Energy Efficient Multicasting Using Smart Antennas for Wireless Ad Hoc Networks in Multipath Environments

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Abstract- **Multicast is an important communication mode in wireless ad hoc networks. Furthermore, adaptive antenna array with Multiple-Input-Multiple-Output(MIMO) channel model are more suitable for wireless multipath environments. In this paper, we study energy efficient one hop multicast in such environment. The problem is formulated as a non-linear programming problem and two heuristic algorithms are proposed to solve the problem.**

I. INTRODUCTION

A wireless ad hoc network is comprised of nodes communicating with each other without infrastructure support. Each node can directly communicate only with nodes in its radio range. To exchange information with nodes beyond its radio range, a node must rely on other nodes to forward the information on its behalf. Such networks are becoming commonplace in many applications including battlefield environments, disaster-relief situations, and hotspot Internet access.

Multicast is an important communication mode in ad hoc networks. In a multicast session, a source node sends packets to a certain set of destination nodes in the network. If the destination node is not directly reachable by the source node, intermediate nodes can be used to forward the packet. A multicast tree which is rooted at the source node and covers all destination nodes is constructed before any data transmission. Once the tree is known, a node in the tree will deliver each multicast packet to all of its one hop children nodes (if it has any).

In conventional wireless ad hoc networks such as those based on IEEE 802.11, where all nodes use omni-directional antennas, multicasting to one hop children nodes is achieved through omni-directional broadcast. However, due to recent advances in technology, it is now possible to build nodes with significantly more capabilities. For instance, one can build nodes with multiple directional antennas to increase network throughput [1] and/or to reduce average energy required to transmit a bit.

A node with directional antennas can adjust its signal lobe to cover only a part of its neighbor nodes with certain physical vicinity. As a result, a node can carefully select one or more configurations of transmitting antenna (and thus the directions of the signal lobe) to minimize the total transmit power needed to deliver a packet to all its children nodes in the multicast tree.

Unfortunately, directional antennas work only in line of sight environments. In rich scattering environments such as in indoor or urban terrain, multiple antennas can be used along with Multiple-Input-Multiple-Output (MIMO) channel models to direct transmitted energy towards desired destinations. Although the use of multiple antennas and MIMO channels is well-studied for point-to-point wireless communications [2], their use in wireless ad hoc networks is thus far fairly limited.

Prior work on use of multiple antennas in wireless ad hoc networks are mostly for unicast communication with directional antennas. For example, Ko [3] and Nasipuri [4] were among the first to propose medium access control (MAC) schemes for ad hoc networks using directional antennas. Power control schemes for unicast communications are proposed in [5], [6], [7], [8], [9], [10]. In network layer, the use of directional antennas to reduce overhead of on demand ad hoc network routing protocols such as AODV was studied in [11]. Energy efficiency issue for unicast routing is proposed in [8]. Energy efficient broadcast/multicast with directional antennas are considered in [5], [12], [13] and the construction of the broadcast/multicast tree is addressed in [14], [15]. Since all of this prior work is on directional antennas, they assume light of sight environment.

In this paper, we study energy efficient multicast in ad hoc networks using adaptive antenna arrays in multipath environments. The goal is to find an antenna configuration(s) such that the transmit power is minimized while all children nodes in the multicast tree correctly receive each packet. We formulate the problem as non-linear programming problem. Since this problem has to be solved by each node prior to the transmission of each packet, we propose two computationally efficient heuristics for solving the problem. We then compare the energy consumption using these two heuristics to that obtained from a computationally expensive simulated annealing based approach. The comparison shows that the one of these heuristics performs very well in terms of energy consumption while it requires still more computation than the

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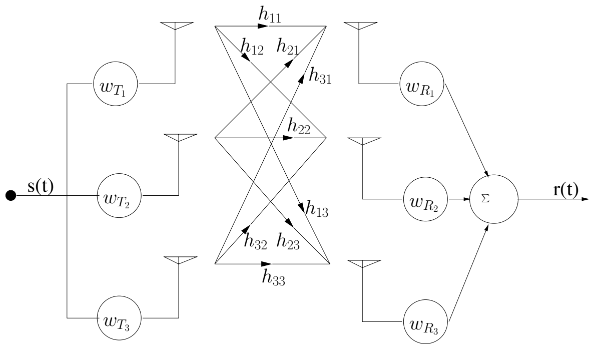

Fig. 1. MIMO system schematic illustrating the 3-antenna case.

other heuristics.

