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Cooperative Routing in Multi-Source Multi-Destination Multi-hop Wireless Networks

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Abstract— In a network supporting cooperative communication, the sender of a transmission is no longer a single node, which causes the concept of a traditional link to be reinvestigated. Thus, the routing scheme basing on the link concept should also be reconsidered to "truly" exploit the potential performance gain introduced by cooperative communication. In this paper, we investigate the joint problem of routing selection in network layer and contention avoidance among multiple links in MAC layer for multi-hop wireless networks in a cooperative communication aware network. To the best of our knowledge, it is the first work to investigate the problem of cooperative communication aware routing in multi-source multi-destination multi-hop wireless networks. Several important concepts, including virtual node, virtual link and virtual link based contention graph are introduced. Basing on those concepts, an optimal cooperative routing is achieved and a distributed routing scheme is proposed after some practical approximations. The simulation results show that our scheme reduces the total transmission power comparing with non-cooperative routing and greatly increases the network throughput comparing with single flow cooperative routings.

I. INTRODUCTION

In this paper, we investigate the joint problem of routing selection in network layer and contention avoidance among multiple links in MAC layer for multi-hop wireless networks in which cooperative communication is exploited as efficient physical layer technology. Multi-source multi-destination multiple flows are served in such networks, which may cause contention among different flows.

In wireless ad hoc and mesh networks, routing is an important factor affecting the system performance. Numbers of routing protocols have been proposed to achieve optimal power consumption or maximize the network throughput, which are summarized in [1]. Among them, little routing scheme ever explicitly leveraged an important property of the wireless media, wireless broadcast advantage (WBA), which was first studied in [2]. This physical layer property significantly changes the route selection problem in network layer. The problem of finding the minimum energy multicast and broadcast tree in a wireless network is studied in [2] and [3].

With the advantage of broadcast in wireless medium, cooperative communication is proposed recently [4], which allows several nodes cooperatively transmit signals to a destination together. Researches have shown that cooperative communication can offer significant performance enhancements in terms of increased capacity, improved transmission reliability, spatial diversity and diversity-multiplexing tradeoff [8-11]. However, under cooperative communication, the sender of a data transmission will no longer be a single node, which causes the concept of a traditional link to be reinvestigated [5]. Thus, the routing scheme, basing on the concept of link, should also be reconsidered to "truly" exploit the potential performance gain introduced by cooperative communication.

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To the best of our knowledge, reference [6] is the first work discussed cooperative communication aware routing. In this work, the authors investigated the energy efficient routing which supports broadcast and cooperative communication. They analyzed the optimal routing selection and proposed a heuristic algorithm. However, as they assume that only one flow exists in the network, the interactions among multiple neighboring flows have not been discussed. As we know, the concurrent transmission of multiple links may cause spatial contention in realistic transmission, thus, a new routing scheme which can avoid link contention should be studied.

In this paper, we will consider the network layer routing problem and MAC layer contention problem jointly, to investigate the cooperative routing for multi-source multi-destination multi-hop wireless network. The key contributions of this work are: 1) it is the first work to investigate the problem of cooperative communication aware routing in multi-source multi-destination multi-hop wireless networks; 2) the concept of virtual node and virtual link is introduced in this paper for the first time to take the place of traditional link and node, and they appropriately reflect the affection to the upper layers of using cooperative communication as a physical layer technique; 3) to avoid collision among links of multiple flows in a network, contention relationship is investigated. Moreover, to support cooperative communication in physical layer, a virtual link based contention model is given, basing on the model, the optimal routing is selected; 4) finally a distributed routing algorithm is presented.

The rest of the paper is organized as follows: Section II gives the motivation of our research. Section III formulates the analytic model of the cooperative routing under multiple flows and solves that problem theoretically. Then, the distributed algorithm of the optimal routing is described in Section IV. Section V presents the simulation results. Finally, the paper is concluded in Section VI.

II. MOTIVATION

In this section, we give an example to show that simple cooperative routing strategy without considering the link contention among multiple flows did not work efficiently for multi-source multi-destination wireless networks, thus may not achieve a global optimization routing.

