Dominating Set and Network Coding-based Routing in Wireless Mesh Networks

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Abstract—Wireless mesh networks are widely applied in many fields such as industrial controlling, environmental monitoring and military operations. Network coding is promising technology that can improve the performance of wireless mesh networks. In particular, network coding is suitable for wireless mesh networks as the fixed backbone of wireless mesh is usually unlimited energy. However, coding collision is a severe problem affecting network performance. To avoid this, routing should be effectively designed with an optimum combination of coding opportunity and coding validity. In this paper, we propose a Connected Dominating Set (CDS)-based and Flow-oriented Coding-aware Routing (CFCR) mechanism to actively increase potential coding opportunities. Our work provides two major contributions. First, it effectively deals with the coding collision problem of flows by introducing the information conformation process, which effectively decreases the failure rate of decoding. Secondly, our routing process considers the benefit of CDS and flow coding simultaneously. Through formalized analysis of the routing parameters, CFCR can choose optimized routing with reliable transmission and small cost. Our evaluation shows CFCR has a lower packet loss ratio and higher throughput than existing methods, such as Adaptive Control of Packet Overhead in XOR Network Coding (ACPO), or Distributed Coding-Aware Routing (DCAR).

Index Terms— Network coding, dominating Set, WMNs

1. INTRODUCTION

Network coding has gained significant momentum after it was first proposed by Ahlswede et al [8]. Many researchers consider it efficient technology for wired and wireless networks to improve network performance [1]. Network coding can remarkably increase network throughput depending on certain factors [2], such as convergence of data flows or coding opportunity. Some existing schemes passively wait for coding opportunities and do not sufficiently consider the influence of routing. Recently it was discovered network performance can be further optimized if the routing is designed in consideration of coding opportunities. This is called coding-aware routing [3].

Most self-organized networks have the characteristics of energy limitation and node mobility. As a result, designers are inclined to distribute the flow of data to different routing to make sure energy consumption is balanced [4]. However, in wireless mesh networks, particularly with fixed backbone, the locations of nodes are static and energy is unlimited. The more the data flow converges to a node, the greater the coding benefit. Since a Connected Dominating Set (CDS) can efficiently cover the network topology [5], dominating nodes are a good choice to converge data flows [6]. In addition, it has been noted that coding collision caused by multi-hop transmission of data flows [7] can have a significant impact on efficient coding.

In this paper, we propose a CDS-based and Flow-oriented Coding-aware Routing (CFCR) mechanism to improve the throughput of wireless mesh networks.

The major contributions of this paper include two components. First, according to features of the fixed backbone and unlimited energy, CFCR constructs the approximate Minimum Connected Dominating Set (MCDS), and can choose dominating nodes to effectively increase coding opportunities. Unlike existing routings based on CDS, we define CDS routing as the routing which includes Dominating Nodes (DNs). We consider that if all nodes in routing are selected from CDS, it will possibly induce the problem of coding collision. As a result, CFCR takes DNs into account first, and then considers normal nodes as candidates for DNs if a coding collision is likely. Hence, in CFCR, the best situation is if all nodes in routing are DNs and the worst situation is if all nodes in routing are normal nodes. Compared with existing algorithms based on CDS, CFCR is more flexible and practical.

Secondly, considering the requirement of multi-hop coding-aware, we design an algorithm to confirm potential coding opportunities in routing, thus guaranteeing the availability of network coding and improving coding efficiency and reliability. Most researchers want to find optimal schemes to maximize coding opportunities. However, in practice, more coding opportunities does not mean better performance. If flows

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excessively converge in some specific routes or nodes, the coding collision will be marked and the performance will be degraded, such as throughput and packet loss ratio. In this paper, CFCR finds a balance between coding opportunities and collisions by the confirmation process of network coding.

CFCR initially detects alternative routings as classical on-demand routing. Then, it excludes routings with coding collision using the confirmation process. Finally, the routing with the most metric benefit is selected. Because estimations of the dominating node and coding opportunity are important factors in routing selection, we analyze these two problems before describing our routing protocol.

The rest of this paper is organized as follows. The second section presents related work about network coding and coding awareness routing of wireless networks. The solution method of CDS, and the definition of CDS routing are introduced in Section 3. Section 4 analyzes the condition of coding awareness. CDS-based and flow-oriented coding aware routing is proposed in Section 5. Section 6 presents the simulation results and analyzes the performance of coding opportunity, packet loss ratio and throughput. A summary of this paper and future work are described in Section 7.

2. Related Work

Network coding was first proposed by Ahlswede et al. [8]. This research highlighted a novel direction for improving network throughput, and as a result, it has attracted significant attention. In 2003, Li et al. successfully proved linear coding could achieve maximum capacity in multicasting [9]. Koetter and Medard proposed the polynomial time algorithm of encoding and decoding [10], and T. Ho et al. extended this algorithm to include random coding [11].

Due to open wireless channels, many researchers found network coding more suitable to wireless networks, and therefore proposed a number of schemes [12,13]. S. Katti designed an original wireless network forwarding framework called COPE [14], which combined network coding theory and practical requirements. COPE can be integrated into an existing network protocol stack, and can work together with TCP and UDP [15].

