Adaptive spreading/coding gains for energy efficient routing in wireless ad hoc networks

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Abstract— **In this paper, we propose several joint rate adaptation and routing solutions for energy efficient communication in CDMA ad hoc networks. The proposed schemes exploit the interactions between layers, by jointly acting at the physical and the network layer to effectively manage the network interference. At the physical layer, an appropriate transmission rate is selected based on the current link quality. At the network layer, routes are determined such as to minimize the end to end energy consumption. To further improve the performance, a coding/spreading technique is used that gives an additional coding gain advantage.**

I. INTRODUCTION

An ad-hoc network is a collection of mobile nodes, which spontaneously form temporary networks, without centralized management. Nodes can communicate with other nodes either directly or via intermediate nodes. The choice of a route in a multi-hop network can influence the overall network performance, measured in terms of energy consumption and in terms of achievable throughput rate for end-to-end transmission. There are many algorithms proposed which emphasize on energy efficient routing. A performance comparison for different protocols such as DSR [7], DSDV [8], AODV [9], and TORA [10], based on energy consumption, is presented in [1]. Some of these protocols have a very good performance, but are not optimized for reduced energy consumption. PAOD, presented in [2], considers physical layer information and optimize power consumption but does not consider throughput optimization. In [3], the emphasis is on energy efficient routing and it is shown that for ad hoc networks, conventional algorithms do not provide optimum performance [15]. These protocols focus on reducing the energy consumption but do not fully utilize the links with better signal to interference ratio. Using these algorithms result in minimum cost-routing which can reduce energy consumption, but does not necessarily provide maximum throughput. Most of these works do not consider joint optimization of the physical layer.

CDMA technology may be an appealing solution for ad hoc networks, due to its attractive properties, such as resistance to jamming and interference, low probability of intercept, and soft QoS degradation with increased interference and channel impairments, but its performance degrades in near-far effect scenarios. One solution to overcome the near-far-effect is to use multi-user detection receivers, but this incurs a high implementation complexity [11], [16]. As an alternate solution to improve the network performance, we propose to use a low rate code to spread the information bits that are transmitted on the channel.

Using this code-spread technique has the advantage of an additional coding gain [5], and can improve the network performance in near-far scenarios.

In this work, we propose to use an adaptive coding/spreading solution for throughput maximization in a CDMA ad hoc network. In assigning the transmission rates for a particular link and the routes for a source-destination pair of nodes we account for the cross-interactions between the physical and the network layer, since both the routing and the rate assignment depend, and have an impact on the level of interference in the system [6] [12][13].

In ad hoc networks the throughput of an end-to-end connection is affected by the number of relaying packets at a particular node in a link. If one of the nodes in the link has a large number of relaying packets, this will reduce the throughput for that particular connection. Routing must be performed in such a way to avoid nodes with lower throughput. We present several schemes that are capable of avoiding congested nodes, while minimizing the energy consumption in the network. All the proposed schemes incorporate physical layer information in the routing metrics. A broad classification of our proposed joint adaptation protocols can be done by considering the scheduling method for transmission of relayed packets at a particular node. In particular, we consider the case in which only one packet can be transmitted in a given time slot (time multiplexing, TM), as well as the case in which many packets may be simultaneously transmitted. In the first case, the throughput is limited by the number of multiplexed flows, while in the second case the throughput limitation is caused by the increased level of interference. As a tradeoff between these two approaches, we also propose a combined approach (MIX) that evenly distributes the interference in the network.

The remainder of this paper is organized as follows. In section II we present the network model. Section III describes the joint spreading/coding and routing technique with an emphasis on the cross-layer model. Section IV presents the proposed routing schemes. Simulations results are discussed in section V, and conclusions are presented in section VI.

II. NETWORK MODEL

We consider a CDMA ad hoc network with *N* mobile nodes, uniformly distributed over a square region with dimensions *b meters x b meters*. We assume that all nodes transmit at all times (their own traffic or relayed traffic) with equal transmission powers. In case a node is transmitting packets simultaneously, the power associated with each node is cumulated from all contributing packets. We assume that the nodes in the network are stationary.

