Does Multi-Hop Communication Reduce Electromagnetic Exposure?

JEAN-PIERRE EBERT, DANIEL HOLLOS, HOLGER KARL AND MARC LÖBBERS

Technical University Berlin, Telecommunication Networks Chair, Germany
Email: ebert|karl@ieee.org

Wide-spread concerns about potential health hazards caused by electromagnetic exposure have been raised in many countries. Although there is no ultimate consensus on radiation power levels and their respective impacts on human health, methods are necessary to reduce exposure as much as possible because of the rapid deployment of wireless communications systems. In our work we scrutinize the exposure reduction potential of the multi-hopping approach for two standardized but different wireless network types: IEEE 802.11b as a representative example for networks with distributed channel access control and HIPERLAN/2 as a representative example for centrally controlled networks. Our results show that multi-hopping has the potential to reduce the received electromagnetic power and energy for both network types although it suffers from a decreased network capacity. When attempting to compensate for this decrease by adapting the data rate used over an individual link, the ensuing transmission power adaptation required to maintain acceptable error rates does not necessarily neutralize the benefit of multi-hopping. We show that the sophisticated use of multi-hopping in conjunction with data rate adaption positively affects the received electromagnetic power and energy.

Keywords: Multi-hop, Electromagnetic exposure, Power control, Rate adaption, IEEE 802.11, HIPERLAN/2

1. INTRODUCTION

In many countries the success and deployment of wireless and mobile communication has been quickly followed by wide-spread concerns about potential health hazards caused by electro-magnetic radiation, which is indispensable for wireless communication. This concern is understandable, especially as some wireless technologies operate in the same frequency bands that are used by microwave ovens. Surely, there must be danger involved? In some countries, e.g., Germany, public concerns have risen to a level that make it difficult for mobile operators to install new base stations, especially in the vicinity of kindergartens or schools.

The reaction of the mobile industry, governments, and the research community has been mostly two-pronged. First, a lot of effort has been spent on assessing the actual health risks by investigating how electro-magnetic radiation in the relevant frequency bands can harm biological tissue, and by looking for statistical evidence that people exposed to such radiation (e.g., living close to base stations) are negatively affected in a statistically significant way. While there have been a number of reports of isolated cases of such effects in the popular press, the overwhelming majority of these research efforts has failed to show any relevant effects. These results notwithstanding, the second reaction has been to attempt to make wireless communication as energy-efficient as possible, trying to limit the power that is radiated by a transmitter – research that is necessary anyway, if only to increase the operational time of a mobile device relying on the limited energy stored in a battery.

Increasing the energy efficiency of wireless communication has been pursued using a number of different mechanisms [1, 2]. One particularly popular approach is using wireless multi-hop communication. This concept is well known and necessary for ad hoc networks where two communicating peers normally are out of reach, but has also been increasingly researched in the context of cellular architectures [3, 4, 5].

The intuition why multi-hopping should improve energy efficiency in the wireless case is the more-than-linear path loss. The power P of a transmitted signal is attenuated over the wireless channel by a factor that is proportional to the distance d between sender and receiver, raised to the path loss coefficient α – put briefly, $P_{\text{received}} \sim P_{\text{transmitted}}/d^{\alpha}$. Hence, to ensure the same received power level (actually, the same signal to noise ratio at the receiver), communication over shorter distances requires considerably less radiated power than over long distances. Consequently, cutting the distance in half and transmitting the same message twice reduces the total radiated power: $d^{\alpha} > 2 \cdot (d/2)^{\alpha}$ for $\alpha > 1$.

Therefore, it appears obvious that multi-hop communication improves energy efficiency and reduces electromagnetic radiation. While this question is not so trivial even for energy efficiency[1], it is also not clear regarding expo-

[1] Many papers on this topic make overly simplistic assumptions on the relationship between actually radiated power and power consumed for transmission. Some even completely neglect the power consumption for

sure. Indeed, the transmission power level can be reduced, but only at the cost of longer transmission times (with only one relay node, a message has to be transmitted twice instead of once), trading off lower transmission power against longer transmission time. This trade-off can be generalized if, for example, adaptive modulation schemes are taken into account: When introducing a relay node, is it preferable to reduce transmission power and increase time? Or is it better to switch to a more complex modulation scheme that requires a better signal-to-noise ratio (SNR), preventing the reduction of transmission power, but also reducing the time in the costly transmission mode.

Such an adaptive modulation scheme in the relaying case also ties in with the capacity question for multi-hop networks. Well-known theoretical results [7] describe the limited capacity of multi-hop networks. One way to combat this effect (up to a certain point) is to use faster modulation schemes that are possible over the shorter communication distances provided by multi-hopping. The question is how to compare systems regarding electro-magnetic radiation. Evidently, relaying can reduce radiation to almost nothing (many hops over close-by relayers), but then the system capacity is severely reduced. Does multi-hopping, therefore, still reduce radiation exposure when adaptive modulation schemes are used to maintain system capacity?

In the remainder of this paper we try to answer this crucial question. For this purpose we scrutinize two different wireless network types: A network with central control and a network with distributed control. Section 2 describes how we use both the distributedly controlled IEEE 802.11b and the centrally controlled HIPERLAN/2 as the basis for this investigations. In Section 3, we describe the metrics that are used to characterize the impact of electromagnetic radiation exposure and then discuss the details of the simulation setup: The network scenarios, the load models, and the placement of points where the received transmission power is measured. In Section 4, we present the measurement results and in Section 5, we discuss these results and draw conclusions of our investigations.

2. MODEL ASSUMPTIONS

Medium access control, transmission power and data rate adaptation, and the routing process are the most relevant aspects in multi-hop communication. The following sections describe these three aspects with respect to IEEE 802.11b [8] and HIPERLAN/2 [9, 10, 11], the two wireless LAN technologies that we chose for this investigation.

2.1. Medium access control

These two technologies represent two fundamentally different approaches to wireless communication. IEEE 802.11b is decentralized in its operation, whereas HIPERLAN/2 employs a Media Access Control (MAC) structure that is strictly organized in time, removing the danger of collisions between data packets at the cost of additional organization overhead.

2.1.1. IEEE 802.11b

IEEE 802.11b is a member of the IEEE 802 standards family. It is particularly designed to support communication in locally limited premises. It is based on a distributed medium access control known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Although central control is optionally possible, it is rarely implemented in commercially available IEEE 802.11b products and therefore rarely used. IEEE 802.11b networks support modulation types with data rates from 1 or 2 Mbit/s up to 5.5 or 11 Mbit/s. IEEE 802.11b networks operate in the 2.4 GHz frequency band, the same one that microwave ovens use. Related standards are IEEE 802.11 (2 Mbit/s), IEEE 802.11a (up to 54Mbit/s), and IEEE 802.11g, which is basically a merger of the aforementioned standards. They work in the same frequency band except IEEE 802.11a, which operates at 5 GHz.

