Constructing Energy-Efficient Broadcast Trees in Wireless Ad Hoc Networks

A. T. Chronopoulos, S. Ponipireddy
Computer Science Department,
University of Texas at San Antonio,
San Antonio, TX 78249
{atc,sponipir}@cs.utsa.edu

J. Sarangapani
Department of Electrical and Computer Engineering,
The University of Missouri-Rolla,
Rolla, Missouri 65401
sarangap@umr.edu

Abstract. The wireless networking environment presents formidable challenges to the study of broadcasting and multicasting problems. Energy efficiency is a measure of performance in broadcast and multicast operations. We consider the problem of broadcast in Ad Hoc wireless networks. We study the feasibility of constructing a broadcast tree while maintaining the quality of service (Qos) in terms of Signal to Interference ratio (SIR). We present simulation results and comparisons.
Key words and Phases: Signal to interference ratio (SIR), Broadcast trees, Energy efficiency, Wireless ad hoc network.

1 Introduction

The wireless networking environment presents formidable challenges to the study of broadcasting and multicasting problems. The problems of broadcasting and multicasting in *all-wireless* networks are being currently studied. Among the most difficult issues related to mobile wireless applications is that of operation in limited-energy environments. In this paper we implement the energy-efficient broadcast algorithm given in [1] and add one of the main Quality of Service features which consider SIR in forming each link. The scheme developed in [1] addresses the issues of transmitting power levels (and hence network connectivity), and multicast tree formation (routing). This approach relies on the 'node-based' nature of wireless communication. The algorithm is a source-initiated broadcasting of 'session' traffic.

One of the most crucial issues in wireless networks is the trade-off between the 'reach' of wireless transmission (namely the simultaneous reception by many nodes of a transmitting message) and the resulting signal interference by that transmission. Therefore, there is a trade-off between reaching more nodes in a single hop by using a higher power level (but at a higher interference cost) versus reaching fewer nodes in that single hop by using a lower power level (but at a lower interference cost). Another crucial issue is that of energy consumption, because of the nonlinear attenuation properties of radio signals. To assess each complex trade-off separately, we assume the following:

- No mobility.
- The availability of a large number of bandwidth resources. (So that contention for channel is not an issue)
- Sufficient transceiver resources are available at each node. (So calls are never blocked)
- The channel conditions are unchanged.

Under these assumptions we focus on the determination of minimum-energy broadcast trees taking into consideration the SIR. In The following sections we study Architectural issues (Section 2), the Wireless model (Section 3), Quality of Service issues (Section 4), Simulation results (Section 5) and conclusions (Section 6).

2 Architectural issues in Ad Hoc Networks

In Ad Hoc wireless networks it is possible to establish a link between any pair of nodes, provided that each has a transceiver available for this purpose and that the SIR at the receiving node is sufficiently high, (i.e above the required threshold). The links in the wireless networks are determined depending on factors such as distance between nodes, transmitting power, error-control schemes, other-user interference, and background noise. Furthermore, in ad-hoc networks no distinction can be made between uplink and downlink traffic. This complicates the interference environment.

The key characteristics of Ad Hoc Networking are:

(1) There is no fixed infrastructure (thus it is rapidly deployable).

(2) It uses wireless multihop communication, which is dynamically set up and reconfigurable as nodes move around.

3 Wireless Communications Model

Here, source-initiated, circuit-switched, multicast sessions have been considered. The network consists of N nodes, randomly distributed over a specific region. Any node is permitted to initiate multicast sessions. Each multicast group consists of the source node plus at least one destination node. Additional nodes may be needed as relays, either to provide connectivity to all members of the multicast group or to reduce overall energy consumption or both. The set of nodes that support a multicast session (the source node, all destination nodes, and all relay nodes) is referred to as a *multicast tree.*

The connectivity of the network depends on the transmission power. Assuming that each node can choose its own power level, which is not to exceed a maximum value P_{max}. We assume that the receiving signal power varies as $r^{-\alpha}$, where r is the range and α is a parameter that typically takes on a value between 2 and 4 depending on the characteristics of the communication medium. Based on this model the transmitting power required to support a link between two nodes, separated by range r, is proportional to r^{α}.

As a result of the wireless multicast advantage, the correct view of the omni-directional wireless communication medium is a node-based environment that is characterized by the following properties:

(i) A node's transmission is capable of reaching another node if the latter is within its communication range, which in turn means that the received signal-to-interference plus-noise ratio exceeds a given threshold. Also, the receiving nodes have allocated receiver resources for this purpose.

(ii) The total power required to reach a set of other nodes is simply the maximum required to reach any of them individually.