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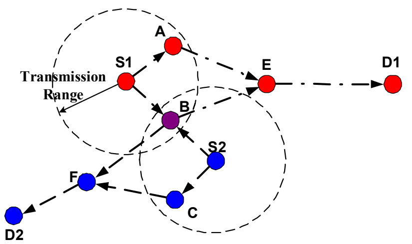


Fig. 1 (a) Transmit scenario obtained by existing cooperative routing strategy which may cause collision

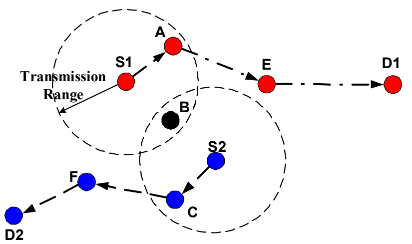


Fig. 1 (b) Possible transmit scenario which can solve the collision problem

As Fig. 1 shows, there are two data flows transmitted simultaneously in the network. Source and destination of flow 1 and flow 2 are S_1, D_1, S_2 and D_2 respectively. We assume that the interference range equals to transmission range. Now *A*, *B* and S_1 are in the transmission range of each other, using traditional cooperative routing for single flows, for flow 1, S_1 will broadcast message to *A* and *B* simultaneously and then, they two will cooperatively forward message to the next hop node e.g. E as Fig. 1(a) shows. Thus, the routing is $S_1 \rightarrow (A,B) \rightarrow E$. Similarly, routing for flow 2 is $S2 \rightarrow (B,C) \rightarrow F$. However, in such scenario, transmission of flow 1 and flow 2 will interfere with each other in node *B*, which is unable to receive data from two individual flows simultaneously and decode it correctly. Thus *B* became the bottleneck node of the network. It can only transmit for flow 1 and flow 2 alternately by time division. Thus, only half of *B*'s throughput can be given to flow 1 and the other half to flow 2, then, the per-flow-throughput under multiple-flow scenario will decrease by 50% compared with single-flow scenario.

However, considering the MAC layer contention, we should choose link $S1 \rightarrow A$ and $S2 \rightarrow C$ to be the next hop instead of the cooperative routing of $S1 \rightarrow (A,B)$ and $S2 \rightarrow (B,C)$, as in Fig. 1(b). Under the new routing, there will be no contention in MAC layer, thus higher throughput can be achieved.

The above example illustrates that existing cooperative routing strategy, when used in the network with multiple flows, may cause collision and result in bottleneck node, thus reduce the overall system performance. Moreover, with the number of flows increasing, the probability of collision will increase dramatically, and performance will degrade catastrophically. Thus, we need to investigate a multi-flow cooperative routing to achieve a reasonable trade-off between energy efficiency and collision avoidance. In the following sections, problem formulation will be given and optimal solution will be presented.

III. PROBLEM FORMULATION

To solve the cooperative routing problem under multi-source multi-destination multi-hop wireless networks, we first

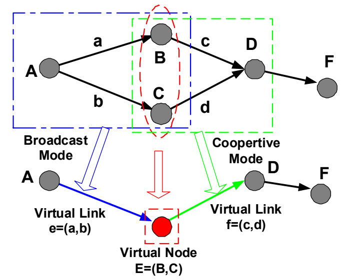


Fig. 2 virtual node and virtual link

introduce some new concept: virtual node and virtual link on aware of the new characteristic of cooperative communication. Then, basing on the new definition of node and link, link cost and path cost is calculated. Also, to express the contention relationship of links in multiple flows, virtual link aware contention graph is constructed. After the introduction of virtual link and new definition of PC, LC, virtual link based contention graph, the original problem can be formulated as an optimization problem which intends to minimize power consume under certain flow constraint and contention constraint. By solving the problem we are able to find the optimal routing for the cooperative multi-source multi-destination network.

A. Concept of Virtual Node and Virtual Link

Cooperative communication brings a great challenge for the upper layer abstraction and design. It breaks two assumptions that usually made on the classical notion of a link [5]: 1) a physical layer link can originate from only one transmitter; 2) concurrent transmissions of multiple transmitters are not allowed because they result in interference. To support the change cooperative communication brings, the concept of virtual node is given to replace the function of multiple nodes that accomplish a function cooperatively. Similarly virtual link is introduced basing on virtual node. In a network supporting cooperative communication, there are three types of transmission: a) ordinary mode: the information is transmitted by single node and received by single node; b) broadcast mode: the information is transmitted by single node and received by multiple nodes; or c) cooperative mode, multiple node simultaneously send the information to a single receiver.

