RISE: Reducing Interference and Saving Energy through Multicasting in Ad Hoc Wireless Networks

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Abstract— **We develop an approach that makes use of directional antennas to improve the performance of multicasting in ad hoc wireless networks. We first assume that multicast trees are known for all the active sessions. The antenna beamwidth at the network nodes is determined in such a way that both the nodes' transmit power and the interference among simultaneous transmissions are reduced, while the signal power at the intended receivers remains unchanged. We propose a model to study the performance improvement that results solely from interference reduction by using directional antennas. The proposed approach is then applied to a simple distributed algorithm for multicast tree construction and the performance is evaluated.**

I. INTRODUCTION

In this paper, we deal with the problem of multicasting in ad hoc wireless networks. Multicasting enables data delivery to multiple recipients in a more efficient manner than traditional unicasting and broadcasting. A packet is duplicated only when the delivery path toward the traffic destinations diverges at a node, thus helping to reduce unnecessary transmissions. For this reason, multicasting is a high desirable feature in ad hoc networks, where bandwidth and nodes' energy are precious resources.

Several multicast protocols for ad hoc networks have been proposed in the literature ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]). In particular, ([10], [11], [12]) focus on the construction of a power efficient multicast tree and discuss some crucial issues. The work in ([10], [11]) point to the broadcast nature of wireless communications: when omnidirectional antennas are used, every transmission by a node can be received by all the nodes in its transmission range. This implies that the higher the transmission power is, the more nodes can be reached. However, trade-offs exist among network connectivity, power consumption, as well as interference caused to other simultaneous transmissions. In [12], both physical layer requirements, expressed as Signal to Interference plus Noise Ratio (SINR), and network layer issues are taken into account in order to derive a multicast tree which minimizes transmission power.

In this paper we consider a multihop network, whose nodes have a limited amount of available energy and access the radio channel by using a CDMA scheme. As a first step, we assume that communication nodes are fixed; thus, multiuser interference and energy consumption are the two main issues that need to be addressed. The goal here is not the construction of an optimal multicast tree that meets the required network constraints. Rather, the objective is to explore the advantage of using directional antennas at the network nodes when multicast sessions are performed. The approach that we propose, named RISE (Reducing Interference and Saving Energy), is therefore intended to be executed on top of many of the multicast protocols that have been proposed.

The system model that we consider is described in further detail in Section II, while the proposed approach based on the use of directional antennas is introduced in Section III. Section V presents a simple algorithm to find multicast trees in a distributed manner and shows preliminary results obtained by applying the RISE technique to the tree construction algorithm. Finally, Section VI concludes the paper and discusses important issues that will be addressed in future research.

II. NETWORK MODEL

We consider an ad hoc network composed of stationary wireless nodes randomly distributed in the network area. We assume source-initiated multicast sessions, for each of which a source-rooted tree is constructed. Each multicast tree includes source, destination(s), and relay nodes that may be needed to provide connectivity between the source and its destination(s). Also, each node can take part in multiple simultaneous sessions.

Communication links are assumed to be bidirectional. Each node can select its own level of transmit power P^t, provided that it does not exceed the maximum allowed transmit power, denoted by P^t_{max}. The value of P^t_{max} may depend on hardware and battery constraints or interference requirements. We define two nodes to be *adjacent* if they see a SINR for the each other's signal transmission that is above a given threshold γ.

We assume that the network nodes are equipped with directional antennas whose beamwidth[1], denoted by θ, can be varied between 0 and 2π. The gain of an antenna in a given direction is denoted by G and is defined as the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. A relationship of inverse proportionality exists between the beamwidth and

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[1] We refer to the antenna horizontal beamwidth; the vertical beamwidth is assumed to be constant.

the gain of the antenna [13],

$$G \propto \frac{1}{\theta}. \tag{1}$$

The path loss between a transmitting antenna with gain G^t and a receiving antenna with gain G^r is given by

$$\Gamma = \frac{(4\pi d/\lambda)^\alpha}{G^t \cdot G^r} \tag{2}$$

where d is the distance between the two antennas, λ is the wavelength, and α is a parameter whose value is usually between 2 and 4. Equations (1) and (2) show that the narrower the beamwidth of the transmitter and the receiver antennas are, the higher their gain and the smaller the path loss.

