Modeling and Optimization of UWB Communication Networks Through a Flexible Cost Function

Pierre Baldi, Luca De Nardis, and Maria-Gabriella Di Benedetto

***Abstract*—The traditional design of communication networks has rarely been able to focus on the optimization of global network properties. Ultra-wideband (UWB) radio is emerging as an attractive physical layer for wireless communication networks offering new opportunities for the principled design and optimization of network properties. We develop a framework for the principled design of UWB wireless networks based on a flexible cost function that can be tailored and scaled to a wide range of networks and applications, ranging from sensor networks to voice and data wireless networks. The function comprises cost terms associated with transmission, connection setup, interference, and quality-of-service. Multihop routing strategies are associated with admissible paths of minimal cost that are computable in linear time. The cost function together with the overall level of requests determine the dynamics of the connections and the equilibrium topology of the network. We report simulation results in the case of simple ring and square lattice networks.**

***Index Terms*—Ad hoc networks, cost minimization, routing, sensor networks, small-world networks, UWB (ultra-wideband) radio, wireless networks.**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) radio is an impulse radio (IR) technique based on the modulation of short, nanosecond, low power pulses that is widely used in radar applications. In recent years, however, UWB has also received increasing attention for its broader applicability to telecommunications systems including ad hoc networks and multiuser wireless systems [1]–[5].

Traditionally, communication networks have not been designed from scratch in a principled way to optimize global network properties. By creating a new physical layer, UWB offers unique opportunities for the principled design of new classes of communications networks based on the optimization of complex tradeoffs between use of resources, quality-of-service (QoS), costs, and other relevant parameters. Our goal here is develop a general methodology for the principled design of UWB-based communication systems by focusing first on the network layer and its optimization. We develop a framework where the design of the network layer is driven by the optimization of a properly tailored cost function in the network layer that is flexible enough to subsume a range of possible applications and systems and to support ad hoc networking.

A. Design Framework

At the most fundamental level, the design of a communication network can be subdivided into a hierarchy of levels or layers. At the top of the hierarchy, the application layer defines the high-level services to be supported by the network. These services are subdivided into classes of services at the network layer, each class having different requirements, for instance in terms of QoS. In the network layer, the overall architecture and communication strategies of the system, such as routing, are defined taking into account the constraints imposed by the application layer and the physical layer through the interface provided by the DLC-multiple access control (MAC) layer. In this perspective, the *de novo* design of a rational communication network should first focus on the network layer taking into account the goal of the network, as well as the fundamental constraints originating from the physical layer.

Here, we develop a cost function on each communication link in the network. This cost function is inherently additive so that costs can be added along multihop communication paths and over the entire network. The cost function comprises several terms including power terms related to connection setup and wireless transmission. Low power is essential for a number of reasons such as increased energy saving and battery duration, increased immunity against detection and jamming in covert/military networks, and decreased levels of interference and exposure. Additional terms in the cost function can be tailored to take into account QoS, for instance, by controlling the total number of hops along a communication path and, hence, the corresponding delay. Minimization of the cost function determines the routing strategies of the network. A related approach is described in [6] for designing an optimized network protocol for minimum energy consumption in mobile wireless networks, and in [7], where a cost metric based on node reliability is proposed to enhance network performance and total throughput.

B. Self-Organizing Networks and Topology

Central to our approach, as well as to other recent developments in the design of wireless mobile telecommunication systems is the concept of self-organizing networks where each mobile node assumes a *double* role of terminal and router [8]. Moving network functionality into the mobile node is very appealing for wireless systems for fundamental reasons including robustness, power consumption, and infrastructure costs and provides a remarkable increase in the level of autonomy with respect to the fixed communication infrastructure

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P. Baldi is with the Department of Information and Computer Science and the California Institute for Telecommunications and Information Technology [CAL(IT)^2], University of California, Irvine, CA 92697 USA (e-mail: pfbaldi@ics.uci.edu).

L. De Nardis and M.-G. Di Benedetto are with the INFOCOM Department, Università degli Studi di Roma La Sapienza, Rome, Italy (e-mail: denardis@inwind.it; gaby@acts.ing.uniroma1.it).

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[9]. Self-organizing networking is currently being considered for both small-scale and large-scale systems. In large-scale wireless systems (ad hoc networks), the complex flexibility inherent of a distributed network must be matched by a corresponding flexibility in the management of resources. This feature in turn requires the adoption of a physical layer transmission technique providing large amounts of resources defined by multiple parameters. UWB radio techniques are ideally suited for this purpose, given the intrinsic flexibility of their transmission parameters (time-hopping codes, pulse duration and shape, power levels, etc.).

When terminals are capable of addressing and routing, they can serve as repeaters in a given communication link. Information then travels along paths made of multihop connections, reminiscent of the old radio bridges. In current ad hoc networks, multihops are used to reach terminals that are located beyond physical reach. In contrast, here multihop connections are viewed from a different perspective and can be used even between nodes that are within physical reach. To set up a connection, a terminal does not necessarily establishes a direct physical link, even when the power of its transmitter is sufficient to achieve a one-hop path. Rather, it might select a multihop path for the connection, in order to reduce emitted power. As a beneficial side effect, interference noise is reduced as well. The drawback is that signaling overhead increases with the number of hops in the path.

The fundamental problem then is the selection of relevant parameters and the construction of an associated cost function to compare and select paths, and solve the routing problem. The cost function should incorporate power constraints, as well as other factors, such as signaling overhead. The strategy should also take into account the possibility of using existing active links between nodes, as possible intermediate hops, whenever setting up a new connection.

The cost function of a network of users, together with their connectivity requests, determines the topology of the network of active links at a given time and its temporal evolution. At equilibrium (depending on the rates of entry and exit of the requests in the network, the typical duration of each communication request, etc.) this topology could for example result in a fully connected graph, with all nodes connected directly to each other, or in a graph in which nodes are connected directly only to their closest neighbors, or in an intermediate case. In particular, the power-cost term of the cost function tends to favor multihop paths. Thus, a cost function dominated by this term will result in a topology where all links are local, each node being connected to many close neighbors. Long-range links must be generated by some external mechanism or through other terms in the cost function aimed at, for instance, minimizing the number of hops. Another important topology that can emerge in communication networks is the “small-world” topology [10], [11], characterized by short minimal paths between pairs of nodes in the network. In any case, analysis of the resulting topologies can be used to assess the quality of the cost function and guide its design.

C. Network Scenarios: From Sensor Networks to Large-Scale Ad Hoc Networks

In principle, UWB technology could be applied to a wide range of scenarios ranging from small-scale sensor networks to large-scale wireless ad hoc systems. Although each scenario comes with very different characteristics in terms of, for instance, bit rates, robustness, energy, and QoS, it is important to incorporate scalability considerations in the design of the cost function. Here are some of the network scenarios that are worth keeping in mind, ranked by increasing order of complexity.

