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SNR-aware and power-efficient multicast cooperative routing algorithm in wireless networks

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Abstract

Power-efficient multicast routing is an active research field in wireless networks because most network nodes are powered by battery. However, this kind of multicast routing only considers the transmission radius coverage without addressing whether the signal quality is able to meet bandwidth requirement of the users. In this article, by leveraging on the Maximum Ratio Combining signal processing technique, a novel cooperative multicast routing scheme that meets the Signal-to-Noise Ratio (SNR) requirements of the traffic demands in power efficient way is developed. This problem is formulated as an optimization problem where the objective is to minimize the total transmission power subject to the SNR constraint. This is a challenging cross-layer design problem to simultaneously consider the cooperative routing in the network layer and the SNR-aware power control in the physical layer. A heuristic algorithm called bandwidth-aware cooperative radius adjustment (BACRA) is proposed to tackle this problem. The basic idea of BACRA is to select the node with the maximum ratio of contributed SNR to the power (denoted as SNR/P) to expand its power one at a time until the SNR requirements are all satisfied. The BACRA is proved to be optimal in terms of the SNR/P performance ratio. Numerical results demonstrate that the BACRA outperforms the other heuristics under all tested cases, especially in stringent SNR requirements and sparse network.

Keywords: Cooperative routing, SNR QoS, Power control, Minimum power broadcast multicast, Wireless multicast advantage

Introduction

In wireless network, node power radiation management is an important issue since most of the network nodes are powered by the battery. One interesting property that only exists in wireless networks but not in wired networks is the Wireless Multicast Advantage (WMA) [1]. For WMA, neighbor nodes that are within the range of a sender's transmission radius can receive the transmitted data. This WMA property can be used to reduce the total power consumption for multicast and broadcast applications. Figure 1 depicts an example of the WMA. In this example, node *A* is the sender node. As the transmission power is large enough to reach, nodes *E*, *B*, *C*, and *D* are also covered. Based on WMA, in Figure 1, the total power to send the data to all the destination nodes is Π_4 instead of $(\Pi_1+\Pi_2+\Pi_3+\Pi_4)$ in wired line communication. Note that the transmission power Π is defined in Section "Cooperative routing model for MPBBA".

Algorithms leverage on the WMA property to minimize the total power consumption is an active research in wireless networks. This kind of minimum total power in broadcasting/multicasting routing problem (denoted as the MPB problem) in wireless networks has been shown to be an NP-hard problem [2] and heuristics [1-5] has been proposed to get the near-optimal solutions. However, the MPB problem only considers the transmission radius coverage. It does not address the cases where signal quality may fail to meet the bandwidth demands of the origin–destination (OD) pairs.

The available bandwidth in the wireless link depends on the signal quality and the modulation scheme. If the received signal quality is below the minimum signal

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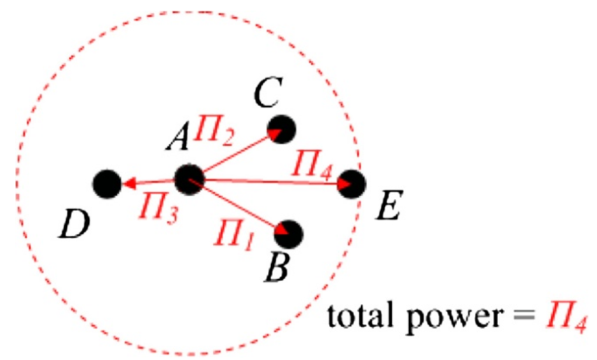

Figure 1 Power savings by WMA.

quality threshold of the modulation scheme, then the receiver could not successfully decode the received information. Therefore, less sophisticated modulation scheme that requires lower signal quality should be adopted to decode the received information. Then, the available bandwidth on this wireless link could be reduced. For example, in IEEE 802.11b, the effective bandwidth could be 1, 2, 5.5, and 11 Mbps [6], which depends on the signal quality of the receiver. In general, when the transmission power at the transmitter is fixed, the shorter the distance between the transmitter and the receiver, the better the signal quality there would be, and more sophisticated modulating scheme (e.g., 64-QAM) could be used to achieve higher data throughput. On the other hand, in the case of long distance between transmitter and receiver, the signal quality is poor so that only ordinary modulating scheme (e.g., QPSK) could be used. Then, the effective bandwidth might fail to meet the traffic demands of the OD pair. This kind of MPB with bandwidth-aware problem (denoted as MPBBA) is different from traditional MPB problem. With considering the bandwidth requirement and power consumption simultaneously, MPBBA problem is more challenging than the MPB problem.

One possible way to tackle the MPBBA problem is first to have the MPB solutions without addressing the bandwidth constraint. Next expanding the transmission radius so that bandwidth requirement could be satisfied. This kind of two-stage algorithm could satisfy the bandwidth requirement but it is not as power efficient as reported in [7]. In [7], we proposed optimization-based heuristic to tackle the MPBBA problem. Even though this optimization-based heuristic in [7] outperforms the two-stage algorithm, there is still room for improvement. In [7], it is a non-cooperative routing scheme where the receiver could only receive data from one sender. In [7], when the receiver received the data from multiple senders, the receiver could only select the data from the sender with the best signal quality. As a matter of fact, the receiver could combine the received signal from all the senders to get better signal quality by using the Maximum Ratio Combining (MRC) [8] signal processing technique. With this MRC technique, the signal power could be linearly combined so that the received Signal-to-Noise Ratio (SNR) is the sum of the SNR contributed from all the senders [8]. To be more specific, by leveraging on the MRC scheme, the power from multiple transmitters could be linear combined at the receiver. It could be expected that the cooperative routing scheme with this MRC technique could be more power efficient than the non-cooperative routing scheme. Figure 2 shows an illustrative example.

In Figure 2, we assume that the data rate demands for all the destination nodes are all 2 Mbps, and the available frequency spectrum at each node is 500 kHz. Hence, the transmitter must use at least the 16-QAM modulation to satisfy the destinations' bandwidth demands. We also assume that the nodes covered within the solid circle (denoted as SNR-aware transmission radius) could get sufficient SNR to decode the 16-QAM data, and the nodes covered within the dashed circle (denoted as transmission radius) but outside the solid circle could only get half of the required SNR.