In our work we consider a self-organizing IEEE 802.11b network with one base station (synonymously referred to as an access point) as a bridge to a backbone network. A key characteristic of such a network is the distributed arbitration of the channel access. Every wireless network node, including the base station, autonomously decides when to access the channel based on local information. For this purpose, a CSMA/CA protocol is used. CSMA/CA resembles a Listen-Before-Talk protocol with a collision avoidance component using a random delay determined by a binary exponential backoff approach. There are several optional MAC protocol additions such as packet fragmentation, hidden terminal handling, power saving, and packet retransmission. The advantages of this type of MAC protocol are flexibility and short access delays. The price to pay is increased complexity in every wireless node and reduced efficiency for higher load conditions. As the load approaches about half of the network capacity, limitations of this MAC protocol begin to appear.

The atomic transmission operation is a data-acknowledgment frame exchange. A station that wants to transmit a frame transmits it immediately if no other ongoing transmission by other nodes is detected. The intended receiver responds immediately with an acknowledgment indicating the correct reception of the packet. If the channel is busy, a potential sender backs off until the channel becomes idle. The sender assumes competition with other potential senders and waits a random amount of time before trying to send its frame after the channel becomes free. The channel is sensed during the backoff and the frame transmission process will start afterwards if no other transmission is detected. If a transmission failure is indicated by a missing acknowledgment, a collision is assumed, although the frame might be corrupted due to other reasons.[2] To avoid further collisions, the channel access of involved nodes

relaying nodes, etc. Reference [6] lists some common misconceptions.

[2] In wireless communication it is hardly possible to differentiate between errors caused by collisions and other reasons.

is "deskewed" by using larger, but still bounded random backoffs in the next access cycle for frame retransmissions.

Building a multi-hop network on the basis of IEEE 802.11b's distributed MAC is easily possible by leaving the physical and MAC layer untouched and adding software for relaying/forwarding and routing issues. But autonomous channel access decisions of wireless nodes are also the pitfall for IEEE 802.11b multi-hop networks, since hidden terminals are the inevitable consequence. Hidden terminals are the main reason for poor network performance as shown in [12]. This may be partially compensated for by using the RTS/CTS mechanism.

FIGURE 1. HIPERLAN/2 MAC frame structure

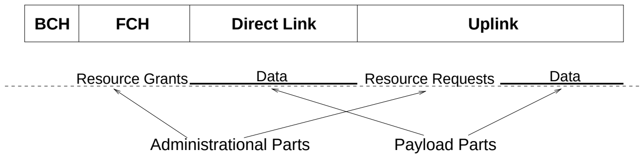

FIGURE 2. H/2 MAC frame layout with polled RRs – relay mode

2.1.2. HIPERLAN/2

HIPERLAN/2 is a wireless LAN system standardized by ETSI for the 5.2 GHz range. It is mostly aimed at low-mobility scenarios and includes modulation schemes of up to 54 Mbit/s. One of its design goals is to maximize the utilization of the radio channel. The main mechanism to achieve this goal (and the most important difference to IEEE 802.11b) is the use of an a priori scheduled medium access. Among a set of stations (a so-called radio cell) one station is declared to be the central controller (CC). Any station that wants to communicate with another station has to announce this to the CC, which then allocates time slots in a periodically repeated frame to this station. Hence, HIPERLAN/2 uses a connection-oriented, centrally scheduled time division multiple access (TDMA) to organize the medium access. The main benefits are collision-free data traffic and straightforward support for priorities or QoS requirements.

A typical HIPERLAN/2 transmission consists of the following steps: First, a station that has data to send announces this by transmitting a query packet (Resource Request) to its CC including the number of packets to send. Second, the CC assigns time slots for this node (Resource Grant) in one of the following MAC frames. The node is allowed to exclusively send in these allocated slots. The consequence of the central organization is the prevention of data packet collisions.

The centralized architecture allows the CC to plan all transmissions in its cell. This planning, also called scheduling, is done on the basis of a MAC frame. A MAC frame has a constant length (2 milliseconds) and is divided into different phases (Figure 1). In the first phase, the CC broadcasts administrative information on the Broadcast Channel (BCH), which, for example, identifies the cell. The Frame Control Channel (FCH) is a directory of the upcoming MAC frame. It tells every node the organization of the remainder of this MAC frame. It particularly determines transmission order and duration for all nodes. The FCH conveys the Resource Grants (RG). Each RG describes one particular transmission for one node, while one transmission may contain many packets.

This FCH-based MAC frame organization ensures that all devices within the cell know about all MAC frame data transfers, since they all receive the FCH. The FCH structure opens up possibilities to realize various MAC-based improvements of wireless communication, like the Direct Link Mode as defined in the Home Extension of the HIPERLAN/2 standard [10]. This extension allows any two nodes being within each other's radio range to directly exchange data (of course under the control of the CC). We use this possibility to realize relayed data communication in HIPERLAN/2 (see below and reference [13]). The FCH-based frame structure leads to additional benefits, for example, polled resource request handling or the possibility to conduct synchronized measurements of the received signal strength of one sender's signal to determine the channel gain between any two nodes (see Radio Maps in [10]).

Resource request handling The main advantage of a centrally scheduled MAC is the avoidance of collisions for any data packets. However, some control packets may collide. If a node has to transmit data, it communicates its details to the CC using resource request packets. Such packets can not be scheduled a priori. In principle, this problem can be solved in two ways: resource requests can be sent during the Random Access Channel (RCH) phase of the HIPERLAN/2 MAC frame, possibly resulting in collisions with other, similar requests. Such a mechanism is defined in the standard to notify stations about the success of their RCH access [9]. Alternatively, the CC of a cell can periodically assign uplink transmission time slots for resource request packets to each node, thus giving them the possibility to request new resources. In this case there are no collisions in the MAC frame at all, at the expense that this permanent polling may produce a large number of control packets depending on the total number of nodes in the cell.

In this paper, we opted for the second solution to filter out ambiguous behavior due to colliding resource requests. The results show the disadvantages of this solution (see Section 4.2). A significant part of the MAC frame is used to (i) signal the uplink transmission to many nodes individually (in the FCH this means a nine-byte slot per node) and (ii) these nodes send their RRs in every MAC frame even if there is not enough space in that MAC frame to schedule real transmissions for all of them. Realizing the above in this model, the MAC frame has the (ETSI standard-conform) layout shown in Figure 2.

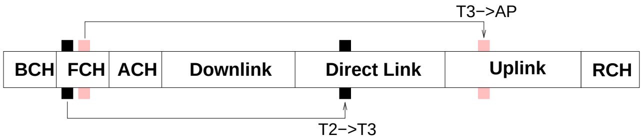

FIGURE 3. Relaying within the HIPERLAN/2 frame structure

HIPERLAN/2 scheduler After receiving these requests the CC scheduler has to decide which nodes are allowed to send and how many slots a node can use in a certain MAC frame. This is trivial as long as the traffic can be served. The load model used here, however, will permanently overload the MAC frames as assumed before. The choice between nodes could be performed on the basis of the individual nodes. In the relaying case, however, this would lead to unfairness, since the relayer nodes may have to carry much more load than the others. Therefore, we schedule the transmission on a flow basis. Our scheduler assigns resources to flows in every MAC frame trading off reduced switching overheads between different flows against additional delays. To ensure fairness between different flows, the scheduler applies a simple round-robin strategy over several frames.