1) Networks of fixed sensors at fixed known positions such as those that could be embedded in a conference room (for person to person communication and interactive gaming or lecturing), in a car (in-vehicle information exchange), or in a building. Typical ranges would be for sensors a few meters apart, and networks in the 100–m range.
2) Networks of fixed sensors initially deployed at locations that are not known with any precision. This is the case, for instance, of a blanket of sensors deployed in a nonsecure zone during a military operation, or a blanket of sensors dropped over a field or urban area. Military applications in particular require robust (immunity to fading/outage) and rapid (on the fly/no spectrum assignment) wireless networking in complex (urban/indoor/ship/cargo container/close to the ground) and hostile (detection/jam) environments.
3) Networks of sensors with mobility in the same ranges as before or on larger scale. For instance, sensors embedded in cars, capable of communicating from car to car, from cars to fixed sensors embedded in the road or along the side of the road, and/or from cars to the fixed land network.
4) Local ad hoc wireless networks (battlefields, local emergencies/crisis management, intracar communication).
5) In the long run, a large-scale architecture for wireless/mobile telephony and data communication.

Note that UWB could also be applied to other settings that do not necessarily require extensive network capabilities (garage openers, merchandise tracking, imaging, etc.) but which are not relevant here.

D. Overview of the Paper

In short, we propose a model for UWB-based distributed wireless systems based on the construction of a realistic set of parameters and associated class of cost functions. The paper is structured as follows. In Section II, we review the principles of UWB transmission systems. In Section III, we develop the general framework. In Section IV, we report the results of simulations that corroborate the methodology and provide directions for future research which are discussed in Section V. A preliminary version of the framework has been presented in [12], [13].

II. REVIEW OF UWB TRANSMISSION PRINCIPLES

In recent years, UWB has received increasing attention for its broader beyond-radar applicability to multiuser wireless communication systems. In particular, Scholtz and Win [1] have proposed a multiuser access scheme for UWB in which users are diversified by time-hopping codes. In this scheme, system performance is monitored and evaluated by the multiuser interference noise which, in turn, can be mitigated by appropriate coding strategies [14]–[16]. As a result, UWB has the potential for allowing simultaneous communication between a large number of users at high bit rates. In addition, the high temporal resolution inherent to UWB provides robustness against multipath fading [17], hence, is particularly attractive for indoor wireless local area network (WLAN) applications [18]–[24].

UWB radio is a carrierless spread-spectrum (SS) technique based on the transmission of very short (subnanosecond) pulses which are emitted in periodic sequences. As outlined in [1], N_S pulses are used for each transmitted symbol. The adopted modulation is a binary PPM. The case of m-ary PPM has been addressed in [25]. The transmitted signal is

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_S-1} g(t - jT_f - b_i\tau) \tag{1}$$

where $g(t)$ represents the pulse, T_f the basic time interval between two consecutive pulses, and $T_b = N_S T_f$ is the bit duration. Information bits are coded in the sequence of b_ks. Multiple access is achieved by using time-hopping codes and, for multiuser communication, the transmitted signal is

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_S-1} g(t - jT_f - c_jT_c - b_i\tau) \tag{2}$$

where $1/T_c$ is the chip rate and c_j is an element of the code word with $0 \leq c_j \leq N_h$ and $N_hT_c < T_f$. Equation (2) shows that the time hopping code provides an additional shift of c_jT_c. When the number of users is N_U and the noise $n(t)$ is additive, the signal at the receiver becomes

$$s(t) = \sum_{k=1}^{N_U} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_S-1} g\left(t - jT_f - c_j^{(k)}T_c - b_i^{(k)}\tau\right) + n(t) \tag{3}$$

where index k refers to user k. Both the choice of the pulse waveform $g(t)$ and the random code selected affect the transmission spectrum.

The optimal receiver for a single communication (with data composed of independent random variables) in an additive white Gaussian noise (AWGN) environment is the correlation receiver described in [1]. The AWGN model is a good approximation also in a multiuser environment, when the number of users is large and the Central Limit theorem can be applied. In this case, the correlation receiver is again the optimum choice, and the signal-to-noise ratio (SNR) at the receiver can be written as follows (see also the Appendix)

$$\text{SNR} = \frac{P}{P_I + P_n} = \frac{(N_S m_p)^2}{N_S \sigma_a^2 (N_U - 1) + \sigma_{\text{rec}}^2} \tag{4}$$

where P is the average power of the useful signal, $P_n = \sigma_{rec}^2$ is the power of the thermal noise, P_I is the power of multiuser interference, N_U is the number of interfering users, $\overline{P}_I = \sigma_a^2$ is the power of the *typical* interference resulting from one of these users on one pulse and m_p is the signal at the correlator's output during the interval T_f. In particular, $\sigma_{rec}^2 = (1/2)kT_S 2B = kT_S B$ where B is the bandwidth of the signal after demodulation. Equation (4) shows that global system performance depends on the amount of multiuser interference, which in turn is determined by the correlation properties of the time-hopping codes. Most often, pseudorandom codes are used, due to their good cross-correlation properties. Pseudorandom codes, however, are not easily addressed. Recently, new code constructions overcoming this problem have been proposed [14], [16].

UWB is also capable of recovering positional information with great precision. This property has been extensively exploited in radar applications, and is attractive for cellular systems as well. The fine time resolution available with UWB, with pulse duration shorter that one nanosecond, allows high precision ranging so that two terminals can determine their distance within a few inches. An even better precision can be achieved by tailoring pulse shapes, leading to well-behaved autocorrelation functions. From the set of precise pairwise distances of a collection of terminals, a complete three-dimensional (3-D) map of their relative positions can be reconstructed (better than the one achievable with global positioning system (GPS), especially in indoor applications) with no additional hardware requirements. In fact, position data can lead to better organization of telecommunication networks, for instance through better resource management and routing. In conjunction, positioning can also help lower power levels by using directivity.

UWB signals, however, are spread over very large bandwidths (from a few Hertz to several gigahertz) and, therefore, unavoidably overlap with other narrowband services [26]. As a consequence, it is reasonable to expect that regulatory bodies will impose severe limitations on UWB power density to avoid interference provoked by UWB onto coexisting narrowband systems. The recent release of UWB devices emission masks by the FCC marks a clear progress in this direction (see http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2002/nret0203.html). These masks by the Federal Communication Commission (FCC) are used as a reference (varying from a minimum value equal to -75 dBm in the band 960 to 1610 MHz, which includes GPS, to a maximum value of -42 dBm above 3.1 GHz, for indoor applications), in which very low power levels are allowed for UWB transmitters in order to meet coexistence requirements with GPS devices. In order to reap all the benefits of UWB technology, it is therefore paramount to take into account power considerations when designing UWB systems, all the way from the single-emitter level to the system level. UWB low-power techniques have the potential for greatly reducing current levels of spectral pollution. FCC requirements are likely to result in an organization of UWB networks based on small cells.