The rest of the paper is organized as follows. In section II, problem formulation is described. In section III, two heuristic algorithms are proposed. Simulation results are shown in section IV. The conclusions end the paper in section V.

II. PROBLEM FORMULATION

We assume that the multicast tree is known and focus only one-hop multicast in a wireless ad hoc network. We consider a typical node (henceforth, called the transmitter) in the multicast tree and assume that it has K children nodes (henceforth called receivers) in the multicast tree. Let $\mathcal{R}$ denote this set of receivers. We further assume that all nodes have N antennas and the nodes are operating in multipath environment.

Fig. 1 illustrates the adaptive antenna array and the multiple input multiple output Multiple Input Multiple Output (MIMO) channel for the case where $N = 3$ antennas are used at both the transmitter and receiver. The modulated signal $s(t)$ to be transmitted is passed through a transmit beamformer, which sends a weighted version of $s(t)$ through each antenna. The received signals at each antenna are weighted and summed to produce the receive beamformer output $r(t)$ which is then demodulated by the receiver to extract the bit stream. The channel between the transmitter and the receiver i can be represented by an $N \times N$ matrix $\mathbf{H}_i$, in which element $H_{i,mn}$ is the channel gain between the transmitter's m^{th} antenna and the receiver i's n^{th} antenna. We assume that the channel condition between each pair of antennas can be estimated prior the transmission of a packet. Furthermore, there is an underlying protocol so that both transmitter and receivers know this estimated channel condition. We also assume that the medium access protocol is similar to IEEE 802.11 in the sense that when a packet is being transmitted all nodes in the interference range of the receivers are idle.

The weights of the transmitter and receivers antenna arrays are $N \times 1$ vectors and are denoted as $\mathbf{W}_t$ and $\mathbf{W}_{ri}$ respectively. The modulated data signal $s(t)$ is first weighted and then sent through the transmitter antennas. At the n^{th} antenna of receiver i, the received signal can be written as

$$x_{i,n}(t) = s(t) \sum_{m=1}^{N} W_{tm} H_{i,mn} + n_{i,n}(t), \qquad (1)$$

where $n_{i,n}(t)$ is the Additive White Gaussian Noise (AWGN) noise picked up by the n^{th} antenna of receiver i. Let $\mathbf{n}_i = [n_{i,1}(t), n_{i,2}(t), \ldots, n_{i,N}(t)]^T$, then the final received signal at node i is

$$\begin{aligned} r_i(t) &= \sum_{n=1}^{N} W_{ri,n} x_{i,n}(t) && (2) \\ &= \sum_{n=1}^{N} \sum_{m=1}^{N} W_{tm} H_{i,mn} W_{ri,n} s(t) \\ &\quad + \sum_{n=1}^{N} W_{ri,n} n_{i,n}(t) && (3) \\ &= s(t) \mathbf{W}_t^T \mathbf{H}_i \mathbf{W}_{ri} + \mathbf{n}_i^T \mathbf{W}_{ri} && (4) \end{aligned}$$

If $||\mathbf{W}_{ri}||^2$ is always forced to be 1, then for normalized signal $s(t)$, the Signal to Noise Ratio (SNR) of the received signal is $\gamma_i = \frac{1}{\sigma^2} \|\mathbf{W}_t^T \mathbf{H}_i \mathbf{W}_{ri}\|^2$, where σ^2 denotes the noise power.

Given channel matrix $\mathbf{H}_i$, $\mathbf{W}_t$ and $\mathbf{W}_{ri}$ should be chosen so that a desired SNR is achieved at all receivers. Let $c_i = \gamma_i \sigma^2$ be the minimum required received power at the receiver i. Then the SNR constraint at receiver i is

$$\|\mathbf{W}_t^T \mathbf{H}_i \mathbf{W}_{ri}\|^2 \geq c_i \qquad (5)$$

The problem then is to minimize the total energy consumption to deliver a multicast packet to all receivers in the receiving set $\mathcal{R}$. This problem can be formulated as follows.