The scheduler also determines which nodes to poll in a certain MAC frame for resource requests. According to the HIPERLAN/2 standard there can be a maximum of 16 RGs per MAC frame including RGs for RRs and RGs for data transmission. This together with the BCH would mean that approximately 30% of the MAC frames are spent for administration. To limit the overhead, we programmed the scheduler in a way that the overhead cannot exceed 20%. This is achieved by limiting the number of nodes that are allowed to register for new resources. Eventually, there is more time for data communication. The nodes to be polled for RRs are selected according to the well-known round-robin strategy.

HIPERLAN/2 relaying extension HIPERLAN/2 per se does not support multi-hop communication. To enable the relaying capability, we developed the Single Hop Relaying (SHR) protocol [13] briefly summarized here. This protocol is specifically geared towards an efficient and simple relaying solution within a single HIPERLAN/2 cell. Other multi-hop extensions to HIPERLAN/2 concentrate on coverage extension of a single access point, are more complex, and have a higher overhead.

As SHR is only expected to work within a single cell, it can make use of the MAC frame information broadcast by the CC. As mentioned before, the CC may assign data communication time slots during the so-called direct link phase of a MAC frame. In this phase nodes can directly send data to each other. The SHR protocol exploits this feature to establish a connection between nodes close to the edge of the cell and their corresponding relayers. Relayers forward data to the CC duirng the uplink phase.

The SHR protocol extension fits well into the HIPERLAN/2 standard and allows route path changes even within every MAC frame without additional protocol overhead.

Differences from the ETSI standard Other than the relaying extension, our HIPERLAN/2 MAC model is mostly compliant with the ETSI specification. Two small simplifications were made so far: (i) We did not implement the RCH phase of the standard HIPERLAN/2 MAC frame, as it is not used; (ii) there are fifteen predefined transmission power levels in the standard, but we used arbitrary integer numbers for transmission power values.

2.2. Data rate and transmission power adaptation

The use of data rate adaption in a multi-hop communication system also requires interdependence considerations of transmission power, signal attenuation and path loss model, signal-to-noise ratio, noise level, and resulting modulation-specific bit or packet error rates.

The possible data rates are a given for both systems:1, 2, 5.5, and 11 MBit/s for IEEE 802.11b, and 6, 12, 18, 27, 36, and 54 MBit/s for HIPERLAN/2.[3] These data rates result from different combinations of modulation and coding on the physical level. For each of these data rates, a mapping from signal-to-noise ratio to BER or PER can be computed. We set a maximum acceptable BER or PER that must not be exceeded in absence of any interference. Using the inverse of this mapping we calculate the required SNR for a given data rate. Hence, the noise level and the path loss model are used to determine the transmission power as a function of the distance between sender and receiver, which should be used to ensure the desired bit or packet error rate. Some aspects are identical for both systems considered here. Some details differ slightly. They are described in the following subsections.

2.2.1. IEEE 802.11b

Determining the transmission power The transmission power for any wireless node is set to achieve a target bit error rate of 10^{-8} at the intended receiver (in absence of any interference). For any given data rate (a combination of modulation and coding) a target bit error rate determines a target SNR.

Once the SNR is known it is easy to calculate the required transmission power [15, 16]. We assume an additive White Gaussian Noise (AWGN) channel and only take the distance into account using a simple line-of-sight path-loss model with a path-loss coefficient of $\alpha = 2.8$.[4] In addition, further assumptions of antenna gain, thermal noise and receiver

[3] There also is a 9 MBit/s data rate in HIPERLAN/2 that is omitted in our experiment for the sake of clarity. For certain PERs and path loss assumptions the SNR versus data rate developes non-monotonous at 9 Mbit/s, making the results harder to analyze. The reason is a signal quality leap due to the use of different coding/modulation scheme combinations for every transmission rate. The particular coding/modulation scheme combination at 9 Mbit/s does more than compensating increased SNR requirements coming along with higher transmission rates [14].

[4] This corresponds to a simple free-space model. Indoor applications would see larger α's, but the principal results of this paper should not be affected by the choice of α.

noise floor are necessary[5]. These calculations are essentially identical for both IEEE 802.11b and HIPERLAN/2.

The more interesting part is the determination of the required SNR. Evidently, it strongly depends on the type of modulation. Given a specific digital modulation scheme, the required SNR is a function of the bit error rate, which in turn depends on the ratio of energy per bit to noise power $\frac{E_\mathrm{b}}{N_0}$:

$$\mathrm{SNR} = \frac{E_\mathrm{b}}{N_0} \cdot \frac{R}{B_\mathrm{T}}, \tag{1}$$

where R is the respective data rate and B_T is the despreaded channel bandwidth of 2 MHz. R can be any of the four IEEE 802.11b data rates 1, 2, 5.5, or 11 MBit/s.

While the 1 and 2 MBit/s rates are straightforward to model, the higher speeds are not trivial. For 5.5 and 11 Mbit/s, Complementary Code Keying (CCK) modulation is used, which can hardly be solved analytically and is demanding to model. Instead we use Quadrature Amplitude Modulation (QAM) for simplicity. A 16-QAM modulation is used for 5.5 Mbit/s and a 256-QAM modulation is used for 11 Mbit/s to permit for an analytically solution. The M-ary QAM modulation is very well documented (see, e.g., reference [17]), and according to references [18] and [19], results comparable to CCK modulation can be expected. Hence the BER can be computed for an Additive White Gaussian Noise (AWGN) channel using Equation (2) for Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) modulation, and Equation (3) for 16-QAM and 256-QAM.

$$\mathrm{BER} = \frac{1}{2} e^{-\frac{E_\mathrm{b}}{N_0}} \tag{2}$$

$$\mathrm{BER} = \frac{2}{m}\left(1 - \frac{1}{\sqrt{M}}\right) \mathrm{erfc} \frac{E_\mathrm{b}}{N_0} \tag{3}$$

The equation above can be solved for E_b/N_0, which in turn can be used to compute the SNR (see Equation 1). The required power at the receiver (P_rx) can be computed as $P_\mathrm{rx} = N + \mathrm{SNR}$, where N is the thermal channel noise simplified. The required power at the sender (P_tx) yields, assuming again a simplified case, the required receiver power taking the path loss power (L) into account: $P_\mathrm{tx} = P_\mathrm{rx} + L$.

Calculating the resulting bit error rate The actual (not the target) bit error rate depends on the transmission power, as explained above. But more than one wireless node can send a frame at the same instant in an IEEE 802.11b multi-hop environment, causing interference. Therefore, the resulting bit error rate is computed on the basis of the SignaltoInterferenceandNoiseRatio (SINR):

$$\mathrm{SINR} = \frac{P_i}{N + \sum_{j=1}^{N} Pj}, \; \forall\, i \neq j. \tag{4}$$

[5]For the sake of simplicity we set both antenna gain and receiver noise floor to zero in our computations.

Here, P_i is the received signal strength of the frame to be decoded, P_j is the received signal strength of simultaneously transmitted frames, if any. With the help of Equation 1 and replacing the SNR with SINR we are able to derive $\frac{E_\mathrm{b}}{N_0}$, which in turn is needed to compute the BER according to the used modulation scheme (see Equations 2 and 3). Using the computed BER the resulting packet error rate (PER) can be easily determined as $\mathrm{PER} = 1 - (1 - \mathrm{BER})^n$ for a packet containing n bits (assuming independent bit errors).