In Figure 2a, every node is within node *A*'s transmission coverage, so it is a feasible solution from the MPB's point of view. However, we could not satisfy the SNR

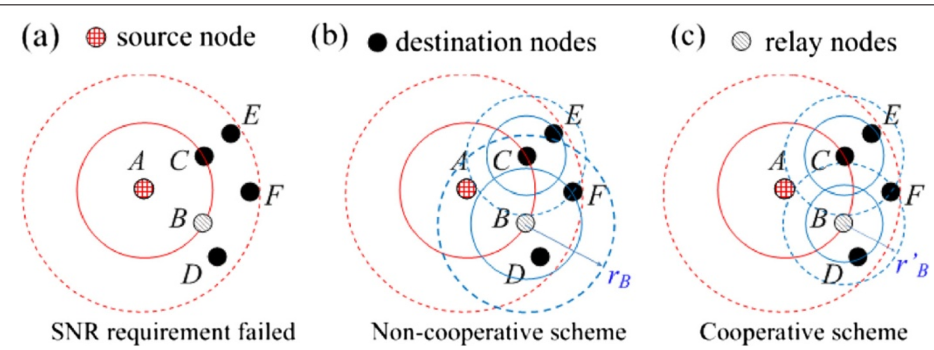

Figure 2 SNR-aware power-efficient cooperative multicast routing.

(bandwidth) requirement for nodes *D*, *E*, and *F* if node *A* transmits its signal with 16-QAM modulation scheme. Nodes *D*, *E*, and *F* could not successfully decode the information because of the poor SNR. In other words, nodes *D*, *E*, and *F* are within the transmission radius of *A* but not within the SNR-aware transmission radius of *A*; therefore, it fails to meet the bandwidth QoS at nodes *D*, *E*, and *F*.

One possible way to satisfy the bandwidth requirement for all the nodes is shown in Figure 2b. In Figure 2b, nodes *B* and *C* turn on their power. Nodes *D* and *F* are within the SNR-aware transmission radius of node *B*, and node *E* is within the SNR-aware transmission radius of node *C*. Then the SNR and bandwidth requirement for all the destination nodes could be satisfied. By carefully examining Figure 2b, we find that there is still room to further reduce the power consumption if the cooperative routing scheme is adopted. To be more specific, in Figure 2b, node *C* contributes half of the required SNR to node *F*. If node *F* could get the other half of the required SNR from node *B*, then the SNR requirement could be satisfied. To put it in a different way, by shrinking the transmission radius of node *B* from r_B to r'_B as shown in Figure 2c, node *F* is within node *B*'s transmission radius to get half of the required SNR. By adopting the MRC signal processing technique, the SNR at node *F* is equal to the sum of the SNR contributed from nodes *B* and *C*. Hence, the SNR at node *F* could meet the minimum SNR requirement to successfully decode the received data by using the 16-QAM modulation scheme. In addition, node *D* is still within node *B*'s SNR-aware transmission radius. Then all the SNR requirements are all satisfied for the destination nodes. This example shows that cooperative routing scheme is more power efficient than the non-cooperative routing scheme. To facilitate the cooperative routing scheme, a new many-to-one communication (e.g., from nodes *B* and *C* to *F*), denote as *convergecasting*, should carefully be designed.

In order to realize the collaborative communication as shown in Figure 2c, several issues needed to be addressed at the same time.

(1) *Modulation scheme*: Modulation scheme should carefully be selected by the transmitter to facilitate two important criteria. The first is to increase the data throughput at the receiver. The data throughput is determined by the frequency spectrum and the modulation scheme. Due to the limited frequency spectrum in wireless networks, adopting sophisticated modulation scheme is a good way to increase the data throughput at the receivers. The second is to make sure the receivers would successfully decode the information. Sophisticated modulation scheme requires better signal quality than ordinary modulation scheme. Hence, the transmitter that uses the sophisticated modulation scheme could cover fewer receivers than the transmitter that uses the ordinary modulation scheme under the same transmission radius. To summarize, there is a tradeoff between SNR-aware coverage and data throughput in selecting the modulation scheme.

(2) *SNR-aware power control:* From the power consumption point of view, the transmission power should be as minimal as possible to minimize the total power consumption. From the signal quality point-of-view, the transmission power should be as large as possible for the receiver to successfully decode the information. Hence, the power control strategy should carefully be designed to be SNR-aware and at the same time to minimize the transmission power.

(3) *WMA-enabled power efficient routing*: Taking advantage of the WMA, the transmission power could significantly be reduced as compared to the wired line communication. Routing protocol in the wireless network should incorporate the WMA for power saving.

(4) *Convergecasting with signal quality aggregation*: By adopting the MRC signal processing technique, the SNR at the receiver is the sum of the contributed SNR from all the transmitters. This raises a new routing protocol (i.e., convergecasting) to facilitate the MRC technique for meeting the SNR requirement at the destination nodes. Unlike traditional one-to-many multicasting communication, convergecasting is a many-to-one communication strategy that requires totally new design philosophy and idea to be power aware and SNR aware simultaneously.

It is noted that the node with capability of selecting the modulation scheme (which is known as adaptive modulation) requires complicated hardware design. In other words, node with adaptive modulation capability is more expensive than the node without adaptive modulation. Besides expensive hardware cost, the additional adaptive modulation circuit incurs larger node processing power. Hence, it is not easy to ask every node in the wireless network to incorporate this adaptive modulation capability. In this article, we will assume that the modulation scheme is fixed for the nodes.

MPBBA problem via cooperative communication is a challenging *cross-layer* (layer 1 + layer 3) design problem that includes SNR-aware transmission and power control in the physical layer and minimum power multicast and convergecast routing in the network layer. This article is a pioneer in addressing the MPBBA problem via cooperative communication by proposing integrated cross-layer heuristics that intelligently perform the SNR-aware minimum power multicast and convergecast routing in wireless ad hoc network to meet the SNR requirements of the destination nodes. In the sequel, we summarize the related works on MPB, MPBBA, and cooperative routing problems.

Several related works address the MPB problem. In [1], three energy-efficient heuristic algorithms are proposed. They are the shortest path-based algorithm, the minimum spanning tree algorithm, and the broadcast/ multicast incremental power (MIP) algorithm. MIP algorithm exploits the WMA in wireless network via minimum incremental transmission power to cover unvisited node. According to the simulation results, shortest path algorithm can achieve excellent performance for small networks and the MIP algorithm works well for large networks. In [3], the performances of the above three algorithms are analytically evaluated. To get optimal solution, three integer linear programming models are proposed in [9]. However, no numerical results are reported to justify the applicability. By using CPLEX optimization solver to the optimization models in [9], we find that optimal solution can only be obtained for small network (less than 30 nodes) in days of computation. The MIP3S algorithm is proposed in [4]. By expanding the transmission power to cover a few more nodes (denote as set Φ), potential power saving is possible by reducing the transmission radius of other nodes that previously cover the nodes in Φ. 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 $O(|N|^3)$ in MIP.