A conceptual framework for the design of high-capacity UWB systems that is robust and leverages positioning information while abiding power constraints was described in [12]. In Section III, we further refine the framework and simulate the underlying model to derive general guidelines for wireless networks based on UWB technology. In particular, we define strategies for setting up connections by optimizing a power-dependent cost function. The resulting power-saving strategy can lead to multihops communication paths even between two terminals that are within reach of each other (physical visibility). We compare the results obtained using the proposed strategies against those derived using traditional routing algorithms.

III. GENERAL FRAMEWORK

A. Overview

We first begin with a somewhat special but important case where the network consists of a set of N nodes with the

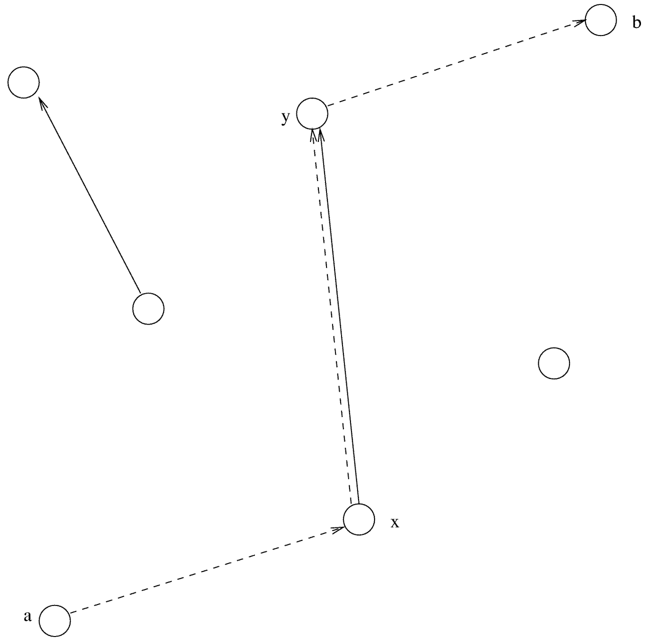

Fig. 1. A portion of a network containing seven nodes with two existing active connections shown in solid lines. Dashed line shows a possible path for a new communication request with source node a and destination node b. The path uses three hops through two intermediate nodes x and y. Setup costs are zero for the (x, y) hop since the link is already active.

following properties: 1) all nodes are fixed; 2) all nodes have the same functionality; 3) connections between nodes have QoS requirements; 4) each node has a limited output bandwidth, which corresponds to the node resource; and 5) each node has a global view of the network and has information about the exact position of each other node and its communication status (active links and resources utilization). While this is a special case, it is closely associated with the first two applications described above and serves as a basic testbed for ideas related to the use of UWB in more complex systems. How to relax these assumptions and, for instance, introduce mobility and related mechanisms of entry and exit, is discussed in Section V. The fact that each node has a global view of the network can easily be satisfied when each node is within physical reach of any other node. However, this is not necessary since one can easily envision a situation where the nodes are not all within physical reach of each other, but where information about each node is progressively propagated throughout the network and acquired by each other node, for instance during a short transitory phase using a common channel.

Each node in the network can play any of the following roles: source node, intermediate node, and destination node (Fig. 1). As a source node it must be capable of setting up new connections, i.e., it must have enough bandwidth. As a destination node it can theoretically accept an unlimited number of connections. As an intermediate node it must accept an incoming link only if it has enough bandwidth to set up the corresponding outgoing link.

To describe the framework and the cost function, consider now such a network in operation at time t, with the arrival of a new communication request with source node a and destination node b. In addition, the request from node a may have other constraints related to QoS, for instance, in terms of rate of transmission R or best effort, overall delay, and possibly bidirectionality. Bidirectionality is important for voice applications but not necessarily in applications centered around networks of sensors. Bidirectional communication often requires using the same path in both directions, but this is also not always an absolute necessity. Naturally, we also assume that the time scale for request arrivals is slow with respect to the switching time scale of the nodes.

With respect to the new request, any link (x, y) in the network can either be admissible or nonadmissible. The link is not admissible if it does not have the capability to implement the communication request from node a. In particular, it is not admissible if y cannot be reached from x, if there is not enough capacity to carry the rate R, if there is too much interference noise to carry R, or if the link is located on a path which does not satisfy possible constraints on the network, such as maximum number of hops, or maximum affordable cost of the path. In the case of a request for bidirectional communication requiring the same nodes in the forward and backward paths, then the admissibility constraints must be satisfied along the link (y, x) simultaneously. Given the request from node a, an admissible communication path π is a path from a to b consisting only of admissible links. If such a path is not available, the request cannot be satisfied and is rejected.

In addition to the concept of admissibility, we associate to each link a cost $C(x, y)$ which is the sum of a number of terms that take into account energy costs but also other considerations, with the general form

$$\begin{aligned} C(x, y) = C(\text{power}) + C(\text{setup}) + C(\text{interference}) \\ + C(\text{quality}) + C(\text{delay}) + C(\text{other}). \end{aligned} \tag{5}$$

$C(\text{other})$ is included to indicate that the function can be tailored to a specific network and only a subset of the terms above may be needed in a specific application. Each term will be discussed in detail in the sections below, but it should be clear that the cost and admissibility of a link vary in time and depend also on the parameters (e.g., R) of the originating request from node a. To avoid cluttering the notation, these dependencies are not included explicitly. The cost of a communication path is the sum of the cost of its links

$$C(\pi) = \sum_{(x, y) \in \pi} C(x, y). \tag{6}$$

In the case of a bidirectional communication with bidirectional paths, the cost of a path is the sum of the costs in the forward and backward direction along the path. In general, there will be many possible communication paths between a and b and the basic routing strategy will be for a to opt for the path with minimal cost which can be computed by dynamic programming (see Section IV-A), or a low cost but not globally optimal communication path obtained by some approximation. When two paths have the same cost, the path with the smaller number of hops is selected.

In summary, in this framework the design of the network layer is to a large extent controlled through two basic mechanisms: the definition of admissibility and the cost function. A link between two nodes is admissible if the two nodes involved in the communication can comply with the requested functionality. An admissible path is formed of admissible links only. A communication cost is attached to each admissible path and the cost of a path is the sum of the costs associated with the links it comprises. Overall, this framework is flexible enough to investigate a large space of possible networks associated with the wide range of possible scenarios described above.

B. Admissibility

Admissibility constraints are used to ensure constraints associated with link budget, QoS, and so forth. Any gross violation of such constraints leads to links that are inadmissible. A best effort request is easily incorporated in this framework by considering that it does come with a weak rate request (very low rates are acceptable) or a weak delay request (long delays are acceptable). While in many cases the concept of admissibility can be defined at the level of individual links, in some cases admissibility must be defined in more global ways involving additional links or even paths. We have already seen an example in the case of bidirectionality requiring the same links in both directions where admissibility must be tested for each link in both directions. An even stronger example is provided by an application which can only tolerate a delay corresponding to a maximum number K of hops. In this case, admissibility must be checked at the level of entire paths in the sense that any path with more than K hops is deemed inadmissible. Another example of nonlocal admissibility is in models where we constrain the global network cost function $NC(t)$, equal to the sum of the costs of all active links at time t, to be always below some constant: $NC(t) < C\max$. A path is admissible then only if this constraint remains satisfied after its addition to the network. Clearly, such a constraint cannot be tested at the level of individual single links, but only incrementally along paths.