Note that a change of the BER during frame reception is also considered since other nodes can arbitrarily start and stop transmissions. This is a more precise model than commonly applied in ad hoc simulations, which faithfully reflects the rather low-level effects that are relevant to assess the impact on received/absorbed power. The packet error rate in turn is used to determine the success/error of an actual packet in a Monte Carlo experiment.

2.2.2. HIPERLAN/2

Determining the transmission power For HIPERLAN/2 we decided to use a target PER of 1% at the receiver. The reason why this differs from the value chosen for IEEE 802.11b (FER $\approx 5.3 \cdot 10^{-7}$ for 54 Byte packets) is that modulation types of HIPERLAN/2 with higher data rates require a rather high SNR. Such a high SNR cannot be achieved by legally limited transmission powers ($P_{\mathrm{Tx,max}} = 200\mathrm{mW}$ [14]). That is a low target PER as we assumed for IEEE 802.11b can never be achieved by HIPERLAN/2 systems using data rates above 27 Mbit/s.

To achieve the chosen PER we used the Carrier to Interference (C/I) mappings presented in reference [14], interpreted as SINR mappings. These curves allowed us to directly compute the required reception power as a function of the target PER, and hence, using the simple path loss model with the same parameters described in Section 2.2.1, we are able to compute the required transmission power for a known distance.

The precise mappings from C/I to packet error rates in reference [14] are somewhat cumbersome to handle. Therefore, we developed a simple exponential fitting for these curves, used as an interpolation [20]. These curves are dercribed by the following equation

$$\mathrm{PER}(s,i) = 10^{a_i s^2 + b_i s + c_i}, \tag{5}$$

where s is the signal-to-noise ratio in [dB] and i denotes the data rate type. The coefficients a_i, b_i, and c_i express the increasing error susceptibility of higher data rates. Particular values are given in Table 1.

The packet error rate is separately calculated during the simulation by the underlying channel model. According to Section 4.2, the PER is not necessarily always exactly 1% because of the power limitation defined in the standard and other simulation-specific circumstances. Whether a packet is correctly received is randomly determined based on the packet error rate. Here the model of packet errors is simpler than for the IEEE 802.11b, since no simultaneous transmissions can occur, which make the computation

Index i	**Modulation** (code rate)	**NBR** (MBit/s)	a_i	b_i	c_i
1	BPSK (1/2)	6	-0.0082614042	-0.0637666870	-0.1966848623
2	BPSK (3/4)	9	-0.0069100746	-0.0117064723	-0.1081958878
3	QPSK (1/2)	12	-0.0096145924	+0.0051584554	-0.1421158176
4	QPSK (3/4)	18	-0.0068952957	+0.0276524790	-0.1096636942
5	16QAM (9/16)	27	-0.0078345999	+0.0819537238	-0.2987070739
6	16QAM (3/4)	36	-0.0070338198	+0.1129774045	-0.5379253079
7	64QAM (3/4)	54	-0.0062322899	+0.1539283419	-0.9948847197

TABLE 1. Parameters for C/I to PER interpolation

of varying bit error rates during a packet transmission superfluous.

2.3. Routing

Beyond the basic question of the medium access and link layer, a multi-hop system has to solve the question which wireless nodes are involved in relaying. A large number of ad hoc routing protocols have been developed to solve this problem [3]. Some are specifically dedicated to minimizing energy consumption (e.g., [1, 4]).

However, solving the routing problem is not the main focus of this paper. We chose the rather simple approach of solving the routing problem off-line based on the knowledge of all node positions. This makes the analysis of the results easier, as the routing overhead can be omitted. Additionally, it is a justifiable simplification. For the HIPERLAN/2 system the routes are explicitly set in the MAC frame by the CC. Since the channel gain matrix is available via synchronized measurements, the scheduler has all the necessary information to chose the optimal paths. Even for the IEEE 802.11b system the scenarios described in the following section are chosen so that only very few hops are necessary to reach the base station. The overhead induced by an ad hoc routing protocol would be small anyway.

The a priori knowledge of node positions allows us to compute the distances and hence the optimal transmission powers between any two nodes based on the data rate dependent transmission power adaptation considerations of Section 2.2. Our results should be interpreted as best case results. They provide insights into the potential and limitations of relaying regarding exposure.

3. EVALUATION

3.1. Metrics

The basic simulation setup used to evaluate the metric received power (as opposed to transmitted power) is shown in Figure 4. The mobile nodes and the base station[6] radiate power. Several measurement points record how much radiation power arrives from every node at any instant. Furthermore, they sum up the received powers resulting in a total received power profile for each measurement point (visualized in Figure 5).

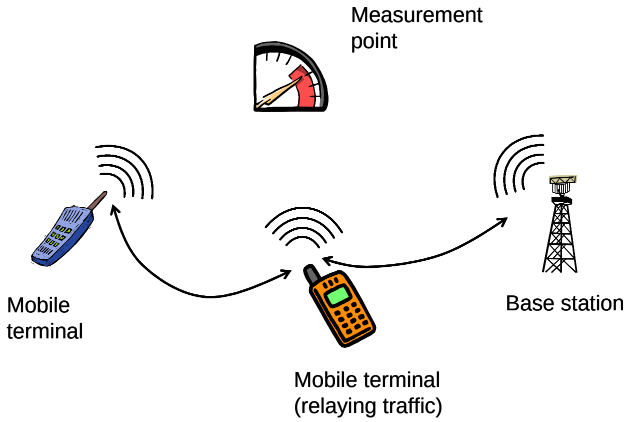

FIGURE 4. Basic measurement setup to capture received power

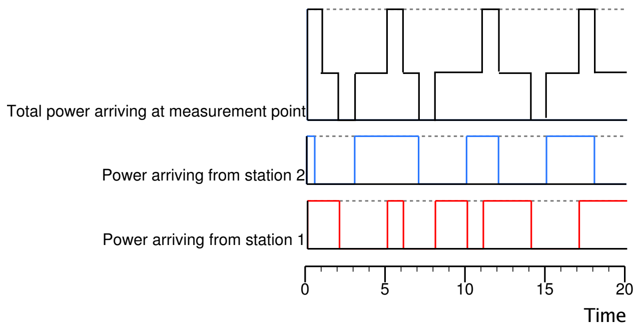

FIGURE 5. Received power profile

These power profiles allow a large variety of aggregated metrics. But evaluating potential health benefits of any mechanism that reduces received power or energy is difficult since the potential risks of electromagnetic exposure are not yet clearly understood. For example, is it more important to consider the received peak power during a longer communication session, or is it more important to reduce the total received energy? It is consequently difficult to express the benefit of multi-hopping in a single metric.

We opted to use the following aggregated representations, averaged over all measurement points and scenarios. A scenario is a particular placement of mobile nodes.

[6] In the rest of the text we also refer to HIPERLAN/2's CC as base station.

Time-weighted average of power What is the time-weighted average of all transmission powers received at a given measurement point? This metric is equivalent to the integral of the total power profile divided by total simulated time.

Distribution of power values What is the relative share of time during which the total received power exceeds a given threshold? We measured the percentage of the time period during which the received power exceeds a certain power level.