Minimize: $P = \mathbf{W}_t^H \mathbf{W}_t$
Subject to: $\|\mathbf{W}_t^T \mathbf{H}_i \mathbf{W}_{ri}\|^2 \geq c_i$ and
$\|\mathbf{W}_{ri}\|^2 = 1 \quad \forall \quad i \in \mathcal{R}$

The above formulation is a non-linear optimization problem with $N \times (K+1)$ variables. The following lemma shows that the above problem is equivalent to another formulation. The proof of the lemma is similar to that in [12] and is not included here due to page length restrictions.

Lemma 1: The optimization problem is equivalent to

$$\begin{aligned} \mathbf{W}_t^{opt} &= \arg\min \mathbf{W}_t^H \mathbf{W}_t && (6) \\ \text{s.t.} \quad \mathbf{W}_t^T \mathbf{H}_i \mathbf{H}_i^H \mathbf{W}_t^* &\geq c_i \quad \forall i \in \mathcal{R} && (7) \end{aligned}$$

and for the given $\mathbf{W}_t^{opt}$, each receiver is a Maximum Ratio Combiner (MRC) receiver:

$$\mathbf{W}_{ri}^{opt} = \frac{\mathbf{H}_i^H \mathbf{W}_t^{opt*}}{\|\mathbf{H}_i^H \mathbf{W}_t^{opt*}\|}; \quad \forall i \in \mathcal{R} \qquad (8)$$

Lemma 1 converts the joint optimization problem into two separate problems. First,the transmitter's antenna weight is chosen by solving the optimization problem in equation (6). Second, given the weight of transmitter antenna, the weights of receivers' antenna can be calculated by equation (8).

Unfortunately, the optimization problem in (6) is still hard to solve. Generally, this problem can be categorized as nonconvex quadratically constrained quadratic programming (QQP) problem. As pointed out in [16], the problem of finding a feasible solution is NP-hard. Generally, to find a finite and exact algorithm that solves large QQP's is probably out of reach. Many methods have been proposed for the QQP problems, these include linearization of quadratic functions, generalized Bender decomposition, reformulated as bilinear programming problem and so on. However, the proposed algorithms are still slow in time and not suitable for real time communication where an optimization problem need to be solved for each packet transmission. In the next section, we propose heuristic algorithms that are simple and fast but still give acceptable performance.