Depending on the modeling situation, some tradeoffs are possible between the admissibility constraints and the cost function. Admissibility is used to enforce constraints in a hard way. When admissibility is defined on individual links, the admissibility constraint may be mapped to the cost function exactly or in a soft way. In the case of more global forms of admissibility, the mapping can only be soft. A hard local admissibility constraint can be mapped onto the cost function by assigning an infinite cost to links that are not admissible. This is to be contrasted with the example of a local rate constraint which can also be enforced in a softer way through the cost function. A global constraint, like a bound K on the maximal number of hops along a communication path, can be enforced softly via the cost function by adding a nominal fixed cost per link (see below) which, at the level of the paths, results in a cost term that is proportional to the number of hops. This alternative leads to a soft treatment of the number of hops which generally tends to be minimized, but occasionally could exceed the bound K.

C. Power

Power optimization is essential for a variety of reasons ranging from duration of autonomy of each node, to bandwidth availability, to control of spectral interference and pollution, to decreased detectability. In fact, the overall tendency toward power minimization drives the design and the introduction of multihopping strategies. The dominant power term is given by

$$C(\text{power}) = C_1 R(a,\, b)\, d^{\alpha}(x,\, y) \tag{7}$$

and is proportional to the rate of transmission $R(a,\, b)$ (QoS) and the Euclidean distance $d(x,\, y)$ raised to the power α, which is related to the propagation characteristic of the channel and typically has a value between two and four.

D. Setup

The setup communication cost associated with setting up a new connection is

$$C(\text{setup}) = C_2 \delta(x,\, y)\, d^{\alpha}(x,\, y). \tag{8}$$

If two nodes already share an active link, then $\delta(x,\, y) = 0$ (no setup cost). Otherwise, $\delta = 1$ and the setup communication cost is added. This term is intended to model the cost associated with the overhead of establishing a new active connection in the network due to synchronization time. Like $C(power)$, it is proportional to $d^{\alpha}(x,\, y)$. In bidirectional communication using the same nodes in each direction, if the link $(x,\, y)$ is already active then there is no setup cost for both $(x,\, y)$ and $(y,\, x)$.

E. Interference

To model interference costs, we assume that each receiver has the ability to monitor its SNR. When a request to communicate according to a rate $R(a,\, b)$ arrives and a possible link $(x,\, y)$ is considered, we can calculate the quantity $\Delta P = P' - P$ by which power should be increased at x in order to transmit the information over the link, while keeping the error rate fixed and not to exceed a nominal value preestablished for the entire network. In the Appendix, we compute the link budget and show how ΔP can be computed as a function of the requested rate R, the SNR at the receiver in y [which depends on N_U and $\overline{P}_I = \sigma_a^2$ through (4)] and the nominal symbol error rate (which for UWB modulation corresponds to the bit-error rate (BER) $P_e = P_b$) so that

$$\begin{aligned} C(\text{interference}) &= C_3 \Delta P(P_b,\, R,\, \text{SNR}(y)) \\ &= C_3 \Delta P(P_b,\, R,\, N_U,\, \overline{P}_I). \end{aligned} \tag{9}$$

In principle, when a new communication path is established, SNRs ought to be recomputed everywhere in the network. Because of the low-power characteristics of UWB, however, this needs to be done only for the nodes that are close to the new path, i.e., nodes contained in a “sleeve” around the path. The thickness of the sleeve of course can be adjusted to fit different modeling situations. Naturally, it is also possible to introduce interference margins and use interference considerations in the admissibility criteria.

F. Quality

In some applications, it may be important to monitor the quality or reliability of a terminal, or of a link $(x,\, y)$. If any of the nodes x or y is experiencing a problem this reliability index should decrease. Likewise, if some of the nodes are mobile, then communicating with them or using them for routing could be a problem. This is often the case in a mobile ad hoc network, where a smart choice of the nodes during the multihop connection setup can dramatically improve the stability of the connection itself. We consider two main kinds of reliability regarding a node.

1) A *physical* reliability, depending on hardware (and/or software) robustness of the terminal and measured by mean time between failures (MTBF) of the node.
2) A *communication/positional* reliability $T(x, y) = t - t_0$ measured by the time elapsed since the occurrence at a time t_0 of a specific communication event involving the nodes x and y. This event could be the first time or the last time a particular communication event occurred between x and y. In one possible implementation, the nodes periodically emit an "hello" message, even in the absence of an active connection to allow each node to maintain an up-to-date knowledge of its neighborhood as in [7]. If the emphasis is on reliability over long time scales, then t_0 could be the beginning of the last uninterrupted sequence of "hello" messages sent from y and received from x ending at the present time t. In this way, a highly mobile node could have a low communication reliability.

These two contributions can be included in the link cost function using two additive terms in the form

$$C(\text{quality}) = \frac{C_4}{\min\{\text{MTBF}_x, \text{MTBF}_y\}} + \frac{C_5}{T(x, y)} \tag{10}$$

which favors stable high-quality nodes. On the other hand, the introduction of this term can lead to an unfair traffic distribution over the network, by concentrating most of the traffic on nodes which are characterized by a high reliability (for example fixed nodes). A possible solution to avoid this undesirable effect will be discussed in the next section.

G. Delay

The delay caused in the communication by each hop in the potential path is one of the QoS metrics to be taken into account in the routing strategy; it can be introduced in a soft fashion in the link cost function in two different ways.

1) In a *static* way by introducing a fixed cost for each hop in the form

$$C(\text{delay}) = C_6. \tag{11}$$

This term of course can be dropped if delays are not important or if the request is on a best effort basis.

2) In a *dynamic* way, by evaluating the delay introduced in each hop (i.e., caused by each intermediate node) based on traffic measurements, by means of a function of the queue length in data units λ (for example the mean value over a certain period), leading to a term

$$C(\text{delay}) = C_6 \cdot f\{\lambda_y\}. \tag{12}$$

The second solution requires an additional exchange of information in the network to obtain the traffic measurements required to take the routing decision, but it offers two main advantages: a) It allows a more precise characterization of the network status and, as a consequence, a more efficient routing decision; and b) It automatically balances the effect of the cost term related to the reliability of nodes. In fact, initially a node with high reliability will tend to receive many traffic requests. As the node accepts more and more requests, the delay-related cost grows and the node progressively becomes less appealing to its neighbors, thus helping to distribute traffic between nodes evenly.

H. Global Network Cost

It is also useful to define the global network cost at time t as the sum of the costs of all the active links (alternatively, one can use the sum of power costs of all the links)

$$NC = \sum_{(x, y)} C(x, y). \tag{13}$$

For some models, it may be useful to impose a constraint of the form $NC(t) < C\max$ at all times.

