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Research Article

On Energy-Efficient Hierarchical Cross-Layer Design: Joint Power Control and Routing for Ad Hoc Networks

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A hierarchical cross-layer design approach is proposed to increase energy efficiency in ad hoc networks through joint adaptation of nodes' transmitting powers and route selection. The design maintains the advantages of the classic OSI model, while accounting for the cross-coupling between layers, through information sharing. The proposed joint power control and routing algorithm is shown to increase significantly the overall energy efficiency of the network, at the expense of a moderate increase in complexity. Performance enhancement of the joint design using multiuser detection is also investigated, and it is shown that the use of multiuser detection can increase the capacity of the ad hoc network significantly for a given level of energy consumption.

1. INTRODUCTION

A mobile ad hoc network consists of a group of mobile nodes that spontaneously form temporary networks without the aid of a fixed infrastructure or centralized management. Ad-hoc networks rely on peer-to-peer communication, where any source-destination pair of nodes can either communicate directly or by using intermediate nodes to relay the traffic. The communication routes are determined by the routing protocol, which finds the best possible routes according to some specified cost criterion. Since, in general, many ad hoc networks will consist of small terminals with limited battery lifetime, routing protocols using energy-related cost criteria have recently been investigated in the literature (e.g., [1–4]).

Aside from "energy-aware routing," other interference management techniques have the potential of improving the system performance, with a direct effect on increasing the network lifetime. For example, joint power control and scheduling have been proposed in [5], and power-aware routing for networks using blind multiuser receivers has been analyzed in [1]. The benefits of power control for wireless networks have been shown in numerous works (see, e.g., [6–9]), but only recently have its interaction with "energy-aware routing" begun to be addressed [10–13].

A power-aware routing protocol design relies on the current power assignments at the terminals, and in turn, optimal power assignment depends on the current network topology, which is determined by routing. It is apparent that there is a strong cross-coupling between power control and routing, due to the fact that they are both affected by, and act upon, the interference level and the interference distribution in the network. Given this strong coupling between layers, we expect that cross-layer interference management algorithms will outperform independently designed algorithms associated with various layers of the protocol stack [14]. On the other hand, a concern associated with crossing the boundaries between layers is that many of the core advantages of the OSI model, such as easy debugging and flexibility, easy upgrading, and hierarchical time-scale adaptation, may be lost [15].

As a tradeoff between the pros and cons of cross-layer design, we propose a hierarchical cross-layer design framework, in which the adaptation protocols at different layers of the protocol stack are independently designed (e.g., power control at the physical layer, and routing at the network layer), while sharing coupling information across layers. Based on this framework, we propose and analyze a joint power control and routing algorithm for code-division multiple-access (CDMA) ad hoc networks. We then extend this algorithm to

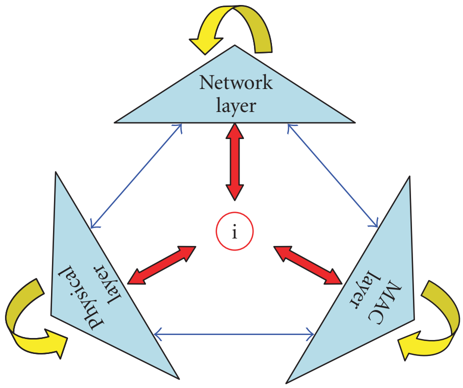


Figure 1: Hierarchical cross-layer design model: interactions among physical, MAC, and network layers.

include multiuser detection, for a further increase in network performance.

The paper is organized as follows: we first present the hierarchical cross-layer design framework in Section 2. We then propose a joint power control and routing algorithm in Section 3, and we add multiuser detection capabilities for the physical layer in Section 4. Finally, Section 5 presents the conclusions.

2. HIERARCHICAL CROSS-LAYER DESIGN FRAMEWORK

As we have already mentioned, a tight coupling exists between different interference management algorithms implemented at various layers of the protocol stack. In this paper we concentrate mainly on interactions between the physical and the network layers, namely, we consider power control and receiver adaptation algorithms at the physical layer, and energy-aware routing at the network layer. While power control and multiuser detection are traditional interference management techniques, energy-aware routing can also be seen as an effective interference management tool, as seeking low-energy routes may lead to a better interference distribution in the network.

Given the tight cross-coupling among these techniques, it becomes apparent that a cross-layer solution that jointly optimizes interference management algorithms across layers is desirable. On the other hand, the OSI classical layered architecture has a number of advantages such as deployment flexibility and upgradeability, easy debugging, and last but not least, an inherent reduced network overhead by implementing adaptability at different time scales. More specifically, fast adaptation can be done locally by the physical layer, while large-scale events can be handled by changes in routing, which implies at least local neighborhood information updates.

Our proposed hierarchical cross-layer design framework seeks to maintain the advantages of the OSI model, by independently optimizing the interference management algorithms based on information sharing among layers. Figure 1 illustrates this hierarchical model for the first three layers of the protocol stack: physical layer, MAC (data link) layer, and network layer. As protocols at different layers act independently to increase the energy efficiency in the network, the information exchange between layers leads to an iterative adaptation procedure, in which layers take turns to adjust and minimize the energy consumption in the network based on the new interference level and distribution. We note that this hierarchical structure raises convergence issues on a vertical plane, and a key issue that should be addressed is how to appropriately define the information shared between layers, as well as how to incorporate this information such that the iterative cross-layer adaptation converges, and does not lead to oscillatory behavior.