Unlike the ordinary mode, under broadcast mode and cooperative mode, multiple nodes can behave cooperatively and simultaneously as one single node, thus, the concept of virtual node is introduced, several nodes that simultaneously received information by a single transmission in broadcast mode or cooperatively sending information to a single receiver in cooperative mode are called a *virtual node* (e.g. virtual node *E* which consists node *B* and *C* in Fig. 2). Under such definition, the traditional link which is consisted by a sender and receiver is also enlarged into *virtual link*, which may sourced in a traditional node and destined in a virtual node under broadcast mode (e.g. virtual link $e=(a,b)$, which work in broadcast mode in Fig. 2), or sourced in a virtual node and destined in a traditional node under cooperative mode (e.g. virtual link $f=(c,d)$ which work in cooperative mode in Fig. 2).

B. Link Cost Formulation

To specify the cost for transmitting in a certain link, link cost (LC) of link *i*, denoted by LC_i, is defined to be the minimum power for transmitting from source of the link, denoted by S_i, to destination of the link, denoted by T_i. Both S_i and T_i could be a virtual node. LC_i is defined and calculated differently, according to which mode link *i* works on.

1. Traditional mode, where $|S_i|=1$, $|T_i|=1$. $S_i=\{s_i\}$, $T_i=\{t_i\}$.
2. Broadcast mode, where $|S_i|=1$, $|T_i|=n>1$. $S_i=\{s_i\}$, $T_i=\{t_1, t_2, \ldots, t_n\}$.
3. Cooperative mode, where $|S_i|=n>1$, $|T_i|=1$. $S_i=\{s_1, s_2, \ldots, s_n\}$, $T_i=\{t_i\}$.

The link cost formulation in each transmission node is defined as in [6] for the Point-to-Point Link, *Point-to-Multipoint Broadcast Link and Multipoint-to-Point Cooperative Link respectively.*

C. Path Cost Formulation

Besides link cost, path cost (PC) is introduced and defined to be the minimum power needed to transmit data along a path from the receiver node of the current link to the destination node of the flow the link serves

$$PC_{ij} = \min_{P} \sum_{k \in P} LC_k,\ \ \forall P,\ s.t. S_P = T_i,\ D_P = D_j \qquad (1)$$

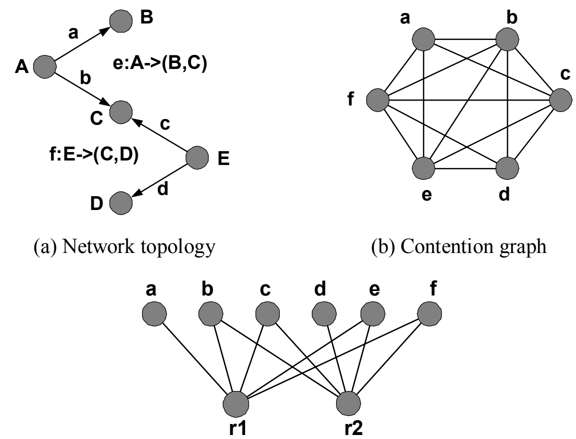
In which, PC_{ij} is the path cost of link *i* for flow *j*, *P* is any path such that source of *P*, denoted by S_P, equals to the transmitter of link *i*, denoted by T_i, and destination of *P*, denoted by D_P equals to the destination of flow *j*, denoted by D_j.

To calculate PC_{ij}, a virtual link based network connection graph $GT=(V_1, E_1)$ is constructed basing on the original network topology $G=(V, E)$, to find the optimal path that minimize path cost of link *i* in flow *j*. In the new connection graph, if the receiver of link *i* is a virtual node, denoted by T_i, $V_1 = V \cup \{T_i\}$; otherwise, $V_1=V$. When cooperative communication is supported, some new path will emerge because of the existence of virtual node. Note that only one end of a link can be a virtual node, therefore, in the path of a flow, between two virtual nodes, there is at least one traditional node between them. Therefore, in the original topology, some new edges are added $E_1 = E \cup E_c$. For node pair (i,j), $\forall i, j \in V_1$, if there exits a virtual node *k* such that (i,k) and (k,j) both are virtual links, $(i, j) \in E_c$. Weight of edge (i,j) is the power needed to transmit data from node *i* to node *j* via virtual node *k*. In the modified new connection graph *GT*, using Dijkstra algorithms, shortest path from node T_i to destination of flow *j* D_j can be found. The cost of the shortest path is PC_{ij}.