Throughput Another interesting metric is the network throughput[7] since it represents the merit or penalty for exposure reduction by the multi-hopping approach.

Energy per goodput bit The average power and the average throughput can be combined into the energy that arrives at a given measurement point per successfully transmitted bit.

These values are averaged over all measurement points (except for throughput, of course) and all mobile node placements. Another obvious metric, the maximum received power, actually contains very little information as it solely depends on the distance of a wireless node to a measurement point. In addition, while relaying has an obvious effect on the maximum, the choice of different modulation schemes does not influence the ratio between direct and relay communication. Hence, we omit the maximum received power from the presentation.

3.2. Simulation setup

We performed simulations with both the IEEE 802.11b model and HIPERLAN/2 model to compute the aforementioned metrics . While these systems are intrinsically different and the results are not directly comparable, we nevertheless used the same basic setup for both systems.

Topology We uniformly distributed 40 nodes over an area of 100 by 100 meters, and additionally placed one base station in the center. This node controls the channel access in HIPERLAN/2 network simulations. 30 nodes actually generate traffic directed towards the base station. The other 10 nodes are solely used for multi-hop relaying, if relaying is activated. All nodes use a given, fixed data rate in a simulation run, either 1, 2, 5.5, or 11 MBit/s for the IEEE 802.11b system simulation or 6, 12, 18, 27, 34, or 54 MBit/s for the HIPERLAN/2 system simulation.

Traffic model As the main objective of our work is to demonstrate the typical received power and energy for these two systems, we assume that both IEEE 802.11 and HIPERLAN/2 are used to maximize the overall throughput. Since the two MAC protocols are basically different, the load models to reach the maximal throughput are different as well.

[7] We actually mean the aggregated end-to-end throughput (goodput).

For the IEEE 802.11 system simulations the 30 traffic generating nodes produce CBR-type traffic with fixed sized packets (54, 1024, 2048 Bytes). The overall network load was adjusted either to constitute approximately 25% of the used transmission rate or exactly 250 kbit/s independently of the transmission rate. The latter is to achieve comparability between setups with different data rates. These network load settings reflect two different usage intentions. In the first case the users are interested in obtaining as much throughput as possible, but especially for IEEE 802.11b, heavy-loaded nodes should be avoided to prevent overtaxing the entire system. In the second case the users are allowed to transmit at a constant rate, which constitutes an overall network of 250 kbit/s. The small 54-byte sized packets are chosen to facilitate the comparison with HIPERLAN/2 while representing a stress test for the IEEE 802.11b-based system.

The HIPERLAN/2 traffic model is simpler for the following reason. Having the centrally controlled, contention-free medium access in mind, the load model cannot decrease the overall system throughput (unlike IEEE 802.11b). Therefore all 30 traffic generating nodes have a packet ready for transmission at any instant. The packet size is fixed to 54 Bytes. Determining the actual number of packets per MAC frame for sender nodes or for data flows is completely up to the CC, which in our case performs a simple fair scheduling (see Section 2.1.2).

In all cases, the ultimate destination of all packets is the base station, which is supposed to transmit this traffic into a fixed network. That is, there is no intra-cell traffic in the network except for the purpose of relaying.

Measurement setup Ten different placements (scenarios) of mobile nodes are randomly created and independently simulated for each combination of traffic, data rate, and system. The resulting (total) received power profiles are accumulated by a grid of measurements points, which are equidistantly placed 10 by 10 meters apart. The measurement point in the middle, which would coincide with the base station, is omitted. Such a placement of mobile nodes, base station and measurement points is sketched in Figure 6. Each measurement point computes its received power profile for each simulation run.

IEEE 802.11b simulations are stopped when a total of 10.000 packets have been correctly received by the base station. The reason for doing so is the high probability of packet collisions. When using a simpler simulated time limit as for HIPERLAN/2 simulations it can happen that just a small amount of packets has been successfully transmitted at the end of a simulation run.

4. RESULTS

4.1. IEEE 802.11b results

The primary metric to look at is the received power averaged over all scenarios, measurement points, and over the entire simulated time. Table 2 shows these values, which are measured in dBm (note that the ratio is therefore the difference of the power values). The table compares the

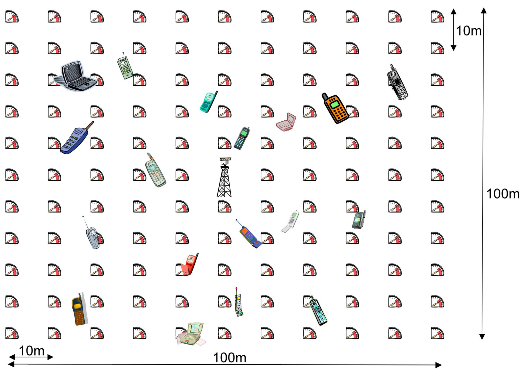

FIGURE 6. Mobile nodes, base station and measurement points

simulation result for relaying versus direct transmission in two different load scenarios (see Section 3.2), for three different packet sizes (50, 1024, and 2048 Bytes) and for every possible transmission rate (1, 2, 5,5, and 11 Mbit/s). Generally, the results clearly state that multi-hopping (relaying) does reduce the average received power depending on the used transmission rate. Typical reductions range from about 3 to 7 dB. The results also reveal that higher date rates lead to a higher exposure and lower gain, which can be explained by the higher RF transmission power necessary to maintain a certain link quality. Smaller packets also result in a slightly higher exposure. This is a result of increasing channel access contention as the packets get smaller but the network load stays at the same value.

These results should be contrasted with the results for the realized network throughput with or without multi-hop relaying. Table 3 shows the expected result. Relaying, if applied in isolation from other mechanisms, reduces the network capacity since the IEEE 802.11b MAC scheme is unable to exploit potential network parallelism and the base station is a bottleneck. For a high network load (25% data rate) and small packets the throughput degradation is considerable. In all other cases there is almost no throughput loss using large packets except for 11 Mbit/s. On the one hand this can be explained by MAC protocol inefficiencies (overhead) for small packets appearing in high load scenarios. On the other hand, the IEEE 802.11 MAC protocol is efficient for higher transmission rates because the ratio of idle times and the actual transmission/reception time becomes worse. Further, small packets introduce additional overhead, which doubles with every relay and takes effect under high load conditions. We conclude that this MAC protocol cannot utilize the available capacity, but the use of larger packets can counteract this inefficiency.

These two tables provide a partial answer to the primary question: How does relaying and data rate adaptation impact capacity and radiation exposure? Relaying will reduce both exposure and throughput, but the latter is an undesirable effect. However, throughput reduction can be compensated by the use of higher transmission rates, which translates in an increased exposure. Therefore, we investigate next, whether a change to the next higher data rate to compensate throughput reduction in the relaying case eats up the relaying exposure gain. For that purpose consider the case of transmitting 1024 Byte packets at a load of 25% of the overall data rate. Table 4 compares the average received power of direct and relay communication, if the data rate in the relaying case is increased to the next higher data rate of the direct case.

