QoS Provisioning for Wireless Ad Hoc Data Networks*

Cristina Comaniciu**
Dept. of Electrical and Computer Engineering
Stevens Institute of Technology
Castle Point on Hudson
Hoboken, NJ 07030
ccomanic@stevens-tech.edu

H. Vincent Poor
Dept. of Electrical Engineering
Princeton University
Princeton, NJ 08544
poor@princeton.edu

Abstract— **Quality of Service (QoS) provisioning for wireless ad hoc networks is a difficult problem due to the self organizing nature of such networks, and due to strict energy constraints which greatly restrict the signaling overhead. This paper discusses distributed resource management techniques for QoS guarantees in ad hoc code-division multiple-access (CDMA) networks. In CDMA networks, resource management represents a key element in providing QoS for data services. In particular, power control has been shown to be crucial for maintaining good performance in cellular CDMA. With tight node energy constraints in wireless ad hoc networks, power control can greatly improve the network performance. On the other hand, the network performance will depend on the current network topology which is influenced by routing. In this paper, joint power control and routing is proposed to maximize the QoS perceived by a data session, where the measure of data QoS is taken to be the energy required for the transmission of one bit of information.**

I. 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 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 limitted battery lifetime, routing protocols using energy related cost criteria have been recently investigated in the literature (e.g. [8],[10],[11],[4]). Aside from "energy aware routing", other intereference management techniques have the potential of improving the system performance, with a direct effect on increasing the network lifetime. For example, joint routing and scheduling have been proposed in [5], and power aware routing for networks using blind multiuser receivers have been analyzed in [4]. Furthermore, power control has been separately investigated for ad hoc wireless networks [2], [9], [6], but its interaction with "energy aware routing" protocols has not been considered. Nevertheless, a power aware routing protocol design will rely on the current power assignments at the terminals, and in turn, optimal power assignment based on the current network topology may further reduce the energy consumption. As the terminals move through the network, both the network configuration and the power assignment can be jointly adapted to minimize the energy consumption. Due to the very nature of ad hoc wireless networks, the joint adaptation protocol must be distributed and must rely on minimal information exchange across the network.

In this paper, we propose joint, distributed power control and routing for Code Division Multiple Access (CDMA) ad hoc networks. The CDMA technology has several advantages for ad hoc networks, such as gracefull degration of network performance with increased interference, low probability of intercept and resistance to jamming. The last two properties are particularly attractive for ad hoc networks deployed in unlicensed bands. In our proposed joint optimization, aside from minimum energy consumption constraints we consider that each active link must meet a target signal to interference ratio (SIR), which reflects the bit-error-rate (BER) constraint. For data terminals, this also ensures a throughput gain, since fewer retransmissions are required for correct reception. We prove that the proposed algorithm is rapidly convergent towards a minimum energy allocation for both powers and routes.

II. SYSTEM 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 bits are detected using a matched filter receiver. 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

---

*This research was supported by the National Science Foundation under Grant CCR-02-05214, the Office of Naval Research under Grant N00014-03-1-0102, and by the New Jersey Center for Pervasive Information Technology.

**This work was completed while the author was with Princeton University.

that node are time multiplexed.

In order to characterize the data QoS measure, we use a data transmission model similar to that in [7]. Data is transmitted in packets of length M, and a packet received in error is retransmitted until correctly received. It is assumed that errors are always detected by sufficiently powerful error detecting codes. There are m information bits within a packet, the remaining $(M-m)$ bits are used for error detection and correction. Because the end to end transmission involves multiple hops, we assume that a packet will not be relayed to its next destination node until it is correctly received from its previous transmission link.

The number of retransmissions required per link for a correct reception of a packet is a geometric random variable K (under the assumption that all retransmissions are statistically independent of one another), and its mean value is equal to

$$E\{K\} = \frac{1}{P_c(\gamma)}, \tag{1}$$

where $P_c(\gamma)$ is the probability of a correct reception, which depends on the achieved SIR, γ. If we assume no correction capabilities, $P_c(\gamma) = (1-BER)^M$.