In what follows, we propose an energy-aware hierarchical joint power control and routing design, which we show is guaranteed to converge across layers. We then study how further enhancements at the physical layer (i.e., multiuser detection receivers in CDMA networks) improve the overall network performance.

3. JOINT POWER CONTROL AND ROUTING

3.1. Network model

We consider an ad hoc network consisting of N mobile nodes. For simulation purposes, the nodes are assumed to have a uniform stationary distribution over a square area of dimension $D^* \times D^*$, but this is not a necessary assumption for the analysis. The multiaccess scheme is synchronous direct-sequence CDMA (DS-CDMA) and all nodes use independent, randomly generated, and normalized spreading sequences of length L. The transmitted symbols (assumed to be binary for the purpose of exposition) are detected using either a matched filter receiver or a linear minimum square error receiver (LMMSE). Each terminal j has a transmission power P_j which will be iteratively and distributively adapted according to the current network configuration. The traffic can be transmitted directly between any two nodes, or it can be relayed through intermediate nodes. It is assumed that each node generates traffic to be transmitted towards a randomly chosen destination node. If traffic is relayed by a particular node, the transmissions for different sessions at that node are time-multiplexed. Also, it is assumed that a scheduling scheme is available at the MAC layer to schedule transmission and reception minislots for each node. This has the role of avoiding exccesive interference between the received and transmitted signals at any particular node. The details of the scheduling allocation are beyond the scope of this paper. For our design, we will use a simplifying worst-case assumption that will consider that each node creates interference at all times, while in reality, some of the time is dedicated only to receiving. This simplifying assumption supports our hierarchical structure, by avoiding interference tracking (routes modification) at the MAC layer time scale.

We address the problem of meeting quality of service (QoS) requirements for data, that is, BER (bit error rate) and minimum energy expenditure for the information bits transmitted, to conserve battery power. We note that for data services, delay is not of primary concern. The target BER requirement can be mapped into a target SIR requirement. We note that an optimal target SIR can be determined (as in [16]) to minimize the energy per bit requirement, under the assumption that data is retransmitted until correctly received.

At a link level, for a given target SIR requirement, the number of retransmissions necessary for correct packet reception is characterized by a geometric distribution, which depends on the corresponding BER-SIR mapping. If the transmission rate is fixed for all links, then the energy can be minimized by minimizing the transmitted powers on each link. At the physical layer level, this is achieved by power control. However, the achievable minimum powers will depend on the distribution of the interference in the network, and thus are influenced by routing. In turn, routing may use power-aware metrics to minimize the energy consumption. The overall cross-layer optimization problem can be formulated as follows:

$$\text{minimize} \sum_{i=1}^{N} P_i \quad \text{subject to } \mathrm{SIR}_{(i,j)}(\mathbf{p}) \geq \gamma^*, \qquad \forall (i,j) \in S_a^r, \quad P_i \geq 0,\ r \in \Upsilon, \tag{1}$$

where $(\mathbf{p})$ is the vector of all nodes' powers, S_a^r is the set of active links for the current routing configuration r, obtained using the routing protocol, and Υ is the set of all possible routes.

From (1), we can see that optimal power allocation depends on the current route selection. On the other hand, for a given power allocation, efficient routing may reduce the interference, thus further decreasing the required energy per bit. We begin our discussion of the joint optimization of these two effects by first considering distributed power control design for a given route assignment, which is a classic distributed power control problem for ad hoc networks.

3.2. Distributed power control

In the cellular setting, a minimal power transmission solution is achieved when all links achieve their target SIRs with equality. For an ad hoc network, implementation complexity constraints may restrict the power control to adapt power levels for each node, as opposed to optimizing it for each active outgoing link for the node. If multiple active transmission links start at node i (Figure 2), then the worst link must meet the target SIR with equality. In our model, these outgoing links correspond to destinations for various flows relayed by the node, and are used in a time-multiplexed fashion.

If we denote the set of all outgoing links from node i as S_i^*, then the minimal power transmission conditions become

$$\min_{k \in S_i^*} \mathrm{SIR}_k = \gamma^*, \qquad \forall i = 1, 2, \ldots, N. \tag{2}$$

We now express the achievable SIR for an arbitrary active link $(i,j) \in S_a^r$:

$$\mathrm{SIR}_{(i,j)} = \frac{h_{(i,j)} P_i}{(1/L)\sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2}, \tag{3}$$

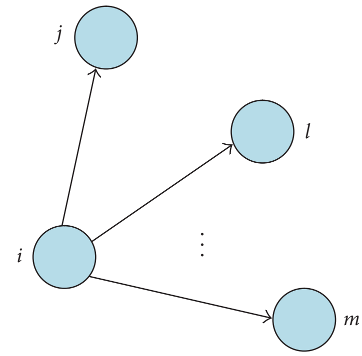


Figure 2: Multiple transmissions from node i.

where $h_{(i,j)}$ is the link gain for link (i,j), and σ^2 is the background noise power.

Condition (2) can then be expressed as

$$\min_{(i,j)\in S_i^*} \frac{h_{(i,j)} P_i}{(1/L)\sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2} = \gamma^*. \tag{4}$$

From (4), the powers can be selected as

$$\begin{aligned} P_i &= \max_{(i,j)\in S_i^*} \frac{\gamma^*}{h_{(i,j)}} \left[\frac{1}{L} \sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2 \right] \\ &= \max_{(i,j)} I_{(i,j)}(\mathbf{p}), \end{aligned} \tag{5}$$

where $\mathbf{p}^T = [P_1, P_2, \ldots, P_N]$.