Besides COPE, there are still many creative XOR-based schemes. Tebatso Nage proposed a new adaptive scheme called ACPO [15] whose objective is to adaptively control the waiting time for monitoring packets stored in a buffer. The aim of this scheme is to achieve a tradeoff between throughput and overhead. The work in [24] considered an algorithm with a lower complexity than COPE, and designed its optimal scheduler considering Phy and MAC constraints. [25] considered pairwise Inter-session Network Coding (IRNC) which allows coding over multihops, however it only limits coding between two original packets. It is designed to correspond with the optimal scheduler and rate controller. The work in [27] exploited the use of directional antennas to network coding-based broadcasting to further reduce energy consumption. The XOR-based and Reed-Solomon based coding algorithms were designed by deterministic broadcast approaches to reduce the number of transmissions in the network in [28]. Abdallah Khreishah et al considered energy efficiency in lossy wireless networks with XOR-based IRNC, and provided a heuristic to solve the IRNC problem [26]. Further more, they proposed a different approach by looking at flows or batches instead of individual packets in [29]. All of these works have made an important contribution to improving the XOR-based network coding algorithm. However, their main focus is to decompose the network into a superposition of small two-hop networks for network coding.

Even though a two-hop network is more convenient for XOR-based network coding, it remains an open problem to discover an algorithm that will find an optimal superposition. If the routing protocol was aware of coding opportunities, this could lead to improving the performance of wireless networks. Based on the COPE approach, the problem of coding-aware routing and scheduling was studied by [23]. Sudipta Sengupta et al. propose XOR-based coding-aware routing called CA-PATH-CODE, which is the shortest path routing with network coding. However, the formulation in [23] involves linear programming computed centrally. J. Le et al. proposed Distributed Coding-Aware Routing (DCAR) which can find available routing and potential coding opportunities [16]. They defined generalized coding conditions (GCCs) that made the network coding scheme more practical. Utilizing the GCCs, the algorithm was proposed to detect coding opportunities out of the two-hop range. In addition, they also discussed the Coding-aware Routing Metric (CRM) that can help estimate the performance of routing. B.Guo et al. formally established coding conditions for a general scenario [17]. They systematically analyzed possible coding scenarios, and developed generalized coding conditions to ensure decoding ability at the destinations. These two papers picked similar routes that satisfied the coding condition. However, they paid little attention to selecting suitable nodes to increase coding opportunities and avoid coding collision.

S. Wang et al. designed a scheme that considered the connected dominating node along with network coding in an ad hoc network when routes were chosen [18]. Though it does have some advantages, they do not consider that multiple coding nodes might exist along a path, and that multiple flows might intersect at one node inducing a coding collision. Furthermore, compared with the mobility of ad hoc networks, a wireless mesh network with fixed backbone is more suitable for utilizing the connected dominating node to increase coding opportunities [19].

In our opinion, practical efficient routing should exploit coding opportunities with dominating nodes, as well as avoiding a coding collision. If the dominating nodes in the backbone were selected as the coding nodes without interference, it is possible to obtain better performance.

3. THE CONNECTED DOMINATING SET ROUTING

To describe CFCR step by step, we introduce the algorithm to select CDS, and provide the definition for CDS routing in this section.

The wireless mesh network is treated as a graph $G=(V,E)$, where V is the vertex set, and E is the edge set. A Connected Dominating Set (CDS) of a graph G is a set D of vertices with two properties:

(1) Any node in D can reach any other node in D by a path that stays entirely within D. That is, D induces a connected subgraph of G.

(2) Every vertex in G either belongs to D or is adjacent to a vertex in D. That is, D is a dominating set of G.

Each node in graph $G=(V,E)$ will be marked as $m(v)$. Where $v \in V$. If v is a dominating node, $m(v)=T$, otherwise $m(v)=F$. Initially, all nodes are set as F. V' denotes the marked dominating node set

while $V'=\{u \mid u \in V, m(u)=T\}$

$G'=G(V')$ indicates the connected graph consisting of the dominating nodes. $N(v)$ denotes the single-hop neighbors of node v while $N(v)=\{u \mid (v,u) \in E\}$. $N[v]$ presents the set of node v, and its single hop neighbors, which is $N[v]=N(v) \cup \{v\}$.

Please refer to the supplement file in Appendix A for marking steps and rules.

In a strict sense, CDS routing is routing where all nodes in the path are dominating nodes except the source and destination node. For example, 3, 6, 7, 9, 12 are dominating nodes in Figure 1. If a source node is 15 and a destination node is 8, the routing 15->12->9->7->8 is CDS routing, and the routing 15->12->11->8 is not because node 11 is not a dominating node. However, CFCR focuses on increasing coding opportunities induced by dominating nodes. To gain more coding opportunities as well as avoid coding collision, it is not practical that all nodes along the route are dominating nodes. Hence, in this paper, we define CDS routing as routing that includes dominating nodes. As a result, the routing 15->12->11->8 is CDS routing because it includes the dominating node 12 even though it does not satisfy the strict definition.

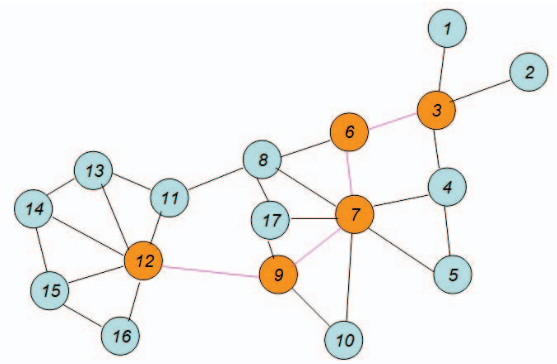

Fig. 1. The connected dominating set and dominate routing

4. THE CONDITION OF CODING AWARENESS

According to different standards, network coding can be divided into different types, such as node oriented or flow oriented, inter-flow or intra-flow, and XOR-based or non XOR-based network coding [17, 20]. COPE and ACPO are typical node oriented inter-flow XOR-based schemes. However, they have two limitations. First of all, nodes can only wait for a coding opportunity and cannot proactively find it during routing. Besides, the network coding condition states the range must be less than two hops. However inter-flow network coding is more suited for a wireless mesh network with multiple flows. In this paper, in order to improve practicability, our network coding algorithm is a flow oriented, inter-flow, XOR-based type. As a scheme for flow coding, we analyze the coding condition in a multi-hop scenario.