Since battery life is limited, the utility per link of an arbitrary terminal j can be measured in the number of information bits correctly received per Joule of energy expended [7].

$$U_j = \frac{mR}{ME\{K\}P_j} = \frac{mRP_c(\gamma_j)}{MP_j}, \tag{2}$$

where R is the transmission rate for terminal j, $R = W/L$, and W is the system bandwidth.
Conversely, we can define the link Quality of Service (QoS) measure for terminal j to be the energy consumed for the correct transmission of an information bit, E_b^j:

$$E_b^j = \frac{1}{U_j}. \tag{3}$$

From (2) and (3) we can see that minimizing the link's energy-per-bit requirement is equivalent to maximizing the terminal's utility for transmission on that particular link. It was shown in [7] that in order to avoid the degenerate solution for the utility function maximization ($P_j = 0$ which gives infinite utility), a power control algorithm should be based on a modified utility function $\tilde{U}$, which considers $\tilde{P}_c = (1-2BER)^M$, instead of P_c. It can than be shown that the link utility is maximized if the target SIR for that particular link is chosen such that the folowing equation holds:

$$\gamma\frac{d\tilde{P}_c(\gamma)}{d\gamma} - \tilde{P}_c(\gamma) = 0. \tag{4}$$

The solution to (4) gives the optimal target SIR, γ^*. Therefore, a link has maximal utility, and operates at minimal energy-per-bit, if the SIR achieved on that particular link is γ^*.

For the numerical results, we have considered a system employing non-coherent frequency-shift-keying (FSK) modulation, for which the BER is given by

$$BER = \frac{1}{2}\exp\left(-\frac{\gamma}{2}\right). \tag{5}$$

III. JOINT POWER CONTROL AND ROUTING

In the previous section we showed that the energy-per-bit for a transmission on a given link can be expressed as an SIR requirement: $SIR = \gamma^*$. The achievable link SIR depends on the transmission powers for all nodes.

Since it can be shown that γ^* is a global maximum of the utility function, if $SIR \neq \gamma^*$ the system overspends energy for the transmission. Specifically, if $SIR < \gamma^*$ many retransmissions are required which also affects the throughput and the transmission delay of the link. On the other hand, if $SIR > \gamma^*$, the surplus gain achieved by a better SIR is overcome by a high required transmission power. Taken into account the above considerations we express the link QoS requirement for an arbitrary link (i,j), $i,j = 1,2,...,N$ as

$$SIR_{(i,j)} \geq \gamma^*,\ \forall (i,j) \in S_a^r, \tag{6}$$

where S_a^r is the set of active links for the current routing configuration r, obtained using the routing protocol. The joint optimization problem at the network level can then be formulated as

$$\begin{aligned} &\text{minimize} \textstyle\sum_{i=1}^{N} P_i \\ &\text{subject to} \\ &\quad SIR_{(i,j)} \geq \gamma^*,\ \forall (i,j) \in S_a^r \\ &\quad P_i \geq 0 \\ &\text{and } r \in \Upsilon, \end{aligned} \tag{7}$$

where Υ is the set of all possible routes. From (7) 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.

A. *Power Control Issues*

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 restrict the power control to adapt power levels for each node, and not for each active link. If multiple active transmission links start at node i (Figure 1), then the worst link must meet the target SIR with equality. If we denote the set of all outgoing links from node i as S_i^*, then the minimal power transmission conditions become

$$\min_{k \in S_i^*} SIR_k = \gamma^*,\ \forall i = 1,2,...,N. \tag{8}$$

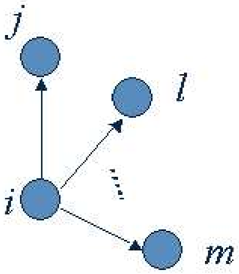

Fig. 1. Multiple transmissions from node i.

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

$$SIR_{(i,j)} = \frac{h_{(i,j)} P_i}{\dfrac{1}{L} \displaystyle\sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2}, \tag{9}$$

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

Condition (8) can then be expressed as

$$\min_{(i,j)\in S_i^*} \frac{h_{(i,j)} P_i}{\dfrac{1}{L} \displaystyle\sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2} = \gamma^*. \tag{10}$$

From (10), the powers can be selected as

$$\begin{aligned} P_i &= \\ &= \max\nolimits_{(i,j)\in S_i^*} \tfrac{\gamma^*}{h_{(i,j)}} \left[\frac{1}{L} \sum_{k=1, k\neq i, k\neq j}^{N} h_{(k,j)} P_k + \sigma^2 \right] \\ &= \max_{(i,j)} I_{(i,j)}(\mathbf{p}), \end{aligned} \tag{11}$$