It can easily be shown that $I_{(i,j)}(\mathbf{p})$ is a standard interference function, that is, it satisfies the three properties of a standard interference function: positivity, monotonicity, and scalability [17]. It was also proved in [17] that $T_i(\mathbf{p}) = \max_{(i,j)} I_{(i,j)}(\mathbf{p})$ is also a standard interference function. Since $T_i(\mathbf{p})$ is a standard interference function, for a feasible system, an iterative power control algorithm based on

$$P_i(n+1) = T_i(\mathbf{p}(n)), \qquad \forall i = 1, 2, \ldots, N, \tag{6}$$

is convergent to a minimal power solution [17], for both synchronous and asynchronous power updates.

Since all the information required for the power updates can be estimated locally, the power control algorithm can be implemented distributively. In particular, a sample average of the square root outputs of the matched filter receiver for link (i,j) will determine the quantity $E\{y_{(i,j)}^2\} = (1/L)\sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + h_{(i,j)} P_i + \sigma^2$. Further, if the link gain $h_{(i,j)}$ is also estimated, all information required for power updates at node i is available locally.

3.3. Joint power control and routing

The previous section has proposed an optimal power control algorithm, which minimizes the total transmitted power given SIR constraints for all active links, for a given network configuration. However, the performance can be further improved by optimally choosing the routes as well. Finding the

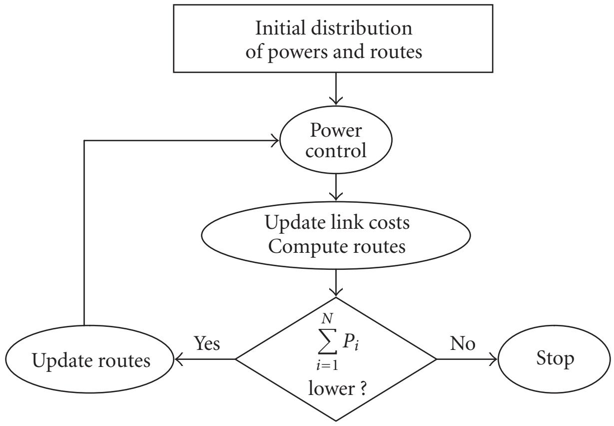


Figure 3: Joint power control and routing.

optimal routes to minimize the total transmission power over all possible configurations is an NP-hard problem.

We propose a suboptimal solution, based on iterative power control and routing, which is shown to converge rapidly to a local minimum energy solution. This solution is compatible with our proposed hierarchical cross-layer framework, by promoting independent protocol updates with information sharing accross layers. More specifically, we propose a joint algorithm that alternates between power control (at the physical layer) and route assignments (at the network layer), until further improvements in the energy consumption cannot be achieved. At each step of the algorithm, the power control optimizes powers based on the current route assignment, while after power assignment, new minimum energy routes are determined based on the current power distribution of the nodes (see Figure 3).

As we have mentioned in Section 3.1, the optimization problem that we are solving can be expressed as in (1), that is, we try to minimize the sum of transmission powers, subject to SIR constraints, by both power control and route assignments. We note that the target SIR requirement is selected such that a BER requirement is met for a fixed prescribed rate allocation, determined by a prescribed spreading gain. Thus, in our system model the transmission rate is fixed.

In the previous section, we have described how the transmission powers are chosen for each node given a current route configuration, and we have shown that for our system model, they are unique per node, no matter which flow is currently relayed by the node.

Thus, the information that the network layer sees is the vector of powers for all the nodes, $\mathbf{p}^T = [P_1, P_2, \dots, P_N]$, which completely characterizes the interference distribution in the system, given a certain location for the nodes.

For routing, we use Dijkstra's algorithm [18, 19] with associated costs for the links. In order to try to minimize further the total transmitted power in the network, a natural choice of costs for the routing would be based on the transmission power spent by a node sending on a given link. However, for convergence reasons for the cross-layer algorithm (which will be explained shortly), the cost for an arbitrary link (i, j) is determined as

$$c(i, j) = \begin{cases} P_i & \text{if } \mathrm{SIR}_{(i,j)} \geq \gamma^*, \\ \infty & \text{if } \mathrm{SIR}_{(i,j)} < \gamma^*. \end{cases} \tag{7}$$

The reason for choosing the link costs as in (7) is that we would like to restrict the pool of links available for routing to include only links that already meet the target SIR. As we will see shortly, this condition will ensure the convergence of the algorithm towards a minimum energy solution.

To determine a better possible routing option, we need to evaluate the new costs for all links, given the current distribution of powers resuling from the previous power control step. In order to determine the routing costs for the links that are not currently active, the achievable SIR for these links must be estimated. This requires that each node i update a routing table which should contain the estimated link gains towards all the other nodes, $h_{(i,j)}$, $j = 1, 2, \dots, N$, $j \neq i$, the transmitted powers of all nodes, P_j, $j = 1, 2, \dots, N$, and the extended estimated interference at all the other nodes, defined as $\widetilde{I}(i, j) = \sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + h_{(i,j)} P_i$, $j = 1, 2, \dots, N$, $j \neq i$. Hence, the estimated SIR for link (i, j) can be expressed as

$$\widetilde{\mathrm{SIR}}_{(i,j)} = \frac{h_{(i,j)} P_i}{(1/L)\big(\widetilde{I}(i, j) - h_{(i,j)} P_i\big) + \sigma^2}. \tag{8}$$

We note that the achievable SIR on any potential link (currently active or not) depends only on the current distribution of nodes, and on the current power assignment, and does not depend on the current assigned routes, and consequently does not change for new route assignments. This property is a result of the fact that multiple sessions are time-multiplexed at a node, and are all transmitted with the same power, such that the transmitted power for a node i is fixed and equal to P_i. This result can be summarized in the following proposition.