Recently, some works based on optimization technique to solve the MPB problem have been proposed. Yuan et al. [10] present a novel MILP model that leads to a sharp lower bound of the optimum via Lagrangian relaxation. In the same article, they also propose a heuristic algorithm 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 algorithm is $O(|N|^3)$. Another optimization-based approach for MPB problem is proposed in [5]. By leveraging on the information from the Lagrangian multiplier, we could construct more power-efficient routing paths. Numerical results demonstrate that the proposed approach in [5] outperforms the MIP and MIP3S for broadcast, multicast, and unicast communications. The above optimization-based approaches are designed for omni-direction antenna scenario. Algorithms for networks using directional antenna can be found in [11,12]. Due to many active research works proposed for resolving the MPB problem, for other kinds of approaches, please refer to the survey article for details [13]. As discussed in Figure 2, these MPB algorithms are not applicable to the MPBBA problem because the bandwidth requirement and signal quality are not considered.

In [7], to the best of the author's knowledge, this article is the first one to address the MPBBA problem. In [7], we tackle the MPBBA problem by using the non-cooperative routing scheme where the receiver could only receive data from one sender. Hence, when the receiver received the data from multiple senders, the receiver could only select the data from the sender with the best signal quality. As discussed in Section "Introduction", by adopting the MRC scheme, the signal quality could linearly be combined at the receiver from multiple transmitters so that it is easier to satisfy the SNR requirement of the receiver. It could be expected that the cooperative routing scheme with this MRC technique could be more power efficient than the non-cooperative routing scheme. In the computational experiments, it is also shown that the proposed cooperative routing algorithm, bandwidth-aware cooperative radius adjustment (BACRA), is more power efficient than the non-cooperative routing scheme as proposed in [7].

The study of Khandani et al. [14] is the first one that studies how energy saving is possible by using the cooperative transmission via WMA property in wireless networks. They devise the power cost function for the cooperative link and prove that the cooperative transmission could be more energy efficient than non-cooperative point-to-point communication. They devise the CAN heuristic for this problem. The idea of CAN is to calculate the non-cooperative shortest path and then try to reduce the total transmission power via cooperation along this shortest path. The authors of [15] prove that the minimum energy cooperative path routing is an NP-complete problem and devise the Cooperative Shortest Path (CSP) heuristic to tackle this problem. The CSP is basically a Dijkstra shortest path algorithm with different link arc weight settings. The link arc weight is defined as the cooperative link cost as defined in [14]. They show that CSP has better performance than the CAN heuristic.

Unlike in [14,15] that only assume single flow in the cooperative routing problem, in [16], the authors consider the multiple flows from multiple sources to multiple destinations. There would be MAC layer contention problem when neighboring flows use the same channel. They devise the heuristic to address this cross-layer (network layer + MAC layer) cooperative communication problem and conclude that the proposed algorithm is better than the single flow algorithm (e.g., CAN, CSP) in terms of network throughput.

As indicated in the previous paragraphs, all the existing literatures on cooperative routing do not address the signal quality or the bandwidth requirement. To the best of the author's knowledge, this article is the first one to address the MPBBA problem by using the cooperative routing scheme. In this article, for the first time, a cooperative routing heuristic algorithm, BACRA, to obtain the minimum power multicast routing in large wireless networks that meets the bandwidth QoS requirement is proposed. BACRA is proven to be optimal in terms of the SNR to power ratio and is superior to the other heuristics under all the tested cases in the computational experiments.

The remainder of this article is organized as follows. In the next section, the cooperative routing model is first studied to give the MPBBA problem formulation and then the BACRA heuristics that is based on maximizing the SNR to power ratio is proposed to minimize the energy consumption with the SNR requirements. In Section "Numerical results", the numerical results for different modulation schemes (SNR requirements) are tested under varieties of large random networks. Finally, a conclusion remark and future works are given.

Cooperative routing model for MPBBA

Cooperative routing model

In cooperative routing path, there are three different kinds of links, namely point-to-point link, point-to-multipoint link, and multipoint-to-point link. Figure 3 shows an illustrative example of cooperative communication. At point-to-point link, there is only one transmitting node and receiving node (e.g., link $A \rightarrow B$). At point-to-multipoint link, there is one transmitting node and multiple receiving nodes (e.g., links $B \rightarrow C$ and $B \rightarrow D$). Because of WMA property, the power consumption at node B is $\max\{\prod(d_{BC}), \prod(d_{BD})\}$, where $\prod(d_{BC})$ is defined as the transmission power for node B with transmission radius d_{BC}. At multipoint-to-point link, multiple transmitting nodes cooperatively transmit data to one receiving node (e.g., links $C \rightarrow E$ and $D \rightarrow E$). Note that since the cooperating routing path (e.g., Figure 3) is neither ordinary single path nor ordinary multicast tree, traditional path model or tree model is

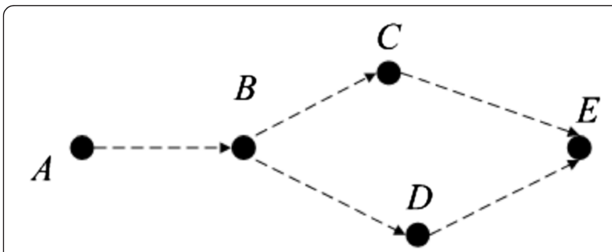

Figure 3 Cooperative routing path example.

not able to characterize cooperative routing path. Then this raises an interesting question to be answered, what is the total cost for multipoint-to-point communication by using cooperative communication.

A new model needs to be devised to characterize the cooperative routing path especially for multipoint-to-point cooperative communication. Let LC(S, T) denote the total cost for nodes in $S = \{s_1, s_2, \ldots, s_n\}$ cooperatively transmit data to node in $T = \{t_1\}$. Khandani et al. [14] derive the minimum total link cost LC(S, T) to make sure the receiver could correctly decode the information only when the SNR at the receiver is above a minimum threshold $\text{SNR}_{\min}$. In point-to-point communication (i.e., $S = \{s_1\}$), the link cost is

$$\Pi(s_1) = \text{LC}(s_1, t_1) = (\text{SNR}_{\min}) \times P_\eta \times d_1^\alpha, \tag{1}$$

where P_η denotes the noise power, d_1 is the distance between s_1 and t_1, and α denotes the power attenuation factor which is usually between 2 and 4. Because it is a point-to-point communication, the link cost is equal to the required power at node s_1 (i.e., $\Pi(s_1)$). Given a modulation scheme, the minimum SNR to successfully decode the information is fixed (i.e., $\text{SNR}_{\min}$ is fixed). In addition, P_η is also constant. Then link cost $\Pi(s_1)$ is a function of distance d_1.