III. The RISE Technique

Let us assume that the multicast trees for the active sessions in the network are known. Given the constraint on the maximum transmit power that can be used by the nodes, multicast trees can be determined by using, for instance, the algorithms in [11] or the distributed solution that we propose in Section V.

Under this assumption, each node taking part in a multicast session is aware of the nodes in its proximity with which it has to establish a network link. The underlying idea of the RISE approach is to set the antenna beamwidth at each node in such a way that *(i)* the node's transmit power can be lowered and *(ii)* the interference to simultaneous transmissions in the node's vicinity is reduced.

For the sake of simplicity, consider that initially all nodes in the network use an isotropic antenna beamwidth (i.e., $\theta = 2\pi$); we denote the corresponding gain by G_I. Network links are established between the nodes according to the structure of the multicast tree of the active sessions. By using the received signal strength indicator (RSSI), each node is able to estimate its distance from the intended receiver(s). Based on this information and on the interference level, it selects its level of transmit power in such a way that the SINR at the furthest intended receiver is greater than γ. For each node, we have

$$P_I^t(\gamma) = \Gamma_I \cdot P_I^r(\gamma) \tag{3}$$

where $P_I^r(\gamma)$ is the required signal power at the receiver depending on the SINR threshold γ, and subscript I indicates that the above values refer to the case where an isotropic antenna beamwidth is applied.

At this point, each node taking part in one or more multicast sessions can compute the minimum antenna beamwidth, θ_m, to be used to transmit/receive traffic to/from its adjacent nodes taking part in the same multicast tree. The antenna gain, G_m, corresponding to the selected beamwidth can be derived from (1). Clearly, the smaller the value of θ_m is, the greater G_m with respect to G_I.

As observed in the previous section, higher values of antenna gain lead to a lower path loss; hence the transmit power of each node can be reduced while still meeting the required signal power at the receiver. By using (1)–(3), we derive the reduction in the nodes' transmit power, S, as

TABLE I

Transmission scheme: odd slots (on the left) and even slots (on the right).

Sender	Receiver
A	B, C, D
F	I, J
G	K
H	L

Sender	Receiver
B	E, F
D	G, H
K	M, N

$$S = \frac{P_I^t(\gamma)}{P_m^t(\gamma)} = \frac{G_m^t \cdot G_m^r}{G_I^t \cdot G_I^r} = \frac{4\pi^2}{\theta_m^t \cdot \theta_m^r} . \tag{4}$$

Eq. (4) suggests that significant benefits can be obtained by properly setting the antenna beamwidth at the network nodes. However, varying the antenna beamwidth involves the use of signal processing procedures, whose complexity and cost should be taken into account while investigating the benefits of using directional antennas. Clearly, a trade-off exists between the increase in system complexity and the reduction in power consumption and multiuser interference that can be achieved.

Notice that due to the decrease in the nodes' transmit power, interference in the network environment is reduced. This allows the nodes to further decrease P^t while still accomplishing the required SINR. Further, network throughput can be improved as well.

IV. Effect on Interference Reduction by using RISE

We assume that simultaneous transmissions do not interfere with each other and that transmissions are always successful, which is not the case in the real world. When directional antennas are used, the interference between simultaneous transmissions is greatly reduced. In order to study the additional saving in power expenditure and improvement in successful transmissions due to the reduced interference, we develop the model described in the next section.

A. Assumptions and Model Description

We assume that the multicast tree has been set up and that the transmission is slotted. The transmission scheme is as follows: in each odd (even) slot, transmissions are performed by the nodes in the odd (even) layer of the tree who have any child/children, while the children of these senders act as receivers. As an example, consider the simple multicast tree shown in Fig. 1. The corresponding transmission scheme is presented in Table I.