Proposition 1. *For a given distribution of nodes in the network, after the convergence of the power control algorithm, the achievable SIR on any arbitrary link depends only on the nodes' transmitted powers and is independent of the current route assignment.*

We note that if sessions are not time-multiplexed at a relaying node, the above proposition does not hold any more (e.g., the total power transmitted by a node is additive over the number of relayed flows for multicode transmission, and thus depends on the routing configuration), and the convergence of the proposed joint power control algorithm is not guaranteed. However, as a disadvantage for the time-multiplexed scheme, the throughput per session is limited by the number of sessions relayed by a node. In an extension of this work [20], we also have proposed a cost modification for the routing to account for this effect, which yielded a more uniform distribution of relayed flows per node over the entire network. Also, in [21], we have compared the performance of a time-multiplexed scheme with the case in which multi-code CDMA is used for simultaneous transmission of all relayed flows (which increases the interference in the system).

Starting from an initial distribution of powers and routes, and assuming that the system is feasible for the initial configuration, the joint power control and routing algorithm is summarized in Figure 3.

Theorem 1. *For a feasible initial network configuration, the joint power control and routing algorithm converges to a locally minimal transmitted power solution.*

Proof. As we previously showed, for a feasible initial network configuration, the power control minimizes the total transmitted power, while ensuring that all active links meet their SIR requirements: $\text{SIR}_{(i,j)} \geq \gamma^*$, for all $(i, j) \in S_a^r$. After the convergence of the power control algorithm, the link costs are estimated and updated according to (7) and (8), and a minimal cost route, equivalent to a minimal transmitted power route, is selected for each session. As a consequence, the new routes are selected such that the sum of all transmitted powers for all active links is minimized, while the SIR constraints are met for all links (from Proposition 1 and (7)). If no power improvements can be achieved, the algorithm stops. Otherwise, the sum of transmission powers decreases after the route selection. Since all the new active links satisfy $\text{SIR}_{(i,j)} \geq \gamma^*$, for all $(i, j) \in S_a^r$, the system is feasible, and therefore, the power control algorithm produces a decreasing sequence of power vectors converging to a minimal power solution [17].

Hence, each step of the iteration (power control or routing) produces an improvement in the total transmitted power, while meeting SIR requirements for all active links. The algorithm stops at a locally minimal transmitted power solution, where no further decrease in transmission power can be achieved by the routing protocol. □

We note that the locally minimal transmitted power solution achieved by the proposed algorithm depends on the initial network configuration chosen. For initialization, we propose an algorithm similar to that which was proposed in [1]. We first select an initial distribution of powers (equal powers or random distribution) and then determine routes by assigning link costs equal to the energy-per-bit consumption, which is proportional to the transmitted power and inverse proportional to the probability of correct reception for a packet [15]. This approach also permits us to quantify the energy requirement improvements of the joint optimization relative to the initial starting point.

We note that the total energy requirement depends on the current initialization for the powers. To improve the expanded energy with minimal complexity increase, the algorithm can be run several times with different random power initializations, and the best energy solution over all runs can be determined.

3.4. Simulations

In this section, we present some numerical examples for ad hoc networks with 55 and 40 nodes, respectively, uniformly distributed over a square area of 200 × 200 meters. The target SIR is selected to be $\gamma^* = 12.5$ (which was shown to be an optimal value that minimizes energy-per-bit consumption for an FSK scheme [16]), and the noise power is $\sigma^2 = 10^{-13}$, which approximately corresponds to the thermal noise power for a bandwidth of 1 MHz. We consider low-rate data users, using a spreading gain of $L = 128$. For this particular example, we choose equal initial transmit powers, 70 dB above the noise floor ($P_t = 10^{-6}$ W), and a path loss model with path loss coefficient $n = 2$.

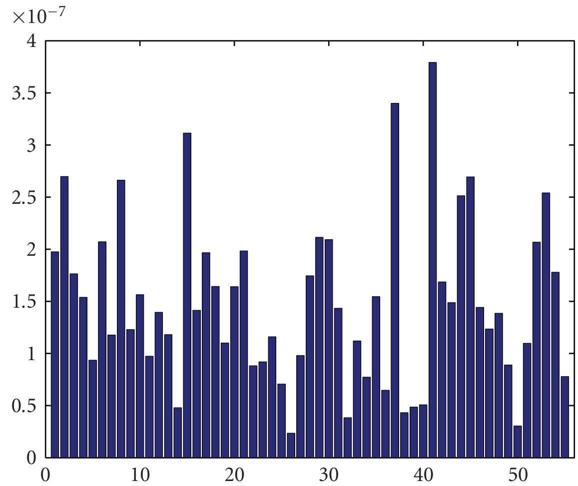


Figure 4: Distribution of powers after convergence.

In Figure 4, we show the final distribution of powers after the convergence of the joint power control and routing algorithm. Figures 5 and 6 illustrate the performance of the proposed joint optimization algorithm. In Figure 5, it can be seen that the total transmitted power in the network progressively decreases as the proposed algorithm iteratively optimizes power and routes. The values in Figure 5 represent the total transmitted power obtained over a sequence of iterations: (power control, routing, power control, routing, power control). In Figure 6, the achieved energy per bit is compared for the same experiment with the first energy value, which represents the energy per bit obtained in the initial state. It can be seen that substantial improvements are achieved by the proposed joint optimization algorithm.