In the multipoint-to-point link, the minimum cooperative link cost LC(S, T) from nodes in $S = \{s_1, s_2, \ldots, s_n\}$ cooperatively transmit data to node t_1 is

$$\text{LC}(S, t_1) = \frac{1}{\sum_{i=1}^{n} \frac{1}{(\text{SNR}_{\min}) \times P_\eta \times d_i^\alpha}} = \frac{1}{\sum_{i=1}^{n} \frac{1}{LC(s_i, t_1)}} \tag{2}$$

If $\text{LC}(s_1, t_1) = \text{LC}(s_2, t_1) = \cdots = \text{LC}(s_n, t_1)$, we have

$$\text{LC}(S, t_1) = \frac{LC(s_1, t_1)}{n} \tag{3}$$

Based on Equation (3), we only need ($1/n$) of the original total transmission power to achieve the same SNR at node t_1 via the cooperative communication. In addition, the required power at each node s_i is

$$\Pi(s_i) = \frac{\frac{1}{LC(s_i, t_1)}}{\sum_{i=1}^{n} \frac{1}{LC(s_i, t_1)}} \times \frac{LC(s_1, t_1)}{n} = \frac{LC(s_1, t_1)}{n^2} \tag{4}$$

Hence, each node only need ($1/n^2$) of the original transmission power to achieve the same SNR at node t_1 via the cooperative communication from n transmitters. From Equations (3) and (4), we can conclude that cooperative communication is more energy efficient than non-cooperative communication not only from total transmission power, but also from individual transmission power at the transmitter. Hence, cooperative communication could not only reduce transmission power, but also implicitly prolong the system lifetime of the wireless networks. Based on these observations, cooperative communication should be encouraged as much as possible. This kind of energy saving is because of the WMA property in wireless networks.

Note that in the above power cost model for cooperative communication, the transmitters use the same modulation scheme to transmit the data to the receiver. This assumption is valid for the MRC scheme because the SNR could only be the sum of the SNR contributed from all the transmitters when they use the same modulation scheme.

Even though this model concludes that cooperative communication is more energy efficient than traditional non-cooperative communication, it only considers one-hop communication. Hence, power control and multi-hop routing issues are not addressed to identify the minimum power routing path from the source to destination nodes. In the sequel, these two important issues to tackle this MPBBA problem by using the cross-layered cooperative routing scheme will be studied.

MPBBA model

The MPBBA problem via the cooperative scheme could formally be stated as: identifying the cooperative routing strategies to minimize total energy consumption subject to the bandwidth requirements of the destination nodes. The multicasting case is considered here; that is, there is one source node and multiple destination nodes with the same bandwidth demands.

Nodes without the adaptive modulation capabilities could significantly simplify the hardware complexity. This will save the hardware cost and node processing power. When the modulation scheme for every node in the network is fixed, then the minimum SNR to successfully decode the received data is also determined to meet the bandwidth requirement. In other words, when the modulation scheme is fixed, the MPBBA problem becomes to minimize total energy consumption subject to the SNR requirements of the destination nodes. This is a valid assumption because energy saving is the most important factor in wireless network. Subsequently, the MPBBA problem without the adaptive communication capability (i.e., modulation scheme is fixed for all nodes) will be focussed on.

Before introducing the MPBBA with SNR requirements and our proposed heuristics, the notations used in the heuristics are first defined.

Input values:

N	the set of nodes
G	the set of destination nodes
R_n	the set of candidate transmission radius for node n
ρ	the minimum SNR to successfully decode the received data
$\Psi(r_n,d_{nm})$	the received SNR at node m, when node n with transmission radius r_n transmits data to node m that is distance d_{nm} away from node n
$\Pi(r_n)$	transmission power for node n with transmission radius r_n
T	be the set of the network nodes; (i.e., $T = N$)

Decision variables:

T_a	be the set of the nodes that the SNR requirements are satisfied
T_b	be the set of the nodes included in set T but not included in set T_a (i.e., $T_b = T - T_a$)
r_n^B	transmission radius assignment at node n before transmission radius adjustment
r_n^A	transmission radius assignment at node n after transmission radius adjustment
S_m^B	the aggregate SNR at node m before any node n in set T_a increasing its transmission radius
S_m^A	the aggregate SNR at node m after any node n in set T_a increasing its transmission radius

The MPBBA problem with SNR requirements could be formulated as Problem (P).

Problem (P):

$$Z_P = \min \sum_{n\in N} \Pi(r_n) \tag{5}$$

Subject to:

$$\rho \le \sum_{n\in N, n\neq m} \Psi(r_n, d_{nm}) \qquad \forall m \in G \tag{6}$$

$$r_n \in R_n \qquad \forall n \in N. \tag{7}$$

The objective function is to minimize the total transmission power. Equation (6) enforces that the SNR requirements should be satisfied for all the destination nodes. The cooperative communication is also facilitated in Equation (6) where the SNR for any destination node m is contributed from the other nodes. Problem (P) is an NP-complete problem because minimum energy cooperative routing problem is proven to be NP-complete problem [15] and minimum energy cooperative routing problem is a special case of problem (P) when the SNR requirement is relaxed. A heuristic algorithm to tackle Problem (P) in the following is proposed.

Methods: BACRA algorithm

The proposed algorithm is denoted as the *BACRA* algorithm. The basic idea of BACRA algorithm is to choose the node to increase the transmission radius that has the maximum increased SNR of the other nodes. Hence, the node in set T_a that contributes the largest ratio of the increased SNR in set T_b to the increased transmission power is selected to expand its transmission radius. This procedure is repeated until the SNR requirements are satisfied for all of the destination nodes, i.e., $G \subseteq T_a$.

In the beginning of the BACRA algorithm, we set T to be all the networks nodes (i.e., $T = N$). The set T_a includes all the nodes that receive SNR above the minimum threshold ρ. Because of $T_b = T - T_a$, all the network nodes not in set T_a are included in set T_b, and the received SNR of these nodes in T_b is below the minimum threshold ρ. Hence, the nodes in set T_a could successfully decode the received data and transmit the data to the nodes in set T_b. When the node in set T_a expands its transmission radius, the received SNR for some nodes in set T_b might be increased so that the received SNR is above the minimum threshold ρ. These nodes in set T_b meeting the SNR requirements will be included into the set T_a. This process will be iterated until all the destination nodes are included in set T_a. Then an important question to be asked is: which node in set T_a should be selected to expand its transmission radius?