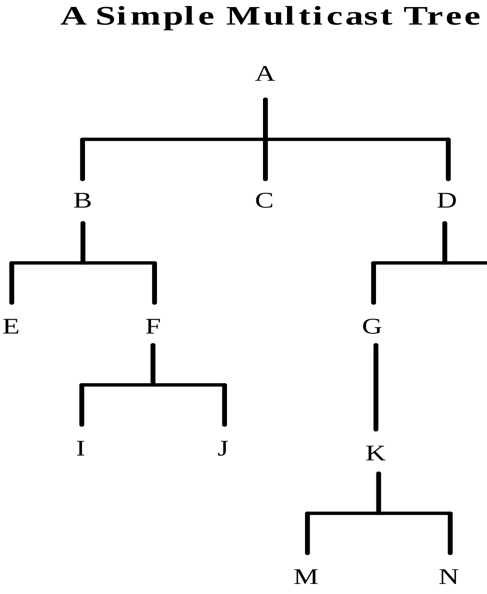

Fig. 1. A simple multicast tree.

Interference caused by simultaneous transmissions is treated as noise. Let $S(i)$ denote the node sending traffic to the receiver node i. A transmission from node $S(i)$ to node i is considered successful when the SINR exceeds a given threshold γ,

$$\frac{P^t_{S(i)}/d^{\alpha}_{S(i)i}}{N_0 + \frac{1}{L}\sum_{k\in\mathcal{I}()\rangle),\|\neq\mathcal{S}()\rangle)} P^t_k/d^{\alpha}_{ki}} \geq \gamma \tag{5}$$

where P^t_k is the transmission power of node k, d_{kj} is the distance between node k and node j, α is the exponent in the path loss model, N_0 is the background noise power, $\mathcal{I}()\rangle)$ is the set of senders whose transmissions reach the receiver node i, and L is the processing gain of the system. For a narrowband system, $L = 1$, while for a spread-spectrum CDMA system, $L > 1$.

We can re-write (5) as

$$P^t_{S(i)}/d^{\alpha}_{S(i)i} - \frac{\gamma}{L}\sum_{k\in\mathcal{I}()\rangle),\|\neq\mathcal{S}()\rangle)} P^t_k/d^{\alpha}_{ki} \geq \gamma N_0. \tag{6}$$

Let $\mathcal{S}$ denote the set of senders in the current slot. Let a parameter $a_{ij} = 1$ indicate that the receiver node j can hear from the sender node i, and $a_{ij} = 0$ otherwise. Thus (5) can be re-written as

$$\frac{1}{d^{\alpha}_{S(i)i}} P^t_{S(i)} - \frac{\gamma}{L}\sum_{k\in\mathcal{S},\|\neq\mathcal{S}()\rangle)} \frac{a_{ki}}{d^{\alpha}_{ki}} P^t_k \geq \gamma N_0. \tag{7}$$

Let $\mathcal{R}$ denote the set of receivers in the current slot. Equation (7) needs to be satisfied for all the nodes in $\mathcal{R}$. Assume that n and m are the number of nodes in $\mathcal{S}$ and $\mathcal{R}$, respectively. The equation array can be written in matrix form, i.e.,

$$\mathbf{\Delta}\tilde{\mathbf{P}^{\mathbf{t}}} \geq \tilde{\mathbf{b}} \tag{8}$$

where $\vec{b} = \gamma N_0 \left[1, 1, \ldots, 1\right]^T$, $\mathbf{\Delta}$ is a matrix defined as

$$\mathbf{\Delta}=\begin{bmatrix} -a_{11}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{11}} & \cdots & \cdots & \frac{1}{d^{\alpha}_{S(1)1}} & \cdots - a_{n1}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{n1}} \\ -a_{12}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{12}} & \frac{1}{d^{\alpha}_{S(2)2}} & \cdots & \cdots & \cdots - a_{n2}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{n2}} \\ \vdots & \vdots & & & \vdots \\ -a_{1m}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{1m}} & \cdots & \frac{1}{d^{\alpha}_{S(m)m}} & \cdots & \cdots - a_{nm}\frac{\gamma}{L}\frac{1}{d^{\alpha}_{nm}} \end{bmatrix} \tag{9}$$