Note that at the end of each iteration pair (routing, power control), the energy is further minimized. However, after new routes are selected, the powers are not yet optimized, so it is possible that previous routes might have better energy-per-bit performance (for the same power allocation, higher SIRs may improve the energy consumption).

As we have previously mentioned, the actual energy results after convergence depend on the initial starting point for the algorithm. In Figure 7, we illustrate the variation in the total transmission power obtained with various initializations (100 trials are considered) for an ad hoc network with 40 nodes. We can see that significant energy improvements can be achieved if the algorithm is run repeatedly with different initializations and the best configuration is selected.

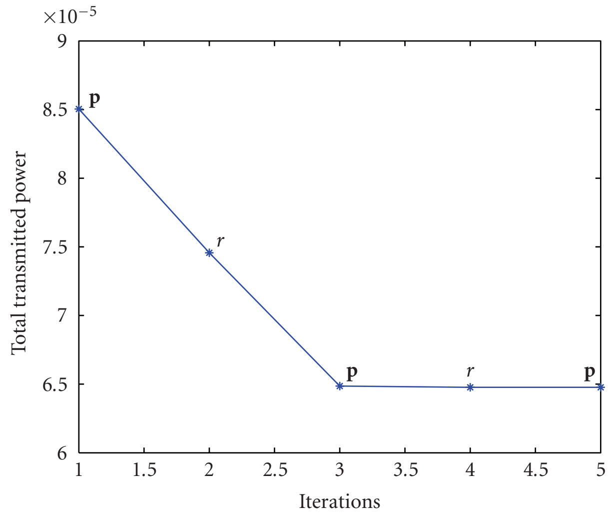


Figure 5: Total transmission power.

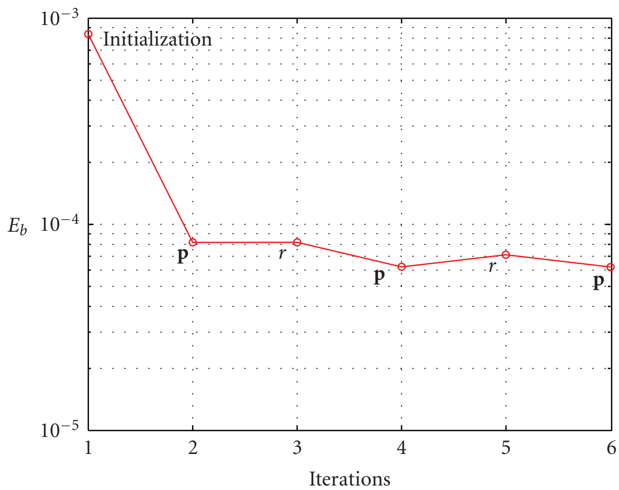


Figure 6: Energy per bit.

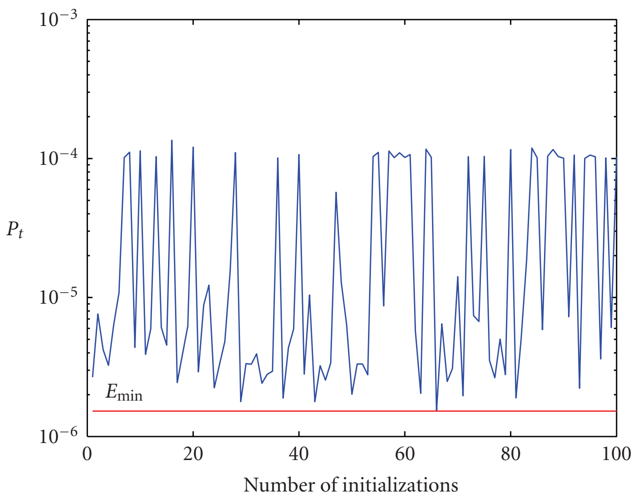


Figure 7: Energy function for different initializations.

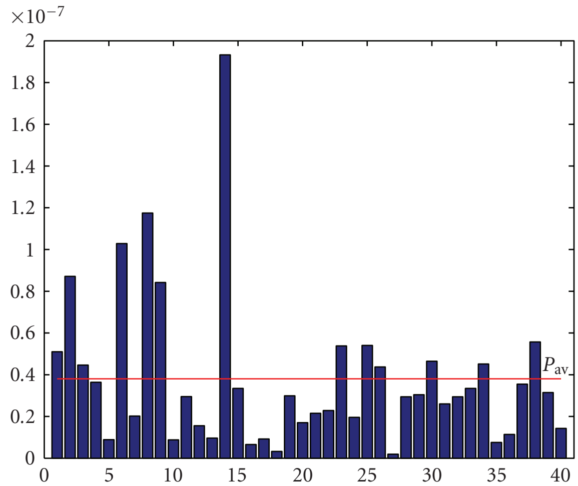


Figure 8: Distribution of powers for the minimal energy solution.

In Figure 8 we show the final distribution of powers for this minimal energy solution.

3.5. Uniform energy consumption

While we saw that the power distribution in Figure 8 gives a very low total energy consumption, this solution leads to unequal power consumption among nodes, which ultimately results in shorter life span for certain nodes (e.g., node 14 in Figure 8). Note that in mobile nodes, this problem is overcome by the fact that node locations change with time, so in the long run, the power consumption tends to be more uniform.