III. PROPOSED SOLUTION

A. Iterative Algorithm

We first propose an iterative algorithm (see Figure 2). There are three phases in this iterative algorithm. At the beginning, a random starting point for the weight of the transmit antenna array $\mathbf{W}_{t0}$ is chosen and scaled to a feasible solution of $\mathbf{W}_t$. Next in the WR-phase, weights of the receiving antenna array $\mathbf{W}_{ri}$ are calculated for the current $\mathbf{W}_t$. Then, with the known $\mathbf{W}_{ri}$, we solve an quadratic optimization problem to compute a new weight of the transmit antenna array as $\mathbf{W}_{t1}$ in the WT-phase. Finally, in the Scale-phase, $\mathbf{W}_{t1}$ is scaled to a minimum-norm feasible $\mathbf{W}_t$. Then the algorithm goes back to the WR-phase with $\mathbf{W}_t$ as obtained in the Scale-phase. In fact, the $\mathbf{W}_t$ obtained in the Scale-phase is a feasible solution for the original optimization problem. Therefore, the transmit power computed in this phase and the minimum power is saved for the current iteration.

```
Random starting point $\mathbf{W}_{t0}$
Scale-phase:
    Scale $\mathbf{W}_{t0}$ to $\mathbf{W}_t$
    Compute transmit power $P$ for $\mathbf{W}_t$
    $min\_power = P$
For $t = 1$ to $T$
    WR-phase:
        Compute $\mathbf{W}_{ri}$  $\forall i \in \mathcal{R}$ given $\mathbf{W}_t$
    WT-phase:
        Compute $\mathbf{W}_{t1}$ given $\mathbf{W}_{ri}$  $\forall i \in \mathcal{R}$
    Scale-phase:
        Scale $\mathbf{W}_{t1}$ to $\mathbf{W}_t$
        Compute transmit power $P$ for $\mathbf{W}_t$
        if $P < min\_power$
            $min\_power = P$
        End if
End for
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Fig. 2. Iterative algorithm

WR-phase: The WR-phase calculates $\mathbf{W}_{ri}$ given transmitter's antenna weight $\mathbf{W}_t$ by using equation (8).

WT-phase: Here, suppose all receiving antenna's weights $\mathbf{W}_{ri}$ are known. With the known channel condition $\mathbf{H}_i$, we denote $\mathbf{S}_i = \mathbf{H}_i\mathbf{W}_{ri}$. Then the constraints of the original optimization problem in equation (5) becomes $|\mathbf{W}_t^T\mathbf{S}_i|^2 \geq c_i$. We further relax these constraints as $\mathbf{W}_t^T\mathbf{S}_i \geq \sqrt{c_i}$ and the optimization problem becomes

$$\begin{array}{ll} \textbf{Minimize:} & P = \mathbf{W}_t^H\mathbf{W}_t \\ \textbf{Subject to:} & \mathbf{W}_t^T\mathbf{S}_i \geq \sqrt{c_i} \quad \forall i \in \mathcal{R} \end{array}$$

The above problem is a standard quadratic programming (QP) problem but the optimal solution of this QP may result in larger $\mathbf{W}_t$ than what is needed.

Scale-phase: Suppose that given any arbitrary vector as the transmit antenna weight $\mathbf{W}_{t1}$, we can always scale the vector as $\mathbf{W}_t = \alpha\mathbf{W}_{t1}$ where α is a scalar. This scaling increases or decreases the vector along the same direction of $\mathbf{W}_{t1}$ to obtain the minimum norm feasible weight as $\mathbf{W}_t$. Here, according to equation (7)

$$\alpha = \max_i \frac{1}{\|\mathbf{H}_i\mathbf{W}_{t1}\|} \tag{9}$$

B. The Best of Omnidirectional Transmission

Most current directional antenna systems use an omnidirectional transmission to complete a multicast or broadcast. Usually, a default antenna is pre-defined for the omnidirectional transmission. In a power controlled scheme, the weight of that antenna is set so that the transmit power is the smallest to reach the receiver who has the worst channel. This is equivalent to set the antenna weight to $[W, 0]$ when W_{t1} is set to be the default antenna and W^2 is the transmit power.

We aconsider omnidirectional transmission, but choose the antenna which will consume the least power. This is equivalent to setting the weight of transmit antenna to N vectors: $E_1\mathbf{e}_1, E_2\mathbf{e}_2, \ldots, E_N\mathbf{e}_N$, and select the vector with the least power. Here E_n^2 is the power needed for the omnidirectional transmission using the transmitter's n'th antenna, and $\mathbf{e}_n = [0\ldots1\ldots0]^T$ where all elements are 0 except that the n'th element is 1. We call this scheme the best of omnidirectional transmission (BestOMNI) and it is described in figure 3.

```
For $n = 1$ to $N$
    For $i = 1$ to $k_j$
        $\mathbf{W}_{ri} = \mathbf{H}_i^H\mathbf{e}_n/\|\mathbf{H}_i^H\mathbf{e}_n\|$
        $E_n^{(i)2} = c_i/\|\mathbf{e}_n^T\mathbf{H}_i\mathbf{W}_{ri}\|^2$
    End For
    $E_n = \max_{(i)} E_{i,n}$
End For
$\mathbf{W}_t = \min_n E_n\mathbf{e}_n$
Return
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Fig. 3. The best of omnidirectional approach

There are two loops in the algorithm. The outer loop compares all N possible values of $\mathbf{W}_t$ as omnidirectional transmissions. The single antenna that transmits the packet to all receiving nodes with the minimum power is selected. The inner loop is used to determine the transmit power for each single antenna. The basic idea is to meet the receiver which requires the most power.

IV. RESULT

In this section, we present simulation results obtained from MATLAB[1]. We compare the performance of the following five schemes.

- Simulated annealing: This method is used to obtain a close to optimal solution. The method is first tuned using the 2-antenna 4-receiver case so that the solution found by the method is within 1% of that obtained through exhaustive search.
- Iterative algorithm: In the iterative algorithm, the number of iterations T affects the speed of the algorithm and the optimality of the solution. Unfortunately, there is no guarantee that the algorithm converges. Our experinece shows that the power does not improve significantly after 25 iterations. Therefore, we set $T = 25$ in our simulation.
- BestOMNI: The best of omnidirectional transmission algorithm as described in Section III-B.
- Random Search: With the scaling equation (9), we can scale any arbitrary $N \times 1$ vector to a feasible solution of $\mathbf{W}_t$. This random search sets up random vectors and scale them to feasible solutions. The minimum power is then chosen from these solutions. Here, 25 random vectors are chosen in order to compare the performance of the iterative algorithm.
- Single antenna: This is the case when nodes only have a single omnidirectional antenna or they have adaptive antenna arrays but only use a single pre-defined omnidirectional antenna for the multicast.

In the simulation, we run each scheme for a packet transmission under the same channel condition. Then we accumulate the transmission power for 500 packet transmission as our measure of the performance for each scheme. Furthermore, we simulate four cases here. They are 2 antennas with 4 receivers, 2 antennas with 8 receivers, 4 antennas with 6 receivers and 4 antenna with 8 receivers respectively.

Figure 4 shows the accumulated power normalized by the power of single antenna case. Therefore, the accumulated power for single antenna scheme is 1 and it is not shown in the figure. From the figure, we see that the multiple antenna based schemes provide considerable power saving as compared to the single antenna scheme. In 2-antenna cases, the power is around 7% of the single antenna case, while the power is less than 1% in 4-antenna case.

To evaluate the effectiveness of the proposed heuristics, we normalize the accumulated power again, but with respect to the result of simulated annealing assuming that it produced a solution close to the optimal solution. Figure 5 shows the normalized power. From the figure, we also observe that, the BestOMNI scheme consumes the largest amount of power among the these three heuristics schemes. On the other hand, this algorithm is the simplest. As the channel conditions are random, the BestOMNI is actually the same as random search, and it only does N random searches.

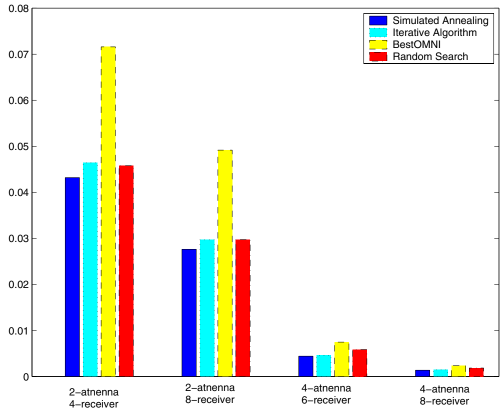

Fig. 4. Power savings compare to single antenna.

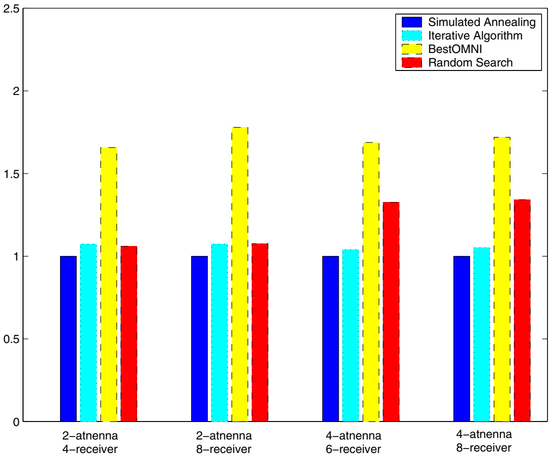

Fig. 5. Normalized transmit power.

In the simulation, both the iterative algorithm and the random search obtain the optimal solution from 25 solutions. The difference is that, the random search get the solution randomly while the iterative algorithm get the result according the the previous one. We can see that, for 4-antenna cases, the power saving is about 30% for the iterative algorithm compare to the random search. However, for 2-antenna cases, random search performs almost the same as the iterative algorithm.

V. CONCLUSION

In this paper, we studied multicast transmission in ad hoc networks using adaptive antenna array on each node. By using adaptive antenna array, nodes has capability of focusing its transmission energy on desired directions thus it can save engergy. Our goal is to select the antenna weights for the

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[1] MATLAB is a registered trademark of The Math Works Inc.

transmitter and receivers so that the transmit power can be minimized while all children nodes in the multicast tree can receive the packet correctly. A salient feature of this work is that it works in rich scaterring environments. We formulated the problem as a non-linear programming problem. We then proposed two computationally efficient heuristics. Simulation results show that the two heuristics can provide considerable power saving as compared to the single antenna case. We also used simulated annealing to solve the non-linear programming problem and the effectiveness of the proposed schemes. In future, spatial reuse can also be explored for the multicast transmission using adaptive antenna arrays. Further research may also include proposing a suitable medium access control scheme for the proposed physical layer schemes.

REFERENCES

[1] S. Yi, Y. Pei, and S. Kalyanaraman, "On the capacity improvement of ad hoc wireless networks using directional antennas," in *Proceedings of the fourth ACM international symposium on Mobile ad hoc networking and computing*, pp. 101–116, 2003.

[2] M. Beach, D. McNamara, P. Fletcher, and P. Karlsson, "MIMO: A solution for advanced wireless access?," in *Antennas and Propagation, 2001. Eleventh International Conference on*, pp. 231 – 235, April 2001.

[3] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Proceedings of INFOCOM*, vol. 1, pp. 13–21, March 2000.

[4] A. Nasipuri, S. Ye, J. You, and R. E. Hiromoto, "A MAC protocol for mobile ad hoc networks using directional antennas," in *Wireless Communications and Networking Conference, WCNC 2000 IEEE*, vol. 3, pp. 1214–1219, Sept 2000.

[5] L. Gruenwald, M. Javed, and M. Gu, "Energy-efficient data broadcasting in mobile ad-hoc networks," in *Database Engineering and Applications Symposium, 2002. Proceedings. International*, vol. 2, pp. 64–73, July 2002.

[6] N. S. Fahmy, T. D. Todd, and V. Kezys, "Distributed power control for ad hoc networks with smart antennas," in *Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall. 2002 IEEE 56th*, vol. 4, pp. 2141–2144, Sep 2002.

[7] A. Nasipuri, K. Li, and U. R. Sappidi, "Power consumption and throughput in mobile ad hoc networks using directional antennas," in *Computer Communications and Networks, 2002. Proceedings. Eleventh International Conference on*, pp. 620–626, Oct 2002.

[8] A. Spyropoulos and C. S. Raghavendra, "Energy efficient communications in ad hoc networks using directional antennas," in *Proceedings of INFOCOM*, vol. 1, pp. 220–228, June 2002.

[9] A. Spyropoulos and D. S. Raghavendra, "Energy efficient communications in ad hoc networks using directional antennas," in *Proceedings of INFOCOM*, vol. 1, pp. 220–228, June 2002.

[10] J. Mundarath, P. Ramanathan, and B. V. Veen, "NULLHOC: A MAC protocol for adaptive antenna array based wireless ad hoc networks in multipath environments," in *Proceedings of Globecom*, 2004.

[11] A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, "On-demand routing using directional antennas in mobile ad hoc networks," in *Computer Communications and Networks, 2000. Proceedings. Ninth International Conference on*, pp. 535–541, Oct 2000.

[12] J. Zhang, A. Sayeed, and B. V. Veen, "Optimal transceiver design for selective wireless broadcast with channel state information," in *Acoustics, Speech, and Signal Processing, 2002. Proceedings. (ICASSP '02). IEEE International Conference on*, vol. 3, pp. 2153–2156, May 2002.

[13] K. Wang, C. F. Chiasserin, J. G. Proakis, and R. R. Rao, "Rise: reducing interference and saving energy through multicasting in ad hoe wireless networks," in *MILCOM 2002. Proceedings*, vol. 2, pp. 826–832, Oct 2002.

[14] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, "On the construction of energy-efficient broadcast and multicast trees in wireless networks," in *Proceedings of INFOCOM*, vol. 2, pp. 585–594, March 2000.

[15] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, "Energy-aware wireless networking with directional antennas: the case of session-based broadcasting and multicasting," *Mobile Computing, IEEE Transactions on*, vol. 1, pp. 176–191, Sept. 2002.

[16] C. Audet, P. Hansen, B. Jaumard, and G. Savard, "A branch and cut algorithm for non-convex quadratically constrained quadratic programming," *Mathematical Programming*, vol. 87(1), pp. 131–152, 2000.