and $\vec{P^t} = \left[P^t_1, P^t_2, \ldots, P^t_n\right]^T$ is the transmission power vector, with $P^t_i \geq 0$ being the transmission power of the ith node in $\mathcal{S}$. Notice that there is only one positive entry in each row in $\mathbf{\Delta}$ corresponding to the signal received from the intended sender, while the negative entries represent the interference from other senders.

B. Omnidirectional Antennas vs. Directional Antennas

In the case of omnidirectional antennas, each node may receive interfering signals from any of the sender nodes, i.e., $a_{ij} = 1$ for any i and j. On the contrary, when directional antennas are used, the senders are no longer heard by all receivers. Consider the example presented in Fig. 1. As shown in Fig. 2, node A transmits to $\{B, C, D\}$, and node F transmits to $\{I, J\}$. If directional antennas are used, A uses the minimum beamwidth that allows A to cover $\{B, C, D\}$, and F uses the minimum beamwidth necessary to cover $\{I, J\}$. The corresponding a_{ij}'s are shown in Table II. Observe that in this case there is interference at node B only.

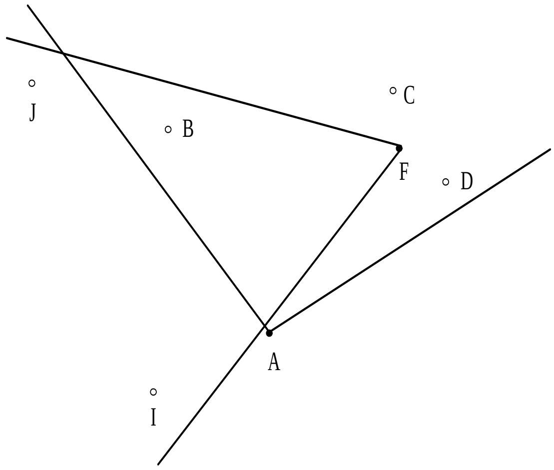

Fig. 2. Use of directional antennas in the multicast tree shown in Fig. 1.

TABLE II
Interference Table.

a_{ij}	B	C	D	I	J
A	1	1	1	0	0
F	1	0	0	1	1

C. A Linear Programming Formulation to Minimize the Total Power Expenditure

In order to minimize the total transmission power, the following linear programming (LP) problem can be formulated

$$\begin{aligned} &\text{minimize} && \sum_{i=1}^{n} P_i^t && (10)\\ &\text{subject to} && \mathbf{\Delta}\tilde{\mathbf{P^t}} \geq \tilde{\mathbf{b}} \\ & && P_i^t \geq 0 \quad \text{for } 1 \leq i \leq n. \end{aligned}$$

We can prove that an optimal solution to (10) exists if and only if there is a feasible solution to (8), i.e., there is at least one set of transmission powers which ensures the successful reception at all receiver nodes.

Theorem 1: There is at least a set of transmission powers which ensure the successful reception at all receiver nodes if and only if there is an optimal solution to the LP problem in (10).

Proof: The converse is obvious. Now let us suppose $\vec{x} = [x_1, x_2, \ldots, x_n]^T$ $(0 < x_j < +\infty, \text{for } 1 \leq j \leq n)$ is a feasible solution to (8). We need to show that there exists an optimal solution to the LP problem in (10).

Although the feasible set may be unbounded, the feasible set that could possibly achieve the minimization is bounded since $0 \leq P_i^t \leq \sum_{j=1}^{n} x_j, \text{for } 1 \leq i \leq n$. Hence an optimal solution to the LP problem exists by virtue of Theorem 3.4 in [15].