In the BACRA algorithm, we select the node α in set T_a that can increase the largest ratio of the increased SNR in set T_b to the increased transmission power. In other words,

$$\alpha = \arg\left\{ \underset{n \in T_a}{\mathrm{Max}} \left(\frac{\sum_{m \in T_b} \mathrm{Min}\left(S_m^A - S_m^B, \rho - S_m^B\right)}{\Pi\left(r_n^A\right) - \Pi\left(r_n^B\right)} \right) \right\} \quad (8)$$

In the numerator of Equation (8), it is equal to the summation of the increased SNR in set T_b. In bandwidth-aware transmission, when the modulation scheme is fixed, the data rate is fixed when the received SNR is over the SNR threshold ρ. In other words, when the SNR requirement is satisfied, increasing the SNR will not increase the data rate. Hence, the received SNR for each node should be upper bounded by ρ. Therefore, the increased SNR is the minimum of these two values (i.e., $\mathrm{Min}(S_m^A - S_m^B, \rho - S_m^B)$). The denominator of Equation (9) is the increased transmission power. This increased SNR to increased power ratio (SNR/P) is basically the larger the better, because it indicates the efficiency of increased transmission power to the increased SNR. By selecting the node in set T_a with the largest SNR/P ratio to expand its transmission radius first would implicitly achieve the objective of minimum transmission power as well as to meet the bandwidth/SNR requirements of the destination nodes.

There are three properties in Equation (8).

1. *Meeting the SNR requirements before transmitting*: The transmitter is selected from the set T_a so as to ensure that the transmitter has enough SNR to successfully decode the information before transmitting.
2. *Power control with respect to the SNR/P*: The numerator of Equation (8) is the total increased SNR in set T_b. The denominator of Equation (8) is the increased transmission power. Then Equation (8) is to select the node in set T_a to expand its transmission radius so that it contributes the largest ratio SNR/P. In other words, the selection of transmission node and its transmission power is based on the performance measure SNR/P.
3. *No loopback*: It ensures after selecting a node in set T_a to expand its transmission radius, it is not possible to reduce the transmission radius of the other node in set T_a to further increase the SNR/P. In other words, selecting the node in set T_a to expand its transmission radius at the later stage will not affect the transmission power assignment for the selected node in set T_a at the earlier stage. This is called the no loopback property. This no loopback property is important to make sure that the BACRA algorithm does not have infinite looping problem. The no loopback property is proven in the Appendix.

Based on these three properties, we claim that the BACRA algorithm is optimal in terms of SNR/P performance measure. We do not claim that the BACRA algorithm is optimal to the MPBBA problem because adaptive modulation scheme is not considered in Problem (P). However, because SNR/P indicates the contributed SNR by additionally increased transmission power, which addresses the signal quality and transmission power at the same time, we will show in the computational experiments that BACRA algorithm is superior to the other heuristics at the MPBBA problem.

Next we perform the complexity analysis for the BACRA algorithm. First, we study the time complexity. It is clear that the most time-consuming part of the BACRA algorithm is the "While" loop. So, we need to know what is the total number of iterations for the "While" loop. In the worst case, the destination node will be the last one to be included to the set T_a. In this case, all the network nodes are examined. In other words, the "While ($G \not\subset \mathrm{T_a}$ and $\alpha \neq 0$)" has to loop for $(|N| - 1)$ times. Next, we observed that there are two steps in the "While" loop. In step 1, there are two layers of "For" loop. In the worst case, there are $\left(|N|/_2\right)$ number of nodes in set T_a and $\left(|N|/_2\right)$ number of nodes in set T_b. In the worst case, the total number of iterations would be $\left(|N|^2/_4\right)$. Then the computational complexity for step 1 is $O(|N|^2)$. In step 2, there is only one layer of "For" loop. In the worst case,

Table 1 Complexity analysis of routing information dissemination and collection in BACRA

	Convergence time	Memory overhead	Control overhead
OSLR [17]	$O(D \cdot I)$	$O(\|N\|^2)$	$O(\|N\|^2)$

$|N|$ number of nodes in the network, I average update interval, and D diameter of the network.

there are $(|N| - 1)$ number of nodes in set T_b. The total number of iterations would be $(|N| - 1)$ for step 2. Then the computational complexity for step 2 is $O(|N|)$. The "While $G \not\subset \mathrm{T_a}$ and $\alpha \neq 0$)" has to loop for $(|N| - 1)$ times in the worst case and the computational complexity of step 1 is $O(|N|^2)$. The computational complexity for the BACRA algorithm is $O(|N|^3)$.

Second, we study the message complexity (communication cost) of the BACRA algorithm. Two sets of information that requires message communication between the nodes in our BACRA algorithm are the transmission radius configuration for each node n (i.e., r_n and $\Pi(r_n)$) and the received SNR for each node m (i.e., $\Psi(r_n, d_{nm})$). These two sets of information, transmission radius configuration and the received SNR information, varies over time and changes from time-to-time in the BACRA algorithm. These two sets of information should be broadcasted periodically to the other nodes. Instead of using the flooding scheme for broadcasting, we adopt the OSLR routing protocol [17] to disseminate the control messages. OSLR protocol proposes a multipoint relaying strategy to minimize the size of the control message and the number of rebroadcasting nodes. By utilizing these two sets of control messages, the signal quality of the wireless network could be acquired timely to determine the available bandwidth. According to the OSLR protocol, the message complexity analysis is summarized in Table 1.

BACRA algorithm

Begin

Input: Network topology, SNR requirements for each destination node;
Output: Routing assignment and transmission radius for each node;
Let set T be the set of the networks nodes; //T=N
T_a = {source node} and T_b = T – {source node};
For ($n \in T$) //initialize r_n^A,r_n^B, S_m^A and S_m^B
Begin

$$r_n^B = 0;\ S_m^A = 0;\ S_m^B = 0;$$

Let r_n^A be the smallest transmission radius in set R_n;

End//For

α=1;
While ($G \not\subset \mathrm{T_a}$ and $\alpha \neq 0$)
Begin

k=0; α=0;
For ($n \in T_a$) //step 1: identify the node that contributes maximum increased SNR to the nodes in set T_b
Begin

For ($m \in T_b$)
Begin

$$S_m^A = \Psi\left(r_n^A, d_{nm}\right) + S_m^B;$$

End; //For m

$$\text{If}\left(k < \frac{\sum_{m \in T_b} Min\left(S_m^A - S_m^B, \rho - S_m^B\right)}{\Pi\left(r_n^A\right) - \Pi\left(r_n^B\right)}\right)$$

$$k = \frac{\sum_{m \in T_b} Min\left(S_m^A - S_m^B, \rho - S_m^B\right)}{\Pi\left(r_n^A\right) - \Pi\left(r_n^B\right)}; \alpha = n;$$