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

Similarly to the cellular case, it can easily be shown that $I_{(i,j)}(\mathbf{p})$ is a standard interference function, i.e., it satisfies the three properties of a standard interference function: positivity, monotonicity, and scalability [12]. It was also proved in [12] that $T(\mathbf{p}) = \max_{(i,j)} I_{(i,j)}(\mathbf{p})$ is also a standard interference function. Since $T(\mathbf{p})$ is a standard interference function, for a feasible system, an iterative power control algorithm based on

$$P_i(n+1) = T(\mathbf{p}(n)),\ \forall i = 1,\ 2,\ ...,\ N, \tag{12}$$

is convergent to a minimal power solution [12], 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 $E\{y^2_{(i,j)}\} = \frac{1}{L}\sum_{k=1,k\neq i,k\neq j}^{N} h_{(k,j)}P_k + h_{(i,j)}P_i + \sigma^2$. Further, if the link gain $h_{(i,j)}$ is also estimated, all information required for power updates at node i is available locally.

B. Joint Power Control and Routing

The previous subsection 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 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. For routing, we use Dijkstra's algorithm [3], [1] with associated costs for the links. The cost for an arbitrary link (i,j) is determined as

$$c(i,j) = \begin{cases} P_i & \text{if } SIR_{(i,j)} \geq \gamma^* \\ \infty & \text{if } SIR_{(i,j)} < \gamma^* \end{cases}. \tag{13}$$

In order to estimate costs for links that are not currently active, the achievable SIR for all links must be estimated. This requires that each node i updates a routing table which should contain the estimated link gains toward all the other nodes, $h_{(i,j)}$, $j = 1, 2, ..., N$, $j \neq i$, the transmitted powers of all nodes, P_j, $j = 1, 2, ..., N$, and the extended estimated interference at all the other nodes, defined as $\tilde{I}(i,j) = \sum_{k=1,k\neq i,k\neq j}^{N} h_{(k,j)}P_k + h_{(i,j)}P_i$, $j = 1, 2, ..., N$, $j \neq i$. Hence, the estimated SIR for link (i,j) can be expressed as

$$\widetilde{SIR}_{(i,j)} = \frac{h_{(i,j)} P_i}{\dfrac{1}{L}\left(\tilde{I}(i,j) - h_{(i,j)}P_i\right) + \sigma^2}. \tag{14}$$

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. This result can be summarized in the following proposition.

Proposition 1: For a given distribution of nodes in the network, the achievable SIR depends only on the nodes' transmitted powers and is independent of the current route assignment.

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 2.

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

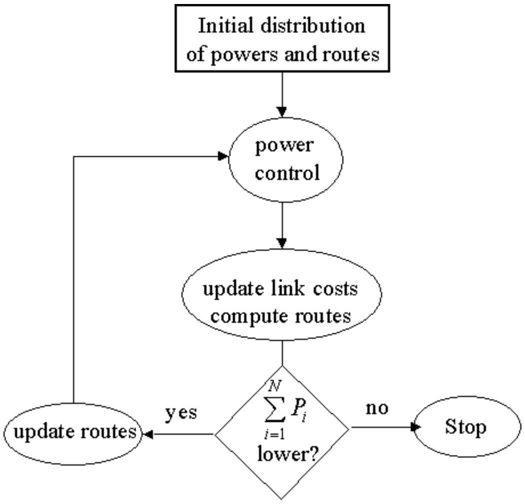

Fig. 2. Joint power control and routing

transmitted power, while ensuring that all active links meet their SIR requirements: $SIR_{(i,j)} \geq \gamma^*$, $\forall (i,j) \in S_a^r$. After the convergence of the power control algorithm, the link costs are estimated and updated according to (13) and (14), 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 (13)). 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 $SIR_{(i,j)} \geq \gamma^*$, $\forall (i,j) \in S_a^r$, the system is feasible, and therefore, the power control algorithm produces a decreasing sequence of power vectors converging to a minimal power solution [12].

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 [4], but for matched filter receivers. We first select an initial distribution of powers (equal powers or random distribution) and then determine routes by assigning link costs equal to the link utility (determined as in (2)). This approach also permits us to quantify the energy requirement improvements of the joint optimization versus 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.

IV. SIMULATIONS

In this section, we present some numerical examples for an ad hoc network with 55 and 40 nodes, respectively, uniformly distributed over a square area of 200×200 meters. The target SIR is selected to be $\gamma^* \approx 12.5$, 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.