A certain target bit error rate (BER) constraint is defined as a physical layer requirement (e.g. 10^{-2} for voice, 10^{-4} for data). The BER constraint can be mapped into an equivalent target signal to interference ratio (SIR) requirement. For the case of data traffic transmission, the packets received in error must be retransmitted until they are correctly received. For this type of users, the energy spent for the correct transmission of a packet data represents an important QoS measure. The energy consumed for the transmission of a data packet can be defined as in [4] and [14], to be

$$E_b = \frac{MP_i}{mRP_C(\gamma)}, \qquad (1)$$

where *M* is the length of the packet, *m* is the number of information bits, *R* is the transmission rate for this node, and $P_C(\gamma)$ is the probability of correct reception.

An optimum target SIR for the physical links can be determined such that (1) is minimized. If SIR is lower that this optimum target, this will trigger more frequent retransmissions, which will result into an energy drain. On the other hand, if the achieved SIR is greater than the optimum SIR, for a fixed transmission power, the transmission rate can be increased in order to lower the energy per bit consumption. Based on the above discussion, the link quality can be characterized by a utility function, defined to be the inverse of the energy per bit consumption for that particular link.

In order to estimate the achieved SIR for a particular link, we consider a simplified path loss model with a propagation exponent $n=2$. Consequently, the received signal power from the i^{th} node, depends on the link gain h_i, and is given by

$$P_r = P_t \frac{\lambda^2}{d^2} = P_t h_i, \qquad (2)$$

where the link gain for user *i*, h_i is defined as

$$h_i = \frac{\lambda^2}{d^2}. \qquad (3)$$

In the above formula, λ is the wavelength, *d* is the distance of the i^{th} node from the receiver and P_t is the power transmitted by the i^{th} node.

The signal to interference ratio for a link between nodes *(i,j)* is then calculated as

$$SIR_{(i,j)} = \frac{h_{(i,j)}P_i}{\frac{1}{L}\sum_{k=1,k\neq i,j} h_{(i,j)}P_k + \sigma^2}, \qquad (4)$$

where $h_{(i,j)}$ is the link gain for link *(i,j)* and σ^2 is the thermal noise power. P_i represents the transmitted power of the i^{th} node and P_r represents the received power from all interfering nodes. *L* is the spreading factor.

Using combined coding/spreading, the bandwidth expansion is achieved by employing a low rate channel code. Starting from *m* information bits, a code word of length $M= m/R$ bits is generated, with R being the rate of the code. This results in the same bandwidth expansion factor *L* as obtained for classic CDMA scheme (where the spreading is achieved by multiplying with a pseudorandom sequence). The resulting code word provides an additional coding gain advantage. This code word is then multiplied with a random sequence and transmitted on the channel. We consider the packet length to be fixed. The number of information bits and redundant bits in a packet can be adaptively modified to obtain various transmission rates. A higher transmission rate is obtained at the expense of a reduced coding gain. For decoding purposes, we assume that the transmitter and the receiver are familiar with the coding methods and are synchronized.

III. JOINT ADAPTIVE SPREADING/CODING AND ROUTING

Our proposed joint spreading/coding and routing algorithms use information across layers to improve the overall network performance. At the physical layer, the achievable link rates are determined according to the current link's utility, which is in turn influenced by the link's achieved SIR. The rate assignment is determined such as to maximize the utility of the link (minimize the energy per bit consumption). For fixed transmission powers, this translates into assigning the highest possible rate for the link, such that the optimum target SIR is met. Recall that the optimum target SIR can be determined by maximizing (1).

For classic CDMA, the rate can be varied by adjusting the spreading gain, whereas for the spreading/coding method, channel codes with different coding rates are used to obtain various spreading gains. It becomes apparent that the coding gain is reduced for higher transmission rates.

At the network layer, the link quality information from the physical layer is used to perform energy efficient routing, The routing protocol considers only high utility links as good candidates to participate in active routes. The proposed joint protocol selects routes characterized by minimum energy consumption. We note that in the context of fixed power transmission, minimum energy routes are equivalent with maximum throughout routes, i.e., the energy per bit and the throughput cost metrics are equivalent.

The routing cost metrics are based on physical layer information, and as the physical layer conditions change, new routes can be adaptively selected to avoid high interference regions in the network.

We propose several joint rate/code assignment and routing algorithms. In these algorithms, link quality information (measured as the assigned transmission rate for that particular link) from the physical layer is utilized by the network layer, to update the routing metric, which is computed as the energy required for successful transmission of an information bit [3].