End;//For n, end of step 1
If ($\alpha \neq 0$)//step 2: node α contributes maximum increased SNR, adjust r_α^B, r_α^A, S_m^B, T_B, T_A
Begin

r_α^B=r_α^A;//adjust the transmission radius of node α
r_α^A moves on to next larger transmission radius in set R_n; //adjust the transmission radius of node α

For ($m \in T_b$)//adjust S_m^B, T_b and T_a
Begin

If ($S_m^B + \Psi(r_\alpha^B, d_{\alpha m}) \geq \rho$)//node m's SNR is satisfied, then include node m in the set T_A

$S_m^B = \rho$; $T_b = T_b - \{m\}$; $T_a = T_a \cup \{m\}$;

Else

$S_m^B = S_m^B + \Psi(r_\alpha^B, d_{\alpha m})$;

End;//For m

End;//If ($\alpha \neq 0$)
Else //$\alpha = 0$

Report "infeasible solution";

End//while

End

Numerical results

We have carried out a performance study on the MPBBA problem by using the BACRA approach, and drawn comparisons with MPB-based heuristics (MIP, MLU, MLiMST in [1], and MIP3S in [4]) and non-cooperative MPBBA heuristics (LGR in [7]) via experiments over a randomly generated network. These MPB-based heuristics have been modified to address the bandwidth QoS requirement for fair comparison because these heuristics do not address the bandwidth QoS requirement.

First, the routing and the transmission radius assignments are obtained by the original algorithm. Then 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. In the next phase, the transmission radius is adjusted for possible transmission power reduction. Hence, these revised MPB-based heuristics are *two-phase* algorithms where the first phase is to determine the routing path and the second phase is to adjust the transmission radius to satisfy the bandwidth QoS requirement. Because of this two-phase adjustment to address the bandwidth QoS, we call these algorithms as MIP2, MLU2, MLiMST2, and MIP3S2, respectively.

We illustrate the modification process with an example in Figure 4. In Figure 4a, the original routing assignment for these four traditional MPB algorithms is to send the data to *C* and then from *C* to *D*. Because *C* is not within the SNR-aware transmission radius of *A*, it fails to meet the bandwidth QoS at node *C*. In this case, *D* is unreachable because *C* is not able to transmit the data to *D* with bandwidth guarantee. In the first phase, we expand *B*'s transmission radius since *B* is within the SNR-aware transmission radius of *A*. Then *C* could transmit the data to *D*. In the second phase, by shrinking the transmission radius of *A* so that *B* is at the edge of the SNR-aware transmission radius, it could be more energy efficient.

Table 2 SNR for modulation scheme in WiMAX [18,19]

Modulation	Code rate	Achievable data rate (20 MHz)	SNR (in dB)
QPSK	1/2 CTC	20 Mbps	$8 < SNR \le 9.4$
QPSK	3/4 CTC	30 Mbps	$9.4 < SNR \le 11.2$
16 QAM	1/2 CTC	40 Mbps	$11.2 < SNR \le 16.4$
16 QAM	3/4 CTC	60 Mbps	$16.4 < SNR \le 18.2$
64 QAM	1/2 CTC	60 Mbps	$18.2 < SNR \le 22.7$
64 QAM	3/4 CTC	90 Mbps	$22.7 < SNR$

The SNR (in dB) could be calculated as follows.

The network nodes are randomly placed in the 25 × 25 km^2 area. Transmission power $\Pi(r_n)$ is set to r_n^α, 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 to 3.0 km. We borrow the SNR parameters from WiMAX [18,19] for the supported modulation scheme at Table 2. Note that the proposed algorithm could be applicable to any wireless network (e.g., ad hoc network). The reason that we choose the SNR parameters from WiMAX is because there is a clear specification for the SNR ratio and the associated modulation scheme.

The SNR (in dB) could be calculated as follows,

$$\boldsymbol{SNR} = P_t + G_t + G_r - PL - \boldsymbol{Noise} \tag{9}$$

where P_t indicates the transmission power, G_t indicates the antenna gain in the transmitter, G_r indicates the antenna gain in the receiver, *PL* indicates the path loss, and Noise indicates the thermal noise power.

In the following experiments, the path loss (in dB) is based on the measurements in line-of-sight (LOS) transmission in WiMAX [20].

$$PL = 110.11 + 21.29 \times \log(d_{tr}) \tag{10}$$

where d_{tr} indicates the distance (in kilometers) between the transmitter *t* and receiver *r*.

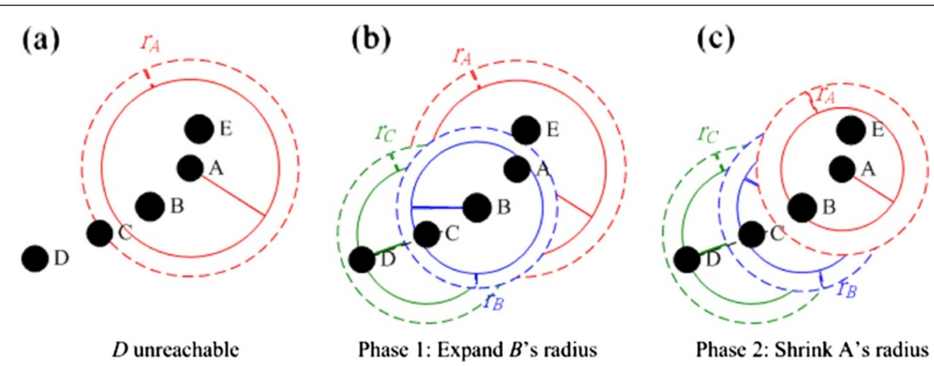

Figure 4 Two-phase modification on MPB algorithms.

The thermal noise power Noise in room temperature is

$$\textbf{\textit{Noise}} = -174\text{dBm} + 10 \times \log(B) \tag{11}$$

When bandwidth (B) is 20 MHz, Noise is equal to −101 dBm. Under the assumption of unity antenna gain, $G_t = G_r = 0$, then we get

$$\textbf{\textit{SNR}} = P_t - 9 - 21.29 \times \log(d_{tr}) \tag{12}$$

Then the variables in Problem (P) of Section "Numerical results" become

$$\Pi(r_t) = P_t = r_t^{\alpha} \tag{13}$$

$$\Psi(r_t, d_{tr}) = \Pi(r_t) - 9 - 21.29 \times \log(d_{tr}) \tag{14}$$

In the following experiments, we assume that the available frequency spectrum is 20 MHz. Because of the fixed allocated frequency spectrum (20 MHz), different modulation scheme requirements mean different bandwidth requirements. Then the achievable data rate with respect to different modulation scheme is shown in the third column of Table 2. For example, when the SNR = 9 dB, the modulation scheme is QPSK with 1/2 CTC code rate according to Table 2. Then we have

$$20\text{MHz} \times 2\text{bps/Hz} \times 1/2 = 20\text{Mbps}$$

In the first set of experiments, the total number of nodes is 2,000. We study the power consumption with respect to the number of destination nodes in the multicast group for different modulation schemes. We have different bandwidth requirements from Figures 5, 6, and 7, which is 20, 40, and 60 Mbps, respectively. From Figures 5, 6, and 7, there are three important observations.