D. Generalized Contention Graph Construction

There are multiple flows in the network. To avoid contention among multiple flows, contention graph (CG) is needed to describe the contention relationship between any two links. In our network, traditional CG is generalized to support virtual node and virtual link through the following modifications.

First, vertices in generalized CG represent both real nodes and virtual nodes. Thus, new vertices representing virtual nodes should be added in traditional contention graph. As Fig. 3(b) shown, vertexes representing virtual link *e* and *f* are added. Then, the contention relation between virtual links should be redefined and new edges should be added correspondingly. Two virtual links don't interfere with each other, if and only if they have no common nodes and any two traditional links separately contained in the two virtual links do not interfere with each other. Thus, two virtual links are edged either they contain common traditional node or certain traditional link which is contained in one of the two virtual link contend with some certain traditional link which is contained in the other virtual link. In Fig. 3(a), virtual links *e* and *f* contain the same traditional node *B*, thus they are edged in Fig. 3(b). For a virtual link and a traditional link, there is no edge between them, if and only if the former one does not contain any one of the two nodes in the latter one and any link appeared in the former one does not contend with the latter traditional link. In Fig. 3, link *b* is contained in link *e* thus they should be edged. Link *e* and link *d* are edged because the latter one contends with link *b* which is contained in the former virtual link. For two links which are both traditional links, it is the same as traditional contention graph.



(a) Network topology (b) Contention graph

(c) Resource allocation graph

Fig. 3 Contention graph and resource allocation graph

Basing on the contention graph $GC=(V', E')$, the resource constraint graph $GR=(V'', E'')$, which captures the various contention regions in the network topology, can be constructed. The resource constraint graph is essentially a bipartite graph with two sets of vertexes being V' and R, where $V''=V' \cup R$ and R represents the set of resource vertices, one for each contention region. The contention regions can be obtained by identifying the various maximal cliques in the flow contention graph. Thus in Fig 3(c), there are six vertexes representing link *a,b,c,d,e,f* and two vertexes r_1 and r_2 representing two maximal cliques $\{a,b,c,e,f\}$ and $\{b,c,d,e,f\}$, respectively. The edges in *GR* correspond to links going from the set V' to set R indicating the membership of the active links in the various contention regions. For example, if edge $(i, j) \in E''$, then, $c_{i,j}$ equals to 1, which means that vertex i ($i \in V'$) in the flow contention graph to the contention region j ($j \in R$), otherwise, $c_{i,j}$ equals to 0. In Fig. 3(c), r_1 is edged to *a, b, c, e, f* and r_2 is edged to *b, c, d, e, f*.

E. Optimization Problem Formulation

We assume that the network support multi-source multi-destination transmission, and there are totally *m* flows. Thus, the objective is to choose the maximum sum of each flow's throughput under the constraint of contention graph.

The problem can be formulated as the following optimization problem.

$$\min_{I(i,j,t)} \sum_{i,j} (LC_i(t) + PC_{ij}(t)) I(i,j,t), \forall t$$

$$s.t.\ \sum_{i \in S_j} I(i,j,t) = 1,\ j = 1,\cdots,m$$
$$\forall k, \sum_{i,j} c_{i,k}(t) I(i,j,t) \le 1$$

In which $I(i,j,t)$ equals to 1 when at time slot t, link i is selected to transmit data for flow j, else $I(i,j,t)$ equals to 0. S_j is the link set whose transmitter node is the node who received flow j at time slot t-1, in another word, it's a potential link set which may be selected for flow j at time t.

The objective of the optimization problem is to minimize the sum of link cost and path cost of the links selected at time t within two constraints: 1) for each flow, select one link to transmit at a certain time slot, 2) the links selected for different flows should not interfere with each other.

