A Novel Optimization-Based Approach for Minimum Power Multicast in Wireless Networks

Hong-Hsu Yen, Steven S. W. Lee, and Florence G. H. Yap

Abstract: **In this paper, we formulate the minimum power multicast problem in wireless networks as a mixed integer linear programming problem and then propose a Lagrangean relaxation based algorithm to solve this problem. By leveraging on the information from the Lagrangean multiplier, we could construct more power efficient routing paths. Numerical results demonstrate that the proposed approach outperforms the existing approaches for broadcast, multicast, and unicast communications.**

Index Terms: **Lagrangean relaxation, minimum power broadcast (MPB)/multicast, optimization, wireless network.**

I. INTRODUCTION

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 radio frequency (RF) transmission, neighbor nodes that are within the range of a sender's transmission radius can receive the transmitted data. This nature can be used to reduce the total power consumption in a network performing multicast and broadcast communications. Such cost reduction property is very different to wired line communications. In [1], this property is called wireless multicast advantage (WMA).

Fig. 1(a) depicts an example of the WMA. In this example, node s is the sender node. As the transmission power is large enough to reach node c. Node a and node b are also covered. Based on WMA, in Fig. 1(b), the total cost to reach the destination nodes is $c1+c2+c5$ instead of $c1+c2+c3+c4+c5$ in wired line communication.

To use minimum total power in broadcasting/multicasting is usually called the minimum power broadcast (MPB) problem for abbreviation. It has been shown that the optimal solution to such problem is a minimum power tree, which is an non-deterministic polynomial-time hard (NP-hard) problem [2]. In [1], three energy-efficient heuristic algorithms are proposed. They are the shortest path based algorithm (MLU), the minimum spanning tree algorithm (MLiMST), and the broadcast/multicast incremental power (MIP) algorithm. According to the simulation results, shortest path algorithm can achieve excellent performance for small networks while the incremental power algorithm works well for large networks. In [3], the performances of these algorithms are analytically evaluated.

To get optimal solution, three integer linear programming models are proposed in [4]. However, no numerical results are reported to justify the applicability. By using CPLEX optimization solver to the optimization models in [4], we find that optimal solution can only be obtained for small network (less than thirty nodes) in days of computation.

The multicast incremental power with potential power saving (MIP3S) algorithm is proposed in [5]. 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 [6], they proposed a mathematical problem based on the set covering model and two solution methods to overcome the huge number of constraints. However, the communication radius is not restricted so that one node is allowed to reach any other node in the graph in order to minimize the total transmission power. This makes the solution approaches in [6] not applicable in existing wireless networks that the transmission radius of a node is often configured with several limited discrete values. Moreover, their proposed solution approach is not scalable to large network.

In this paper, we propose a Lagrangean based heuristic algorithm to obtain the minimum power tree in large wireless networks. The problem is first formulated as a mixed integer linear programming (MILP) problem in which the total energy consumption is to be minimized. We apply Lagrangean relaxation to decompose the problem into two solvable independent subproblems according to a set of Lagrangean multipliers generated through subgradient-based iterations. In addition, by using the multipliers, we could arrive at a better solution to MIP3S by using the MIP algorithm in our getting primal heuristic algorithm.

The remainder of this paper is organized as follows. In Section II, we first give the problem formulation. In Section III, we present the Lagrangean relaxation approach and the new primal heuristic algorithm. In Section IV, we demonstrate numerical results for broadcast, multicast, and unicast communications under a large random network. In Section V, we discuss the routing overhead of the routing information collection and dissemination for our purposed algorithm. Finally, a conclusion remark is made in Section VI.