While there is no direct match, Table 4 shows that the throughput loss is more than compensated by using a higher data rate for relaying. Although radiation power increases with the use of higher data rates, exposure does not increase — quite the contrary is the case. This comparison of realized throughput and resulting average received power can be further formalized by putting the average received power in relation with the realized throughput, obtaining the average received energy per goodput bit (in the sense of $\mathrm{W}/(\mathrm{bit/s}) = \mathrm{Ws/bit} = \mathrm{J/bit}$).

Table 5 shows these results. Evidently, under this perspective, multi-hopping is an attractive mechanism. It is obvious that relaying of data considerably reduces exposure. Only for very small 54 Byte packets, high network loads, and transmission rates of 5.5 Mbit/s or 11 Mbit/s the average received energy increases. The reason is the inefficiency of the IEEE 802.11 MAC protocol to handle small packets, which increases with the transmission rate and the use of relays. Table 5 also reveals that the average received energy decreases for larger packet sizes as well as for smaller transmission rates for direct transmission.

As we outlined before we do not want to determine which of the metrics most impacts human health. Another approach is to look at the peak power levels to which users are exposed, as it could be beneficial to modify the exposure pattern to smaller values for a longer time, even if the total energy or another metric would be increased, as long as the peak levels are decreased. This information is contained in the distribution functions which show the relative share of time during which a given threshold value is exceeded. Figure 7 illustrates this type of result. It compares the complementary distribution functions for the 1 Mbit/s and 11 MBit/s cases, both direct and relaying, as the probability that a given threshold value of average received power is exceeded. The two curves clearly show that multi-hop relaying shifts the probability mass to smaller values. In addition, multi-hopping only shows disadvantages for very small threshold values (< -83 dBm for 1 Mbit/s and < -76 dBm at 11 Mbit/s).

4.2. HIPERLAN/2 Results

The HIPERLAN/2 results are somewhat different, reflecting its fundamentally different structure compared to IEEE 802.11b. Similar to the previous case we start with the time-weighted received power average shown in Figure 8.

The difference between the direct and relay average received power values is considerable, about $2-6$ dB for all data rates except 54 Mbit/s. This high data rate

	Network load: 25% of data rate				**Network load: 250Kbit/s**			
	50 Byte packets				50 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	-56.87	-55.44	-53.12	-49.98	-56.87	-57.05	-54.16	-51.88
Relay	-63.69	-62.32	-56.34	-53.69	-63.69	-62.47	-58.60	-56.14
Ratio	6.82	6.88	3.22	3.17	6.82	5.42	4.44	4.26
	1024 Byte packets				1024 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	-59.18	-56.75	-51.34	-48.14	-59.18	-59.47	-58.59	-58.47
Relay	-64.69	-62.75	-56.13	-52.98	-64.69	-65.58	-63.48	-63.12
Ratio	5.51	6.00	4.97	4.84	5.51	6.11	4.89	4.65
	2048 Byte packets				2048 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	-59.57	-56.67	-51.53	-48.60	-59.57	-60.08	-59.06	-59.15
Relay	-65.07	-62.75	-56.80	-53.03	-65.07	-65.97	-64.23	-63.53
Ratio	5.50	6.08	5.27	4.43	5.50	5.89	5.17	4.38

TABLE 2. Averaged received power values [dBm] for two types of load, three different packet sizes, and four different data rates

	Network load: 25% of data rate				**Network load: 250Kbit/s**			
	50 Byte packets				50 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	250.0	472.2	673.1	752.9	250.0	250.2	250.1	250.0
Relay	111.7	166.5	252.0	193.6	111.7	239.0	249.5	247.1
Ratio	0.44	0.35	0.37	0.25	0.44	0.95	0.99	0.98
	1024 Byte packets				1024 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	250.2	500.6	1375.3	2749.4	250.2	250.4	250.1	250.0
Relay	250.2	500.2	1365.5	1978.4	250.2	250.3	248.6	242.5
Ratio	0.99	0.99	0.99	0.71	0.99	0.99	0.99	0.96
	2048 Byte packets				2048 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	250.3	500.6	1375.4	2749.4	250.3	250.3	250.2	250.0
Relay	250.2	500.4	1363.6	2424.2	250.2	250.3	248.2	238.8
Ratio	0.99	0.99	0.99	0.88	0.99	0.99	0.99	0.95

TABLE 3. Throughput values (in kbits/s) for two types of load, three different packet sizes, and four data rates

requires a rather high SNR, but the transmission power is legally limited. Therefore, it is not possible to achieve the target PER for the used distances at transmission speeds of 27, 36, and 54 Mbit/s. Even if relayers are used, the target PER is not achieved on the individual hops for 54 Mbit/s. A higher PER means more retransmissions (and interference) causing higher received power averages and a better exposure performance for the direct transmission case at 54 Mbit/s. Nevertheless, if the target PERs can be achieved, multi-hopping is beneficial.

Note that the somewhat volatile behavior of the relay curve in Figure 8, e.g., the average received power in the relay case is only slightly higher for 12 Mbit/s than for 6 Mbit/s, is a simulation model artifact. Short distances and/or low transmission rates imply transmission power values ($P_{\mathrm{Tx}} < 1$ mW) that were rounded up by the simulator to the nearest integer, one. In practice this means that the packets were transmitted using the same power level for the two lowest data rates. In this case exposure only slightly differs.

Comparison example	**Capacity** [Mbit/s]		**Transmission rate** [Mbit/s]		**Average received power** [dBm]	
	direct	relay	direct	relay	direct	relay
1	0.250	0.500	1	2	-59.18	-62.75
2	0.500	1.365	2	5.5	-56.75	-56.13
3	1.375	1.978	5.5	11	-51.34	-52.98

TABLE 4. Achievable capacity and resulting average received power without/with relaying in IEEE 802.11b (1024 Byte packets)

	Network load: 25% **of data rate** 50 Byte packets				**Network load: 250Kbit/s** 50 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	8.219	6.061	7.265	13.25	8.219	7.873	15.34	25.96
Relay	3.822	3.476	9.434	31.94	3.822	2.334	5.557	9.884
Ratio	0.46	0.57	1.30	2.41	0.46	0.29	0.36	0.38
	1024 Byte packets				1024 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	4.821	4.222	5.346	5.579	4.821	4.510	5.529	5.689
Relay	1.358	1.061	1.061	2.686	1.358	1.105	1.823	1.991
Ratio	0.28	0.25	0.20	0.48	0.28	0.14	0.33	0.35
	2048 Byte packets				2048 Byte packets			
	1	2	5.5	11	1	2	5.5	11
Direct	4.404	4.302	5.112	5.018	4.404	3.918	4.957	4.862
Relay	1.243	1.060	1.541	1.989	1.243	1.011	1.532	1.827
Ratio	0.28	0.24	0.30	0.40	0.28	0.25	0.31	0.38

TABLE 5. Average received energy [nJ] per bit for IEEE 802.11b, shown for different load models, and link data rates

The average power values should be set into relation with the throughput. Figure 9 shows the transmission rate versus successfully received packets. As expected, the throughput (actually the goodput) increases with the transmission rate. The throughput decrease at 54 Mbit/s is a result of a PER, which is higher than the target PER because of the legally limited RF transmission power. As also described above, the highest data rate of 54 MBit/s is not able to overcome long distances resulting in a decreased goodput. Note that the relay signaling overhead is insignificant. Only one additional Resource Grant (0.6% of the MAC frame) is needed for forwarding (see also Section 2.1.2).