Before analyzing the network coding condition, let us define symbols. f indicates a data flow. $a \in f$ denotes node a belongs to the routing of data flow f while the source node is s and the destination node is d. $N(a)$ means the single-hop neighbor set of node a. $For(a,f)$ indicates the forwarding nodes set of node a in the routing of data flow f. $Bac(a,f)$ indicates the backward nodes set of node a in the routing of data flow f. For example, in Figure 2, $For(3,f_1)=\{1,2\}$, $Bac(3,f_1)=\{4\}$, $For(3,f_2)=\{5\}$, $Bac(3,f_2)=\{6,7\}$. Generally, if two flows intersect in a node and satisfy the network coding conditions, the packets of flow can then be encoded, and transmitted by the crossing node.

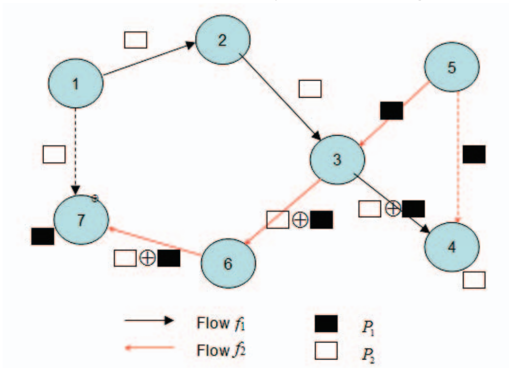

Fig. 2. Multi-hop coding awareness

Coding condition: *For the flow f_1 and f_2 which intersect at node c, if the following conditions are satisfied, network coding is feasible* [17].

(1) Existing node $d_1 \in Bac(c,f_1)$ while $d_1 \in N(s_2) \wedge s_2 \in For(c,f_2)$ or $d_1 \in For(c,f_2)$

(2) Existing node $d_2 \in Bac(c,f_2)$ while $d_2 \in N(s_1) \wedge s_1 \in For(c,f_1)$ or $d_2 \in For(c,f_1)$

5. THE CDS-BASED AND FLOW-ORIENTED CODING-AWARE ROUTING (CFCR) IN A WIRELESS MESH NETWORK

Generally, in a wireless mesh network, backbone nodes are static with unlimited energy. Hence, we can focus on improving performance.

5.1 The procedure of routing

To assist understanding, we illuminate the routing procedure of CFCR in Figure 3. To begin with a node estimates whether it is the destination. Second, the destination node feeds back the RREP (Routing REPly) packet to the source node. Third, relay nodes judge whether they are dominating nodes using the algorithm in Section 3 and whether they have coding opportunity using the scheme in Section 4. Fourth, routing with the smallest value of CFCR is selected by the algorithm in Section 5.4.

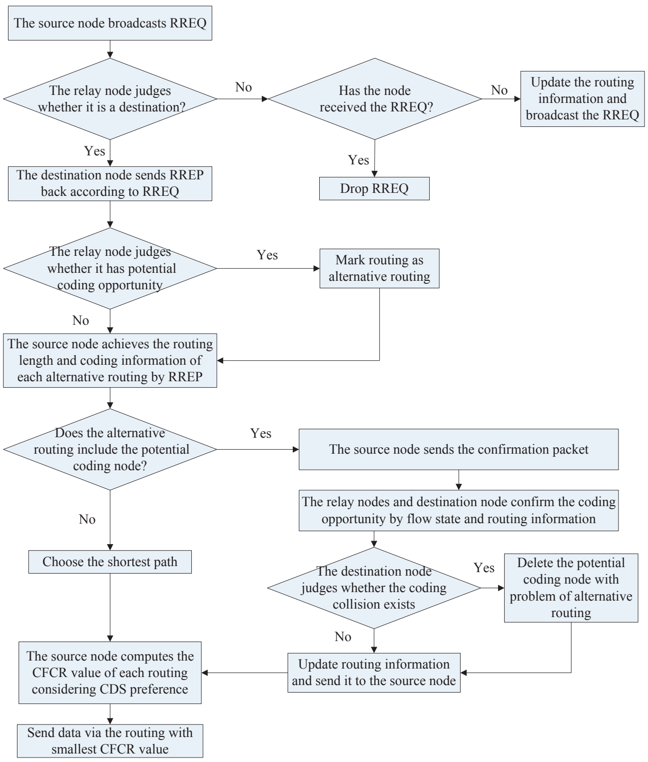

Fig. 3. The procedure of CFCR

5.2 The confirm process of network coding

Due to the possibility that different flows may interfere with each other, the problem of coding collision does affect the performance of routing.

Coding collision: *When a flow joins the network, it selects the routing with more coding opportunity which satisfies the coding condition. However, due to excessive coding, the packets may not be decoded.*

As in Figure 4(a), for example, there are two flows, f_1 and f_2. At some time, flow f_3 joins the network. According to the definition in Section 3, flow f_1 and f_3 satisfy the network coding condition in view of node R1, and flow f_2 and f_3 satisfy the network coding condition in view of node R_2. However, after node R_1 codes $P_1 \oplus P_3$, and broadcasts it, node R_2 receives $P_1 \oplus P_3$, which is not the expected packet P_3. As a result, node R_2 XORs $P_1 \oplus P_3$ and P_2, and broadcasts $P_1 \oplus P_2 \oplus P_3$. In this case, node D_2 cannot decode the packet and achieve P_2, due to excessive coding. In other words, flow f_3 induces the coding collision problem.