The network consists of N nodes having uniform stationary distribution. Each node is transmitting data to a randomly selected destination node. We assume that each node transmits at all times (their own traffic or relayed traffic with equal transmission powers. This represents a worst case scenario.

The nodes in the network can relay packets in two different ways. One approach is to place received packets in a queue, and transmit serially. For this case, all the received packets are time multiplexed. Since the transmitted power per packet is fixed, the amount of interference contributed to the network, by each node, irrespective of the number of relaying packets, remains fixed. The throughput for a link deteriorates as the number of relaying flows increases. The neighboring nodes perceive the same level of interference, irrespective of the routing configuration. If a node leaves or enters the network, or changes activity status, new SIR values for all links are calculated, and new rates are assigned for all the links, based on the newly updated SIR values.

Alternatively, the nodes can relay packets simultaneously (using multiple codes). The power of each packet is added at the transmitter. The contribution to interference depends on the number of relaying packets, and impacts on the achievable throughput. A limit can be imposed on the number of simultaneous relays in order to avoid high interference points in the network (a single node generating too much interference). Imposing this limit has the effect of distributing the interference more evenly over the network, to avoid unnecessary bottlenecks.

Since for the first scenario, the throughput is limited by the time multiplexing of multiple flows, and for the second scenario, the performance is interference limited, we also propose a solution which combines time multiplexing and simultaneous transmission based on the local network configuration and interference level.

IV. ROUTING SCHEMES

Based on the above described network scenarios, we propose four different solutions for the joint rate adaptation and routing algorithm. A step-by-step description of the proposed adaptations is provided below.

Scheme 1:Time multiplexing (TM)

In this scheme, all the incoming traffic at a node is placed in a queue and then transmitted serially. We assume that the queue has infinite length. We also assume that each node can measure the received interference and calculate the link gain to its neighboring nodes.

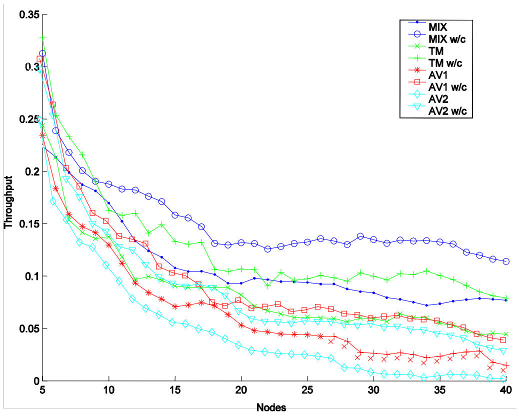

Figure 1. Average throughput for the proposed algorithms

Based on these measurements, the link SIR can be estimated, and an optimal code is selected for spreading. If the link SIR is above the threshold SIR, a higher rate code is used. This increases the information rate and reduces the energy per bit. On the other hand, if the link SIR is below the threshold, the link transmission rate is reduced up to a minimum rate. The assignment of a minimum transmission rate for a low quality link, as opposed to completely disabling the link, will ensure that the network connectivity can be maintained, at the expense of higher energy consumption due to retransmissions. While all links are considered to be available for routing purposes, the routing protocol will give preference to highest quality links (characterized by high transmission rate), and the low rate links will be selected only when this is required to maintain the connectivity.

The cost metric used for routing is the energy per bit required for an end to end transmission between a source and a destination node. The time multiplexing approach has an interference decoupling effect, since the rate assignment will not change the interference level, and thus routes can be independently selected.

For a reduced number of nodes in the network, the performance of this scheme resembles the one achieved for minimum-hop routing. In this scenario, the nodes are evenly distributed and approximately receive the same interference. As the number of nodes increases, the interference pattern becomes uneven, and the routing protocols selects routes that avoid high interference areas, which leads to an increased hop count per route.
The limit imposed on the number of relayed traffic flows per node achieves a more even spread in the battery consumption over all nodes. The algorithm is summarized as follows.

1. Measure the interference at all nodes
2. Assign rates to meet target SIR (spreading/coding)

3. Adjust routing metric based on the newly assigned rate
4. Determine routes

Scheme 2: Average interference with Simultaneous Transmission (AV1)

For this proposed scheme, we consider that the nodes can transmit packets simultaneously. Consequently, a strong coupling between the physical layer and the network layer occurs, as the interference changes with the number of simultaneously relayed packets, with a direct effect on the rate assignment, which in turn affects the routing metrics.