II. MPB PROBLEM FORMULATION

We propose the MILP for the MPB problem. The basic idea of this formulation is to minimize the total transmission power under the condition that there is a routing path for every source destination (SD) pair. Furthermore, every link on the routing path must be covered by the tail node (i.e., the transmission node) of

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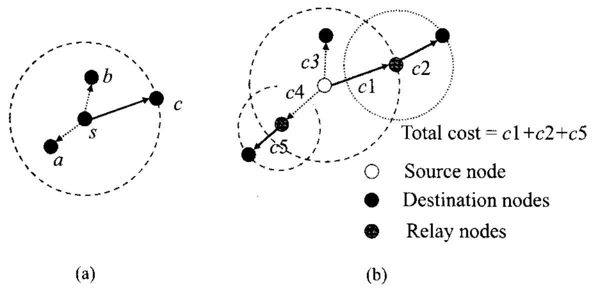

Fig. 1. Wireless multicast advantage: (a) Example of WMA and (b) cost reduction in wireless with WMA.

Table 1. Summary of acronyms.

Given parameters	
N	The set of nodes
L_n	The set of links outgoing from node $n \in N$
W	The set of SD pairs
P_w	The set of candidate paths for SD pair $w \in W$
δ_{pl}	= 1, if path p adopts link l = 0, otherwise
T_n	The set of candidate transmission radius for node n
ϕ_{nt}	Transmission cost for node n to transmit at radius t
σ_{ntl}	= 1, if node n with transmission power t is large enough to cover link $l \in L_n$ = 0, otherwise
Decision variables	
x_p	= 1, if path p is chosen = 0, otherwise
r_{nt}	= 1, if transmission radius t is selected for node n = 0, otherwise

the link. Hence, the transmission radius of the tail node must be larger than or equal to the distance of the link.

The notations used in the formulation are listed in Table 1. Based on the given notations, the problem of determining MPB can be formulated as the following mathematical programming problem

$$Z_{IP} = \min \sum_{n \in N} \sum_{t \in T_n} \phi_{nt} r_{nt} \qquad \text{(IP)}$$

subject to

$$\sum_{p \in P_w} x_p = 1, \qquad \forall\ w \in W, \qquad (1)$$

$$\sum_{w \in W} \sum_{p \in P_w} x_p \delta_{pl} \leq |W| \sum_{t \in T_n} r_{nt} \sigma_{ntl}, \ \forall\ n \in N, l \in L_n, \quad (2)$$

$$x_p = 0 \text{ or } 1, \qquad \forall\ p \in P_w, w \in W, \qquad (3)$$

$$r_{nt} = 0 \text{ or } 1, \qquad \forall\ n \in N, t \in T_n, \qquad (4)$$

$$\sum_{t \in T_n} r_{nt} \leq 1, \qquad \forall\ n \in N. \qquad (5)$$

Basically, the size of P_w will grow exponentially with number of nodes (i.e., $|N|$). So it is almost impossible to enumerate all possible paths at large network size. We will show in Section III that we do not need to enumerate all possible paths for P_w. The Lagrangean multipliers associated with decision variable x_p enable us to identify the shortest path for every SD pair $w \in W$ by using the Dijkstra's shortest path algorithm. Hence, unlike commercial optimization package (e.g., CPLEX) that we need identify all the values for P_w, P_w is just a notation for our proposed Lagrangean relaxation scheme. More specifically, we do not need to select any candidate path for an SD pair.

In considering the total power consumption, energy consumption in the idle mode is significant such that the sleep/awake mechanism for nodes plays an important role to minimize the total power consumption. In this paper, we only address the transmission cost instead of total power consumption for the MPB problem. Therefore, the sleep/awake mechanism is outside the scope of this paper.

The objective function is to minimize total transmission cost. Constraints (1) and (3) require that each SD pair selects exactly one path. Constraints (4) and (5) state every node either turning off its transmitter or selecting at most one transmission radius $t \in T_n$. We call (2) as transmission coverage constraint (TCC). When TCC is enforced, WMA characteristic is also facilitated. The basic idea of TCC could be modeled as

$$\sum_{p \in P_w} x_p \delta_{pl} d_l \leq R_n, \forall w \in W, n \in N, l \in L_n \qquad (2')$$

where the d_l is the distance of link l and decision variable R_n is the transmission radius of node n. Constraint (2') is to ensure that if the link l is included on the routing path of any SD pair, then the transmission power for the tail node of link l must be larger than the distance of link l. Even though (2') is intuitive, it might lead to loose lower bound by using the Lagrangean relaxation technique. In order to deal with this problem, we remodel it as (2).