This optimization problem has a linear objective function and linear constraint functions. Thus it can be solved by linear optimization algorithms, such as, simplex algorithm.

IV. DISTRIBUTED ALGORITHM

In previous section, by solving the optimization problem, optimal links which is able to minimize the transmission power under the constraint of contention relationship is selected, thus, the optimal routing is formed step by step. However, it is hard to be directly implemented in a distributed manner in the realistic systems, because of the global information needed in the calculation of PC and CG. Thus in this section, we propose a distributed algorithm which aims to approach the optimal routing but with some reasonable and practical approximations.

Firstly, link cost and path cost for each link is calculated in a comparatively long time interval basing on the periodically updated network topology. For a period, each node does a physical-layer probing using incremental power level and broadcast the probing result. LC and PC are calculated basing on the probing information. It is assumed that in the interval of two probing, LC and PC is not changed.

Secondly, to avoid flooding overhead, we introduce a local contention graph (LCG), which need only two-hop transmission range information exchange, to replace global contention graph. In [7], the authors proved that LCG is sufficient for the collision resolution. Moreover, we use an average LCG, instead of time-varying LCG. Basing on the average LCG, using methodology introduced in section III.C, the generalized LCG which support cooperative communication is constructed.

Lastly, at each time slot, the links which potentially have information to be transmitted notify its neighbor links of their potential transmission. Thus, the global source set of each flow is replaced by the local source set of flows. When making the routing decision, only the transmissions of two-hop-range flows are considered, instead of doing global optimization.

Basing on the above approximation, our distributed algorithm is as follows. For each link, LC and PC are calculated periodically basing on the updated network topology. LCG is constructed by each link via two hop neighbor information exchange. If at one time slot, one node received some packets of a flow, it will inform its two hop neighbors that the links sourced at this node will potentially transmit some packets in the next hop. At each timeslot, if one link is sourced at a new added source node of a flow, it construct a LCG, in which each vertex has a weight representing the total cost which is initiated as 0. When the link received a potential transmission notification of a certain link, it sets the weight of the corresponding link as the sum of LC and PC of that link. It also sets the weight of the potential links of its own flow the sum of LC and PC of that link. On the weighted LCG, the maximal independent set (MIS) is calculated and the sum of nodes' weight in the MIS is calculated. Choose the MIS with the smallest weight sum, if the link is in the MIS, the link is selected to forward the packets of the flow.

V. SIMULATION RESULT

In this section, we will show the performance evaluation of the multi-flow cooperative routing we proposed. We simulate networks of a varying number of nodes, N, placed randomly within a 1000 meters ×1000 meters area. We randomly choose M pairs of nodes, with each pair to be the source and destination of a flow respectively. It is assumed that the maximum transmission range is 250 meters. Note that only nodes in each other's transmission range can do cooperative communication. The radio transmission lose constant is assumed to be equal to 2 and channel gain invert to the d^2, where d is the distance between source and destination. For each plot shown, the results are averaged over 1000 randomly generated network instances. It is assumed that a virtual node consist at most two real nodes. We will compare the energy savings and throughput gain of our routing algorithm MFCR-2 (Multi-Flow Cooperative Routing-2) over non-cooperative routing to that of the traditional cooperative routing scheme PAN-2 and PC-2 proposed in [6]. Also, node densities and total flow number is changed to show the relation between performance improvement and different network factors.

As Fig. 4(a) shows, when number of nodes increases, aver age energy savings of three cooperative routing schemes comparing with non-cooperative scheme increase. It is because with more nodes existing in a certain area, node density increases. Thus, the chance of finding a suitable neighboring node to do cooperative communication increases. As a result, more energy is saved. As we can see, when number of nodes equals to 60, as much as 20% of total transmission power can be saved by cooperative communication. Here, the number of flows is set to be 3 by default. The throughput gain of various cooperative routings comparing with non-cooperative routing is shown in Fig. 4(b). It is shown that the throughput of CAN-2 and PC-2 is 90% as much as that of non-cooperative routing. That is because as cooperative communication is supported, more nodes involved in the transmission, thus, probability of contention is increased, which causes a lower throughput. However, using our multi-flow cooperative routing scheme, the throughput dramatically increased by 50%-150%. The throughput is increased because contention of multiple flows is avoided when choosing the next hop nodes, with the probability of collision decreased, the network throughput increased dramatically. However, the throughput gain is not achieved without any cost. The energy savings of MFCR-2 is less than CAN-2 and PC-2 as shown in Fig. 4(a). We made a trade-off between transmission power and network throughput. As a result, by losing less than 5% of energy saving, we achieve more than 100% throughput gain comparing with single flow cooperative routings.