For fixed nodes, or slow moving ones, we overcome this problem by selecting a set of alternate "good routes" (N_s routes) and their corresponding power distributions. The routes (and power vectors) are then randomly assigned, such that the power consumption variance among nodes is minimized. A route i and its corresponding power vector $\mathbf{p}_i$ are selected from the initial set of "good routes," with probability w_i. The probabilities w_i, $i = 1, \ldots, N_s$, are assigned to routes such that the following conditions hold:

$$\begin{gathered}\min_{\mathbf{w}} \|\mathbf{P} - P_{\text{av}}\|_2^2,\\ 0 \le w_i \le 1, \quad i = 1, \ldots, N_s,\\ \sum_{j=1}^{N_s} w_j = 1,\end{gathered} \tag{9}$$

where $\mathbf{w} = [w_1, w_2, \ldots, w_{N_s}]$, $\mathbf{P} = [\mathbf{p}_1, p_2, \ldots, \mathbf{p}_{N_s}]$, and P_{av} is the average power consumption across nodes obtained for the minimal energy solution.

Alternatively, routes can be assigned deterministically, such that w_i represents the fraction of time route i and its corresponding power vector are selected for transmission. In Figure 9 we illustrate how the power distribution changes in the ad hoc network when $N_s = 9$ "good routes" are selected. These routes (and their corresponding power distribution)

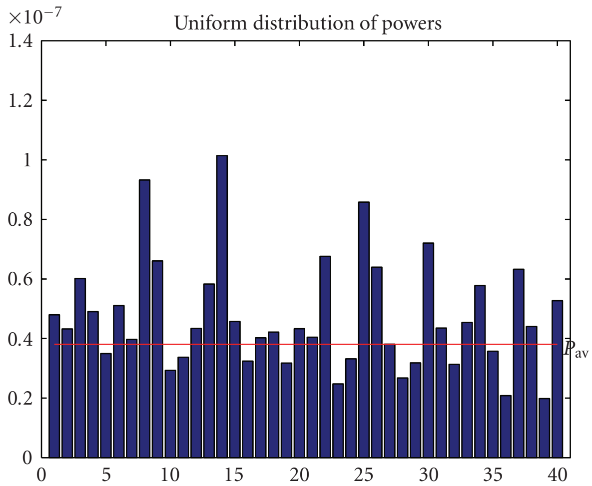


Figure 9: Energy per bit.

are selected to be within 10% of the minimal energy solution obtained with 100 different random initializations. Comparing the results from Figure 9 with the ones in Figure 8, we can see a more uniform consumption across all nodes in the ad hoc network.

4. JOINT POWER CONTROL, ROUTING, AND MULTIUSER DETECTION

To extend the above-described joint power control and routing algorithm to include receiver optimization, we build on results on iterative, distributed, joint power control, and minimum mean square error multiuser detection presented in [22]. In [22], an iterative two-step integrated power control and multiuser detection algorithm was proposed, for which, in the first step, the LMMSE filter coefficients are adjusted according to the current vector of powers $\mathbf{p}$ (10), then in the second step, a new power vector is selected for the given filter coefficients.

Step 1. Optimize filter coefficients given the power vector $\mathbf{p}^T = [P_1, P_2, \ldots, P_n]$:

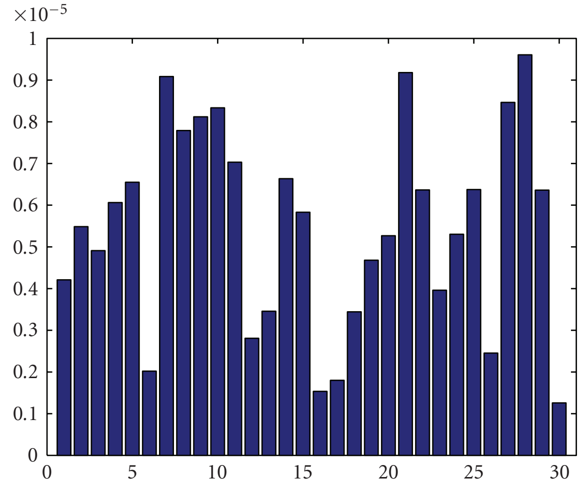
$$\hat{\mathbf{c}}_i = \frac{\sqrt{P_i(n)}}{1 + P_i(n)\mathbf{s}_i^T \mathbf{A}_i^{-1}(\mathbf{p}(n))\mathbf{s}_i} A_i^{-1}(\mathbf{p}(n))\mathbf{s}_i, \qquad (10)$$

where $\mathbf{c}_i$ and $\mathbf{s}_i$ are the filter coefficients vector, and the signature sequence vector for user i, respectively, n is the iteration number, and $\mathbf{A}_i$ is defined as $\mathbf{A}_i = \sum_{j \neq i} P_j h_{ij} \mathbf{s}_j \mathbf{s}_j^T$.

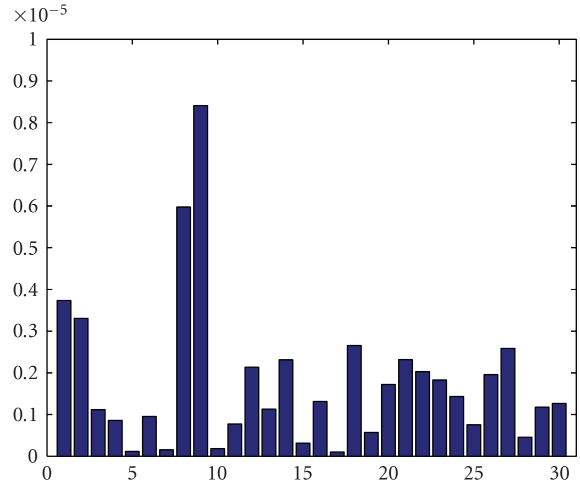
Step 2. Optimize powers based on currently selected filter coefficients:

$$P_i(n+1) = \frac{\gamma_i^*}{h_{ii}} \frac{\sum_{j \neq i} P_j(n) h_{i,j} \left(\hat{\mathbf{c}}_i^T \mathbf{s}_j\right)^2 + \sigma^2 \hat{\mathbf{c}}_i^T \hat{\mathbf{c}}_i}{\left(\hat{\mathbf{c}}_i^T \mathbf{s}_i\right)^2}. \qquad (11)$$

Given the above algorithm, to extend our joint power control and routing scheme to include receiver optimization, we simply replace the simple power control adaptation at the physical layer by the above joint power control and multiuser detection algorithm.