1. *Larger transmission power in sophisticated modulation scheme*: In sophisticated modulation scheme, the SNR requirements are higher than the ordinary modulation scheme. According to the results in these three figures, it is observed that each algorithm will get larger total transmission power in more stringent SNR requirements.
2. *Saturated power increasing at larger number of destination nodes*: When in smaller number of destination nodes (e.g., 100 to 200 nodes), the transmission power is almost linearly increasing. When the number of destination nodes are close to the broadcasting case (e.g., 1,900 to 2,000 nodes), the transmission power will be saturated to an upper value especially in high SNR requirements (i.e., 64 QAM modulation). It is intuitive to have this result at larger number of destination nodes since most of the nodes in the network are transmitted at the maximum power so that the destination nodes could meet the SNR requirements.
3. *Superior performance of BACRA to the other algorithms*: From Figures 5, 6, and 7, we observe BACRA outperforms the other algorithms. We define the superior performance ratio (SR) to be the

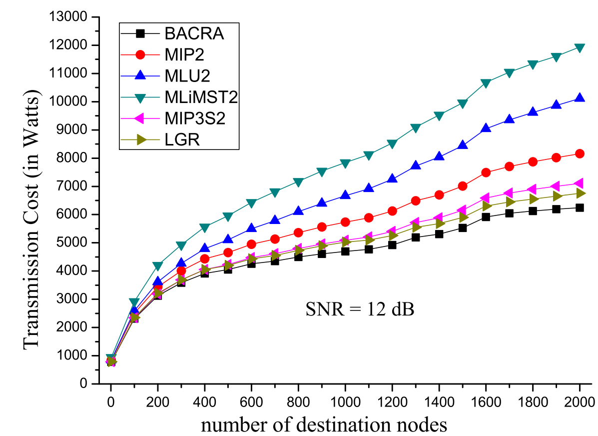

Figure 6 Power consumption 16 QAM modulation.

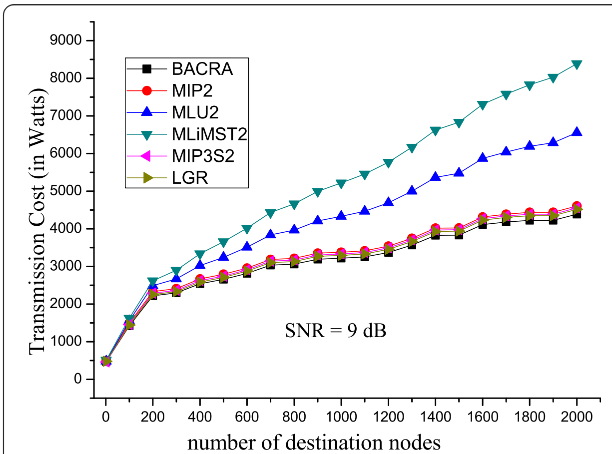

Figure 5 Power consumption in QPSK modulation.

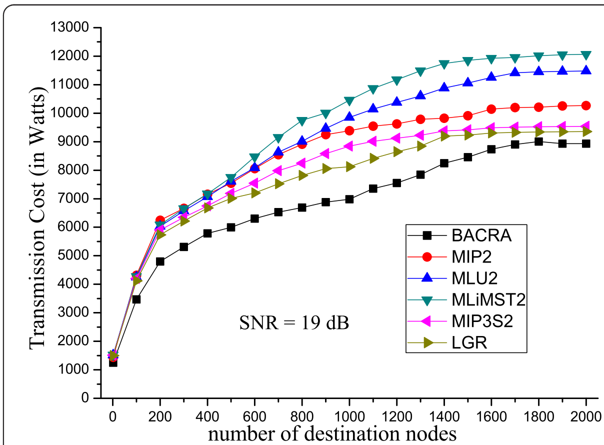

Figure 7 Power consumption in 64 QAM modulation.

Table 3 SR

SR of BACRA over	QPSK (%)	16 QAM (%)	64 QAM (%)
MLU2	49	62	41
MLiMST2	91	91	49
MIP2	5	31	34
MIP3S2	4	14	27
LGR	3	8	20

performance metric for making comparison with the other five algorithms where SR $= (\bar{A} - \bar{B})/\bar{B}$ in percentage, where $\bar{B}$ and $\bar{A}$ are the mean transmission power of the BACRA algorithm and the other algorithms. We summarize SR at Table 3. From Table 3, we found that we have more significant power reduction (i.e., at least 20% improvement) at 64-QAM modulation scheme. This is because unlike the two-phase MPB heuristics and non-cooperative LGR, the BACRA algorithm considers the signal quality via the cooperative communication scheme in determining the routing path so that it is easier to identify the energy efficient path in stringent SNR requirements.

In the second set of experiments, we study the power consumption with respect to the network density for different modulation schemes. Intuitively, in the dense network (e.g., 2,700 nodes), the distance between the nodes is smaller so that it is easier to satisfy the SNR requirements. On the other hand, in the sparse network (e.g., 1,500 nodes), the distance between the nodes is larger so that more transmission power is needed to satisfy the SNR requirements. In this set of experiments, broadcasting case is considered where every node in the network is the destination node. Through this setting, we try to explore the impact of network density with respect to different SNR requirements in the broadcasting case.

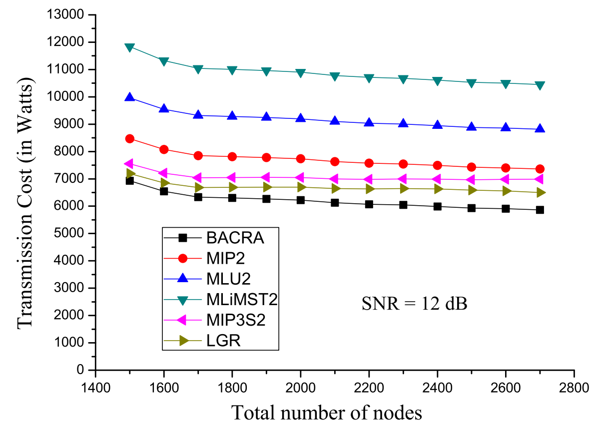

Figure 9 Power consumption in 16-QAM modulation.

As shown in Figures 8, 9, and 10, we have two important observations.