Theorem 1 shows that we can use (10) to find out if there exists a feasible transmission power scheme such that the SINR at every receiver is guaranteed, and if such a scheme exists, the solution to the LP problem gives us the optimal transmission power scheme such that the total power expenditure is minimized.

For a given set of senders, spreading gain L, node distribution, and multicast tree, the solution to the LP problem may not exist. In this case, we consider that the transmission in that slot failed. We define a *multicast failure* as the event that there is no solution to the LP problem either in the odd slot, or in the even slot, or in both. We define *power saving* as the ratio of the total power expenditure when omnidirectional antennas are used to that obtained when directional antennas are used. The simulation results will be presented later.

V. A DISTRIBUTED MULTICAST ALGORITHM AND PERFORMANCE ASSESSMENT

In order to study the performance of the RISE technique, we need an algorithm to construct the multicast tree. In this section, we present a distributed algorithm, named NBMA (Neighbor Based Multicast Algorithm), that aims at constructing an energy-efficient multicast tree. Results are derived by applying the RISE technique on top of this algorithm, as well as of the Multicast Incremental Power (MIP) scheme [11].

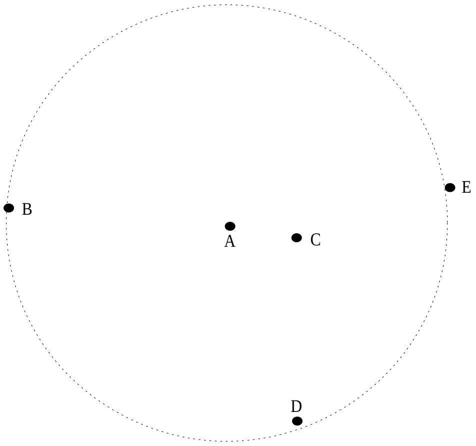

Fig. 3. A simple five-node network.

TABLE III
NEIGHBORS AND COVERED SETS FOR EACH NODE IN THE NETWORK.

Node	$\mathcal{N}$	$\mathcal{C}$
A	$\{B, C\}$	$\{B, C, D\}$
B	$\{A\}$	$\{A\}$
C	$\{A, D, E\}$	$\{A, D, E\}$
D	$\{C\}$	$\{C\}$
E	$\{C\}$	$\{C\}$

A. The NBMA Scheme

We draw upon the work in [14], where the goal is to define an energy efficient network protocol. In [14], a node transmits only to some of its adjacent nodes, which serve as relays; these nodes, called *neighbors*, are found by using a localized search procedure. Here, we assume that all the nodes in the network have already discovered their neighbors by using this algorithm. Then, we construct a broadcast tree and obtain the multicast tree by pruning the broadcast tree.

The algorithm that we propose works in a recursive way; we use the simple network shown in Fig. 3 as an example to explain how the algorithm works. We assume that node A is the traffic source. Let $\mathcal{N}(X)$ denote the set of neighbors of the generic node X and d_{XY} be the distance between node X and Y, $X, Y \in \{A, B, C, D, E\}$. We define the *covered* set of X as $\mathcal{C}(X) = \{Y \mid d_{XY} \leq \max_{Z \in \mathcal{N}(X)} d_{XZ}\}$. Note that $\mathcal{N}(X) \subset \mathcal{C}(X)$; Table III reports the $\mathcal{N}$ and $\mathcal{C}$ sets associated with each node in the network.

As a first step, A broadcasts a setup packet to establish the broadcast tree. Let $\mathcal{R}$ be the set of nodes that have not received the broadcast setup packet; R is initialized to be equal to $\{B, C, D, E\}$. We define $\mathcal{C}'(X) = \mathcal{C}(X) \bigcap \mathcal{R}$, and assume that each node transmits at a power level equal to the minimum between the power required to reach the furthest node in its set $\mathcal{C}'$ and $P^t_{_{max}}$.