In [1] a Broadcast Incremental Power (BIP) Algorithm (based on Prim's minimum spanning tree algorithm) [9] is determined to get the minimum-power tree being routed at the source node that reaches all the other nodes in the network. This algorithm exploits the wireless multicast advantage in the construction of the broadcast tree, but the QoS issues are not considered in [1]. This paper includes one of the main QoS issue i.e. SIR at the receiving nodes.

4 Quality of Service issue

Our goal is to maintain a required SIR threshold for each network link while the transmitting power is adjusted so that the least possible power is consumed. Suppose there are N nodes in the network. Let G_{ij} be the power loss(gain) from the transmitting node i to the receiving node j. It involves the free space loss, multi-path fading, shadowing, and other radio wave propagation effects, as well as the spreading/processing gain of CDMA transmissions [8]. To keep things simple, we assume that all G values are equal to 1, and do not change with time (no mobility). In reality G's undergo rapid stochastic fluctuations with time-varying statistics due to node mobility.

Calculation of SIR R_i at node i, [5]

$$R_i = \frac{G_{ii} * P_i}{(\Sigma_{j \neq i} G_{ij} * P_j + \eta_i)} \quad , \tag{1}$$

where $i,\ j \epsilon \{1, 2, 3, ..., N\}$, P_i is the i^{th} node transmitting power and $i > 0$ is the thermal noise at the receiver node by transmitting i. For each link i there is a lower SIR threshold γ_i, reflecting a certain QoS the link has to maintain in order to operate properly. Therefore, we require that

$$R_i \geq \gamma_i \tag{2}$$

for every $i = 1, 2, 3, .., N$. An upper SIR limit is also set, so that the transmitting power of a link is minimized, which in turn will decrease the interference due to its transmitting power at the other receiving nodes. Therefore, we check that:

$$R_i \leq \delta \quad . \tag{3}$$

The above condition is used to minimize the transmitting power but it is not mandatory. If the equation (2) fails (i.e $R_i < \gamma_i$) then the transmitting power of the transmitting has to be increased to increase the SIR at its receiver, according to the following equation

$$P_i(k+1) = \frac{\gamma_i * P_i(k)}{R_i(k)} \tag{4}$$

where $k = (1, 2, 3, ..)$ (see [5] - [7]). If $P_i(k+1) > P_{max}$, the new link is not added to the tree because that receiving node of the new link is unacceptable and cannot be added to the tree.

If (3) fails (i.e. $R_i > \delta$) then the power will be decreased, according to the following equation

$$P_i(k+1) = \frac{\delta * P_i(k)}{R_i(k)} \tag{5}$$

If the power slips under the minimum threshold power $P_i(k+1) < r^\alpha$ (the minimum power needed to form a link), then we maintain it at the previous power level.(i.e $P_i(k+1) = P_i(k)$).

SIR protection of an active link

For any active link i, that we have $R_i(k) \geq \gamma_i \quad => R_i(k+1) \geq \gamma_i$. This implies that a new link is added to the tree if and only if the new state of the system is stable, i.e. none of the existing links are broken.

We next present the distributed algorithm for constructing a multicast tree with power control. We denote the local source node by SN.

Algorithm:

1. Each SN receives the position (i.e. coordinates of each node) of a subset of the nodes to be directly linked to it.
2. SN starts the broadcast tree formation according to the BIP algorithm in [1]. Before adding a new link to the tree:
   a. Each future receiver node calculates the SIR and checks against its threshold.
   b. The new SIR will be sent to SN.
   c. SN checks the SIR, if any of the conditions (2) or (3) is not satisfied then the new transmitting powers are calculated according to the equations (4) and(5) respectively.
4. If any new nodes are still unlinked then, Go to step 1. Else tree construction is complete.

The final tree is the minimum-Energy broadcast tree, for the given set of N nodes.

5 Simulation Results

We wrote a simulation code implementing our algorithm. We Considered a group of 10 nodes placed in an area or 5×5 square units (Figure 1). Using their coordinates, the distance table (distance between every 2 nodes) is calculated. The above broadcast algorithm is run in two different ways (I) Single session and (II) Two simultaneous sessions.