In Fig.5, energy savings and throughput gain of various routing schemes are studied when number of flows increase.

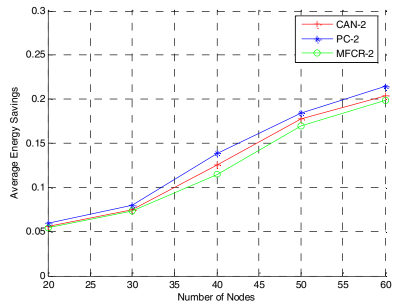


Fig. 4(a) Averange energy savings vs. number of nodes

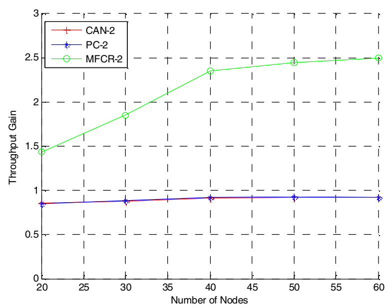


Fig. 4(b) Throughput gain vs. number of nodes

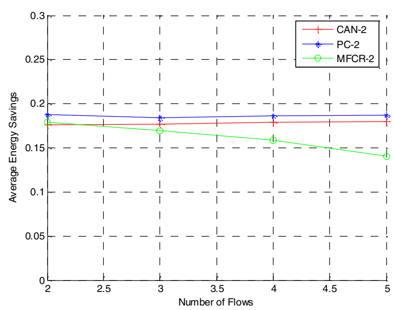


Fig. 5(a) Averange energy savings vs. number of flows

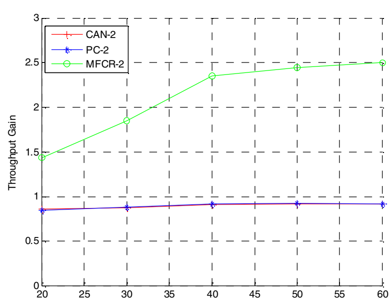


Fig. 5(b) Throughput gain vs. number of flows

Here the total number of nodes is set to be 50. With the number of flows increasing, energy savings of MFCR comparing with non-cooperative routing is slightly decreased, that is because, with more number of flows simultaneously transmitted, more links are contending the same wireless medium, probability of collision increased, to avoid the collision which is much more likely to be happened, more cost on energy should be paid, thus, energy savings of MFCR is decreased comparing with single flow cooperative routing schemes. Although it is decreased, it still saves as much as 15% of energy. On the other hand, the throughput gain of MFCR increases dramatically with the number of flows increasing, as shown in Fig. 5(b). Because of the increased probability of collision when number of flows increasing, performance of both non-cooperative routing and single flow cooperative routing will be degraded dramatically. Comparing with them, MFCR, which avoid collision successfully, manages to achieve a much better throughput performance. When number of flows equals to 5, throughput of MFCR can be 5 times as much as that of CAN-2 and PC-2, which also justify the importance of taking multiple flows into consideration when making routing decisions.

VI. CONCLUSION

In this paper, we formulated the problem of finding optimum cooperative routing under multi-source multi-destination multi-hop wireless networks. We defined new concept virtual link and virtual node to explore the characteristic of broadcasting and cooperative communication. We construct virtual link based contention graph to express the contention relationship of multiple links in multiple flows. We convert routing decision into an optimization problem under our model and solved it by linear optimization. Through some reasonable and practical approximations, a distributed routing scheme is proposed. The simulation results show that our cooperative routing scheme can achieve 20% energy savings comparing with non-cooperative routing and dramatically increase network throughput by several times comparing with traditional single flow cooperative routing. The great benefit is achieved by jointly consideration of routing in network layer and collision avoidance in MAC layer over multiple flows.

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