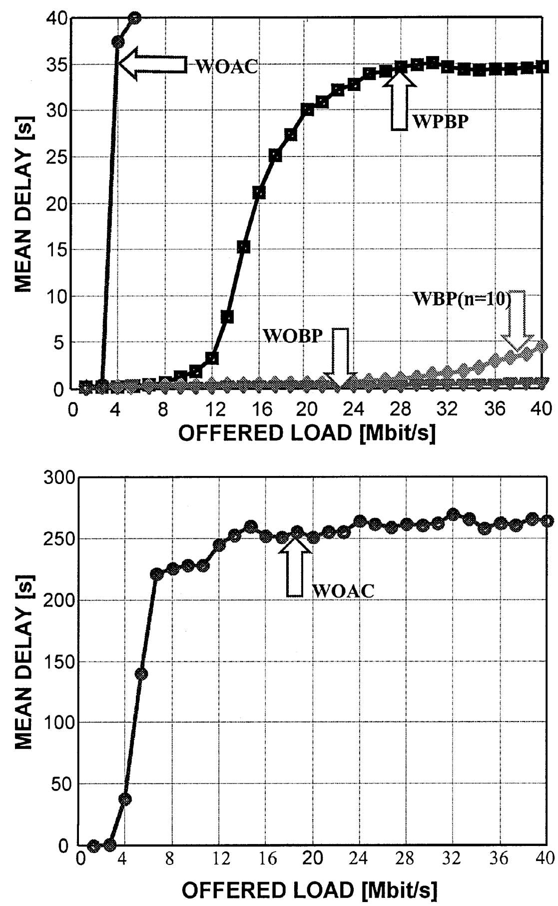
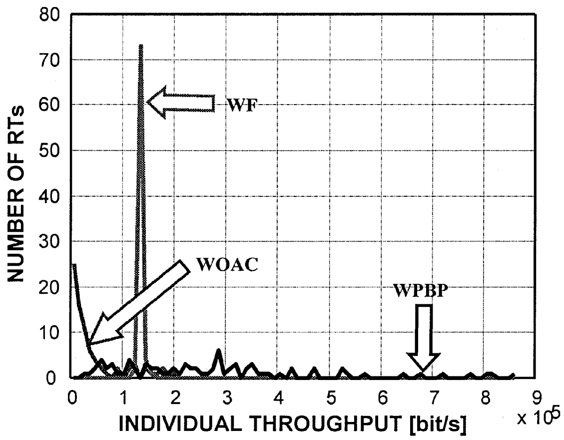


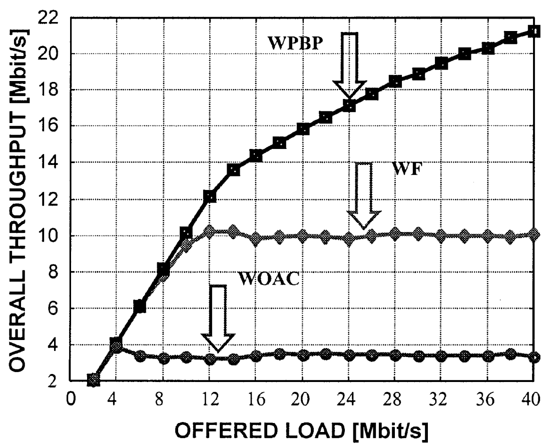
Fig. 10. Mean delay.

negligible, whereas burst losses due to protocol behavior are as heavy as the number n of attempts is low; in the case of WPBP, the protocol does not discard any burst, but if the offered load increases, backoff time increases and burst loss, due to buffer overflow, exceeds the total burst loss probability of WBP.

Nevertheless, although WPBP (for a low offered load) and WBP (for a high offered load) result in the algorithms achieving the maximum throughput, there is a tradeoff between the throughput itself and the mean delay, as we can see in Fig. 10. In particular, the higher the number of attempts, the higher the mean delay perceived by a burst. However, the admission rule in (13) produces a positive impact on burst



(a)



(b)

Fig. 11. Performance of the with fairness admission control.

delay: the procedures with admission control actually ensure reduced delays compared with those measured for the WOAC.

Finally, we analyzed the fairness behavior of the proposed admission rules (13) and (14). Fig. 11(b) shows the overall throughput as a function of the offered load for WPBP (optimization without fairness), WOAC and optimization with fairness constraints (WF). In this latter case, the overall throughput saturates to an intermediate level because nonoptimum transmissions are also accepted, so long as they are found to be convenient along the line of the fairness constrained admission rule, even though they cause an overall throughput reduction. Fig. 11(a) represents the histograms reporting the number of RTs that have achieved specific throughput values for a fixed value of the offered load (1.2 burst/s for each RT). In the case of the optimization rule (13) with no fairness constraint, the variance of the throughput distribution is maximum compared with the other algorithms, but the mean individual throughput is also maximized. When the joint optimization-fairness criterion (14) is used, throughput distribution is concentrated, whereas the mean individual throughput is reduced. Performance obtained without any admission control (WOAC) is the worst. In other words, Fig. 11 confirms that the aim to guarantee some fairness in resource sharing can be achieved only by paying a price in terms of a worse performance compared with the optimization admission rules.