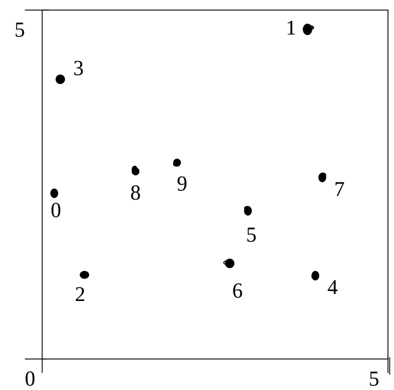

Fig. 1. Sample network

(I) In single session, there is only one main source node trying to broadcast the data to all other nodes. The above algorithm is coded and the sample network given above is given as input. We set $\alpha = 2$. Thermal noise is assumed to be the same at all the nodes (*i.e.* $\eta = 0.25$). Initially, we set the lower threshold SIR $\gamma_i = 0.1$ (for simplicity γ_i is assumed to be same for all $i's$). The maximum SIR is set equal to 0.5, and $P_{max} = 10$. The following is the final tree:

Node 6 is the source, and nodes 0, 7 and 9 are intermediate transmitting nodes. The total power of the above-formed tree is the sum of the transmitting powers of the nodes 6, 0, 7 and 9 (Total Power = 16.482). The change in SIR's with iterations is plotted in Figure 4. In this plot we can observe the stable state in the end at 15th iteration (i.e. all SIR's are greater than the threshold and all of them are also less than the maximum SIR value).

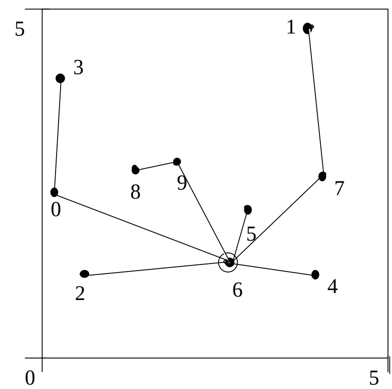

Fig. 2. Final tree with node 6 as source

(II) We assumed every node has enough transceivers. Two simultaneous sessions generating their own broadcast trees with their own links interfering with all the other nodes.

Node 9 is the source for $session_1$ and node 6 for $session_2$. To simulate two sessions simultaneously. Two Posix threads are created and each thread generates a broadcast tree for its session. Here the interference is added by both the sessions for the SIR calculation at each receiving nodes.

Here two cases are considered:

(a) (With Sleep) Tree generation of the first session is finished before the second tree is generated. The changes of SIR with the iterations is shown in Figure 5 and Figure 6. The broadcast tree of the session with source 9 is in Figure 3 and the tree of the session with source 6 is in Figure 2. The total transmitting powers for the trees are:

For $session_1$ (with source node 9) = 11.937

For $session_2$ (with source node 6) = 18.399

(b) (Without Sleep) Both sessions trees are generated simultaneously. The total transmitting powers for the trees are:

For $session_1$ (with source node 9) = 13.162

For $session_2$ (with source node 6) = 16.371

The SIRs of this run are plotted in Figure 7 (source node 9) and Figure 8 (source node 6).

In all simulations (Figures. 4-8) we added nodes starting from the source node. We can see new curves emanating from the x-axis for

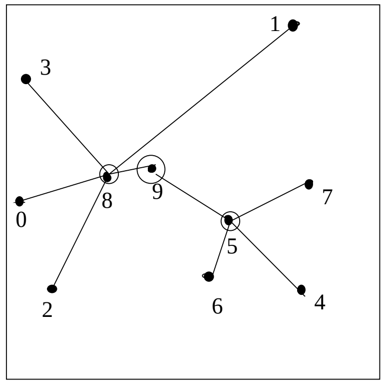

Fig. 3. Final tree with node 9 as source

each newly added node. We can observe that in the region after all nodes have been added a steady state has been achieved for SIR. This also implies that we do not need to adjust the power as long as we maintain the same nodes in the system.

6 Conclusions

In [1] the broadcast tree generation algorithm (BIP) is explained. However, no QoS issues are considered. In [5] the aspect of SIR, which is one of the main QoS issue, is introduced. We consider the broadcast with SIR as QoS. We give an algorithm, which generates an energy efficient broadcast trees in an ad hoc wireless network taking into account SIR's at the receiving nodes. We run simulations that demonstrate the feasibility of our algorithm.

Acknowledgments

This research was supported, in part, by research grants from (1) NASA NAG 2-1383 (1999-2001), (2) State of Texas Higher Education Coordinating Board through the Texas Advanced Research/Advanced Technology Program ATP 003658-0442-1999

References

[1] A. Ephremides, J. E. Wieselthier and G. D. Nguyen, "On the Construction of Energy-Efficient Broadcast and Multicast Trees in Wireless Networks". pp.585-594, IEEE INFOCOM 2000.

[2] M. Nagy and S. Singh, "Multicast scheduling algorithms in mobile networks" Cluster Computing, 1, pp.177-185, December 1998.

[3] K. Makki, N. Pissinou and O. Frieder, "Effecient solutions to multicast routing in communication networks" MONET, 1, pp.221-232, 1996.

[4] M. H. Ammar, G. C. Polyzos and S. K. Tripathi, "Special Issue on network support for multipoint communication" IEEE Journal on Selected Areas in Communications, 15, April 1997.