A comparison of the average received power (Figure 8) and the throughput (Figure 9) is shown in Table 6. We picked a data rate in the relaying case that achieves a comparable capacity for a given capacity in the direct case at a given link data rate. Hence, the comparison of direct case and relaying at a comparable capacity shows that the average received power does not change or decreases slightly. In effect, relaying does reduce exposure. If we use a higher data rate on the individual hops to compensate the capacity loss, the advantage decreases. However, we assume that the benefit of relaying increases considerably for higher path loss coefficients (α).

Now let us have a look at the metric received energy per goodput bit, which is generated out of the average received power and the network capacity as shown in Figure 10. It can be seen that relaying is not beneficial in every case. Remember that all data has to be transmitted twice in the relaying case, which leads to an increased exposure. This is more than compensated by the reduction of the received power via relaying for a data rate of 12,18, and 27 Mbit/s. Because of the reasons above mentioned, i.e. for 6, 36, and 54 Mbit/s, the transmission power is the same for directly sending and relaying. In these cases relaying will lead to an increase of the received energy. Nevertheless, putting the simulation artefacts and legal transmission power limits aside relaying demonstrates its potential for reducing the received energy .

We also examined the percentage of time during which the received power exceeds a certain power level threshold. Figure 11 shows this complementary distribution function for direct transmission and all data rates. The corresponding multi-hop (relay) figure looks quite similar but the probability mass is moved towards smaller values. For the sake of simplicity, Figure 12 only focuses on two data rates for both direct transmission and relaying. While the positive effect of relaying is smaller for a data rate of

[t]

Comparison example	Capacity [bit/s]		Transmission rate [Mbit/s]		Average received power [dBm]	
	direct	relay	direct	relay	direct	relay
1	4.51	4.51	6	12	-63.11	-64.82
2	8.88	10.22	12	27	-60.98	-60.31
3	13.19	13.55	18	36	-57.76	-57.63
4	19.42	17.82	27	54	-56.64	-54.85

TABLE 6. Achievable capacity and resulting average received power vs. direct transmission and relaying in HIPERLAN/2

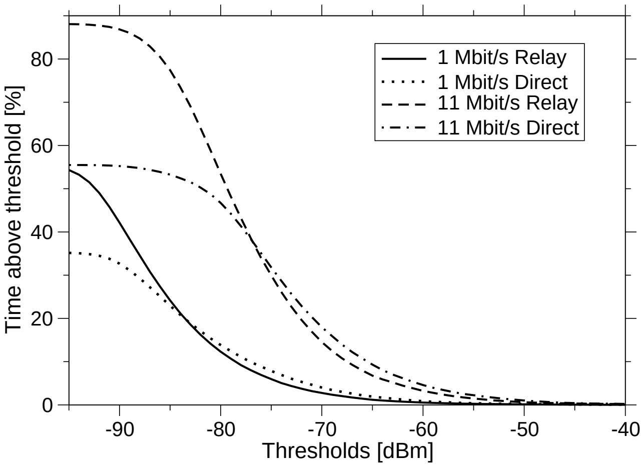

FIGURE 7. Comparison of distribution functions of relative share of time for which a given threshold value is exceeded, 1024 Byte packets, 25% load

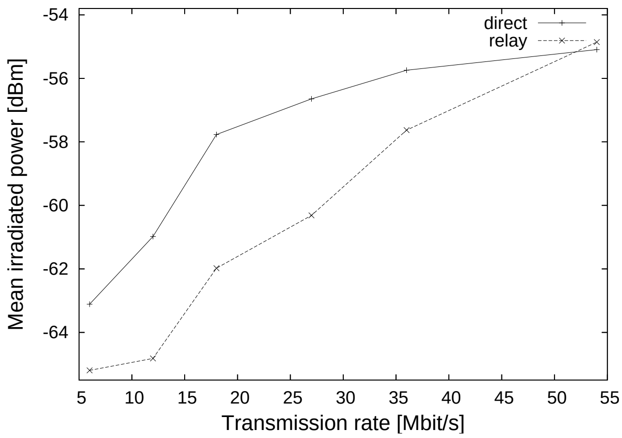

FIGURE 8. Time-weighted average of received power for different parts of MAC frames

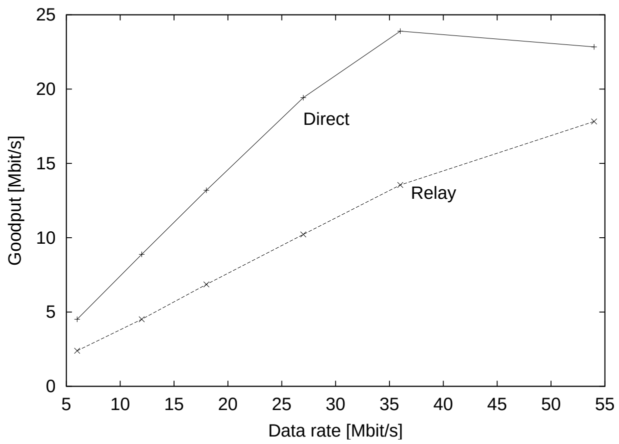

FIGURE 9. The resulting network capacity (throughput)

54 Mbit/s, a quite considerable improvement of about 20% can be seen at a data rate of 6 Mbit/s.

5. CONCLUSIONS

Multi-hop relaying in wireless networks evidently has the potential to reduce the transmission power of an individual wireless node. This potential directly translates into a reduced electromagnetic exposure of the human user. The main problem is the need to compensate the relaying overhead by increasing the data rate and hence transmission power to maintain system throughput. Therefore, maintaining the practical usability of the entire system counteracts to a certain degree the intended reduction of received power and received energy. We have shown that under these opposing trends, relaying combined with rate adaption to combat throughput loss is indeed beneficial for exposure reduction in most cases. It is interesting to see that this principal conclusion is valid for both distributed or centralized MAC schemes.

The answer to whether relaying is good or not regarding health concerns is indeed quite complicated. We revealed that relaying has a positive influence on all metrics. It is particularly very well suited to positively influence the shape of the probability distribution that describes the probability of being exposed to electromagnetic radiation of a given level. The ultimate answer depends on further medical insights: Is it more important to reduce average received power levels or the total energy? The answer to the question, which metric is more important could lead to more directed protocol optimizations. An important area of research to substantially reduce exposure further is to increase the efficiency of relaying protocols so that link data rates and hence transmission power do not have to be increased to compensate for the relaying overhead.