VII. Conclusion

The work presented here focuses on radio resource sharing issues in ad hoc networking exploiting UWB communications. The research effort synthesized in this work is twofold.

From a system point of view, the ad hoc concept based on UWB radio is developed and guidelines for the design of the MAC protocol are laid out. The basic steps in access procedures involving both measurements and MAC signaling are defined.

As regards radio resource sharing, key issues are the power and capacity assignment principles and algorithms. For this purpose, the power and rate allocation problem has been formulated for both elastic bandwidth data traffic and reserved bandwidth traffic, the latter being characterized by bandwidth guaranteed and/or delivery delay thresholds. Assignment has been posed as an optimization problem that becomes an optimum power assignment for guaranteed quality (RB) traffic and a joint power/rate allocation problem in the case of DB traffic.

The need for a distributed algorithm means that suboptimum algorithms are defined, that assume a step-by-step approach. The major point here is that, even though (sub) optimization also requires the application of an admission control rule for DB traffic, good performance is obtained in terms of throughput and delay. The fairness issue has also been considered within this framework.

Further directions for the development of this research are: 1) the assessment of performance analysis when both classes of traffic are considered; 2) the impact of routing: data bursts can travel from source to destination by means of a multihop route; there is a strict relationship between optimum route choice and optimum radio resource assignment on each given link; 3) energy consumption requirements should be introduced, that would contribute a reduction in power/rate intrinsic unfairness; and 4) the effect of a moderate mobility should be considered; this will also reduce unfairness, but could imply a higher signaling load and resource allocation stability.

References

[1] M. Z. Win and R. Scholtz, “Impulse radio: How it works,” *IEEE Commun. Lett.*, vol. 2, pp. 10–12, Jan. 1998.

[2] M. Z. Win and R. A. Scholtz, “Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communication,” *IEEE Trans. Commun.*, vol. 48, pp. 679–690, Apr. 2000.

[3] [Online]. Available: http://www.UWB.org

[4] F. Ramirez-Mireles and R. A. Scholtz, “N-Orthogonal time-shift-modulated signals for ultra-wide bandwidth impulse radio modulation,” in *Proc. IEEE Communication Theory Mini Conf.*, Nov. 1997.

[5] S. S. Kolenchery, J. K. Townsend, and G. Bilbro, “Report on performance of local power control in peer-to-peer impulse radio network with bursty traffic,” in *Proc. IEEE GLOBECOM ’97*, Nov. 1997, pp. 910–916.

[6] F. Ramirez-Mireles and R. A. Scholtz, “Multiple access performance of ultra-wideband spread spectrum impulse radio using block waveform modulation,” in *Proc. IEEE ICC*, vol. 2, June 1988, pp. 775–779.

[7] ——, “Wireless multiple-access using SS time-hopping and block waveform pulse position modulation, part 1: Signal design and part 2: Multiple-access performance,” in *Proc. ISITA Symp.*, Oct. 1998.

[8] M. Frodigh, P. Johansson, and P. Larsson, “Wireless Ad Hoc networking—The art of networking without a network,” *Ericsson Review*, vol. 4, 2000.

[9] J.-P. Hubaux, T. Gross, J.-Y. Le Boudec, and M. Vetterli, “Toward self-organized mobile Ad-Hoc networks: The terminodes project,” *IEEE Commun. Mag.*, vol. 39, pp. 118–124, Jan. 2001.

[10] J. C. Haartsen, "The bluetooth radio system," *IEEE Pers. Commun.*, vol. 7, pp. 28–36, Feb. 2000.

[11] B. P. Crow, I. Widjaja, L. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Commun. Mag.*, vol. 35, pp. 116–126, Sept. 1997.

[12] F. Ramirez-Mireles, M. Z. Win, and R. A. Scholtz, "Signal selection for the indoor impulse radio channel," in *Proc. IEEE VTC Conf.*, vol. 3, May 1997, pp. 2243–2247.

[13] M. Z. Win, R. A. Scholtz, and M. A. Barnes, "Ultra-Wide bandwidth signal propagation for indoor wireless communications," in *Proc. IEEE ICC*, June 1997, pp. 56–60.