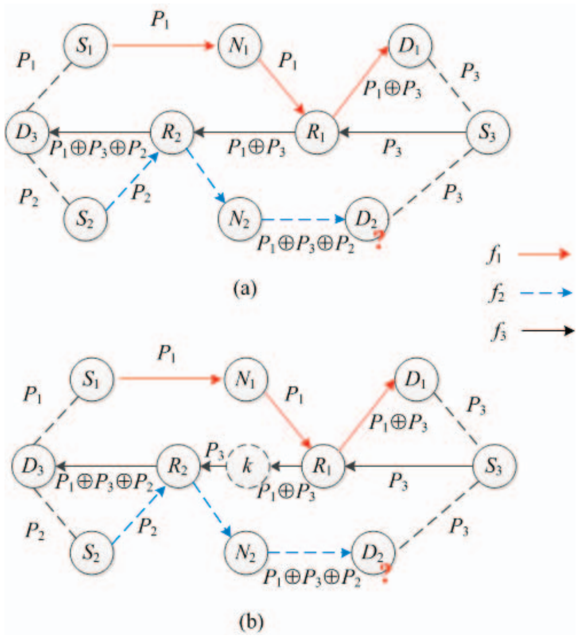

Fig. 4. Multiple potential coding nodes exist in the same routing

As we know, the routing selection process is launched via a source node in on-demand routing which CFCR belongs to. When routing information is sent backward from the destination node to the source node, the relay nodes can judge whether they are potential coding nodes [16]. For example, if flow f_1 and f_2 exist in figure 4(a), R_1 is the potential coding node, and R_2 is not the potential coding node in the routing of flow f_3. Accordingly, if the situation occurs in Figure 4(b), both R_1 and R_2 can potential coding nodes. As previous analysis demonstrates, judgment of coding opportunity needs information from relay nodes. However, if information is added to the header of the RREQ (Routing REQuest) packet, the network load is observably increased by broadcasting. In order to satisfy the network coding condition with minimum network overload, we design a lightweight confirmation process exploiting unicast to estimate whether the relay node is a potential coding node.

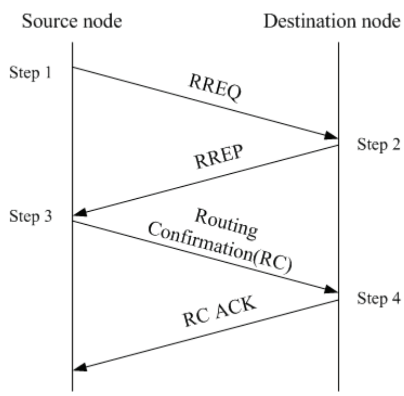

Fig. 5. The four steps in the confirm process

Figure 5 describes the interactions between the source and destination node. In a sense, it is a simplified version of Figure 3. There are four steps in Figure 5 which are RREQ, RREP, RC (Routing Confirmation) and RC ACK (RC ACKnowlegement). In the RREQ and RREP process, the source node detects alternative routes to the destination node with potential coding nodes. Then, the source node sends unicast to the destination node by each alternative routing in the RC process. In this process, potential coding nodes in each route check whether there exists any coding collision. After RC, ACKs provide feedback about the situations to the source node, and the source node then marks potential coding nodes as normal nodes if these nodes have the potential to cause a coding collision.

From Figure 5, we find the first two steps are necessary in on-demand routing. The other two steps are different with existing protocols such as DSR [21] and DCAR. It is worth noting that only RREQ needs broadcasting, and the other three steps rely on unicasting. In addition, the last two steps are only executed in alternative routing. These two steps aim to verify whether the potential coding node induces coding collision at low cost. As a result, it can effectively decrease the packet loss ratio by reducing the possibility of decoding failure. If routing does not contain potential coding nodes, the last two steps are unnecessary and routing becomes normal on-demand routing.

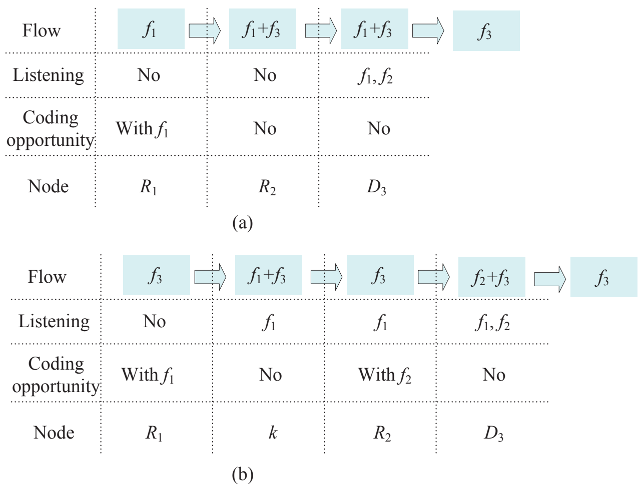

Fig. 6. Routing information of the confirmation process

For example, from Figure 4(a), there are two potential coding nodes (R_1 and R_2) in the alternative routing of flow f_3 after RREP and RREQ. In step three, when RC reaches node R_1, we find the flow satisfies the network coding condition. However, when the RC arrives at node R_2, a coding collision occurs if the packet $P_1 \oplus P_3$ is encoded with P_2. Hence, R_2 cannot be a potential coding node. As a result, the potential coding node in the alternative routing of flow f_3 is R_1 after four steps, while step three confirms the coding condition, and step four turns back acknowledgement. Figure 6 presents the routing information stored in a source node after the confirmation process which mainly corresponds to step three and four. Figure 6(a) and 6(b) demonstrate the situation in the examples of Figure 4(a) and 4(b) respectively. From Figure 6, the source node can realize the situation of the flow, plus the listening and coding opportunity in relay nodes and the destination node. The listening nodes indicate the nodes belonging to the listening range of the source node. This information is very useful to help the source node select routes.