To ensure the convergence of the joint rate assignment and routing algorithm, the routing tables are determined based on initial interference estimation at each node. The interference estimates will be updated every time the activity pattern of a node changes, but will remain fixed for a given configuration (they are not re-adjusted based on the new rate assignment at the physical layer, since this may lead to an oscillating behavior).

As in the previous discussed scheme, the number of simultaneous transmissions is limited, which restricts the total interference generated by a node. This also ensures a more even battery utilization across nodes. A step by step description of the algorithm follows.

1. Estimate average interference at each receiving node
2. Assign rates according to estimated interference
3. Adjust routing metric based on the rate assignment
4. Select routes
5. Measure interference received from all nodes
6. Re-assign rates to meet target SIR

Note: Step 1 is implemented iteratively between route and rate assignments, until the average interference is estimated (typically a few iterations are required).

Scheme 3: Maximum interference with simultaneous transmissions (AV2)

This scheme is similar with the previous one, except that in step 1, initial route allocations are made under the assumption that all the nodes transmit simultaneously the maximum number of allowed packets. This represents a worst case estimate of interference. After the route selection, the spreading is adjusted using a repetition code (classic CDMA) or an error correcting code (code-spread CDMA). The algorithm is described below.

1. Assume maximum interference at each receiving node
2. Assign rates to meet target SIR
3. Adjust routing metric
4. Select routes
5. Measure interference received from all nodes
6. Re-assign rates to meet target SIR

Scheme 4: Simultaneous implementation of TM and AV1 (MIX)

MIX represents a combination between scheme 1 (TM) and scheme 2 (AV1). The nodes can be configured in both modes, i.e., time multiplexing (TM) and simultaneous transmission (AV1), based on the network configuration and the current interference levels in the neighborhood. The nodes that are relatively more isolated from the congested areas can use simultaneously transmission mode, as they have no neighboring nodes that will suffer from increased interference. Nodes located in congested areas use time multiplexing scheme, thus creating a constant, minimal interference for their neighbors. The algorithm is summarized as follows.

1. Measure interference at all nodes
2. Assign rates to meet target SIR (spreading/coding)
3. Based on local interference levels, select TM or AV1 for a particular node
4. Update the routing metric, determine routes

V. SIMULATION RESULTS

We have simulated a CDMA ad hoc network with *N* nodes, uniformly distributed over a region of dimension *b meters x b meters*, in which source nodes transmit to a randomly chosen destination nodes.

Performance comparisons for all the proposed schemes, in terms of achievable average throughput and energy per bit consumption are illustrated in Figure 1 and 2, respectively.

As we have expected, the more versatile scheme, MIX performs the best, by achieving the highest throughput and the lowest energy consumption. The time multiplexing scheme, TM has very similar energy consumption performance as the MIX scheme, but a lower achievable throughput. This can be explained by the fact that TM controls well the interference in the network, but at the expense of a reduced throughput per node. The lowest performance is associated with the simultaneous transmission based schemes, which do not tightly control the interference level in the network.

We can also see that there is a significant performance advantage for using the code/spreading CDMA. The gains obtained by using coding for bandwidth expansion become more evident for the energy consumption measure (Figure 2). This is due to the fact that, while a minimal throughput is guaranteed for all links, using the poor quality ones will significantly increase the energy expenditure for the network.

VI. CONCLUSION

In this paper, we have presented several solutions for designing joint rate adaptation and routing protocols for increased network throughput and minimal energy consumption. The proposed schemes exploit the interactions between layers, by jointly acting at the physical and the network layer to effectively manage the interference.

At the physical layer, an appropriate transmission rate is selected based on the current link quality. At the network layer, routes are determined such as to minimize the energy consumption, which effectively translates into routes that avoid high interference regions.

To further improve the performance, a coding/spreading technique is used that gives an additional coding gain advantage.

Our results show that the best management approach is to account for the local network topology (local interference pattern) at both layers of the protocol stack. While all our proposed methods implement routing based on local interference levels, the best performing scheme (MIX), also adjusts the interference levels at the physical layer. This is achieved by selecting the number of simultaneous transmissions that are allowed for a particular node based on the local interference pattern.