At the beginning, $\mathcal{C}'(A) = \mathcal{C}(A) = \{B, C, D\}$. A designates the furthest node in $\mathcal{C}'(A)$, B, to be the next 'work node' and sets its transmit power in such a way that all the nodes in $\mathcal{C}'(A)$ receive its transmission. Then, A updates R to be equal to $\{E\}$ and sends the setup packet, which includes R and the designated work node. B compares its set $\mathcal{C}$ with R. Since $\mathcal{C}(B)\bigcap\mathcal{R}=\emptyset$, B does not need to forward the setup packet to anyone; it just sends back to A an ACK indicating that it has finished its job. A then designates D, the next furthest node in $\mathcal{C}'(A)$, as the next work node. D discovers that its only neighbor C is not in R and sends an ACK back to A. Finally, A designates C as the next work node. Since $\mathcal{C}(C)=\{A,D,E\}$ and $\mathcal{C}'(C)=\{E\}$, C forwards the setup packet to E including the updated $R=\emptyset$. At this point, all nodes have received the broadcast setup packet. Node E sends an ACK to its parent node C, C forwards the ACK back to A, and the procedure is terminated.

After the broadcast tree is set up, every node remembers its set $\mathcal{C}'$ and transmits the broadcast packet accordingly. For instance, in our example, only A and C are in charge of forwarding the broadcast packets. Given the destinations of the multicast session, the multicast tree is obtained from the broadcast tree by eliminating the unnecessary transmissions.

Observe that the neighbor discovery and broadcast tree setup algorithm are completely distributed and the complexity of the NBMA grows linearly with the number of network nodes.

B. Simulation Results

B.1 Results on Interference Reduction

We study the performance in interference reduction when the RISE technique is applied to the MIP scheme [11]. We add an additional power limitation - the transmission power of each node cannot exceed a certain power threshold P^t_{max}. If an optimal solution to the LP problem exists but one (or more) of the transmission powers exceed(s) P^t_{max}, the transmission in that slot is considered failed. While applying the RISE technique, we assume that the beamwidth of a directional antenna can take only M values. To derive the results shown in the following, we have chosen: $L=16$, $\alpha=2$, $\gamma=6$dB, $N_0=0.1$, and $P^t_{max}=5\times10^4$. The nodes are randomly and uniformly distributed in a 100×100 region, and the multicast source and destinations are randomly chosen. The Matlab function 'linprog' (available in the Optimization toolbox) is used to solve the LP problem in (10).

The average power saving and multicast failure rate for a 30-node system are shown in Fig.s 4 and 5, respectively. We compare the performance gain when $M=3$ and $\theta\in\{\frac{2\pi}{3},\frac{4\pi}{3},2\pi\}$, and $M=6$ and $\theta\in\{\frac{\pi}{3},\frac{2\pi}{3},\pi,\frac{4\pi}{3},\frac{5\pi}{3},2\pi\}$. The lower multicast failure rate, and the power saving when no antenna gain factor is included, are due to the reduction in interference. Shown together In Fig. 4, we present results obtained both in the case when the antenna gain is considered and when it is not taken into account. Clearly, when the antenna gain is considered, a greater reduction in interference is achieved because a lower power can be used by the transmitters.

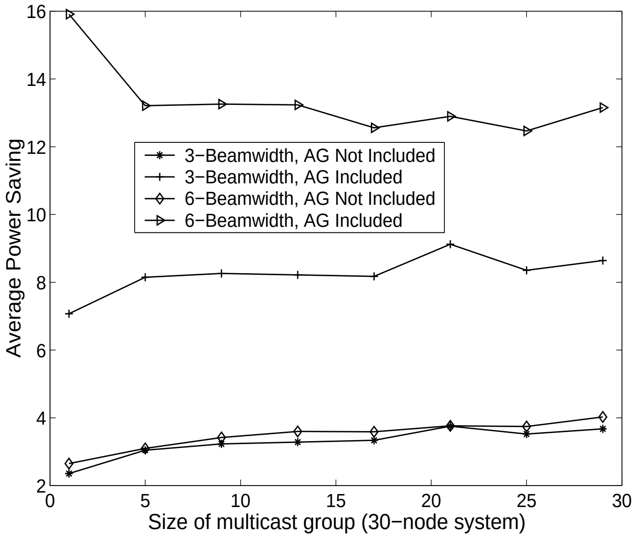

Fig. 4. Average power saving when directional antennas and the MIP scheme are used in a network with 30 nodes.