I. Routing

At the most basic level, routing is based on dynamic programming (Dijkstra [27] or Viterbi's [28] algorithm) for finding the least costly path in the network, avoiding the study of an exponential number of paths. Assume that terminal a wants to send data at rate R to terminal b at time t. The routing algorithm proceeds as follows.

1) Compute the cost of all links using the previous definition of the cost function.
2) Find the path of lowest cost using Dijkstra's algorithm.
3) Update all the parameters in the network (available capacities, SNRs, etc.). Wait for the next communication request and go back to the first step.

In cases of bidirectional communication, roundtrips may be optimized rather than single trips.

Dijkstra's algorithm works well when all the weights in the graph are nonnegative which is our case. If there are N vertices and M edges, the algorithm takes $O(M + N \log N)$ steps. For directed acyclic graphs the time can be reduced to $O(M + N)$ without assumptions about the edge weights. In principle, M could be as large as $O(N^2)$ yielding an algorithm that scales like $O(N^2)$.

In UWB networks, however, in general, the number of edges is much smaller due to the physical layout of the N nodes in $\mathbb{R}^d$, and the low power constraints. In particular, edges correspond to physical reachability so that a node is connected by an edge to all its neighbors within some radius r. In general, r will be small compared with the size of the network and, therefore, the graph is sparse with a number of edges linear in N. A typical node will have k neighbors yielding a total of $O(kN)$ edges. For instance, we can assume that typically there are no two nodes at distance s or less. This means that each node has typically at most k neighbors, with $k < (r + 0.5s)^d/(0.5s)^d$ in dimension d as a crude bound, with an approximate bound of $(2r/s)^d$ on k when r is large compared with s. In sparse graphs, Dijkstra's algorithm takes $O(kN + N \log N)$ steps. For N large, this is

$O(N \log N)$. In a sparse UWB network, it is easy to see that the optimal path can be searched or approximated within a directed acyclic graph. In this case, the routing algorithm takes time $O(kN)$, linear in the number of nodes.

This approach to routing requires each terminal to have a global view of the network. This view could be achieved through a dedicated channel, or through low-cost repeated propagation of location and activity messages by each terminal. Alternatively, optimal routing could be approximated with sub-optimal paths obtained by local propagation algorithms.

J. Clusters

In some implementation it is useful to introduce a notion of cluster. Again several definitions are possible but the basic idea is that within a cluster: 1) all nodes are in direct physical reach of each other; and 2) particular resources, such as the choice of codes, are coordinated. If r is the typical radius of direct physical reachability, then the first condition implies that clusters have typical radius $r/2$. Furthermore, in a completely distributed network where all nodes have the same functionality, each node should be the center of its own cluster rather than having rigid clusters with artificial boundaries assigned to geographical areas or particular master nodes.

Clearly the cluster of node x is included in the area of coverage of node x, but it is typically smaller depending upon factors such as radio channel conditions and network load. The resource management module of a node also coordinates resource sharing between the node and its neighbors in the cluster. Thus, the motivation for the concept of cluster is also directly related to physical and MAC layer requirements.

A complete study of the notion of cluster in relation to these complex motivations is beyond the scope of this paper, however in the simulations below we have implemented one possible mode of local intracluster coordination between nodes using the double requirement that: 1) each hop be contained inside a cluster; and 2) no two hops be contained inside the same cluster, with the exception of the last hop to the destination node that could be contained in the same cluster of another link along the same communication path.

The low-level cluster requirements do not change the overall routing strategy but impact the routing algorithm because whether a link is admissible or not becomes a dynamic notion. On the other hand, it is easy to see that routing can be implemented using the plain version of Dijkstra algorithm on a new graph which is the line graph of the original graph. In the line graph, the nodes are the edges of the original graph. And two nodes in the line graph are connected if the two corresponding edges in the original graph are linked to each other (i.e., share a node). In the line graph, all the edges associated with double hops contained in the same cluster in the original graph are inadmissible. The cost of an edge $(X, Y) = (x, y, z)$ in the line graph is the sum of the costs of the links in the original graph associated with the nodes $X = (x, y)$ and $Y = (y, z)$ in the line graph. If the original graph is sparse with $O(N)$ edges, the line graph is also sparse with $O(N)$ nodes, but also $O(N)$ edges and, therefore, the linear scaling of the routing algorithms remains unchanged.

For all practical purposes, in the simulations described below, the size of a cluster is best seen as an additional parameter that can be used to control the granularity of multihop strategies, since hops are allowed only between nodes that are members of a same cluster. Note that each node still has a global view of the network that goes beyond its cluster.

IV. SIMULATION RESULTS FOR A NETWORK-OF-SENSORS SCENARIO

We have developed a network simulator to test variants of the cost function and routing algorithm, as well as different spatial arrangements of nodes, such as square or ring lattices, in small to medium size networks, with different cluster sizes. This allows us to study the topology of the networks and the properties of various routing algorithms. A few representative examples are reported here using the simple energy cost function $C(\text{power}) + C(\text{setup})$, with or without a global maximum constraint of the form $NC(t) \leq C\max$.

A. Routing and Topology

In a first set of preliminary simulations to test the effect of routing strategies on topology, we consider a set of 25 fixed nodes regularly positioned on the vertices of a square 5 × 5 lattice and assume that each node can physically reach any other node (single cluster or area of coverage). Note that due to the way the cost function is defined, multihops are favored during initial stages. In fact, when no link is active, a multihop route is selected over a direct link since it leads to lower power consumption. However, as new connections are formed, some of the nodes saturate in terms of capacity. Moreover, active links are favored because they lead to lower signaling cost. New connections, thus, start using shortcuts to reach destination nodes whenever directionally favorable preestablished active links are present. We estimated the probability that the routing path associated with a new connection request contains an active hop. This parameter may help understanding which type of network topology is generated after a number of connections are formed. Results show that the probability of using an existing hop rapidly tends to a high value (about 0.85), suggestive of a small-world topology [10], [11], [29]. Small-world networks are characterized by having a small average path length between nodes versus a high degree of local connectivity. This emerging small-world topology is a positive feature since both power consumption (high-density of local connections) and signaling overhead are reduced.

Naturally, larger simulations are need to further establish this behavior and also test any related power-low distribution of connectivity [33].