On the left hand side of (2), it calculates the number of SD pairs adopting link l on their routing paths, and it is at most $|W|$. On the right hand side of (2), if node n turns on its power, and it locates a transmission radius t that is long enough to cover the distance of link l (i.e., $\sigma_{ntl} = 1$), then $\sum_{t \in T_n} r_{nt} \sigma_{ntl} = 1$. If node n does not turn on its power, then $\sum_{t \in T_n} r_{nt} \sigma_{ntl} = 0$. Hence, there are only two possible values (i.e., 0 and $|W|$) for the right hand side of (2). Constraint (2) states that if link l is included on the routing path of any SD pair, then the tail node of link l (say node n) must select one transmission radius t that is longer than the distance of link l.

When the node is powered by battery, residual energy becomes an important factor to determine the lifetime of the wireless networks. In this case, fairness becomes an important design criterion for wireless networks. This paper focuses on energy-efficient multicast routing algorithm in the wireless networks, which may inherently deals with the fairness issue so as to prolong the lifetime of the wireless networks. Nevertheless, to specifically address the fairness issue in the wireless networks, based on the proposed model and algorithm, the following mechanisms may be adopted directly:

1. The proposed algorithm may be re-executed periodically or on an event-driven basis. When the residual energy of a node is below a certain level, this node is reserved for future use unless it is absolutely necessary.
2. Also execute the proposed algorithm periodically or on an event-driven basis, where the energy consumption function $\phi_{nt} r_{nt}$ for each node n may be multiplied by a factor at each decision stage to reflect a penalty caused by short of energy.

III. LAGRANGEAN RELAXATION APPROACH

A. Lagrangean Relaxation

The proposed algorithm is based on Lagrangean relaxation. By introducing Lagrangean multiplier vector μ to (IP), we dualize (2) to obtain the following Lagrangean relaxation problem (LR). Basically, the more constraints are relaxed, the looser duality gap between the solutions to the dual problem and the primal problem. Loose duality gap might indicate that the solution to the primal problem might be too far from the optimal solution. On the other hand, if too little constraints are relaxed, we might not be able to solve the Lagrangean dual problem optimally. Then the solution to the dual problem is not the true lower bound of the primal problem. As we will show in the following paragraph, by relaxing (2) in (IP), the dual problem is optimally solved. In the meantime, a tighter duality gap could be located. Problem (LR):

$$Z_{LR}(\boldsymbol{\mu}) = \min \sum_{n\in N}\sum_{t\in T_n} \phi_{nt} r_{nt}$$

$$+\sum_{n\in N}\sum_{l\in L_n}\mu_{nl}\left[\sum_{w\in W}\sum_{p\in P_w} x_p\delta_{pl} - |W|\sum_{t\in T_n} r_{nt}\sigma_{ntl}\right]$$

subject to (1), (3), (4), and (5).

We decompose (LR) into two independent subproblems. Subproblem (S1):

$$Z_{S1}(\boldsymbol{\mu}) = \min \sum_{w\in W}\sum_{p\in P_w}\sum_{n\in N}\sum_{l\in L_n} \mu_{nl} x_p \delta_{pl}$$

subject to (1) and (3).
Subproblem (S2):

$$Z_{S2}(\boldsymbol{\mu}) =$$
$$\min \sum_{n\in N}\sum_{t\in T_n}\phi_{nt} r_{nt} - \sum_{n\in N}\sum_{l\in L_n}\sum_{t\in T_n}|W|\mu_{nl} r_{nt}\sigma_{ntl}$$

subject to (4) and (5).

(S1) can be further decomposed into $|W|$ independent shortest path problems. For each SD pair $w \in W$, we have nonnegative arc weight μ_{nl} 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 SD pair.