To help destination and source nodes estimate, each node in routing should maintain some routing information. Table 1 presents the routing information of flow f_3 in Figure 4(a). The fifth row in Table 1 indicates whether it is CDS routing. The judgment method is described in Section 3. Furthermore, nodes must store a different routing table for each flow that passes through them. In this table, we also provide the recommended size for each part. Hence, the storage overhead of each flow is approximately 122 bits.

TABLE 1

THE DATA STRUCTURE OF ROUTING INFORMATION

Flow (8b)	f_3			
Nodes in routing (48b)	S_3	R_1	R_2	D_3
Flow state (48b)	f_3	f_1+f_3	f_1+f_3	f_3
Listening nodes (16b)	D_1、D_2			
CDS routing (2b)	True			

5.3 The routing metric of CFCR

The objective of our algorithm is to improve mesh network performance, which is measured by the length of path, the flow coding benefit, and the flow coding opportunity in routing. For example, in Figure 1, routing 15->12->11->8 has three hops and the routing 15->12->9->7->8 has four hops. If the metric is only related to the shortest path, the former is better. However, the dominating node has more opportunity for coding. If certain flows, such as 17->9->10 and 13->12->16 join the network, the dominating node will save two transmissions. As a result, the throughput of routing 15->12->9->7->8 is higher. As the backbone of a wireless mesh network is static and energy is unlimited, the dominating nodes are feasible for coding to optimize performance. We intend to design the routing metric that can present these factors uniformly.

1. The flow coding benefit

There are two factors that influence the coding benefit. One is the routing length, and the number of coding nodes in the routing. The other is the matching degree of interactive flows.

(a) The routing coding benefit

In order to describe this more accurately and concisely, we first define some symbols. $F=\{F_i, 1\le i\le k\}$ denotes the alternative routes set of the new flow, while k presents the number of alternative routings. For route F_i, $\beta(F_i)$ indicates the coding benefit of the route. $dnum(F_i)$ denotes the decreased number of transmission in routing

F_i. $H(F_i)$ presents the hop number of route F_i between the source and destination node. $H_{\min} = \min_{1 \le i \le k} H(F_i)$ indicates the hop number of the shortest route.

Regardless of data matching, the question remains as to how much benefit the coding node can produce. As we know, network coding is technology transmitting multiple packets using broadcasting to improve performance. For example, one transmission can be saved if two packets are coded. If we use this analogy, n-1 transmissions can be saved if n packets are coded in a node. For the sake of simplification, we consider the decreased transmission number as the decreased hop number. For routing F_i, the number of flows through the coding node a_j is denoted by $n(a_j)$, which can be computed from the flow state of routing information. The total number of decreased hops is $cnum(F_i) = \sum_{1 \le j \le m} n(a_j)$, while m presents the number of coding nodes in routing F_i.

As a result, if there are coding nodes in routing, the routing coding benefit is defined as follows:

$$\beta(F_i) = cnum(F_i) - (H(F_i) - H_{\min}) = \sum_{1 \le j \le m} n(a_j) - (H(F_i) - H_{\min}) \quad (1)$$

(b) Data matching

In the transmission process of a data flow, other flows coded with this one may end sooner or later. As a result, some coding opportunities disappear, and the coding benefit of the data flow will be lower than when computed with equation (1).

Hence, considering the data flow matching problem, if the flow coding opportunity disappears when one half of the data in flow has been sent, the routing coding benefit will be defined as follows.

$$\beta(F_i) = \sum_{1 \le j \le m} n(a_j)/2 - (H(F_i) - H_{\min}) \quad (2)$$

Accordingly, the matching factor $\gamma(a_j)$, which denotes the ratio between the data quantity of old flow B_{old}, and the data quantity of new flow B_{new}, in coding node a_j is continually modified.

$$\gamma = \begin{cases} 1 & B_{\text{old}} \ge B_{\text{new}} \\ \dfrac{B_{old}}{B_{new}} & B_{\text{old}} \le B_{\text{new}} \end{cases} \quad (3)$$

Therefore, the actual decreased hop number is $\gamma(a_j) \times n(a_j)$. The total decreased hop number is $cnum(F_i) = \sum_{1 \le j \le m} (\gamma(a_j) \cdot n(a_j))$. This means the routing coding benefit is presented as follows.

$$\beta(F_i) = \sum_{1 \le j \le m} (\gamma(a_j) \cdot n(a_j)) - (H(F_i) - H_{\min}) \quad (4)$$

It should be noted the data quantity of the flow is not easy to compute. In this paper, we adapt an approximate method by the length of the buffer queue to estimate the matching factor γ. In practice, CFCR only needs to compute the ratio between the length of the coding node output queue $Q(a_j)$, and the length of the source node packet queue $Q(s)$.

$$\gamma = \begin{cases} 1 & Q(a_j) \ge Q(s) \\ \dfrac{Q(a_j)}{Q(s)} & Q(a_j) \le Q(s) \end{cases} \quad (5)$$

2. The coding-aware routing metric

Based on previous analysis, we find the more dominate nodes in routing, the more benefits received. According to our metric, if there are two routes with the same benefit, CFCR will select the one with more dominate nodes. The reason is these dominating nodes may provide future coding opportunities. According to equation (4) and (5), we can obtain

$$CFCR(F_i) = H(F_i) - \sum_{1 \le j \le m} (\gamma(a_j)\ n(a_j)) \quad (6)$$

$CFCR(F_i)$ denotes the length of route F_i after the coding benefit is transformed. To encourage it to choose dominate nodes, we define an incentive factor λ. The value of λ is adjustable, and is determined by the CDS routing preference of CFCR. As a result, the $CFCR(F_i)$ is defined as follows.