B. Routing and Communications: Average Number of Hops and Percentage of Accepted Requests

In a second set of simulations, we consider a network with a regular ring lattice structure with a $C\max$ bound on the global cost function of the network. In addition, we assume that: 1) the connection requests are described by a Poisson model, i.e., the time between two consecutive requests follows

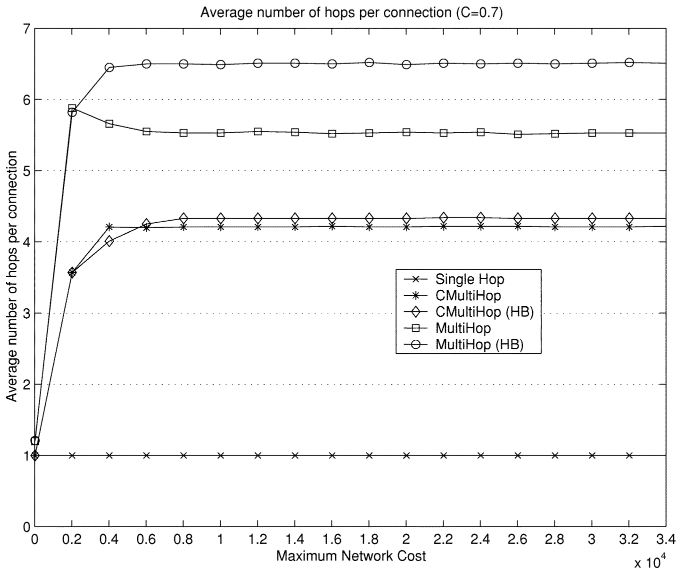

Fig. 2. Average number of hops per connection as a function of the maximum network cost value. Each curve characterized by a different dot shape corresponds to a different path selection strategy. HB corresponds to high bandwidth availability in each terminal.

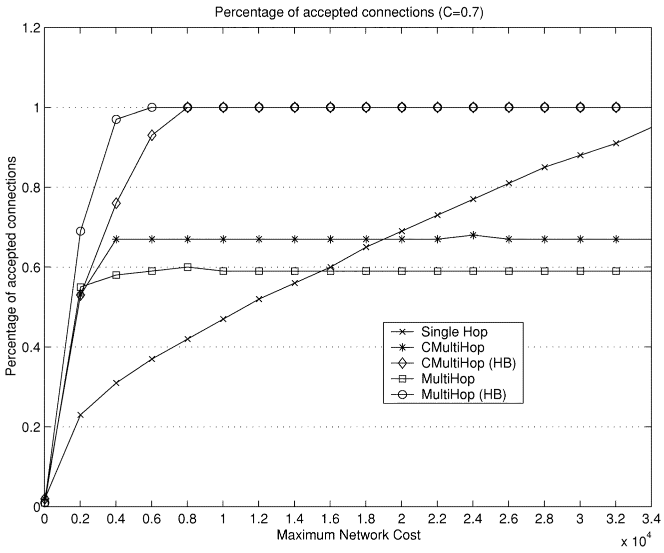

Fig. 3. Percentage of accepted connections as a function of the maximum network cost value. Each curve characterized by a different dot shape corresponds to a different path selection strategy. HB corresponds to high bandwidth availability in each terminal.

a negative exponential distribution, with average value equal to 1 s; 2) the duration of the connections also follows a negative exponential distribution, with average 180 s; and 3) source and destination nodes are selected with a uniform distribution over all nodes. We have used various cluster sizes but here we report the results for clusters of size five (node plus two immediate neighbors on each side) and ∞ corresponding to the case where each node can in principle be reached in a single hop. We compare the performance of the routing algorithm in three different regimes.

1) *Single-Hop*: infinite clusters, only single-hop connections are admissible, $C\max$. Thus, a node tries to connect directly to its destination. If the connection is admissible it is accepted otherwise it is rejected.
2) *Multi-Hop*: infinite clusters, $C\max$. Thus, a node will use whichever path is least costly under the global $C\max$ constraint (Dijkstra on original graph).
3) *Clustered-Multi-Hop or CMulti-Hop*: clusters of size five, $C\max$. Similar to the previous case, except that hops are allowed only between nodes that belong to the same cluster and no two hops are in the same cluster, with the exception of the link associated with the destination node (Dijkstra on line graph).

The comparison of the three algorithms should allow one to better understand the tradeoffs between power saving and QoS in a UWB multihop low-interference network. The three algorithms are tested and compared for a value of the setup cost coefficient C_2 (8) equal to 0.7, which corresponds to a high setup cost environment, while varying the NC maximum value $C\max$. Other parameters are set as follows: $\alpha = 2$, $C_1 = 1$, R randomly selected over an uniform distribution. In order to analyze the properties of the network, we compute the following quantities: 1) average number of hops per connection (basically a QoS indicator); and 2) percentage of accepted requests (an important parameter in a limited-cost environment).

Simulation results are presented in Figs. 2 and 3 (average number of hops and percentage of accepted connection requests, respectively, as a function of NC maximum value $C\max$). In both figures, $C\max$ varies from an extremely low (20) to a very large value (35 920). Results show that in a high setup cost environment with a strong constraint on maximum cost (left side on both figures) the Single-Hop algorithm leads to a low percentage of accepted requests and allows only a small number of active connections. With the use of the Multi-Hop algorithm, on the contrary, the number of accepted connections grows much faster for increasing $C\max$, and the average number of hops is high. Also note that with the assumed value of available bandwidth, there is a saturation effect due to the heavy use of local links, and the system converges to rejecting any connection request even for an unlimited $C\max$. We, thus, increased the available bandwidth at each node (HB curves in the figures) and verified that in this case the Multi-Hop algorithm behaves in a saturation-free fashion, i.e., it quickly converges to 100% of accepted requests. The CMulti-Hop algorithm leads to higher percentage values of accepted requests than both Single-Hop and Multi-Hop. The saturation effect is still present but happens at higher percentages than the Multi-Hop, with standard bandwidth values. As predicted, the cluster structure induces a reduction in the number of hops compared with the Multi-Hop (Fig. 2) and limits local links usage. In summary, the CMulti-Hop algorithm leads to a lower average number of hops which is a positive fact under QoS constraints while guaranteeing a high percentage of accepted requests also in the case of limited available bandwidth at the node.

V. EXTENSIONS AND CONCLUSION

In this paper, we propose a model for a distributed wireless system and construct a realistic set of parameters and associated class of cost functions. We provide results obtained by simulation that corroborate the above methodologies, and provide directions for future research. The peculiar characteristics of the

UWB radio channel offer new solutions and opportunities for resource management and networking. The introduction of a cluster structure, based on localization information, allows us to develop a local routing algorithm which takes into account UWB requirements (high setup cost, power limitation) and at the same time leverages UWB advantages such as precision ranging.

The proposed CMulti-Hop algorithm allows a high number of connections to be instaured while limiting the number of hops. Furthermore, its variable cluster size enables fine performance tuning. Thus, CMulti-Hop appears to be a good solution for local level routing, which can be applied in combination with a more scalable routing protocol, for example AODV (Ad Hoc On-demand Distance Vector) [30], for global level routing. In the framework described, optimization of the communication path is based on the premise that each node has a global view of the network. In particular, each node must know not only the position of each other node, but also the SNR, available power, identity (for instance Internet protocol (IP) address) and available capacity of each node. This information, including the position in the case of mobile nodes, varies in time and must be periodically updated. Thus, three problems must be addressed: 1) how to get the information; 2) how to broadcast it across both small and large networks; and 3) how to deal with mobility. It is clear how each node can monitor available power and SNR. Thus, the first question boils down to position information.