(S2) can also be further decomposed into $|N|$ independent problems. For each node $n \in N$, we have

$$\min \sum_{t\in T_n}\phi_{nt} r_{nt} - \sum_{l\in L_n}\sum_{t\in T_n}|W|\mu_{nl} r_{nt}\sigma_{ntl}$$

subject to

$$r_{nt} = 0/1 \forall t \in T_n \; and \; \sum_{t\in T_n} r_{nt} \le 1.$$

We observe that if node n does not turn on its transmission power (i.e., all r_{nt} are 0), the objective value will be zero. When node n turns on its transmission power, since T_n is a discrete set, we could exhaustively try all possible radius assignment $t \in T_n$ to identify the optimal r_{nt} with the smallest objective value. If this value is smaller than zero, then node n turns on its transmission power to corresponding power level t, otherwise node n should turn off its transmission power. The complexity of the above algorithm is $O(|L||T_n|)$ for each node.

Based on the above algorithms, we can effectively solve (LR) optimally. By the weak duality theorem [7], given any nonnegative multiplier, $Z_{\rm LR}$ is a lower bound to $Z_{\rm IP}$. We can use subgradient method to calculate the tightest lower bound [7].

B. Primal Heuristic Algorithm

Note that the solutions to the dual problem (LR) might not be feasible to the primal problem (IP) due to (2) is relaxed. There are two approaches to get the primal feasible solutions. The first heuristic is based on the routing assignment variable x_p in (S1) to identify the smallest transmission radius in T_n to cover the selected links going out from all the links on the routing path (i.e., satisfy (2)). Since the routing is based on subproblem (S1), the computational complexity is $O(|N||T_n|)$ to identify the smallest transmission radius in T_n for transmission coverage.

The second heuristic is to leverage on MIP algorithm [1] and introducing Lagrangean multipliers on the link arc weight to get better solution quality. The arc weight assignment for link l is $d_l^\alpha(1 + \mu_{nl})$, where node n is the tail node of link l, d_l is the distance of link l, and α is the signal attenuation constant ($\alpha = 2 - 4$). The first term, d_l^α, is identical to the definition in original MIP algorithm but the second term, $d_l^\alpha\mu_{nl}$, is used here to be a cost penalty for violating TCC constraint. Note that the physical meaning for μ_{nl} is the violation cost for TCC. Thus, incorporating $d_l^\alpha\mu_{nl}$ on the arc weight of link l is to jointly consider the transmission power, TCC and WMA at the same time. The computational complexity of this heuristic is $O(|N|^3)$.

According to the computational experiments, the first heuristic performs well in unicasting case and the second heuristic performs better in multicasting/broadcasting case. Note that in unicasting case, the WMA does not introduce any transmission power reduction. In this case, the shortest path based algorithm (i.e., the first heuristic) would be the most power efficient one. On the other hand, when in multicasting (especially in broadcasting) case, the WMA would play a significant factor to reduce the power consumption. Hence, the second heuristic that addresses the WMA would perform much better than the first heuristic. Therefore, we incorporate these two heuristics as our getting primal feasible heuristic (denote as logical grid routing (LGR)-primal). The computational complexity of LGR-primal is $O(|N|^3)$.

The computational complexity for the complete algorithm (denote as LGR, as shown in Algorithm 1) which includes the solution procedure for two subproblems and getting primal feasible solution. The computational complexity for LGR algorithm is $O(|N|^3)$ for each iteration.

IV. NUMERICAL RESULTS

We have carried out a performance study on the LGR approach, and drawn comparisons with MIP, MLU, and MLiMST in [1] and MIP3S in [5] via experiments over a randomly generated network. For LGR, *"Max Iteration Number"* and *"Quiesceince Threshold"* are set to 1000 and 30, respectively. The

Table 2. Superiority ratio.