$$CFCR(F_i) = \begin{cases} H(F_i) - \sum_{1 \le j \le m} (\gamma(a_j) * n(a_j)) & F_i \text{ is not in CDS routing} \\ \lambda * \left(H(F_i) - \sum_{1 \le j \le m} (\gamma(a_j) * n(a_j)) \right) & F_i \text{ is in CDS routing} \end{cases}$$

CFCR metric presents the path length, the coding benefit and opportunity. The metric also reflects the situation of network resource occupation. A smaller CFCR value indicates lower consumption of network resources in routing. In addition, the CFCR metric has certain differences with the coding benefit of routing $\beta(F_i)$ in equation (4). The most obvious difference is that $\beta(F_i)$ may be positive or negative, but $CFCR(F_i)$ is always positive. If $\beta(F_i)$ is minus, it means routing consumes more network resources than routing without dominating nodes. If $\beta(F_i)$ is plus, it means the coding benefit of routing decreases the network resource consumption. However, $CFCR(F_i)$ denotes the length of routing after transformation, and no matter whether it is CDS routing, $CFCR(F_i)$ cannot be less than zero. The other difference is the route with the smallest $CFCR(F_i)$ will be selected as the transmitting route. $\beta(F_i)$ only illuminates the benefit of a routing. Even if $\beta(F_i)$ is the largest, the consumption of network resources may not be the smallest.

Compared with other metrics of existing coding-aware routing, the proposed metric of CFCR has the following characteristics.

(1) The metric of CFCR is suitable for both CDS, multi-hop coding-aware routing and non-CDS, non-coding routing. For the latter, the metric of CFCR degenerates into the number of hops.

(2) As the source node needs enough information to estimate whether a coding collision exists, and how much the coding benefit is, the metric can be calculated after all confirmation packets return from the destination node, unless it is overtime.

(3) The metric of CFCR has good extendibility. For example, if the phenomenon of losing packets is serious, the expected transmission count can also be considered in the metric.

5.4 The algorithm of routing selection

In our algorithm, when the source node receives all confirmation packets, it excludes all non-coding routing except the shortest. It then computes each CFCR value of the alternative routing, and selects the best routing with the smallest CFCR value. The pseudocode for routing selection is as follows.

Algorithm1：The selection of routing
Input: F_i , $1\le i\le k$（From the confirmation packets）
Output: The optimization routing F^*
$F^*=\varnothing$; $H_{min}=\infty$; CFCR*=∞;
for i=1; 1≤i≤k; i++ // Computing the shortest path
  Computing the value of $H(F_i)$;
  if $H(F_i)\le H_{min}$ then
   $H_{min}=H(F_i)$
  end
end
for i=1; 1≤i≤k; i++ // Computing CFCR
 CFCR(F_i)=∞;
 if(ismin(F_i)) then CFCR(F_i)= H_{min};
 if (isCDS(F_i) | | iscode(F_i)) then
  if(iscode(F_i)) then // judging whether it is alternative routing

$$CFCR(F_i) = H(F_i) - \sum_{1\le j\le m}(\gamma(a_j)\, n(a_j));$$

  end
  if（isCDS(F_i)） then // judging whether it is CDS routing
   CFCR(F_i)=λ · CFCR(F_i);
  End
 End
 if CFCR(F_i)≤ CFCR* then
  CFCR*= CFCR(F_i);
  $F^*= F_i$;
 End
End
Return F^*

6. Simulation Results and Analysis

In order to verify the performance of CFCR, we utilize NS2 to simulate and analyze the results. ACPO [15] is an extended scheme of COPE [14], which is a typical scheme in network coding. The CA-PATH-CODE [23] and DCAR [16] are coding-aware routings. CA-PATH-CODE is a centralized algorithm and DCAR is a distributed algorithm, with a similar routing selection process to CFCR. Hence, we compare these three schemes with our algorithm.

Please refer to the supplement file in Appendix B for topology and parameters of the simulation.

6.1 The influence of CDS

Through previous analysis, we know CFCR tends to select the dominating nodes in routing discovery. However, if all flows converge to a certain dominating node, there will be a bottleneck in the network. As a result, CFCR will balance some flows to routing including normal nodes when the network traffic is heavy. To estimate the influence of the CDS metric, we individually simulate the CFCR algorithm with and without the CDS metric. Figure 7(a) and 7(b) show the movement of total throughput with different flow rates in grid and random topology. Obviously, in both topologies, we find that CFCR with a CDS metric has a bigger total throughput. This means the flow centralization of the CDS metric increases network coding opportunities as a whole.