In Figures 3 and 4 we show the initial distribution of powers, as well as the optimal power distribution after convergence when the proposed algorithm is employed.

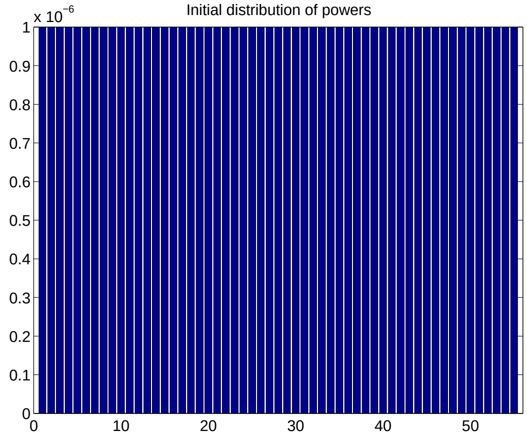

Fig. 3. Initial distribution of powers

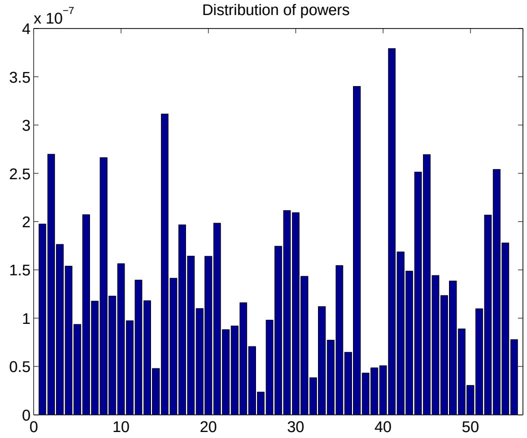

Fig. 4. Distribution of powers after convergence

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.