SR of LGR over	Unicast	Multicast	Broadcast
MLR ($O(\|N\|^3)$)	1.2% (3 ms)	49.2% (9 ms)	57.5% (15 ms)
MLiMST ($O(\|N\|^3)$)	7.3% (3 ms)	21.7% (3 ms)	24.5% (3 ms)
MIP ($O(\|N\|^3)$)	1.2% (4 ms)	9.3% (11 ms)	10.2% (21 ms)
MIP3S ($O(\|N\|^4)$)	1.2% (19 ms)	8.7% (48 ms)	6.5% (96 ms)

Algorithm 1: LGR algorithm

Begin
Input: Network topology, data source nodes;
Output: routing path for every SD pair;
Initialize Lagrangean multiplier vector μ;
UB = a very large number (e.g., 10^{10});
LB = a very large negative number (e.g., -10^{10});
//upper and lower bounds, respectively
quiescence age = 0 and *step size* = 2 //
For iteration = 1 to *Max Iteration Number* do:
Solve (S1) and (S2)
Compute $Z_{LR}(\mu)$ in (LR);
If $Z_{LR} > LB$
$LB := Z_{LR}(\mu)$ and *quiescence age*:= 0;
Else *quiescence age*:= *quiescence age* + 1;
If *quiescence age* = *Quiescence Threshold*
$step\ size := step\ size/2$ and *quiescence age*:= 0;
Run LGR-primal;
Compute the new upper bound ub;
If $ub < UB$ then $UB := ub$;
Update the *step size*;
Update the Lagrangean multiplier vectors.
End For
End.

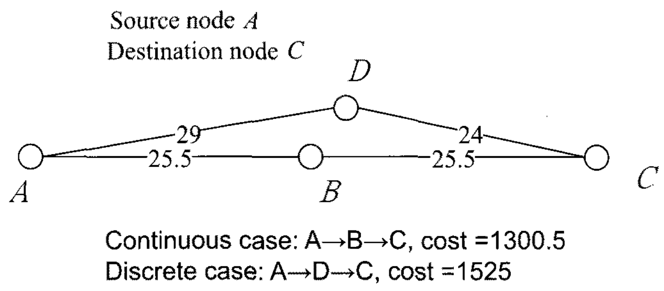

Fig. 2. Optimal routing in continuous and discrete communication radius.

"step size coefficient" is initialized to be 2 and will be halved when the objective function value of the dual problem does not improve for iterations up to *"Quiesceince Threshold"*.

The network consists of 100 nodes randomly placed in a 250 × 250 square area. The signal power attenuation is set to $d_l^{-\alpha}$ and $\alpha = 2$ for link l (i.e., $\phi_{nt} = t^2$). As compared to the continuous radius assumption in [1], [5], and [6] the set of possible communication radius is a discrete set starting from 0 with step size 5 to largest communication radius. For example, in Fig. 3, radius 55 means that the set of candidate radius $T_n = \{0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55\}$ for each node n. Note that in discrete radius case, the shortest path does not guarantee the optimal unicast routing. Fig. 2 illustrates an example. In Fig. 2, routing path A-B-C has total transmission cost 1300.5 (= $25.5^2 + 25.5^2$), which is optimal in continuous radius case. However, in discrete radius case, because 25.5 is bigger than 25, the transmission radius must be set to 30 to cover the receiver. In this case, routing path A-B-C has total transmission cost 1800 (= $30^2 + 30^2$), which is greater than routing path A-D-C with total transmission cost 1525 (= $30^2 + 25^2$). Hence, as compared to the continuous radius, the discrete radius increases the difficulty of finding the optimal solution.

From Figs. 3–5, we study transmission cost with respect to the communication radius. Theoretically, large maximum communication radius can get smaller transmission cost because of its larger feasible region. We could observe that the transmission cost for MLU and MLiMST algorithms do not change with respect to maximum communication radius. This is because the shortest path algorithm or minimum cost spanning tree algorithm always choose the link with smaller arc weight so that links with large arc weight (i.e., large transmission radius) is unlikely to be selected. On the other hand, the other three algorithms (LGR, MIP3S, and MIP) will adjust the transmission radius to see if further power saving is possible. Hence, it is possible to choose large communication radius for facilitating the WMA. This power saving from larger communication radius is significant at large group size (especially for broadcasting) for LGR algorithm. This indicates that LGR can fully utilize the larger radius set for more efficient transmission.