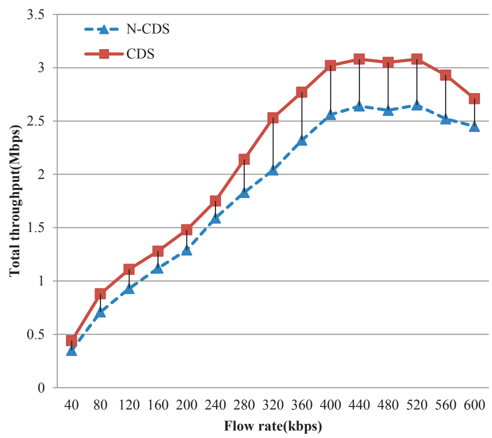

Fig. 7(a). Flow rate vs the total throughput in grid topology

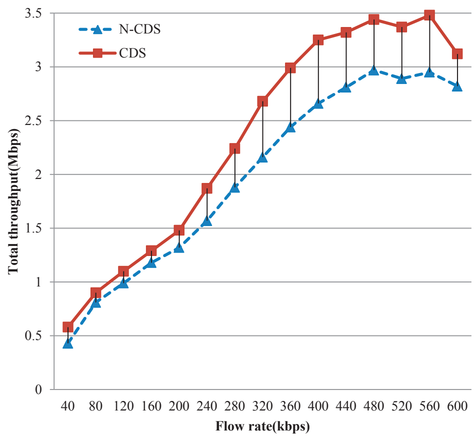

Fig. 7(b). The flow rate vs total throughput in random topology

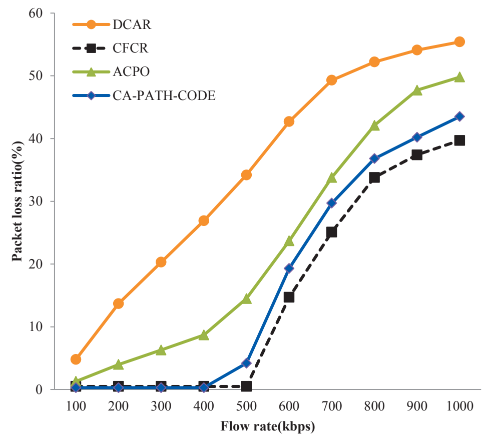

Fig. 8(b). The flow rate vs the packet loss ratio in random topology

On the other hand, there is an interesting phenomena that does not always increase the total throughput. When the flow rate is low, the total throughput with a different metric climbs smoothly, and the difference is small. When the flow rate increases, the total throughput grows quickly, and the difference continues to become larger. When the flow rate reaches a certain level, the total throughput fluctuates and decreases while the difference becomes smaller and smaller. The reason is the CDS metric induces opportunities and interference for network coding at the same time. If the flow rate is too high, the influence of interference is larger than the coding benefit. Finally, if the flow rate is sufficiently large, the new routing has to choose normal nodes. This means the throughput will degrade, which is the same as the scenario without the CDS metric.

In addition to this, because the number of selectable routes in the grid are fewer than in random topology, the difference of total throughput is accordingly smaller, and reaches the fluctuation and decline status quicker.

6.2 The effective coding opportunity

To present the effective coding opportunity, we analyze the packet loss ratio, encoded ratio and the decoded ratio respectively. We compare the performance between DCAR, CFCR, ACPO and CA-PATH-CODE.

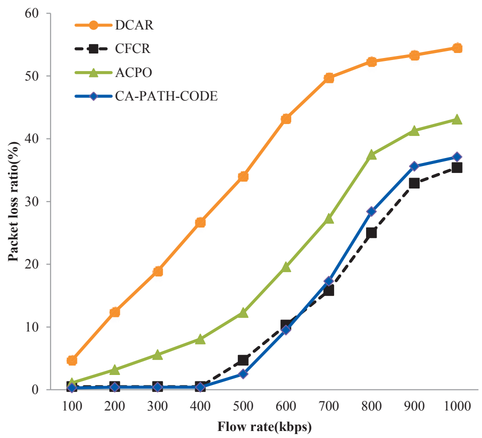

Fig. 8(a). The flow rate vs the packet loss ratio in grid topology

Figure 8(a) and 8(b) show the packet loss ratio of DCAR, CFCR, ACPO and CA-PATH-CODE with different flow rates in grid and random topology. From these figures, we see the packet loss ratio is lower in the CA-PATH-CODE and CFCR than in other algorithms. When the flow rate is in low speed, the packet loss ratio of CA-PATH-CODE and CFCR maintains stability at a very low level, while the flow rate of DCAR and ACPO continuously ascends. There are two reasons that result in packet loss.

(i) Network congestion induces the buffer to overflow with nodes.

(ii) Encoded packets can't be decoded when they reach the destination node.

Obviously, the loss of packets is not induced by: (i) a low flow rate. This situation demonstrates the CA-PATH-CODE and CFCR can more effectively guarantee the ratio of packet decoding. When the flow rate increases, congestion leads to a higher packet loss ratio. Even though the CA-PATH-CODE can decrease coding interference by routing selection, it doesn't consider the situation of coding collision. As a result, the packet loss ratio of the CA-PATH-CODE is higher than CFCR when the flow rate reaches a threshold. The packet loss ratio of CFCR rises from 400kbps in grid topology and 500kbps in random topology. Due to more optional routings in random topology, the packet loss ratio can maintain a stable status for a longer period of time.

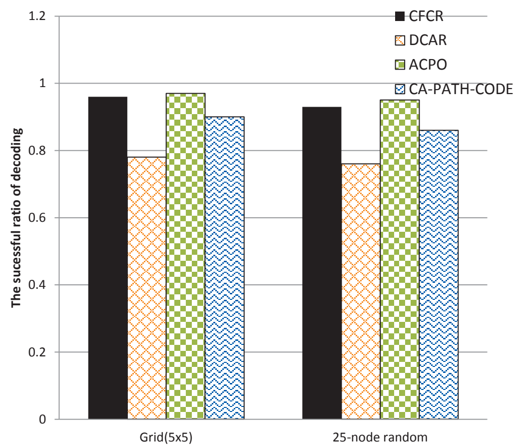

Fig. 9. The comparison of successful decoding ratio

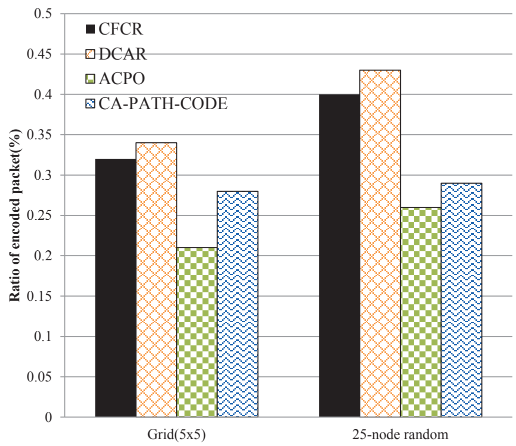

Fig. 10. Comparison of the encoding ratio

Accordingly, Figure 9 presents the comparison of the successful decoding ratio in four algorithms. Because ACPO only deals with two-hop coding, the successful decoding ratio of ACPO is the highest. Due to the coding confirmation process and consideration of coding interference, CFCR and CA-PA-CODE has a higher successful decoding ratio than DCAR.