A. Position Information and Precision Ranging

In some applications with fixed nodes, the position may be known in advance (sensors in a building structure) and "hardwired." In the case of a blanket of sensors deployed on the fly, even if the sensors are fixed their location relative to each other must be determined. In three dimensions relative position with respect to four other points in general position completely determines the relative location. UWB being originally a radar technique, it should in principle allow for precision ranging. The basic scheme that can be used is to first use power to find local distances approximately and then use delays to get a more accurate estimate of the relative distances. In this respect, it may be easier to deal with short distances. Thus, in a dense blanket of sensors, each sensor could determine the relative distance of its most immediate neighbors with good precision. Mixed schemes involving GPS techniques could be envisioned in some cases but are likely to be much less desirable because they would be more costly, consume more power, and would not function properly in indoor environments.

B. Broadcasting Information, Common Channel, and Large Networks

Once the position information has been gathered (this could be done once for all or periodically) the nodes could start broadcasting to each other positional and other relevant information, some of which (SNR, capacity, etc.) is likely to be more dynamic than the positional information. Additional information may be broadcasted in order to synchronize clocks and get clock stability in the gigahertz range using slower standard quartz clocks operating in the megahertz range using network synchronization. A common channel in frequency or rather time could be reserved for the broadcast of this network information. The signaling common channel to broadcast positional and routing information is a feasible solution as long as we consider a situation in which every node is reachable by all other nodes: in the case of a large scale network (i.e., a network with a spatial diameter which far exceeds the radio-coverage of a single node) an additional protocol based on information relaying between neighboring nodes is required to broadcast the routing information across the network. Two main objectives for such a protocol can be identified.

1) To minimize the number of signaling-packets transmissions, avoiding as much as possible multiple transmissions of the same signaling packet: this is obviously a main issue in a limited-power ad hoc network, in which signaling packets reduce the available power for data traffic.
2) To allow a fast diffusion of up-to-date routing information all over the network, reducing routing errors due to stale or erroneous information about network topology and link congestion: this is a key property in a network of mobile nodes, where topology changes are frequent.

Flooding is an example of broadcasting algorithm, adopted in several wide area networks, starting from ARPANET [31]. This protocol requires a node to broadcast an update information packet to all neighbors every time it detects a topology change. In turn, each node which receives an update information packet must relay it to all its neighbors, except the originator of the packet, until the packet has been received by each node in the entire network. The algorithm uses sequence numbers to avoid multiple transmission of the same packet and to distinguish new and old information, combined with periodic updates to solve problems related to occasional errors in sequence numbers due to hardware or software failures. Variants without sequence numbers have also been proposed, such as the Shortest Path Topology Algorithm of [32].

C. Mobility

Finally, the use of positional information and flooding in ad hoc wireless networks becomes particularly challenging when the nodes are mobile. While a study of mobility in UWB ad hoc networks is beyond the scope of this paper, it is clear that mobility and its parameters must be tied with specific applications. In particular, if a UWB network is to handle mobility, then the computing power and switching speed of the nodes and their ability to localize other nodes with reasonable precision even when they are moving must be matched against the velocity of the nodes, their typical distance separation, and the density of movement in the network. Different approaches are likely to be necessary to address different regimes ranging from the intractable case of a very dense network of highly mobile nodes moving at very high speeds to the case of a network where at any time very few nodes are moving at very low speeds. If very few nodes are moving at very low or even medium speeds, the framework above can be used with minor modifications. All the nodes, whether fixed or mobile, have a global view of the entire network and can optimize routing strategies using a version of the algorithm described above that takes into account motion considerations. Mobile nodes could be allowed only as

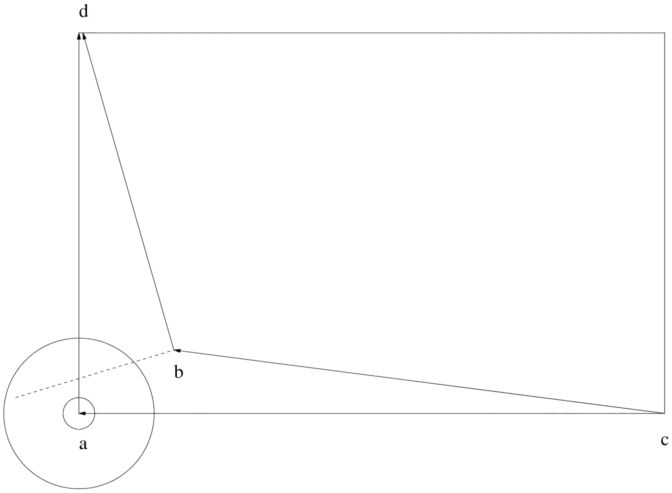

Fig. 4. A portion of a network containing 4 nodes and a multihop communication path including a hop from c to a, and one from a to d. b is moving relative to the three other nodes. a follows the motion of b in the ring around a delimited by the radiuses r and R. a hands over its hopping function along the communication path to b. For $\alpha \geq 2$ and everything else being equal, as long as b remains inside the rectangle in the figure, the power cost associated with the hop through b is less than the power cost of the hop through a.

sources or destinations of links, but not used as intermediate steps. In this view, motion is handled as a small "hindrance." As the fraction of moving nodes at any given time is increased, this approach becomes less and less efficient since the number of nodes available for intermediate routing purposes diminishes accordingly. However, as long as the velocity of the nodes remains relatively small compared with the computing and other resources of each node, it may be possible instead to take advantage of motion, especially in a dense network of highly mobile, but slow, nodes. This could be the case, for instance, of an ad hoc wireless network on a ground battlefield or in a conference center. Indeed, let us assume that nodes can easily compute the position and velocity of nodes in their neighborhood. We can also introduce a minimal separation distance to avoid excessive angular velocities—in other words, a node in the network follows the motion of objects located inside a ring delimited by two radiuses r and R (Fig. 4). Now consider two nodes a and b, assuming for simplicity that a is fixed and b moving through the ring around a. A simple "ball game" algorithm can be described where, in its most simple form, a hands over to b all the connections that can benefit from the general motion direction of b. Likewise, b may hand over to or exchange similar corresponding links with a. In practice, the computation of whether a given direction of motion is advantageous with respect to a given communication path can be more complex and involve other factors, including the location of multiple nodes (as a minimum: a, b and the immediate neighbors of a in the corresponding path). Naturally, in this scheme each node ought to maintain a prioritized list (depending on multiple criteria from QoS, to velocities, etc.) of active links and hand over only some of them to passing nodes. The hand over of course is different depending whether a is the source, sink, or intermediate node of the corresponding communication and may require coordination with at least two other participating nodes (Fig. 4). Thus, in this regime, the nodes are playing a sort of gigantic ball game, where each player passes one or several balls to any other player that is running in the "right" direction. The ball game algorithm is completely distributed, robust, and has a tendency to further reduce link length and power consumption.