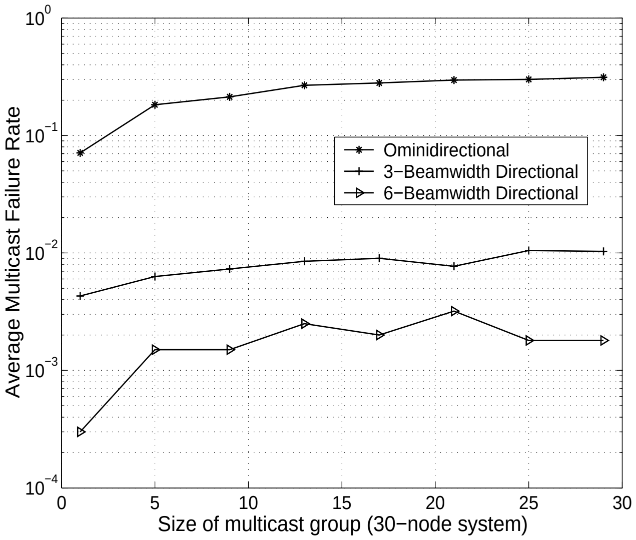

Fig. 5. Average multicast failure rate when directional antennas and the MIP scheme are used in a network with 30 nodes.

The results for a 72-node system are shown in Fig.s 6 and 7. Observe that a greater performance improvement is achieved by using directional antennas as the number of nodes in the system increases.

B.2 Performance of RISE & NBMA w/o Including Interference Reduction

We compare the performance of the NBMA with that of the MIP scheme [11]. The performance of these algorithms are then compared with the results obtained when the RISE technique is applied on top of them.

While applying the RISE technique, we assume that the beamwidth of a directional antenna can take only M values. For example, for $M=6$, $\theta\in\{\frac{\pi}{3},\frac{2\pi}{3},\pi,\frac{4\pi}{3},\frac{5\pi}{3},2\pi\}$. Each transmitting node uses the smallest beamwidth θ that enables it to cover all the nodes in its set $\mathcal{C}'$.

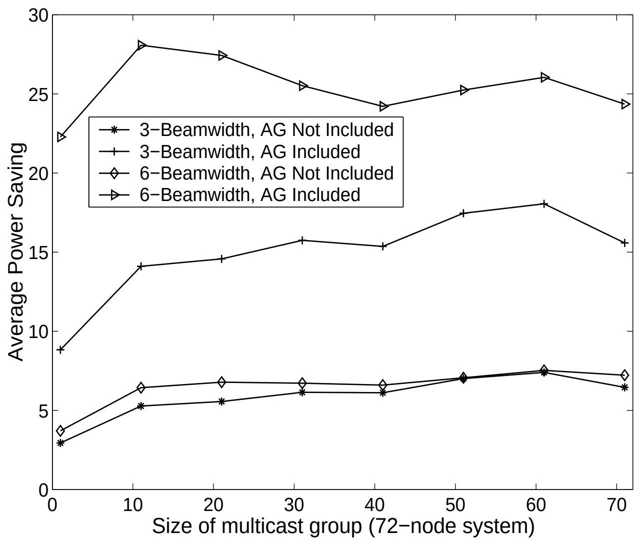

Fig. 6. Average power saving when directional antennas and the MIP scheme are used in a network with 72 nodes.