We define superiority ratio (SR) to be the performance metric for making comparison with the other four algorithms. SR is defined as $(\overline{A} - \overline{\mathrm{LGR}})/\overline{\mathrm{LGR}}$ in percentage, where $\overline{\mathrm{LGR}}$ and $\overline{A}$ are the mean transmission cost of the LGR algorithm and the other algorithm. Finally, we summarize the performance comparisons in Table 2. From Table 2, we can observe that LGR outperforms the other four algorithms under all test cases.

In the Table 2, we also show the computational complexity and computational time for each algorithm under different number of destinations. Institutively, the larger the number of destinations, the larger the computational time would be. However, in MLiMST algorithm, we observe that the computational time is the same regardless of the number of destinations. This is because MLiMST algorithm will always construct a minimum cost spanning tree, then the routing path for each SD pair will be confined in this tree. Recall that the computational complexity for LGR algorithm is $O(|N|^3)$ for each iteration. The computational time for LGR under unicast/multicast/broadcast is 33/41/49 mini-seconds (ms) for each iteration. Hence, for total 1000 iterations, the computational time for the LGR algorithm will be less than one minute.

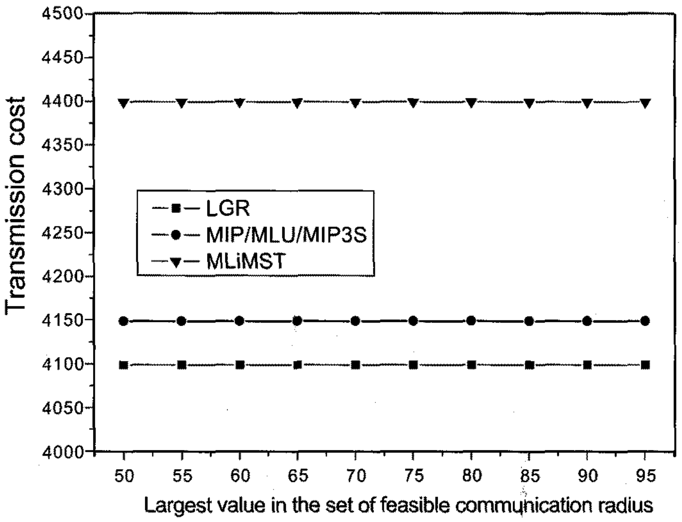

Fig. 3. Performance comparison for unicasting.

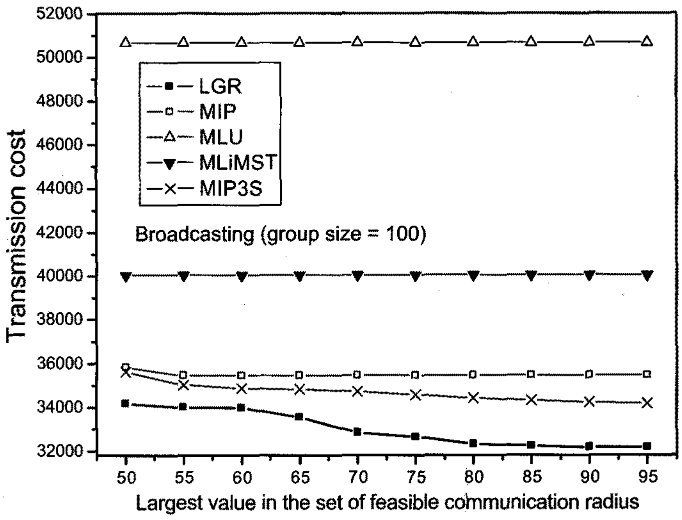

Fig. 5. Performance comparison for broadcasting.