1. *Larger transmission power in sparse networks than in dense networks*: The computational results from Figures 8, 9, and 10 are intuitive that larger transmission power is needed in sparse network to meet the SNR requirements. Not only the transmission power is larger in the sparse network, but also it is not easy to identify feasible solutions when the SNR requirements are stringent. For example, at 64-QAM modulation (SNR = 19 dB), two-phase MPB heuristics (MIP2, MLU2, MLiMST, and MIP3S2) could not locate feasible solutions when the number of nodes is smaller than 1500, 1700, 1800, and 1500 nodes, respectively.
2. *Superior performance of BACRA over the other algorithms*: We summarize the performance comparison of BACRA and the other algorithms at

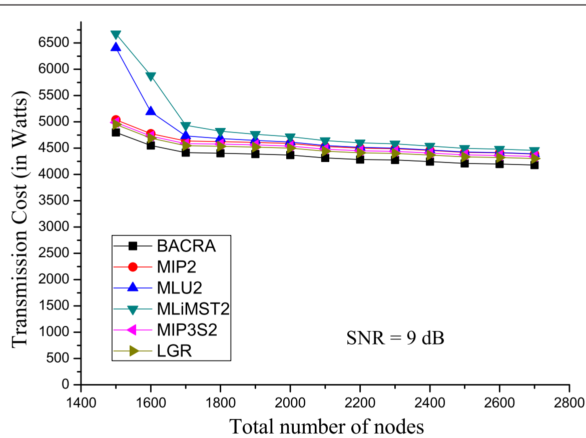

Figure 8 Power consumption in QPSK modulation.

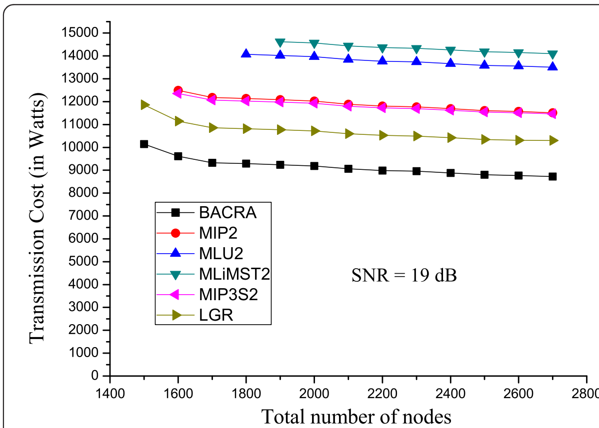

Figure 10 Power consumption in 64-QAM modulation.

Table 4 SR with respect to network density

SR of BACRA over	QPSK (%)	16 QAM (%)	64 QAM (%)
MLU2	33	50	55
MLiMST2	39	78	62
MIP2	5	25	32
MIP3S2	4	19	31
LGR	3	11	18

Table 4. It is observed that BACRA algorithm is superior to the other algorithms at all the tested cases, especially in 64-QAM modulation. Unlike the other MPB heuristics, the BACRA algorithm could still locate feasible solution at 1,500 nodes. Note that the SR value at the 64-QAM is calculated only in feasible solutions.

Conclusions and future work

Existing MPB algorithms without addressing the signal quality transmission are not applicable to the emerging wireless applications with bandwidth QoS requirements. In this article, for the first time, the novel SNR-aware and power-aware cooperative multicasting routing scheme, BACRA, is proposed to tackle this MPBBA problem. The basic idea of BACRA algorithm is to choose the node to expand its transmission radius that can increase the largest ratio of the increased SNR to the increased transmission power. Unlike the other heuristics that are two-phase algorithms and do not take advantage of cooperative communication, BACRA is an integrated cross-layer design algorithm that realize the advantage of cooperative communication via MRC scheme. Through optimizing the SNR/P performance measure, BACRA implicitly considers the SNR-aware power control and energy-aware cooperative routing simultaneously to meet the SNR requirements in energy-efficient ways. In addition, as compared to the two-phase MPB heuristics and non-cooperative LGR, the BACRA algorithm intelligently considers the signal quality via the cooperative communication scheme in determining relay nodes so that it is easier to identify the energy-efficient path in sparse network and stringent SNR requirements. According to the computational results, the proposed BACRA algorithm is superior to the other heuristics, especially in sparse network and stringent SNR requirements.

In the MPB and the MPBBA problems, they consider the path loss and attenuation in the signal propagation impairments. Besides path loss and attenuation, the signal transmission impairments in wireless network also include shadowing, multipath propagation, and interference. Shadowing occurs when there are obstacles between the transmitter and receiver so that there is no LOS transmission. Multipath propagation indicates that besides LOS transmission, there is non-LOS transmission that might incur inter-symbol interference. Interference indicates that some other signal on the same frequency band might interfere with the desired signal. Even though these three impairments play a non-negligible role in signal transmission, we only focus on the path loss and attenuation for simplifying the MPBBA model. This simplifying would enable us to grasp the whole picture more easily and understand the basic idea of the MPBBA problem as compared to the MPB problem. In the future, we will also consider other transmission impairments in the MPBBA problem so that it is more applicable in real wireless applications.

Appendix

Proof of Property 2 (no loopback property) in Section "Numerical results"

Prove by contradiction.

Given $n_1, n_2 \in T_a$, n_1 is selected at the earlier stage and then n_2 is selected at the later stage with transmission radius $r^A_{n_2}$. Now assume that after n_2 is selected, we could decrease the transmission radius of n_1 for further increasing the SNR/P ratio. In other words,

$$\left(\frac{\sum_{m\in T_b} \operatorname{Min}\left(\overline{S^A_m} - S^B_m, \rho - S^B_m\right)}{\Pi\left(r^A_{n_2}\right) - \Pi\left(r^B_{n_2}\right)} > \frac{\sum_{m\in T_b} \operatorname{Min}\left(S^A_m - S^B_m, \rho - S^B_m\right)}{\Pi\left(r^A_{n_2}\right) - \Pi\left(r^B_{n_2}\right)} \right) \tag{15}$$

where $\overline{S^A_m}$ indicates the aggregate SNR at node m after n_2 increases its transmission radius; $\overline{S^A_m}$ indicates the new aggregate SNR at node m after n_2 increases its transmission radius and n_1 decreases its transmission radius.

By decreasing the transmission radius of the node n_1, the received aggregate SNR of the any node m in set T_b will either be the same or be decreased. In other words, $\overline{S^A_m} \leq S^A_m$. Then, Equation (15) will not hold. This violates the initial assumption that after n_2 is selected, we could decrease the transmission radius of n_1 for further increasing the SNR/P ratio.

This proves the no loopback property.

Competing interests

The authors declare that they have no competing interests.

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