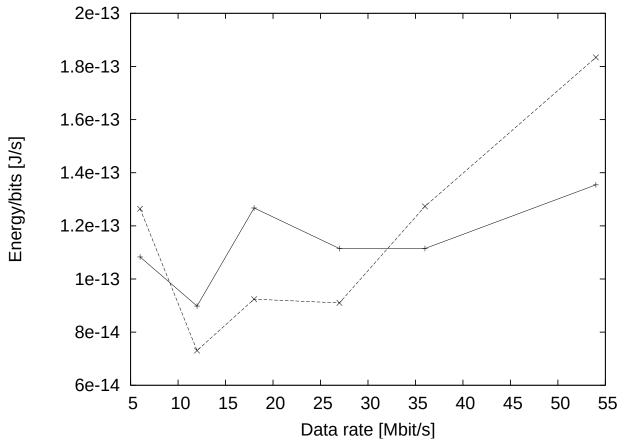

FIGURE 10. Received energy per goodput bit vs. data rate when comparing relaying with direct tranmission

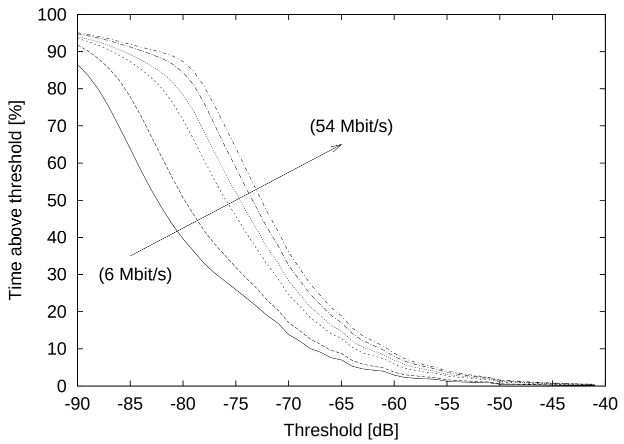

FIGURE 11. Percentage of time for which the received power exceeds a given threshold level; all data rates are shown; direct case

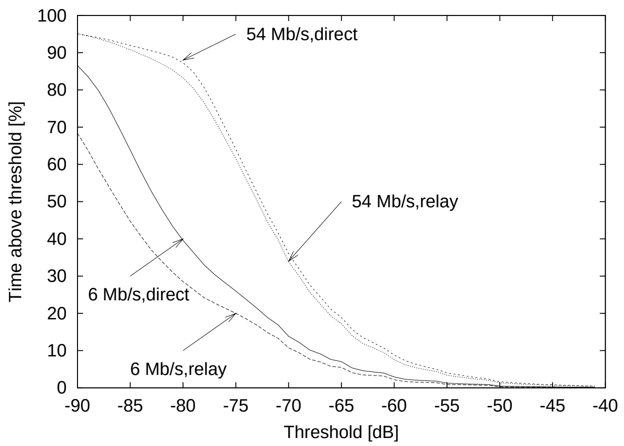

FIGURE 12. Percentage of time for which the received power exceeds a given threshold level; highest and the lowest data rate for the direct and the relay case are shown

Our investigation demonstrates that relaying is already a viable option. Nevertheless, there is still additional potential for technical research. An evident extension to our work is to consider true link adaptation mechanisms, which set transmission power and data rate individually on a per link basis. Additionally, other non-uniform random placements of nodes should also provide some interesting insights.

ACKNOWLEDGEMENTS

We would like to thank the reviewers for their helpful criticism, our student Björn Matzen for his work on a previous version of the simulator, and our colleagues Martin Kubisch, Seble Mengesha, and Adam Wolisz for their discussion and constructive remarks.

REFERENCES

[1] M. Zorzi (eds.) (1998) Energy Management in Personal Communications and Mobile Systems. *IEEE Personal Communication*, **5**.

[2] Sivalingam, K. M., Chen, J.-C., Agrawal, P., and Srivastava, M. (2000) Design and analysis of low-power access protocols for wireless and mobile ATM networks. *ACM/Baltzer Wireless Network Networks*, **6**, 73–87.

[3] Royer, E. M. and Toh, C.-K. (1999) A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks. *IEEE Personal Communications*, **6**, 46–55.

[4] Heinzelman, W. R., Chandrakasan, A., and Balakrishnan, H. (2000) Energy-Efficient Communication Protocol for Wireless Microsensor Networks. *Proc. 33rd Hawaii Intl. Conf. on System Sciences*, Hawaii, USA, January 10 pp.

[5] Qiao, C. and Wu, H. (2000) iCAR : An Integrated Cellular and Ad-hoc Relay System. *Proceedings of the Int'l Conf. on Computer, Communications, and Networks*, Las Vegas, NV, October, pp. 154–161.

[6] Min, R. and Chandrakasan, A. (2003) MobiCom poster: Top Five Myths about the Energy Consumption of Wireless Communication. *ACM SIGMOBILE Mobile Computing and Communications Review*, **7**, 65–67.

[7] Gupta, P. and Kumar, P. R. (2000) The Capacity of Wireless Networks. *IEEE Transactions on Information Theory*, **46**, 388–404.

[8] 802.11b (1999) *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY): Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band*. Institut of Electrical and Electronics Engineers, Inc. USA.

[9] ETSI TS 101 761-1 (2000) *HIPERLAN Type 2; Data Link Control (DLC) Layer*. ETSI. France.

[10] ETSI TS 101 761-4 V1.3.2 (2002) *ETSI Hiperlan/2 Extension for Home Environment*. ETSI. France.

[11] ETSI TS 101 475 V1.3.1 (2000) *ETSI HIPERLAN Type 2; Physical (PHY) layer*. ETSI. France.

[12] Weinmiller, J., Woesner, H., Ebert, J.-P., and Wolisz, A. (1995) Analyzing the RTS/CTS Mechanism in the DFWMAC Media Access Protocol for Wireless LAN's. *Proceedings of IFIP TC6 Workshop Personal Wireless Communications (Wireless Local Access)*, Prague, Czech Republic, April, pp. 117–130. Verlag der Augustinus Buchhandlung.

[13] Hollos, D. and Karl, H. (2002) A Protocol Extension to HiperLAN/2 to support Single-Relay Networks. *Proc. of 1st German Workshop on Ad-Hoc Networks*, Ulm, Germany, March,

pp. 91–108. http://www-tkn.ee.tu-berlin.de/publications/papers/frame2.pdf.

[14] Khun-Jush, J., Malmgren, G., Schramm, P., and Torsner, J. (2000) HIPERLAN Type 2 for Broadband Wireless Communication. *Ericsson Review*, **2**, 108–119. http://www.ericsson.com/review/2000_02/files/2000026.pdf.

[15] AN9804 (1998) *Tutorial on Basic Link Budget Analysis*. Harris Semiconductor. USA.

[16] Sklar, B. (1988) *Digital Communications - Fundamentals and Applications*, International edition. Prentice Hall, Indianapolis, USA.

[17] Rappaport, T. S. (1998) *Wireless Communication: Principles and Practice*. Prentice Hall, Indianapolis, USA.

[18] Cameron, F., Zukerman, M., and Gitlits, M. (1999) Adaptive transmission parameters optimisation in wireless multi-access communication. *Proceedings of IEEE ICON '99*, Brisbane, Australia, September, pp. 91–95.

[19] Holland, G. D., Vaidya, N. H., and Bahl, P. (2001) A rate-adaptive MAC protocol for multi-hop wireless networks. *Proceedings of the Seventh Annual ACM/IEEE Conference on Mobile Computing and Networking (MOBICOM)*, Rome, Italy, July, pp. 236–250.

[20] Osche, T. (2001) HiperLAN/2 PHY Layer Simulation in C++. Studienarbeit Technische Universität Berlin, Fachgebiet Telekommunikationsnetze Berlin, Germany.