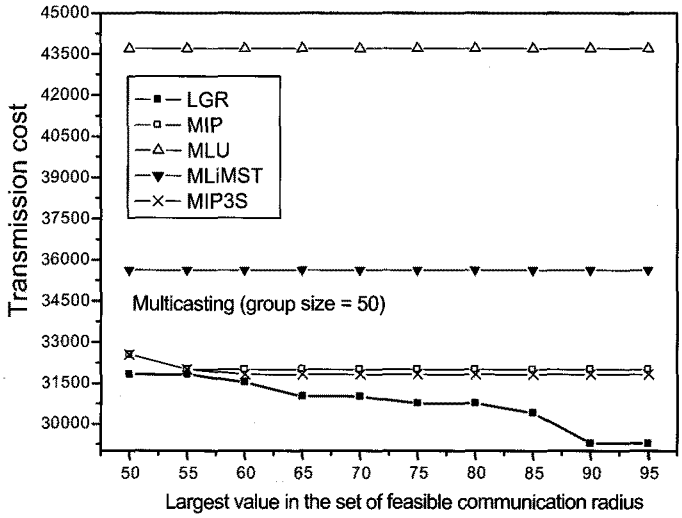

Fig. 4. Performance comparison for multicasting.

V. ROUTING INFORMATION DISSEMINATION AND COLLECTION

Two sets of information that require in our LGR algorithm are the transmission radius configuration for each node n (i.e., T_n and ϕ_{nt}) and the transmission coverage information (i.e., L_n and σ_{ntl}). After the transmitter receive these two sets of information, the transmitter will responsible for calculating the minimum power multicast tree based on the LGR algorithm. Note that the transmission radius configuration is fixed, so it only needs to be broadcasted only one time. When every node has the same transmission radius configuration, this information does not need to be broadcasted. In other words, the transmission configuration information need only to broadcast one time or do not need to broadcast when the configuration is the same for all nodes.

For the second set of information, transmission coverage information might change from time to time because the node is mobile. This transmission coverage information should be broadcasted periodically to the other nodes. If every node is equipped with global positioning system (GPS), the transmission coverage information could be derived by broadcasting its location. In this case, the existing distance routing effect algorithm for mobility (DREAM) routing protocol [8] could be adopted to disseminate this location information.

On the other hand, if GPS is not equipped, then the hello-acknowledge mechanism is adopted. In this mechanism, the node sends hello message to the neighbor nodes, and neighbor nodes within its transmission radius will acknowledge after receiving the hello message. By collecting the acknowledge message from the neighbor nodes, transmission coverage information could be derived and it could be broadcasted to other nodes. Note that this hello message is only one hop transmission, i.e., neighbor nodes that receive a hello message will not broadcast again to other nodes. Then the node will construct a transmission coverage table and broadcast to the other nodes. Instead of using the flooding scheme for broadcasting, we adopt the optimized link state routing protocol (OLSR) [9]. OLSR protocol proposes a multipoint relaying strategy to minimize the size of the control message and the number of rebroadcasting nodes.

It is clear that the second set of transmission coverage information will dominate the overhead of routing information dissemination. Then, the complexity analysis will be based on the second set of routing information, which is summarized in Table 3.

VI. CONCLUSIONS

Optimization-based heuristics is proposed in this paper to address the MPB problem. Lagrangean multiplier associated with the TCC helps the shortest path algorithm and MIP algorithm to consider the transmission power, TCC and WMA at the same time so as to get better solution quality. According to the computational experiments, the proposed LGR approach holds 7.3% (in unicast) to 57.5% (in broadcast) performance improvement than the existing approaches in a 100-node random network.

Table 3. Complexity analysis of routing information dissemination and collection in LGR, where $|N|$ is the number of nodes in the network, I is an average update interval, and D is a diameter of the network.

	Convergence time	Memory overhead	Control overhead
With GPS (DREAM [8])	$O(\|N\| \times I)$	$O(\|N\|)$	$O(\|N\|)$
Without GPS (OLSR [9])	$O(D \times I)$	$O(\|N\|^2)$	$O(\|N\|^2)$

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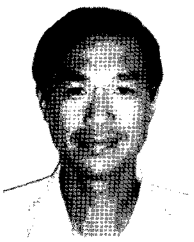

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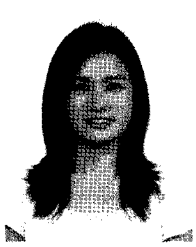

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