APPENDIX

The probability of error P_e is given by

$$P_e = \left(1 - \frac{1}{L}\right) erfc\{y\} \tag{14}$$

where

$$y^2 = \frac{E_b}{N_0} \times \frac{3\log_2 L}{2(L^2-1)} \frac{1}{(1-\gamma/4)(1+\gamma)} \tag{15}$$

or

$$y^2 = \frac{\mathrm{SNR}}{\frac{2}{3}(L^2-1)(1-\gamma/4)}. \tag{16}$$

In these equations, L is the number of symbols, E_b is the energy per bit, N_0 noise power spectral density, γ roll-off of the transmission filter. In our case, $L = 2$ and $\gamma \approx 0$ yield

$$P_e = P_b \approx \frac{1}{2} erfc\left(\sqrt{\frac{\mathrm{SNR}}{2}}\right). \tag{17}$$

Let P be the power of the useful signal, P_n the power of thermal noise, and P_I be the power of multiuser interference. The thermal SNR is $\mathrm{SNR}_T = P/P_n$, and the interference SNR is $\mathrm{SNR}_I = P/P_I$. The global SNR is given by

$$\mathrm{SNR}_G = \frac{P}{P_n + P_I} = \left(\mathrm{SNR}_T^{-1} + \mathrm{SNR}_I^{-1}\right)^{-1}. \tag{18}$$

Suppose that the network must operate at a fixed probability of error P_e which corresponds to a given SNR value SNR^* in the form

$$P_e \approx \frac{1}{2} erfc\left(\sqrt{\frac{\mathrm{SNR}^*}{2}}\right) \tag{19}$$

when only thermal noise is present. In this case, $\mathrm{SNR} = \mathrm{SNR}_T$. When interference noise is also present, then SNR drops down to SNR_G. In order to maintain the same error P_e, SNR_G must be increased to a new value SNR'_G such that $\mathrm{SNR}'_G = \mathrm{SNR}^* = \mathrm{SNR}_T$. This can be achieved by increasing P to P', all the rest being equal, so that

$$\mathrm{SNR}'_G = \frac{P'}{P_n + P_I} = \frac{P}{P_n} = \mathrm{SNR}_T \tag{20}$$

or, equivalently

$$\frac{P'}{P} = \frac{\mathrm{SNR}_T}{\mathrm{SNR}_G} = 1 + \frac{P_I}{P_n} \tag{21}$$

yielding $\Delta P = P' - P$ in decibels

$$\Delta P = 10\log_{10}\left(1 + \frac{P_I}{P_n}\right). \tag{22}$$

In particular

$$P_n = \frac{1}{2} kT_S \times 2\frac{f_L}{2}(1+\gamma) \tag{23}$$

and if $\gamma = 0$

$$P_n = \tfrac{1}{2} kT_S f_L \tag{24}$$

where $f_L = N_S R$ is the pulse repetition rate, i.e., the number of pulses per second, R is the transmission rate (bits per second), and N_S is the number of pulses per bit. Thus

$$P_n = \tfrac{1}{2} k T_S N_S R. \tag{25}$$

From [1],

$$P_I = N_S \sum_{k=2}^{N_U} P_I^{(k)} \tag{26}$$

in which $P_I^{(k)}$ is the interference power of user k referred to a single pulse at the receiver and N_U is the number of interfering users. If $\overline{P}_I$ is the average interference [or under the hypothesis of perfect power control all $P_I^{(k)}$ at the receiver are identical and equal to $\overline{P}_I$] then

$$P_I = N_S (N_U - 1) \overline{P}_I. \tag{27}$$

Thus, in summary

$$\frac{P'}{P} = 1 + \frac{P_I}{P_n} = 1 + \frac{N_S (N_U - 1)\overline{P}_I}{\frac{1}{2} k T_S N_S R} = 1 + \frac{(N_U - 1)\overline{P}_I}{\frac{1}{2} k T_S R}. \tag{28}$$

In order to express ΔP as a function of SNR_G, one can write

$$\begin{aligned}\frac{P'}{P} &= 1 + \frac{P_I}{P_n} = \left[\frac{P_n}{P_n + P_I}\right]^{-1} \\ &= \left[1 - \frac{P P_I}{P(P_n + P_I)}\right]^{-1} = \left[1 - \frac{SNR_G}{SNR_I}\right]^{-1}. \end{aligned} \tag{29}$$

The interference term in the cost function should be a function of P'/P, i.e., $f(P_b, R, N_U, \overline{P}_I)$.

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Pierre Baldi received the Ph.D. degree in mathematics from the California Institute of Technology, Pasedena, in 1986. From 1986 to 1988, he was a Postdoctoral Fellow at the University of California, San Diego.

He is a Professor in the Department of Information and Computer Science and Application Layer Leader of the California Institute for Telecommunications and Information Technology [CAL(IT)2], University of California, Irvine (UCI). From 1988 to 1995, he held Faculty and Member of the Technical Staff positions at the California Institute of Technology and at the Jet Propulsion Laboratory. He was CEO of a startup company from 1995 to 1999 and joined UCI in 1999. He is the author of over 100 scientific articles and three books. His research focuses on probabilistic modeling and statistical inference, data mining, machine learning, bioinformatics, and communication networks.

Dr. Baldi is the recipient of a 1993 Lew Allen Award at the Jet Propulsion Laboratory and a Laurel Wilkening Faculty Innovation Award at UCI.

Luca De Nardis received the Laurea degree in telecommunications engineering from the University of Rome, La Sapienza, Italy, in 2001, with a thesis on wireless network topologies in the framework of the European project whyless.com. Currently, he is working toward the Ph.D. degree in information and communication theory in the INFOCOM Department of the University of Rome.

His research focuses on UWB technology, ad hoc communication networks organization, and routing protocols.

Maria-Gabriella Di Benedetto received the Laurea degree in electrical engineering (*magna cum laude*) in 1981 and the Ph.D. degree in electrical communications in 1987, both from the University of Rome, La Sapienza, Italy.

In 1991, she joined the Faculty of the University of Rome, La Sapienza, where she is currently a Full Professor of information and communication theory in the INFOCOM Department. She has held Associate Professor and other visiting positions at the Massachusetts Institute of Technology, Cambridge, the University of California, Berkeley, and the University of Paris (Paris Sud), France. Her research interests include speech analysis and synthesis, and digital communication systems. She has also been involved in consulting activities, including standardization and performance evaluation work. From 1995 to 2000, she directed four European projects (Median, Secoms, Cobuco, and Mostrain) for the design of the third-generation European mobile radio system UMTS. Since 2000, she has been active in fostering the development of UWB telecommunication systems in Europe. Currently, she is the Director of two European projects (whyless.com and UCAN) for the design and implementation of UWB wireless systems and a national project on multicarrier CDMA WLANs.

Dr. Di Benedetto received the Mac Kay Professorship Award from the University of California, Berkeley, in 1994.