[14] F. Cuomo and C. Martello, "MAC principles for an ultra wideband wireless access," in *Proc. IEEE GLOBECOM*, San Antonio , TX, Nov. 2001, pp. 3548–3552.

[15] S. Lal and E. S. Sousa, "Distributed resource allocation for DS-CDMA-based multimedia Ad-Hoc wireless LAN's," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 947–967, May 1999.

[16] C. Martello and D. Bocchetta, "Power controlled MAC protocols for wireless Ad-Hoc networks," *Proc. European Wireless*, pp. 319–326, Feb. 2002.

[17] E. M. Royer and C. K. Toh, "A review of current routing protocols for Ad Hoc mobile wireless networks," *IEEE Pers. Commun.*, vol. 6, pp. 46–55, Apr. 1999.

[18] N. Bambos, "Toward power-sensitive network architectures in wireless communications: Concepts, issues, and design aspects," *IEEE Pers. Commun.*, vol. 5, pp. 50–59, June 1998.

[19] S. Lu, V. Bharghavan, and R. Srikant, "Fair scheduling in wireless packet networks," *IEEE/ACM Trans. Networking*, vol. 7, pp. 473–489, Aug. 1999.

[20] A. Baiocchi, F. Capriotti, F. Cuomo, and C. Martello, "Distributed radio resource sharing with UWB radio," in *Proc. IST Mobile Communications Summit*, Barcelona, Spain, Sept. 2001, pp. 753–758.

[21] D. Kim, "Rate-regulated power control for supporting flexible transmission in future CDMA mobile networks," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 968–977, May 1999.

[22] I. F. Akyildiz, D. A. Levine, and I. Joe, "A slotted CDMA protocol with BER scheduling for wireless multimedia networks," *IEEE/ACM Trans. Networking*, vol. 7, no. 2, pp. 146–158, Apr. 1999.

Francesca Cuomo received the Laurea degree in electrical and electronic engineering in 1993 (*magna cum laude*), and the Ph.D. degree in information and communications engineering in 1998 from the University of Rome "La Sapienza," Italy.

In 1995, she joined Coritel, Rome, Italy, a research institute on telecommunications, and was responsible for two consecutive years of the SWAP project in the radio access area. Since 1996, she has been a Researcher at the INFOCOM Department at the University of Rome. She participated in the European ACTS INSIGNIA project dedicated to the definition of an Integrated IN and B-ISDN network. She is now participating in the European IST Whyless.com project focusing on adoption of the ultra-wideband radio technology for the definition of an open mobile access network. In this project, she is responsible for the WP4–Network Resource Manager. She participated also in several national research projects. Her main research interests focus on modeling and control of broadband integrated networks, intelligent networks, architectures and protocol for wireless networks, mobile and personal communications, QoS guarantees, and real-time service support in the Internet.

Cristina Martello received the Laurea degree in electronic engineering (*magna cum laude*) from the University of Rome "La Sapienza," Italy, in 2000. Currently, she is working toward the Ph.D. degree in information and communications engineering at the same university.

She is participating in the European Whyless.com project on a mobile access network based on ultra-wideband radio technology. She also collaborates with Co.Ri.Tel. in the INFOCOM Department, University of Rome "La Sapienza," (a research consortium on telecommunications) for the development of dynamic radio resource control in the third-generation of mobile wireless systems. Her main research interests include radio resource control techniques adaptive to traffic conditions and radio channel quality for cellular radio systems and the synthesis of MAC protocols for ad hoc oriented networks.

Andrea Baiocchi (M'91) received the Laurea degree in electronics engineering in 1987 and the Dottorato di Ricerca (Ph.D. degree) in information and communications engineering in 1992, both from the University of Roma "La Sapienza," Italy.

Currently, he is an Associate Professor in communications at the University of Roma "La Sapienza." His main scientific contributions are on traffic control in ATM networks, queuing theory, and radio resource management in cellular mobile networks. His current research interests are focused on traffic models and dimensioning algorithms for IP networks and on mobile computing, specifically TCP adaptation and packet scheduling over the wireless access interface. These activities have been carried out also in the framework of national and international (European Union, ESA) projects, and have resulted in about sixty publications in international journals and conference proceedings.

Fabrizio Capriotti received the Laurea degree in telecommunication engineering (*magna cum laude*) from the University of Rome "La Sapienza," Italy, in 2001.

Currently, he works with Co.Ri.Tel., in the INFOCOM Department, University of Rome "La Sapienza," (a research consortium on telecommunications). He is participating in the European Whyless.com project on a mobile access network based on the ultra-wideband technology; his work regards the definition of MAC protocols for ad hoc oriented networks and the interworking with IP networks supporting QoS.