(a)



(b)

Figure 10: Joint power control, multiuser detection, and routing: distribution of powers versus node number, (a) initially, (b) after convergence (final distribution of powers).

Simulation results show a very similar convergence behavior and energy savings for the joint power control, multiuser detection and routing algorithm, compared to the solution with matched filters (see Figures 10, 11, and 12). We also note a significant capacity increase when multiuser detection is employed. We use as a capacity measure the total throughput that can be supported by the network such that the power control is feasible for a target SIR of $\gamma^* = 12.5$. We note that the power control feasibility depends on the actual network topology. To determine the maximum load for the network, we randomly generated 100 different topologies (for the same number of users) and we selected the maximum number of users (for a given spreading gain) that yielded feasible topologies 95% of the time, for a given initial power distribution for the nodes.

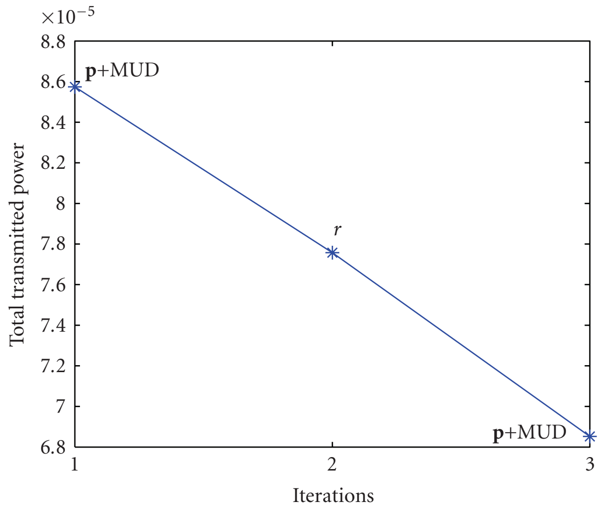


Figure 11: Total transmission power: joint power control, multiuser detection, and routing.

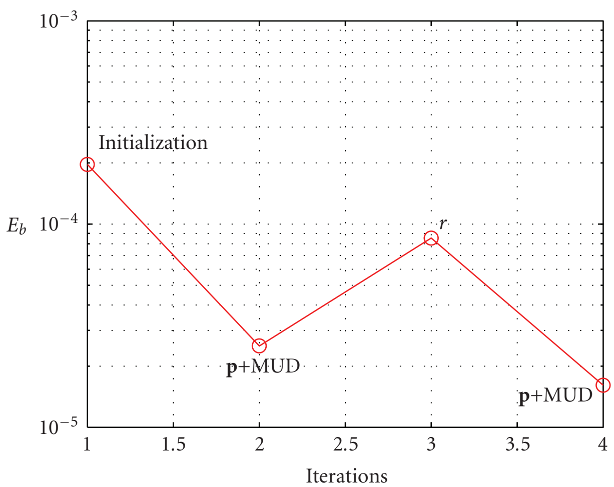


Figure 12: Total energy consumption: joint power control, multiuser detection, and routing.

For the matched filter case, we selected $L = 128$ and the maximum number of users that met the feasibility condition was determined to be $N = 55$. For the LMMSE case, since the capacity increases significantly, to reduce the complexity of the simulation (the number of nodes), we have selected $L = 32$, with a resulting capacity of $N = 30$. This yielded a total normalized throughput gain for the LMMSE case of

$$T_{g(\mathrm{LMMSE})} = \frac{N_{\mathrm{LMMSE}} \times L_{\mathrm{MF}}}{L_{\mathrm{LMMSE}} \times N_{\mathrm{MF}}} = 2.18. \qquad (12)$$

To illustrate the performance of the joint power control, multiuser detection and routing protocol, we have considered similar network parameters as before, with the sole difference of selecting $N = 30$ and $L = 32$. Random initial transmission powers were selected, approximately 70 dB above the noise floor.

Figure 10 shows the initial distribution of powers, as well as the optimal power control distribution after convergence.

Figures 11 and 12 illustrate the performance of the proposed joint optimization algorithm with multiuser detection. In Figure 11, it can be seen that the total transmitted power in the network progressively decreases as the proposed algorithm iteratively optimizes power, filter coefficients, and routes. The values in Figure 11 represent the total transmitted power obtained over a sequence of iterations: (power control + MUD, routing, power control + MUD, routing, power control + MUD).

In Figure 12, the achieved energy per bit is compared for the same experiment with the initial energy value (with randomly selected powers). It can be seen that substantial improvements are achieved by the proposed joint optimization algorithm (approximately one order of magnitude).