In order to evaluate the influence of the coding benefit, Figure 10 indicates the ratio of encoded packets in CFCR, DCAR, ACPO and CA-PATH-CODE. Note that DCAR and CFCR have the similar coding opportunity and ACPO has the lowest opportunity. Because the goal of the three coding-aware routing algorithms is to find more coding opportunities, they have a higher encoded packet ratio. In addition, the CA-PATH-CODE adapts to a tradeoff between routing flows "close to each other" in order to utilize coding opportunities and "away from each other" to avoid wireless interference. Hence, it has the least number of encoded packets in each of the three schemes. The CDS metric can help CFCR find more coding opportunities. However, some opportunities are denied in the confirmation process of CFCR. Hence, the number of encoded packets is largest in DCAR.

In addition, we can refer to the supplement file in Appendix C for some additional simulation results.

Finally, we list a comparison of the ACPO, DCAR, CA-PATH-CODE and CFCR in Table 2. In order to distinguish effectiveness, we define 1 as the worst level and 3 as the best level.

TABLE 2

COMPARISON BETWEEN THE THREE SCHEMES

	ACPO	CA-PATH-CODE	DCAR	CFCR
Coding type	Node oriented	Flow oriented	Flow oriented	Flow oriented
Algorithm type	Centralized	Centralized	Distributed	Distributed
Routing protocol	Classical routing such as DSR or AODV	Coding aware routing	Coding aware routing	Coding aware and confirm routing with CDS considered
Information needed by relay nodes	Single hop neighbor node list; packets in the cache of single hop neighbors	Neighbor nodes list and the data queues in their cache; the data flows through itself	Neighbor nodes list and the data queues in their cache; the data flows through itself	Neighbor nodes list and the data queues in their cache; the data flows through itself
The routing path choosing metric	Routing length	Routing length, network coding benefit	Routing length, network coding benefit	Routing length, network coding benefit, CDS routing
Network coding range	Two-hop	Multi-hop	Multi-hop	Multi-hop
Network coding opportunity	Normal	Many(1)	Many(3)	Many(2)
Packet loss ratio	Low(1)	Low(2)	High	Low(3)
Decoding ratio	Medium(3)	Medium(2)	Medium(1)	High
Initialization	Simple	Simple	Complex	Complex
Routing overhead	Light	Medium(3)	Medium(2)	Medium(1)
Network throughput	Normal	High(2)	High(1)	High(3)

7. Conclusions and Future Work

In this paper, we proposed a novel CDS-based and Flow-oriented Coding-aware Routing (CFCR), which focused on utilizing the characteristics of the wireless mesh network to enhance performance. Our scheme selected the appropriate coding node from the connected dominating set. In order to solve the coding collision problem and decrease the packet loss ratio, we designed a method to confirm potential coding opportunities in the process of route selection. In particular, we designed the routing metric to uniformly present many factors such as length of routing, the benefit of network coding and coding opportunities. Considering the requirement in practice, our scheme was inclined to select dominating nodes but not just ones limited to connected dominating sets. To optimize the benefit of CDS routing and flow coding, CFCR analyzes the routing metrics using a formalized method, and verifies them by simulation.

The future work of CFCR is as follows:

(1) We will research a more precise computing method to solve the problem of data flow matching when computing the flow coding benefit.

(2) We will compare the advantage and disadvantage of the flow-oriented and node-oriented methods. We believe the hybrid method will perform better because the node-oriented coding method deals with a small amount of data, and the flow-oriented method deals with a large amount of data.

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REFERENCE

[1] A. Khreishah, I. M. Khalil and J. Wu,"Distributed network coding-based opportunistic routing for multicast," *Proceeding of the 13th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pp. 115-124 , 2012.

[2] P. Li, S. Guo, S. Yu, A.V. Vasilakos, "An opportunistic feeding and routing protocol for reliable multicast with pipelined network coding," *Proceeding of the IEEE INFOCOM. Orlando,* FL, USA,pp. 100-108 , 2012.

[3] J. Chen, T. Li, R.Y. Du,"Efficient Reliable Opportunistic Network Coding Based on Hybrid Flow in Wireless Network,"*China Communication*, pp. 125-131 , 2011.

[4] Z. Lin, L. Xu, D. Wang, J. Gao, "A Coloring Based Backbone Construction Algorithm in Wireless Ad Hoc Network," *Proceeding of the* GPC 2006, pp. 509-516, 2006

[5] J. Wu, M. Cardei, F. Dai and S.H. Yang. "Extended Dominating Set and Its Applications in Ad Hoc Networks Using Cooperative Communication,"*IEEE Transactions on Parallel and Distributed Systems*, 17(8),pp. 851-863 , 2006.

[6] Q. Yuan, I. Cardei, and J. Wu. "An Efficient Prediction-Based Routing in Disruption-Tolerant Networks," *IEEE Transactions on Parallel and Distributed Systems*, 23(1), pp. 19-31, 2012.

[7] J. Wang, J.P. Wang, K.J. Lu, Y. Qian, B. Xiao and N.J. Gu, "Optimal Design of Linear Network Coding for information theoretically secure unicast,"*Proceeding of the IEEE INFOCOM. Shanghai,* China, pp. 757-765,2011.

[8] R. Ahlswede, N. Cai, et al. ,"Network information flow," *IEEE Transactions on Information Theory*, 46(4),pp. 1204-1216,2000.

[9] S.-Y .R. Li, R .W. