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A novel optimization-based bandwidth-aware minimum power multicast routing algorithm in green wireless networks

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Abstract Multicast routing in wireless networks that possess the wireless multicast advantage could significantly reduce the power and energy consumption. However, this kind of multicast routing that only addresses the transmission radius coverage might not be able to meet the bandwidth requirement of the users. As a result, additional transmissions are required to incur more energy consumption and carbon dioxide emissions that make existing algorithms not applicable to bandwidth constrained applications. In this paper, for the first time, we address the bandwidth aware minimum power multicast routing problem in wireless networks where the objective function is to minimize the total power consumption subject to the users' bandwidth requirements. This problem is a challenging cross-layer design problem that requires seamless and sophisticated integrated design in the network layer (multicast routing) and physical layer (bandwidth-aware wireless transmission and power control). We first formulate this problem as a mixed integer linear programming problem and then propose a Lagrangian relaxation based algorithm to solve this problem. Numerical results demonstrate that the proposed approach is a sound green networking algorithm that outperforms the existing power efficient multicast routing approaches under all

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tested cases, especially in large bandwidth request, fine radius granularity, large group size and sparse network.

Keywords Bandwidth QoS · Minimum power broadcast/multicast · Cross-layer design · Wireless network · Optimization

1 Introduction

1.1 Background

Green networking is a new driving force to enable the wireless network technologies toward power consumption aware design. In wireless networks, due to the battery powered nature of network nodes, without proper power management, the network will be disconnected. Replacing the battery will incur additional power consumption. In other words, efficient power management algorithms are more important in wireless networks than in wired networks to foster green networking. In this paper, we address the power-aware and bandwidth-aware multicasting routing problem in wireless networks and propose a cross-layer (layer 3 + layer 1) algorithm that not only realizes the idea of green networking but also satisfies the bandwidth demands of the destination nodes.

In a battery powered wireless network, node energy radiations need to be carefully planned to reduce total power consumption. Due to the broadcast nature in RF transmission, neighbor nodes that are within the range of a sender's transmission radius can receive the transmitted data. This property is known as Wireless Multicast Advantage (WMA) [1]. Figure 1 depicts an example of the WMA. In this example, Node s is the sender node. As the transmission power is large enough to reach the farthest Node c, the closer Node a and Node b are also covered. Hence, Node a and Node b could also receive the data from Node s when Node s is transmitting to Node c. As compared to the wired line communications, the Node s need to transmit three copies of the data (or equivalently total power $c1 + c3 + c4$) to reach these three nodes. In wireless communications, the Node s needs only to transmit one copy of the data (or equivalently total power $c1$) to reach these three nodes. Then, in Fig. 1(b), the total cost to reach all the destination nodes is $c1 + c2 + c5$ in wireless communication instead of $c1 + c2 + c3 + c4 + c5$ in wired line communication.

This kind of Minimum total Power in Broadcasting/multicasting routing problem (usually denoted as the MPB problem) in wireless networks has been shown to be an NP-hard problem [2]. Several heuristic algorithms have been proposed to get the near-optimal solutions [1–3]. However, the MPB problem only considers the transmission radius coverage without addressing the signal quality so that it fails to meet the traffic demands of the Origin-Destination (OD) pairs.

1.2 Motivation

In wireless networks, adaptive modulation can increase throughput or reduce required transmit power by taking advantage of wireless channel conditions [5]. The basic idea

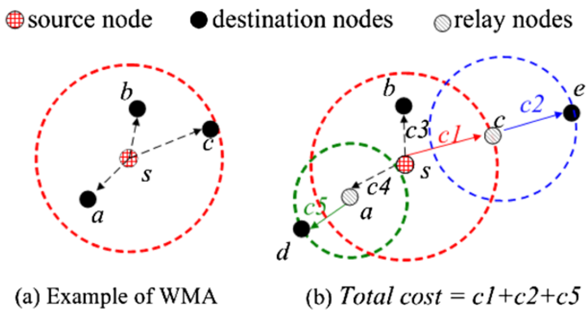


Fig. 1 Cost reduction in wireless networks with wireless multicast advantage (WMA)

of adaptive modulation is to estimate and calculate the signal quality at the receiver and feedback the channel information to the sender to select the right modulation scheme. When the signal quality is good, more sophisticated modulating scheme (e.g., 64-QAM) could be used at the sender to achieve higher data throughput. On the other hand, in the case of poor signal quality, only ordinary modulating scheme (e.g., QPSK) at the sender could be used. In this case, the achievable data rate at the receiver for sender modulated with 64-QAM scheme is three times higher than for sender modulated with QPSK scheme. Hence, the effective bandwidth depends on the signal quality. For example, in IEEE 802.11b, the effective bandwidth could be 1, 2, 5.5, and 11 Mbps, which depends on the signal quality at the receiver.

In general, the shorter the distance between the sender and the receiver, the better the signal quality there would be. For the nodes that are within the sender's transmission radius, they might not have the same signal quality because of the distance to the sender is different. In this case, the nodes that are far from the sender could not have good signal quality to successfully decode the received information via sophisticated modulation scheme even though they are within the transmission coverage. For example, in Fig. 1(b), 64-QAM modulation is used at the source Node s to meet the bandwidth requirements of the destination nodes. Nodes a and b could correctly decode the received information but Node c could not correctly decode the received information because of its weak received signal power. In this case, Node c could not relay the data further to Node e. Hence, only considering the transmission coverage could fail to meet the bandwidth demands of the OD pairs. In other words, existing MPB algorithms are not applicable in MPB with bandwidth QoS requirements. We denote such kind of MPB problem with BAndwidth QoS requirements in wireless networks as the MPBBA problem.

Figure 2 shows an example of the power adjustment procedure for the MPBBA problem. Note that the transmission power calculation of Fig. 2(b) and Fig. 2(c) is based on the objective function of (WP) in Sect. 2, which is (6). In Fig. 2, the dashed circle means the transmission radius and the solid circle means the bandwidth-aware transmission radius (i.e., transmission radius that meets the bandwidth requirement of the OD pairs). The nodes are placed in a 16×16 area. In Fig. 2(a), the routing for traditional MPB algorithms is to send the data to C and then from C to D. However, in Fig. 2(a), we observe that even though C is within the transmission radius of A, but C is not within the bandwidth-aware transmission radius of A, so that it fails to meet the bandwidth QoS at node C. In this case, D is unreachable because C

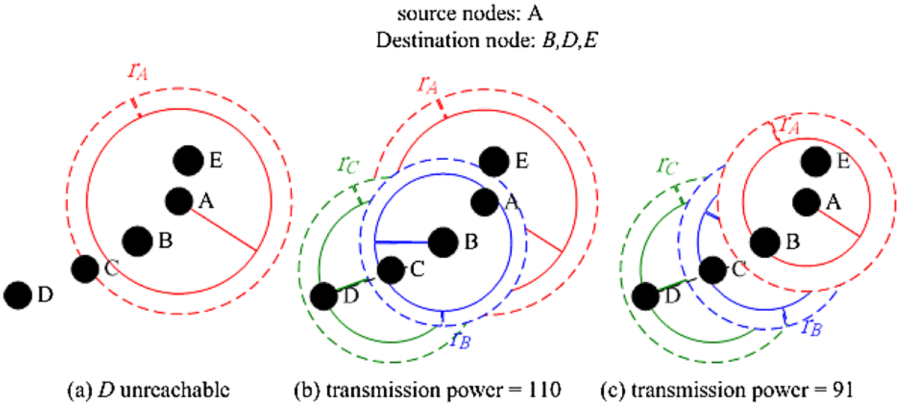


Fig. 2 Power adjustment procedure for the MPBBA problem

is not able to transmit the data to D with bandwidth guarantee. As B is within the bandwidth-aware transmission radius of A, one possible way to solve the problem of Fig. 2(a) is to let B transmit the data to C and then let C transmit the data to D, which is shown in Fig. 2(b). However, more energy efficient communication is to reduce the transmission radius of A so that B is at the edge of the bandwidth-aware transmission radius as shown in Fig. 2(c). This example shows that MPBBA problem is more challenging than the MPB problem because of the bandwidth requirement.

The characteristics for MPBBA problem are summarized as follows:

(1) Bandwidth-aware wireless transmission: the sender should identify the right modulation scheme to encode the information so that the bandwidth requirement could be satisfied and at the same time the receiver could decode the information correctly.
(2) Power control: transmission power for the sender should be configured not only to cover the receiver but also to guarantee the signal quality at the receiver is good enough to successfully decode the information.
(3) Multicast routing: multicast routing scheme in MPBBA should be designed not only to be power efficient but also to satisfy the bandwidth requirements at the destination nodes.

As compared to MPB problem that only addresses the energy efficient multicast routing in the network layer, the *MPBBA problem is a cross-layer design problem that requires seamless and sophisticated integrated design in the network layer (multicast routing) and physical layer (bandwidth-aware wireless transmission and power control)*. More specifically, the MPBBA problem should consider the energy efficiency from the system power perspective and bandwidth assurance from the users' perspective simultaneously. To the best of our knowledge, the MPBBA problem has not been addressed before. In this paper, for the first time, we tackle the MPBBA problem and propose an optimization-based algorithm to simultaneously realize the idea of green networking and meet the bandwidth demands of the multicast groups in wireless networks.

1.3 Related works

Several related works address the MPB problem. The minimum power broadcast problem has proved to be NP-complete [6]. Since minimum power broadcast problem is a special case of minimum power multicast problem, both kinds of MPB problems are NP-complete. The most straightforward way to handle the problem is to model the problem as a mixed integer linear programming (MILP) problem and then apply integer programming solving technique to obtain the exact solution. In [7], three MILP models are proposed. However, no numerical results are reported to justify the applicability. By using CPLEX optimization solver to the optimization models in [7], we find that optimal solution can only be obtained for small network (less than thirty nodes) in days of computation. In [8], the authors present an MILP model for bandwidth-constrained minimum-energy multicast problem in a TDMA-based ad hoc network. Experiment results show that in a small network with 20 nodes, the optimal solutions can be obtained using CPLEX optimization solver.

Instead solving the problem exactly, researchers have proposed heuristic algorithms to tackle the problem. Spanning tree based method is the most popular algorithm for the MPB problem [1]. In [1], three energy-efficient heuristic algorithms are proposed. They are the Shortest Path Tree (SPT) algorithm, the Minimum Spanning Tree (MST) algorithm, and the Broadcast/Multicast Incremental Power (BIP/MIP) algorithm. The BIP and MIP are the most widely used benchmarks for performance comparisons. The computation complexity are $O(|N|^2)$ for both SPT and MST, and $O(|N|^3)$ for BIP/MIP. In [3, 9, 10], the approximation ratio for SPT, MST, and BIP are at least $(|N|-1)/2$, $|N|-1$, and $|N|-2-O(1)$, respectively. According to the simulation results of [3], shortest path algorithm can achieve excellent performance for small networks and the MIP algorithm works well for large networks. The MIP3S algorithm is proposed in [4]. By expanding the transmission power to cover a few more nodes, potential power saving is possible. It is shown that MIP3S performs better than MIP. However, the computational complexity of MIP3S is $O(|N|^4)$. It is higher as compared to $O(|N|^3)$ for MIP.

In addition to spanning tree based approaches, some local search algorithms for MPB problem have been proposed in the literature. Those algorithms try to improve the performance from an initial tree. Sweep is one of the most famous local search algorithm, which has low time complexity, O($|N|^2$)[11, 12]. The other algorithms include the r-Shrink proposed by Das et al. [13] with time complexity O($|N|^4$) and the B and B2 algorithms with time complexity O($|N|^3$) proposed by Nguyen [14]. For more local search algorithms, please refer to [15–17].

Recently, some work based on relaxation technique has been proposed. In [18], the authors present a novel MILP model that leads to a sharp lower bound of the optimum via Lagrangian relaxation. In the same paper, the authors also propose a heuristic named Successive Power Adjustment (SPA). The algorithm combines enhanced version of Sweep and Shrink algorithms to achieve a feasible upper bound solution. The computational complexity of SPA is $O(|N|^3)$. Another Lagrangian relaxation based approach for MPB problem is proposed in [19]. By leveraging on the information from the Lagrangian multiplier, we could construct more power efficient routing paths. Numerical results demonstrate that the proposed approach outperforms the MIP and MIP3S for broadcast, multicast, and unicast communications.

The references mentioned above are designed for omni-direction antenna scenario. Algorithms for networks using directional antenna can be found in [20, 21]. Due to many active research work proposed for resolving the MPB problem, for other kinds of approaches, please refer to the survey paper authored by Guo and Yang for details [15].

These MPB heuristics only consider the minimum power transmission coverage problem. As indicated in the Sect. 1, only considering the transmission radius coverage without addressing the signal quality will fail to meet the bandwidth demands of the users. To successfully tackle the MPBBA problem, it requires sophisticated cross-layer design in the network layer (multicast routing) and physical layer (bandwidth-aware wireless transmission and power control).

The remainder of this paper is organized as follows. In Sect. 2, we derive the bandwidth-aware wireless multicast advantage model and give the MPBBA problem formulation. In Sect. 3, we present the Lagrangian relaxation approach and the new primal heuristic algorithm. In Sect. 4, we demonstrate numerical results for broadcast, multicast, and unicast communications under a large random network. Finally, a concluding remark is made in Sect. 5.

2 MPBBA problem formulation

2.1 Bandwidth-aware wireless multicast advantage model

In WMA, for any neighbor node n that is within the range of sender m's transmission radius can receive the transmitted data. This kind of WMA could be formally modeled as

$$d_{mn} \leq r_m \tag{1}$$

In the WMA model, it only considers the transmission coverage which is not valid in bandwidth-aware communication. In this section, we study the bandwidth-aware WMA model and then propose the mathematical formulation for MPBBA problem based on this bandwidth-aware WMA model.

The receiver could correctly decode the information only when the signal to noise ratio (SNR) at the receiver is above a minimum threshold $SNR^b_{\min}$ under the modulation scheme b. In point-to-point communication, the link cost between s and t (denote as $\mathrm{LC}(s,t)$) [22] is shown in (2).

$$\Pi(s) = \mathrm{LC}(s,t) = \left(SNR^b_{\min}\right) \times P_\eta \times d^\alpha \tag{2}$$

where P_η denotes the noise power, d denotes the distance between s and t and α denotes the power attenuation factor which is usually between 2 to 4. Because of its point-to-point communications, the required transmission power at node s (denote as $\Pi(s)$) is equal to the link cost. Then the required transmission power at the sender is proportional to the minimum threshold $SNR^b_{\min}$. In general, more sophisticated modulation scheme requires higher $SNR^b_{\min}$ to have the same bit error rate (BER) at the receiver to successfully decode the information. If we set the 10^{-3} BER as the minimum signal quality to successfully decode the information, under the assumption of additive white Gaussian noise (AWGN) for MQAM modulation scheme [5] at BER $= 10^{-3}$, we have

$$\left(SNR_{\min}^{b_{64}}\right)_{\text{dB}} = \left(SNR_{\min}^{b_{16}}\right)_{\text{dB}} + 5 = \left(SNR_{\min}^{b_4}\right)_{\text{dB}} + 9 \tag{3}$$

where $SNR_{\min}^{b_{64}}$, $SNR_{\min}^{b_{16}}$, and $SNR_{\min}^{b_4}$ indicate the minimum SNR ratio for 64-QAM, 16-QAM, and QPSK, respectively.

Based on (3), there is 9 dB difference in $SNR_{\min}^{b}$ between 64-QAM and QPSK. In this case, we can get the relation of the transmission power between 64-QAM and QPSK as shown in (4), where $\Pi_{64}(s)$ indicates the transmission power for 64-QAM and $\Pi_4(s)$ indicates the transmission power for QPSK.

$$\Pi_{64}(s) = \Pi_4(s) \times 8 \tag{4}$$

Based on (4), the required transmission power is eight times higher for 64-QAM than in QPSK. The above argument implies that if the received SNR is $SNR_{\min}^{b_4}$ at the edge of the coverage area, then the received SNR is $SNR_{\min}^{b_{64}}$ at half of the transmission radius when the power attenuation factor $\alpha = 3$. That is, when $\alpha = 3$ and the modulation scheme is 64-QAM, the receiver could successfully decode the information only if the distance between the sender and the receiver is less than half of the transmission radius.

When the available frequency spectrum is fixed, the modulation scheme to satisfy the destination's bandwidth requirement is also known. For example, if the frequency spectrum is 1 MHz, and the bandwidth requirement is 6 Mbps, then the modulation scheme needs to be at least 64-QAM. In other words, the modulation scheme is determined under fixed frequency spectrum and bandwidth requirements. Based on these understandings, *Bandwidth-Aware Wireless Multicast Advantage* (*BAWMA*) is

$$\lambda_t \le \Psi(r_s, d) \tag{5}$$

where λ_t is the bandwidth requirement of node t and $\Psi(r_s, d)$ indicates the supported bandwidth at distance d from node s with transmission radius r_s.

Recall that the WMA in (1), it only requires the transmission coverage without considering the bandwidth requirement. In (5), the bandwidth requirement is addressed by the sender's power control scheme (i.e., choose the sender's transmission radius to satisfy the destination's bandwidth requirement). Based on this BAWMA property, we introduce the MPBBA problem to satisfy the bandwidth demands of the multicast group in power efficient way.

In this paper, we consider the path loss and attenuation in the signal propagation impairments. Besides path loss and attenuation consider in this paper, the signal transmission impairments in wireless network also include shadowing, multipath propagation and interference [5]. Shadowing occurs when there are obstacles between the transmitter and receiver so that there is no line-of-sight (LOS) transmission. Multipath propagation indicates that besides LOS transmission, there is non-LOS transmission that might incur inter-symbol interference. Interference indicates some other signal on the same frequency band might interfere with the desired signal.

Even though these three impairments play a nonnegligible role in signal transmission, we only focus on the path loss and attenuation for simplifying the MPBBA model. This simplifying would let us more easily to get the whole picture and basic idea of the MPBBA problem as compared to the MPB problem.

2.2 MPBBA model and formulation

The basic idea of MPBBA model is to minimize the total transmission power under the condition that there is a routing path for every OD pair. Furthermore, every link on the routing path must be covered within the bandwidth-aware transmission radius of the source node of the link (e.g., link $\overline{AE}$ is covered within the bandwidth-aware transmission radius of A in Fig. 2). Hence, bandwidth QoS requirement is enforced.

In the wireless networks, the nodes could be operated in the four modes (i.e., transmitting, receiving, idle, and sleep). According to the experimental wireless sensor node, MEDUSA, which is a low power node developed by UCLA [23]. The power consumption in the transmitting mode is the highest, and the power consumption in the sleep mode that turn off the radio is the smallest. The node in the receiving mode and idle mode that turn on its radio consume almost the same power. In this paper, like other previous works on the MPB problem, we assume the nodes in the wireless network are all in the idle mode (i.e., the radio is on) waiting for transmitting and receiving. Based on this assumption, the power consumption difference among the nodes will only be on the transmitting or not transmitting. Then the key to minimize the total power is to minimize the transmission power. Basically, the nodes not in the multicast tree could be in the sleep mode to further reduce the power. Hence, the output of the proposed algorithm could not only determine transmission radius of every node but also determine which nodes are not in the multicast tree (i.e., nodes not transmitting or receiving). By putting the nodes in the multicast tree in the idle mode and the nodes not in the multicast tree in the sleep mode, this could further reduce the total power consumption.

The notations used in the formulation are listed as follows:
Input values:

N: the set of nodes;
L_n: the set of links outgoing from node $n \in N$;
W: the set of OD pairs;
P_w: the set of candidate paths for OD pair $w \in W$;
δ_{pl}: $=1$, if path p adopts link l; $=0$, otherwise;
R_n: the set of candidate transmission radius for node n;
λ_w: traffic demands (bandwidth) for OD pair $w \in W$;
$\Psi(r_n, d_l)$: supported bandwidth at distance d_l from node n with transmission radius r_n;
$\Pi(r_n)$: transmission power for node n with transmission radius r_n;

Decision variables:

x_p: $=1$, if path p is chosen; $=0$, otherwise;
r_n: transmission radius assignment for node n.

Problem (WP):

$$Z_P = \min \sum_{n \in N} \Pi(r_n) \tag{6}$$

Subject to:

$$\sum_{p \in P_w} x_p = 1 \quad \forall w \in W, \tag{7}$$

$$\sum_{p \in P_w} x_p \delta_{pl} \lambda_w \le \Psi(r_n, d_l) \quad \forall w \in W,\ n \in N,\ l \in L_n, \tag{8}$$

$$x_p = 0/1 \quad \forall p \in P_w,\ w \in W, \tag{9}$$

$$r_n \in R_n \quad \forall n \in N \tag{10}$$

The objective function (6) is to minimize total transmission power. Constraints (7) and (9) require that each OD pair selects exactly one path. We call (8) as *Bandwidth-Aware Transmission Coverage Constraint* (*BATCC*). When BATCC is enforced, WMA characteristic is also facilitated (e.g., B and E are both covered by A in Fig. 2). The basic idea of BATCC is to ensure that if the link l is included on the routing path of any OD pair w, then the supported bandwidth at the termination node of link l must be larger than the λ_w. As compared to the BAWMA in (5), BATCC also addresses the routing decision assignment to make sure that there is a bandwidth-aware routing path to every destination node. In conjunction with the objective function to minimize the total transmission power, problem (WP) identifies a bandwidth-aware and power-aware routing path to every destination node.

Note that we do not need to generate all candidate paths (i.e., P_w) for each OD pair. In Sect. 3, we will show that by using the associated Lagrangian multiplier as the link arc weight, the shortest path algorithm (e.g., Dijkstra) could be used to identify x_p.

3 Lagrangian relaxation approach

By relaxing the BATCC constraint (i.e., Constraint (8)), the MPBBA problem is a MPB problem. In other words, the MPB problem is a special case of MPBBA problem without the bandwidth requirements. Because the MPB problem in wireless networks has been shown to be an NP-hard problem [2], the MPBBA problem is also an NP-hard problem. Due to no polynomial time algorithm could be devised to solve the NP-hard problem, we tackle the MPBBA problem by the Lagrangian relaxation approach to devised efficient optimization-based heuristics by utilizing the solution and useful information from the Lagrangian dual problem.

3.1 Lagrangian relaxation

The proposed algorithm is based on Lagrangian relaxation. By introducing Lagrangian multiplier vector μ to (WP), we dualize Constraint (8) to obtain the following Lagrangian relaxation problem (LR). The reason that we dualize Constraint (8) is because (WP) is an NP-hard problem. By dualizing Constraint (8) into the objective function, we could solve the Lagrangian dual problem optimally and the information from the Lagrangian dual problem could give us useful information on getting good primal feasible solutions.

$$Z_{\mathrm{LR}} = \min \sum_{n \in N} \Pi(r_n) + \sum_{w \in W} \sum_{n \in N} \sum_{l \in L_n} \mu_{wnl} \left(\sum_{p \in P_w} x_p \delta_{pl} \lambda_w - \Psi(r_n, d_l) \right)$$

subject to: (7), (9) and (10).

The reason that we relax Constraint (8) is because there are two coupling decision variables (x_p and r_n) to make it difficult to deal with. By relaxing Constraint (8) into the objective function, we could decompose (LR) into the following two independent subproblems. In this way, there are only one decision variable in each subproblem and we could solve each subproblem optimally.

$$\text{(S1): } \min \sum_{w \in W} \sum_{p \in P_w} \sum_{n \in N} \sum_{l \in L_n} \mu_{wnl} x_p \delta_{pl} \lambda_w$$

subject to (7) and (9).

$$\text{(S2): } \min \sum_{n \in N} \Pi(r_n) - \sum_{w \in W} \sum_{n \in N} \sum_{l \in L_n} \mu_{wnl} \Psi(r_n, d_l)$$

subject to: (10).

(S1) can be further decomposed into $|W|$ independent shortest path problems. For each OD pair $w \in W$, we have nonnegative arc weight μ_{wnl} on link $l \in L_n$ for $n \in N$. Each problem can be solved using Dijkstra's shortest path algorithm. The computational complexity is $O(|N|^2)$ for each OD pair.

(S2) can also be further decomposed into $|N|$ independent problems. For each node $n \in N$, we have $\min \Pi(r_n) - \sum_{w \in W} \sum_{l \in L_n} \mu_{wnl} \Psi(r_n, d_l)$ subject to $r_n \in R_n$. Since R_n is a discrete set, we could exhaustively try all possible radius assignment $r_n \in R_n$ to identify the optimal r_n with the smallest objective value. The complexity of the above algorithm is $O(|R_n|)$ for each node.

Based on the above algorithms, we can effectively solve (LR) optimally. By the weak duality theorem [24], given any nonnegative multiplier, Z_{RL} is a lower bound to Z_P. We can use subgradient method to calculate the tightest lower bound [24], as shown in (11), (12), and (13).

3.2 Primal heuristic algorithm

Note that the solutions to the dual problem (LR) might not be feasible to the primal problem (WP) due to BATCC (i.e., Constraint (8)) is relaxed. One possible way to get the primal feasible solutions is based on the routing assignment variable x_p in (S1) to identify the smallest transmission radius in R_n to cover the selected links on the routing path and in the mean time to satisfy the BATCC. Another possible way to get the primal feasible solutions is to incorporate the BATCC in identifying the routing assignment variable x_p for each OD pair. From the computational experiments, we observe that the second way provide better results.

According to the Lagrangian multipliers updating shown in (11)$\sim$(13), the multiplier μ will increase its value at the next iteration when the BATCC constraint (i.e., Constraint (8)) is violated. In other words, the value of multiplier μ could indicate how much the BATCC constraint is violated. The more BATCC constraint is violated, the larger the value multiplier μ. From this observation, we set the link arc weight for link l which is originated from node n to be $d_l^\alpha(1+\mu_{wnl})$. The first term, d_l^α, is the transmission power consumption and the second term, $d_l^\alpha \mu_{wnl}$, is used here to be a cost penalty for violating BATCC. Based on this link arc weight assignment, we could jointly consider the transmission power and BATCC at the same time when selecting the routing path for the destination node.

After the routing path is determined, the transmission radius for each node is adjusted for possible transmission power reduction (e.g., node A in Fig. 2(c)). We denote the second way of getting primal heuristic algorithm as *PA*. The computational complexity of *PA* is $O(|N|^3)$.

In the LGR algorithm, the multiplier vector μ at iteration $(y+1)$ is updated according to the subgradient method [24],

$$\mu^{y+1} = \mu^y + \beta^y S^y \tag{11}$$

where

$$S^y(\mu) = \left(\sum_{p \in P_w} x_p \delta_{pl} \lambda_w - \Psi(r_n, d_l) \right). \tag{12}$$

and the step size

$$\beta^y = \delta \frac{Z_{\mathrm{IP}}^y - Z_{\mathrm{LR}}(\mu^y)}{\|S^y\|^2} \tag{13}$$

where Z_{IP}^y is the best primal objective function value found until iteration y (an upper bound on optimal primal objective function value), $Z_{\mathrm{LR}}(\mu^y)$ is the Lagrangian dual value at iteration y, and the *step_size* δ is a constant $(0 \le \delta \le 2)$.

The computational complexity for the complete algorithm (denote as *LGR*) which includes the solution procedure for two subproblems and *PA* is $O(|N|^3)$ for each iteration.

Next, we study the message communication scheme in the LGR algorithm. In the case of no base station, some messages need to be communicated among the nodes in the networks. The information that is required to communicate between the nodes are the transmission radius for each node n (i.e., r_n) and the supported bandwidth parameter from node n (i.e., $\Psi(r_n, d_l)$). Note that these two sets of information might change from time to time because every node might change its transmission radius. The transmission radius information of each node should be broadcasted periodically to the other nodes. After receiving the transmission radius information from the other node, the supported bandwidth would be determined if the distance data (i.e., d_l) is also available. By equipped each node with GPS, the distance data information could be derived by broadcasting its location. In this case, the existing DREAM routing protocol [26] could be adopted to disseminate this location information. According to the DREAM protocol [26], the convergence time has the complexity $O(|N| \cdot I)$, where I is the average update interval. The memory overhead and control overhead has the complexity $O(|N|)$.

LGR Algorithm

Begin
Input: Network topology, bandwidth demands for each OD pair;
Output: Routing assignment of each OD pair and transmission radius for each node;
Initialize Lagrangian multiplier vector μ to be the zero vector;
UB $= \infty$ and LB $= -\infty$; //upper and lower bound
quiescence_age $= 0$ and *step_size* $= 2$;
For *iteration* $= 1$ to *Max_Iteration* do the following:
Begin
Solve subproblem 1;
Solve subproblem 2;
Compute Z_{LR} as in (LR).
If $Z_{\mathrm{LR}} > LB$
$LB = Z_{\mathrm{LR}}$ and *quiescence_age* $= 0$;
Elseif *quiescence_age* $=$ *quiescence_age* $+ 1$;
If *quiescence_age* $==$ *Quiescence_Threshold*
step_size $=$ *step_size*$/2$ and *quiescence_age* $= 0$;
Run Primal heuristic algorithm (*PA*); //Compute the new upper bound *ub*
If ub $<$ UB
UB $=$ ub;
Update the *step_size*;
Update the Lagrangian multiplier vector μ;
End For
End

4 Numerical results

We have carried out a performance study on the MPBBA problem by using the LGR approach. In *LGR* algorithm, *Max_Iteration* and *Quiescence_ Threshold* are set to 1000 and 30, respectively. Due to the fact that the MPB based heuristics (MIP, MLU, MLiMST in [1], MIP3S in [4], and Optimized MPB heuristics [19]) do not address the bandwidth QoS requirement, these MPB heuristics could not locate feasible solutions for most of the tested cases in the computational experiments. In order to verify the performance of our proposed LGR algorithm, we modify the existing MPB heuristics to be a two-phase algorithm where the first phase is the original heuristic that only address the transmission coverage and the second phase is to meet the bandwidth QoS constraint by using our proposed power adjustment procedure as shown in Fig. 2. To be more specifically, in the first phase, the routing assignment and transmission radius assignment is obtained by the original algorithm. In the second phase,

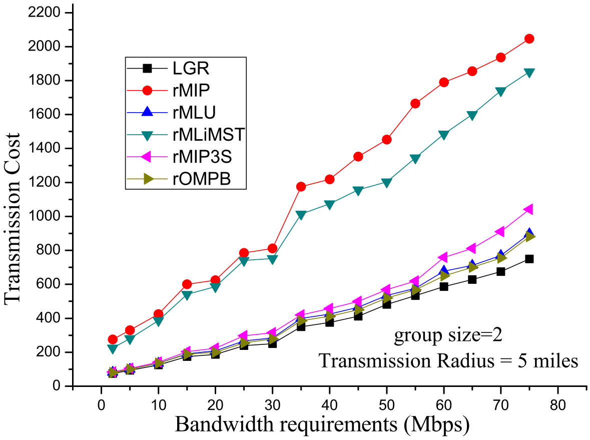


Fig. 3 Performance comparison for unicasting in fixed radius

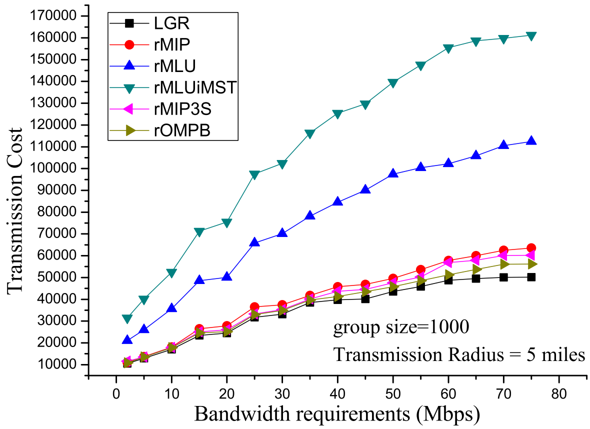


Fig. 4 Performance comparison for multicasting in fixed radius

if the bandwidth QoS could not be satisfied on any relay node or destination node in the routing path, the other nodes on the routing path that meet the bandwidth QoS will try to transmit the power to this node with bandwidth QoS (e.g., Node B to Node C in Fig. 2(b)). Finally, the transmission radius is adjusted for possible transmission power reduction (e.g., Node A in Fig. 2(c)). Hence, these five MPB based heuristics are revised as a *two-phase* algorithm where the first phase is its original algorithm to determine the routing path and the second phase is to adjust the transmission radius to satisfy the bandwidth QoS requirement. We prefix the computational results of the MPB heuristics with "r" to indicate that the algorithm is a revised version of original one that considers the bandwidth requirement. For example, the MIP is revised as rMIP.

The network consists of 2,000 nodes randomly placed in the 250×250 square miles area. Transmission power $\Pi(r_n)$ is set to r_n^{α} (in dBm), where the signal power attenuation constant $\alpha = 3$. The set of possible communication radius is a discrete set starting from zero with step size 0.5 mile to maximum communication radius. We borrow the bandwidth parameters from WiMAX [25] to determine

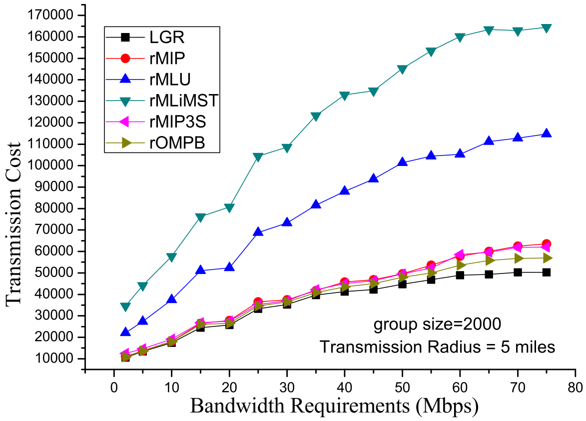


Fig. 5 Performance comparison for broadcasting in fixed radius

the supported bandwidth configuration variable, $\Psi(r_n, d_l)$. From Figs. 3, 4, 5, we set 2, 5, 10, 20, 30, 40, 75 Mbps for distance of 5, 4, 3, 2, 1.5, 1, 0.5 miles when the transmission radius is 5 miles. Note that the proposed algorithm could be applicable to any wireless network (e.g., ad hoc network). The reason that we choose the bandwidth parameters from WiMAX is because there is a clear specification for the SNR ratio and the associated modulation scheme in various distance and transmission radius configurations.

In Fig. 3, there are only two members in the group (one is source node and the other is destination node), so it is a unicasting case. In Fig. 4, it is a multicasting case where a half of the total nodes are included in the group. In Fig. 5, it is a broadcasting case where every node is included in the group. From Fig. 3 to Fig. 5, we can observe that LGR outperforms the other five algorithms under all test cases, especially in high bandwidth requirements. This is because unlike the other four heuristics that are *two-phase* algorithm, the LGR algorithm considers the BATCC in determining the routing path so that it is easier to identify the energy efficient path in high bandwidth request.

We observe that the rMIP performs poorly in unicasting case but has good solution quality in multicast and broadcast cases. It is because MIP routing algorithm is designed for the multicasting traffic. On the other hand, the MLU algorithm is designed for the unicasting traffic, so it works well in unicasting but it loses accuracy at larger group size. rMIP3S based on potential power saving has better solution quality than rMIP. rOMPB heuristic has the best performance among these two-phase MPB heuristics, but it does not consider the bandwidth constraint in determining the routing path so that it is inferior to the proposed LGR heuristic.

We define *Superiority Ratio* (SR) to be the performance metric for making comparison with the other five algorithms. SR is defined as $(\overline{A} - \overline{LGR})/\overline{LGR}$ in percentage, where $\overline{LGR}$ and $\overline{A}$ are the transmission cost of the LGR algorithm and the other algorithm. Finally, we summarize the performance comparisons in Table 1 under $radius = 5.0$ miles.

In the first set of computational experiments, there is only one transmission radius. Hence, each node could either set its transmission radius to be 5 miles or do not turn on its radio. In the second set of computational experiments, we set multiple

Table 1 Superiority Ratio (SR)

SR of LGR over	Unicast	Multicast	Broadcast
rMLU	12%	112%	115%
rMLiMST	182%	213%	222%
rMIP	222%	15%	11%
rMIP3S	22%	10%	11%
rOMPB	10%	6%	7%

Table 2 Supported bandwidth configurations ($\Psi(r_n, d_l)$)

Radius	2 Mbps	5 Mbps	10 Mbps	20 Mbps	30 Mbps	40 Mbps	75 Mbps
5 Miles	5	4	3	2	1.5	1	0.5
4 Miles	4	3	2	1	0.8	0.5	0.3
3 Miles	3	2	1.3	0.8	0.5	0.4	0.2
2 Miles	2	1.2	0.7	0.5	0.4	0.2	0.1

transmission radius parameters to see how the algorithm could adjust its transmission radius in finer radius granularity.

Note that in WiMAX [25], the transmission radius of the base station is usually fixed and do not support dynamic configurable radius. In general, when the transmission radius of the transmitter is fixed, the shorter the distance between the transmitter and receiver, the better the signal quality there would be at the receiver. The better the signal quality, the better the modulation scheme could be used to increase the data rate with fixed frequency spectrum. According to the above argument and (5), we assume the supported bandwidth configurations at Table 2 when the transmission radius is equal to 5, 4, 3, 2 miles. For example, when the radius is 3 miles, the distance between the sender and the receiver must be within 1.3 miles to guarantee 10 Mbps bandwidth. Instead, when the radius is 4 miles, the distance could be 2 miles to guarantee 10 Mbps bandwidth.

From Figs. 6, 7, 8, we observe that each algorithm gets better result as compared to the first set of experiments. This is because in fine radius granularity, after the routing path is determined, the transmission radius could be fine tuned to reduce the transmission power. We observed that LGR still could get the best results. In addition, in Table 3, we also observe that the SR of LGR over rOMPB in the second set of computational experiments has increased from 6% to 9% in multicast and 7% to 10% in broadcast than in the first set of computational experiments. This indicates that considering the BATCC constraint in determining the routing path could achieve further power reduction at fine radius configurations.

In the first and second set of experiments, the number of nodes in the group is 2, 1,000, and 2000 are tested in the unicasting, multicasting and broadcasting cases. Even though this reveals some results on the performance with respect to the algorithms in unicasting, multicasting and broadcasting cases, experiments on finer group size (i.e., more varieties of the number of nodes in the group) will help to get better conclusions on the performance of the algorithm with respect to the group size

Fig. 6 Performance comparison for unicasting in configurable radius

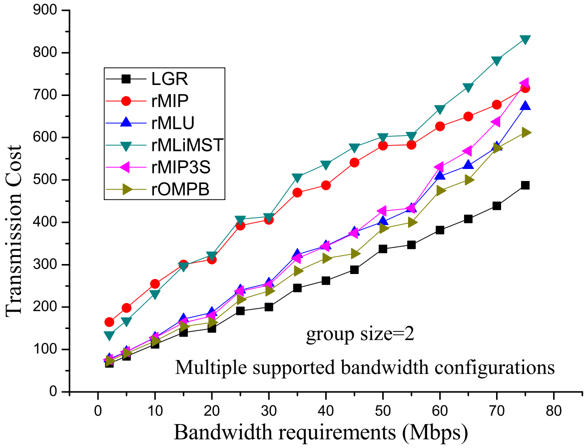


Fig. 7 Performance comparison for multicasting in configurable radius

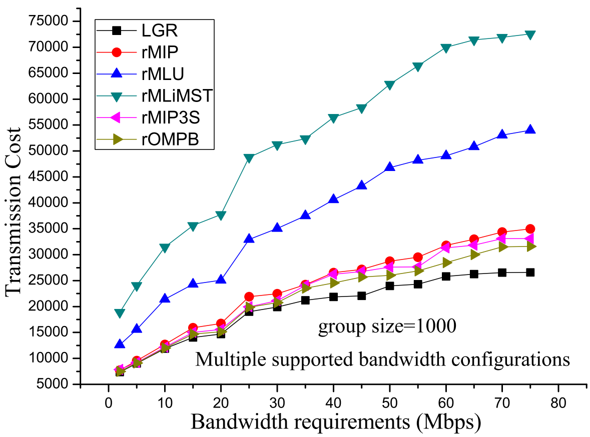


Table 3 SR in multiple bandwidth configurations

SR of LGR over	Unicast	Multicast	Broadcast
rMLU	26%	84%	90%
rMLiMST	95%	162%	176%
rMIP	92%	18%	18%
rMIP3S	27%	13%	14%
rOMPB	17%	9%	10%

parameter. In the following, we tested the algorithms in varieties of group size at high bandwidth request (e.g., 75 Mbps) for one transmission radius and multiple transmission radiuses as defined in Table 2. From Fig. 9 and Fig. 10, it is observed that LGR outperforms the other heuristics at all group size. Interestingly, we observe that the transmission cost for all the algorithms are saturated at the group size with 1,000 nodes. This is because that at the high network density (i.e., 2,000 nodes in

Fig. 8 Performance comparison for broadcasting in configurable radius

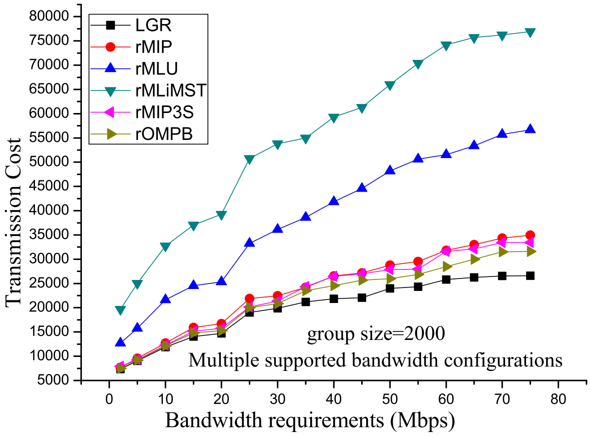


Fig. 9 Performance comparison with respect to group size in fixed radius

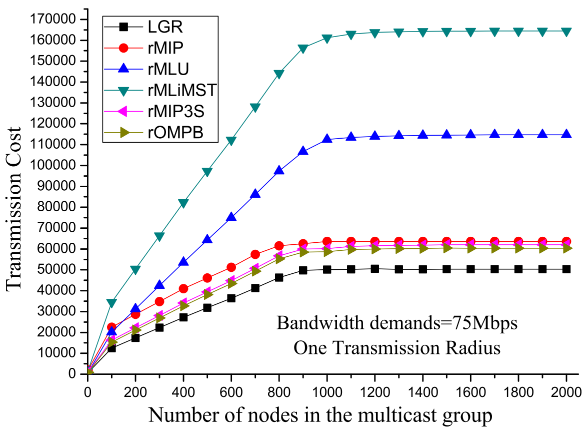
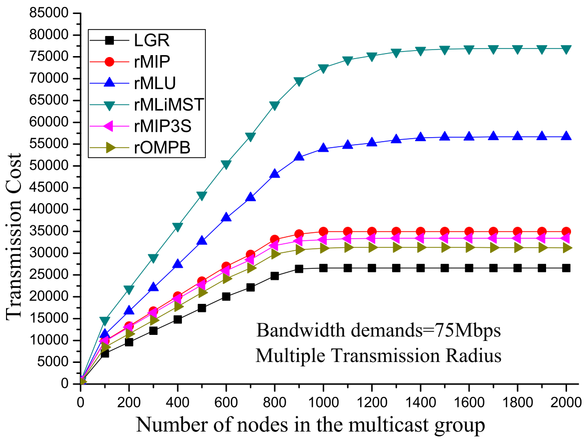


Fig. 10 Performance comparison with respect to group size in configurable radius



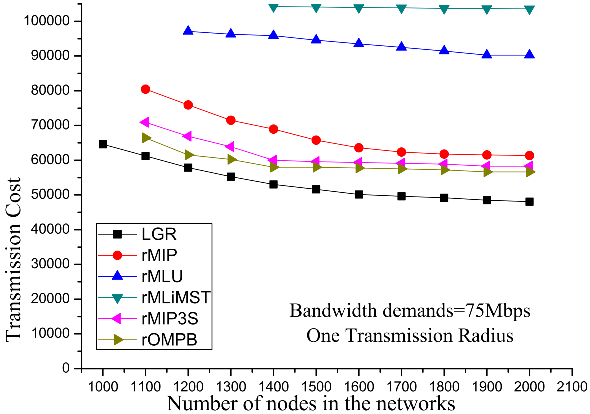


Fig. 11 Performance comparison with respect to network density in fixed radius

the deployed area), almost all the nodes will be covered within the bandwidth-aware transmission radius when there are 1,000 destination nodes. In other words, every node will satisfy the bandwidth requirement even though it is not a destination node. Based on this understanding, in the following, we will study how the network density will impact the performance of the algorithms.

In the following, we examine the performance comparison of the algorithms with respect to the network density in the multicasting case where there are 1,000 destination nodes. When the number of nodes is 1,000, this is a broadcasting case. The bandwidth requirements are all 75 Mbps. Intuitively, we could expect that at dense network, it is easier to locate relay nodes because more nodes are within the bandwidth-aware transmission radius of the transmitter. On the other hand, at sparse network, it will be more difficult to locate relay nodes so that the transmission cost will be higher as compared to the case in dense network. The computational results justify the above idea. Besides higher transmission cost at the sparse network, some of the algorithms could not locate feasible solutions at sparse network. For example, in Fig. 11, the rOMPB, rMIP3S, and rMIP could not locate feasible solution at 1,000 networks nodes. rMLU and rMLiMST could not locate feasible solutions when there are less than 1,200 and 1,400 nodes, respectively. In Fig. 12, rMLU and rMLiMST also could not locate feasible solutions at 1,000 network nodes. On the other hand, LGR algorithm could locate feasible solutions at sparse network in Fig. 11 and Fig. 12.

5 Conclusion

Traditional MPB algorithms that only consider the transmission coverage without addressing the signal quality might fail to meet the bandwidth requirement at the destination nodes. Incorporating this bandwidth-aware transmission, this MPBBA problem is more challenging than MPB problem because it is a cross-layer (layer 1 and layer 3) design problem. In this paper, we propose the mathematical formulation that successfully captures the idea of MPBBA problem and the optimization-based

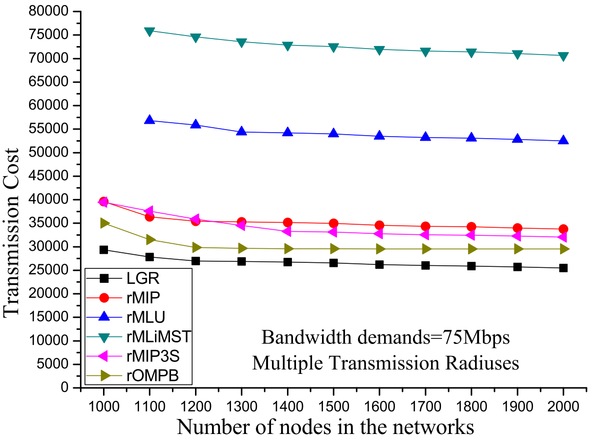


Fig. 12 Performance comparison with respect to network density in configurable radius

heuristics are proposed to tackle this MPBBA problem. Lagrangian multiplier associated with the BATCC helps the shortest path algorithm to consider the transmission power, BATCC and WMA at the same time so as to get better solution quality. According to the computational experiments, the proposed LGR approach holds 6% to 222% power improvement than the existing approaches in a wireless network with randomly populated 2,000 nodes. This indicates that the LGR is a novel bandwidth-aware and power-aware green networking algorithm.

There are two interesting new research areas for the future research of this paper. The first is the mobility issue. When the nodes are mobile, the receivers that are within the sender's bandwidth-aware transmission radius might travel outside the coverage during the data transmission. In this case, the receiver might not have good signal quality to meet its bandwidth requirement. In other words, in mobile wireless networks, it will be more challenging to tackle this MPBBA problem. The second is besides the bandwidth requirements, what is the impact of other quality of service measures (e.g., delay or loss) on the MPB problem. In considering these two performance metrics, besides signal quality, traffic load and intensity should also be taken into consideration to successfully capture the delay and loss performance metrics. This raises a new interesting research question in the MPBBA problem.

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