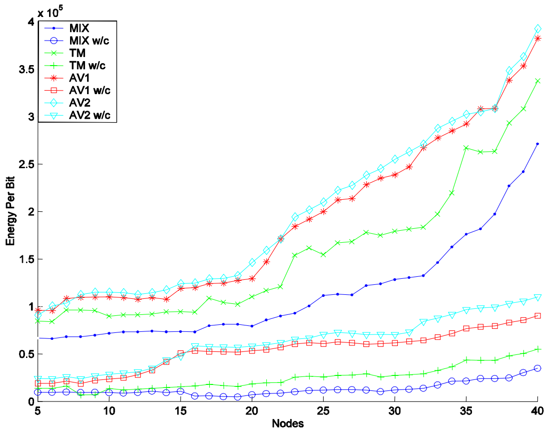

Figure 2. Energy per bit consumption for the proposed algorithms

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REFERENCES

[1] Manzoni, P., Cano, J. C., " A performance comparison of energy consumption for mobile ad hoc network routing protocols," in *Proc. 8th Intl. Symp. Modeling, Analysis, and Simulation of Computer and Telecommunication Systems*, 2000, pp. 57-64.

[2] Wang Kun, Xu Yin-long, Chen Guo-liang, Wu Ya-feng, "Power-Aware On-Demand Routing Protocol for MANET," *in Proc. 24th International Confcerence on Distributed Computing Systems Workshop*, January 2004.

[3] Singh, S., Woo, M., and Raghavendra, C. S., "Power-Aware routing in mobile and ad hoc networks," in *Proc. 4th Annu. ACM/IEEE int. Conf. Mobile Computing and Networking*, Dallas, TX October 1998, pp. 181-190

[4] Goodman, D, Mandayam, N, "Power control for wireless networks", in *Mobile Multimedia Communications, 1999 (MoMuC '99) IEEE International Wrokshop on*, 15-17 Nov. 1999, pp 55-63.

[5] Veeravalli,V.V,Mantravadi,A, " The coding-spreading tradeoff in CDMA systems", Selected Areas in Communications, IEEE Journal on , Volume: 20 , Issue: 2 , Feb. 2002 Pages:396 – 408

[6] Shakkottai, S., Rappaport, T.S., Karlsson, P.C.," Cross-layer design for wireless networks", *Communications Magazine, IEEE*, Volume: 41, Issue 10, Oct. 2003, pp 74-80

[7] D. B. Johnson, D.A. Maltz, and J. Broch, "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks", Internet Draft, MANET Working Group, draft-ietf-manet-dsr03.txt, Novenber 1999.

[8] C. E. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for mobile computers," Computer Communications, October 1994, pp 234-244

[9] C. Perkins and E. Royer, " Ad Hoc On-demand Distance Vector (AODV) Routing", Internet Draft, MANET working group, draft-ietf-manet-aodv-05.txt, March 2000.

[10] V. Park and M. Corson, "Temporally-Ordered Routing Algorithm (TORA) Version 1 – Functional Specification", Internet Draft, MANET working group, draft-ietf-manet-tora-spec-02.txt, October 1999.

[11] C. Comaniciu, H.V. Poor, "On the Capacity of Mobile Ad Hoc Networks with Delay Constraints", IEEE Transactions on Wireless Communications

[12] Shakkottai, S.; Rappaport, T.S.; Karlsson, P.C., "Cross layer Design for Wireless Networks", Communications Magazine, IEEE , Volume: 41, Issue: 10 , Oct 2003

[13] Wing Ho Yuen; Heung-no Lee; Andersen, T.D, "A simple and effective cross layer networking system for mobile ad hoc networks", Personal, Indoor and Mobile Radio Communications, 2002. The 13th IEEE International Symposium on , Volume: 4 , 15-18 Sept. 2002 Pages:1952 - 1956 vol.4

[14] Comaniciu, C., Poor, H.V., "QoS provisioning for wireless ad hoc data networks", Decision and Control, 2003. Proceedings. 42nd IEEE Conference on , Volume: 1 , 9-12 Dec. 2003 Pages:92 - 97 Vol. 1

[15] Singh, S., Raghavendra, C.S., " Power efficient MAC protocol for multihop radio networks", Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on, Volume: 1 , 8-11 Sept. 1998 Pages:153 - 157 vol.1

[16] Grossglauser, M., Tse, D.N.C.," Mobility increases the capacity of ad hoc wireless networks", Networking, IEEE/ACM Transactions on, Volume: 10 , Issue: 4 , Aug. 2002 Pages:477 - 486