[5] N. Bambos, "Towards Power-Sensitive Network Architectures in Wireless Communications:concepts, issues and Design Aspects". IEEE Personal Communications, pp.50-59, June 1998.

[6] N. Bambos, S. Chen and G. J. Pottie, "Channel Access Algorithms with Active Link protection for Wireless Communication Networks with Power Control". IEEE ACM Transactions on networking, pp.583-597, October 2000.

[7] G. J. Foschini and Z. Miljanic, "A Simple Distributed autonomous power control algorithm and its convergence". IEEE Tran. Veh. Tech., vol.42, pp.641-646, April 1993.

[8] T. S. Rappanport, "Wireless Communications, Principles and Practices", book Prentice Hall, 1999.

[9] T. H. Cormen, C. E. Leiserson, R. L. Rivest, "Introduction to Algorithms", book MIT Press and McGraw-Hill, 1990.

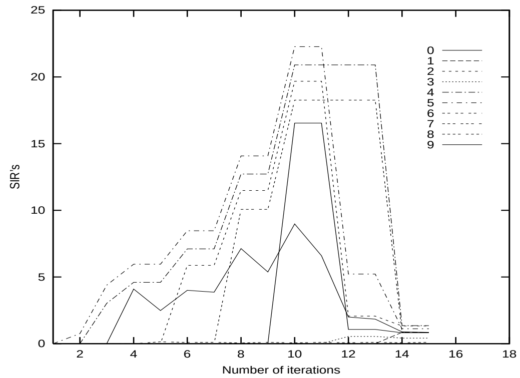

Fig. 4. Single Session (source 6)

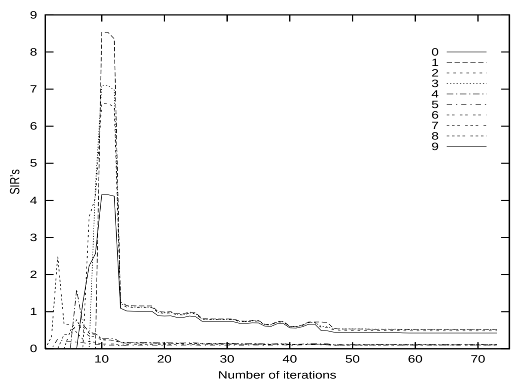

Fig. 5. Two Sessions; $Session_1$ without sleep (source 9)

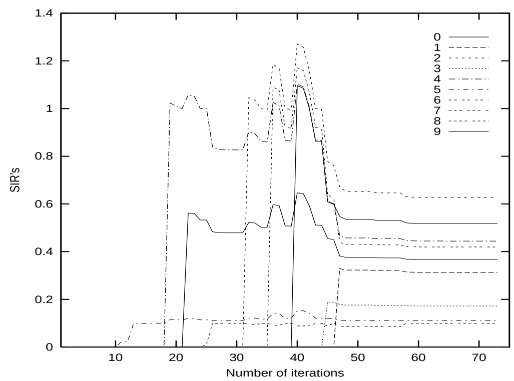

Fig. 6. Two Sessions; $Session_2$ without sleep (source 6)

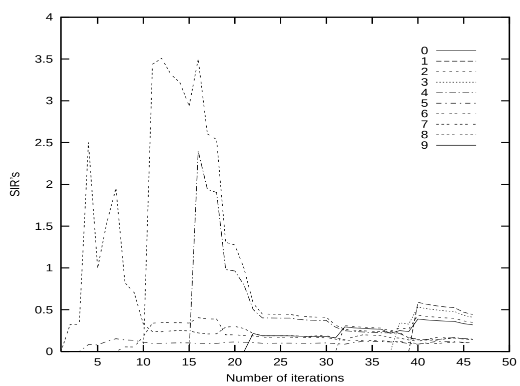

Fig. 7. Two Sessions; $Session_1$ with sleep (source 9)

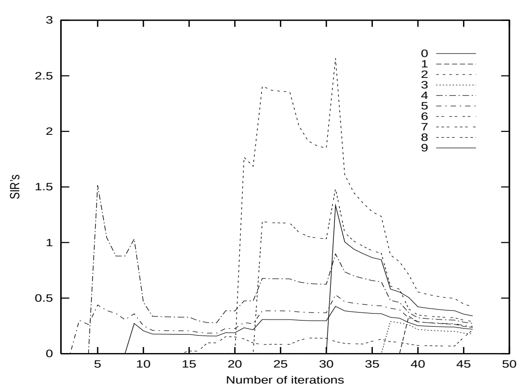

Fig. 8. Two Sessions; $Session_2$ with sleep (source 6)