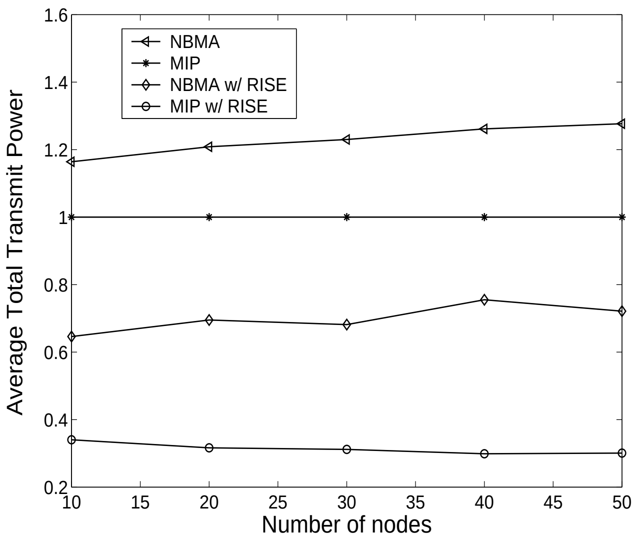

Fig. 8. Average total transmit power as a function of the number of nodes in the network obtained through the proposed algorithm and the MIP scheme. The performance of the two algorithms are compared with the results obtained when the RISE technique is applied.

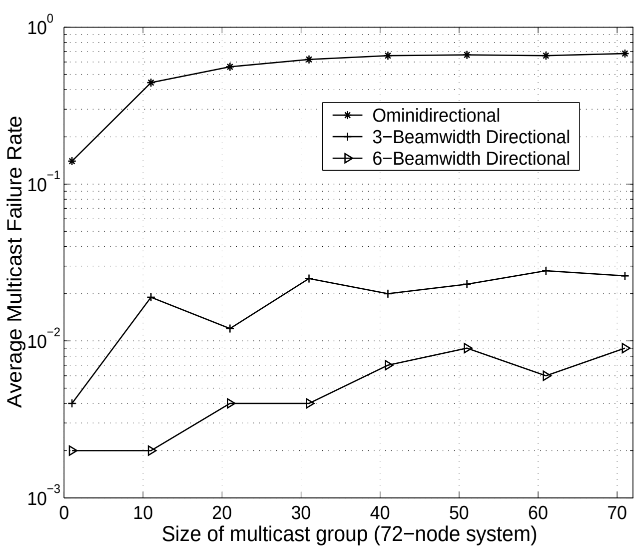

Fig. 7. Average multicast failure rate when MIP is applied in a network with 72 nodes.

Preliminary simulation results are shown in Fig. 8, where the total transmit power is plotted as a function of the number of nodes in the network. Results are normalized to the average total transmit power of the MIP scheme (without sweeping, see [11] for details). Given the number of nodes in the network, the transmit power consumed when the RISE technique is applied to the multicast algorithms is computed as the ratio of the transmit power consumed when an isotropic beamwidth is used to the value of S. The figure shows that, although NBMA is a very simple distributed algorithm, it has good performance relative to the MIP scheme, and that the RISE technique significantly improves the performance of both the multicast algorithms.

VI. Conclusions and Discussion

We presented an approach based on the use of directional antennas that aims at reducing power consumption and multiuser interference in ad hoc wireless networks supporting multicast sessions. First, we assumed that the multicast trees are known and we focused on improving the system performance by properly setting the antenna beamwidth at the network nodes. We proposed a model to study the potential performance improvement (in terms of power saving and multicast failure rate) that resulted solely from using directional antennas. Then, we applied the proposed RISE technique to a simple algorithm that determines source-rooted multicast trees in a distributed manner. Results showed that a significant reduction in the nodes' transmit power can be achieved by using the RISE approach.

We would like to emphasize that the goal of this work was to investigate the potential benefits of using directional antennas in wireless multicast communications. A great deal of work still need to be done. For instance, the effects of using directional antennas in a mobile network environment have to be evaluated. Also, trade-offs among the increase in signal processing complexity, the reduction in power consumption and multiuser interference, as well as the network connectivity need to be investigated.

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