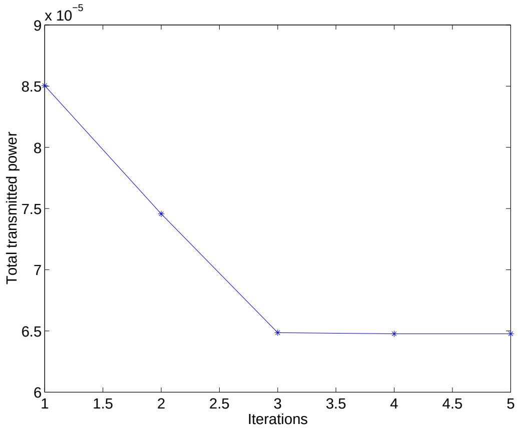

Fig. 5. Total transmission power

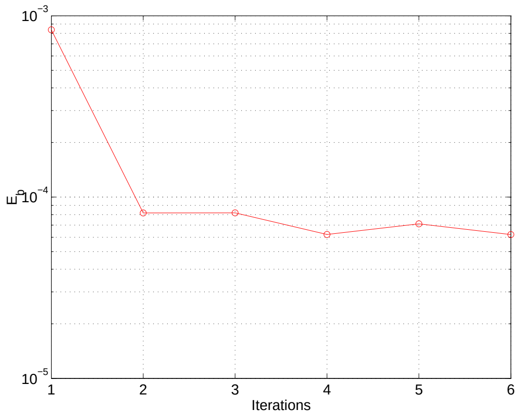

Fig. 6. Energy per bit

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

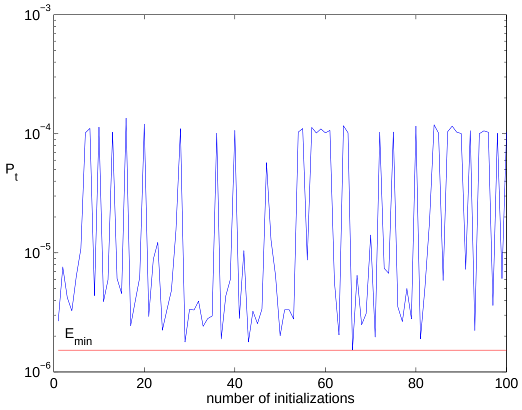

Fig. 7. Energy function for different initializations

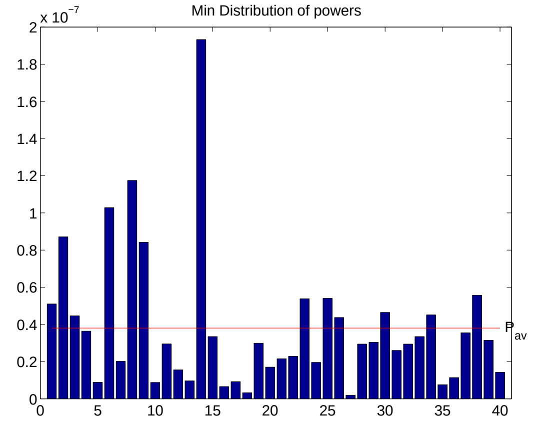

Fig. 8. Distribution of powers for the minimal energy solution

V. UNIFORM ENERGY CONSUMPTION

While we saw that 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

$$\min_{\mathbf{w}} \parallel \mathbf{P} - P_a v \parallel_2^2;$$

$$\begin{cases} 0 \leq w_i \leq 1, \; i = 1 \ldots, N_s; \\ \sum_{j=1}^{N_s} w_j = 1, \end{cases} \tag{15}$$

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) 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.

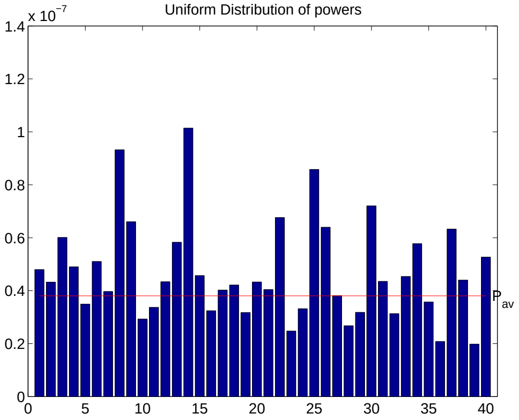

Fig. 9. Energy per bit

VI. CONCLUSIONS

In this paper, we have proposed joint power control and routing optimization for wireless data ad hoc networks, with energy constraints. We defined the data QoS to be the energy required for the transmission of one bit of information, and we showed that this energy can be minimized if the total transmission power is minimized while all links meet a target SIR requirement. The proposed power control is distributive and the joint optimization algorithm is shown to converge rapidly towards a local minimum energy. Significant energy gains compared to power aware routing algorithms are illustrated in simulations. The rapid convergence of the power-routing protocol makes it suitable for implementation in mobile ad hoc networks.

VII. REFERENCES

[1] Bayes net toolbox for Matlab. www.cs.berkeley.edu/ murphyk/Bayes/bnt.html.

[2] S. Agarwal, R. H. Katz, S. V. Krishnamurthy, and S. K. Dao. Distributed power control in ad-hoc wireless networks. In *Proceedings of 12th IEEE Personal, Indoor and Mobile Radio Communications Conference*, pages F–59 – F–66, Sep/Oct 2001.

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

[4] 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 IEEE International Parallel and Distributed Processing Symposium*, pages 428 – 433, 2002.

[5] T. ElBatt and A. Ephremides. Joint scheduling and power control for wireless ad-hoc networks. In *Proceedings of 21st IEEE INFOCOM*, volume 2, pages 976 – 984, 2002.

[6] M. Ettus. System capacity, latency, and power consumption in multihop-routed SS-CDMA wireless networks. In *Proceedings of IEEE Radio and Wireless Conference (RAWCON)*, pages 55 – 58, Colorado Springs, CO, August 1998.

[7] D. J. Goodman and N. B. Mandayam. Power control for wireless data. *IEEE Personal Communications*, 7(2):48 – 54, April 2000.

[8] 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 IEEE 11th International Conference on Computer Communications and Networks*, pages 565 – 569, 2002.

[9] T. J. Kwon and M. Gerla. Clustering with power control. In *Proceedings of IEEE Military Communications Conference (MILCOM)*, volume 2, pages 1424 – 1428, Atlantic City, NJ, 1999.

[10] 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)*, volume 2, pages 884 – 893, 2001.

[11] S. Tragoudas and S. Dimitrova. Routing with energy considerations in mobile ad-hoc networks. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, volume 3, pages 1258 – 1261, Chicago, IL, 2000.

[12] R. Yates. A framework for uplink power control in cellular radio systems. *IEEE Journal on Selected Areas in Communications*, 13(7):1341 – 1348, September 1995.