5. CONCLUSIONS

In this paper, we have proposed joint power control and routing optimization for wireless ad hoc data networks with energy constraints. Both energy minimization and network lifetime maximization have been considered as optimization criteria. We have shown that energy savings of an order of magnitude can be obtained, compared with a fixed transmission power, energy-aware routing scheme. Our proposed algorithm is based on a hierarchical cross-layer framework which maintains the advantages of the OSI layered architecture, while allowing for protocol optimization based on information sharing between layers. The network capacity has been further enhanced by employing multiuser detection, with a similar obtained energy performance. Our simulation results show that our distributive joint optimization algorithm converges rapidly towards a local minimum energy. The rapid convergence of the power-routing protocol makes it suitable for implementation in mobile ad hoc networks.

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REFERENCES

[1] Z. Cai, M. Lu, and X. Wang, "Minimum average transmission power routing in CDMA ad hoc networks utilizing the blind multiuser detection," in *Proceedings of the 16th International Parallel and Distributed Processing Symposium (IPDPS '02)*, pp. 428–433, Fort Lauderdale, Fla, USA, April 2002.

[2] D. Kim, J. J. Garcia-Luna-Aceves, K. Obraczka, J. Cano, and P. Manzoni, "Power-aware routing based on the energy drain rate for mobile ad hoc networks," in *Proceedings of the 11th IEEE International Conference on Computer Communications and Networks (ICCCN '02)*, pp. 565–569, Miami, Fla, USA, October 2002.

[3] X.-Y. Li, P.-J. Wan, Y. Wang, and O. Frieder, "Constrained shortest paths in wireless networks," in *Proceedings of IEEE Military Communications Conference (MILCOM '01)*, vol. 2, pp. 884–893, McLean, Va, USA, October 2001.

[4] S. Tragoudas and S. Dimitrova, "Routing with energy considerations in mobile ad-hoc networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC '00)*, vol. 3, pp. 1258–1261, Chicago, Ill, USA, September 2000.

[5] T. ElBatt and A. Ephremides, "Joint scheduling and power control for wireless ad-hoc networks," in *Proceedings of the 21st IEEE Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '02)*, vol. 2, pp. 976–984, New York, NY, USA, June 2002.

[6] S. Agarwal, R. H. Katz, S. V. Krishnamurthy, and S. K. Dao, "Distributed power control in ad-hoc wireless networks," in *Proceedings of the 12th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '01)*, vol. 2, pp. F-59–F-66, San Diego, Calif, USA, September-October 2001.

[7] M. Ettus, "System capacity, latency, and power consumption in multihop-routed SS-CDMA wireless networks," in *Proceedings of IEEE Radio and Wireless Conference (RAWCON '98)*, pp. 55–58, Colorado Springs, Colo, USA, August 1998.

[8] T. J. Kwon and M. Gerla, "Clustering with power control," in *Proceedings of IEEE Military Communications Conference (MILCOM '99)*, vol. 2, pp. 1424–1428, Atlantic City, NJ, USA, October-November 1999.

[9] F. Meshkati, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, "An energy-efficient approach to power control and receiver design in wireless data networks," *IEEE Transactions on Communications*, vol. 53, no. 11, pp. 1885–1894, 2005.

[10] F. Bertocchi, P. Bergamo, G. Mazzini, and M. Zorzi, "MAC and routing solution for energy saving in ad hoc networks: distributed power control," in *Proceedings of the Joint Conference of the 4th International Conference on Information, Communications and Signal Processing, and the 4th Pacific Rim Conference on Multimedia (ICICS-PCM '03)*, vol. 2, pp. 1061–1065, Singapore, December 2003.

[11] C. Comaniciu, N. B. Mandayam, and H. V. Poor, *Wireless Networks: Multiuser Detection in Cross-Layer Design*, Springer, New York, NY, USA, 2005.

[12] C. Comaniciu and H. V. Poor, "QoS provisioning for wireless ad hoc data networks," in *Proceedings of the 42nd IEEE Conference on Decision and Control*, vol. 1, pp. 92–97, Maui, Hawaii, USA, December 2003.

[13] A. Yener and S. Kishore, "Distributed power control and routing for clustered CDMA wireless ad hoc networks," in *Proceedings of the 60th IEEE Vehicular Technology Conference (VTC '04)*, vol. 4, pp. 2951–2955, Los Angeles, Calif, USA, September 2004.

[14] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Communications*, vol. 9, no. 4, pp. 8–27, 2002.

[15] V. Kawadia and P. R. Kumar, "A cautionary perspective on cross-layer design," Tech. Rep., University of Illinois at Urbana-Champaign, Urbana, Ill, USA, 2003.

[16] D. Goodman and N. Mandayam, "Power control for wireless data," *IEEE Personal Communications*, vol. 7, no. 2, pp. 48–54, 2000.

[17] R. Yates, "A framework for uplink power control in cellular radio systems," *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 7, pp. 1341–1348, 1995.

[18] "Bayes Net Toolbox for Matlab," http://bnt.sourceforge.net/.

[19] D. Bertsekas and R. Gallager, *Data Networks*, Prentice-Hall, Upper Saddle River, NJ, USA, 1992.

[20] Y. Xing, N. Nie, and C. Comaniciu, "Avoiding throughput bottlenecks for energy efficient joint power control and routing in ad hoc wireless networks," in *Proceedings of the Conference on Information Sciences and Systems*, Princeton, NJ, USA, March 2004.

[21] H. Mahmood and C. Comaniciu, "Adaptive spreading/coding gains for energy efficient routing in wireless ad hoc networks," in *Proceedings of the 61st IEEE Vehicular Technology Conference (VTC '05)*, vol. 4, pp. 2454–2458, Stockholm, Sweden, May-June 2005.

[22] S. Ulukus and R. Yates, "Adaptive power control and multiuser interference suppression," *ACM Wireless Networks*, vol. 4, no. 6, pp. 489–496, 1998.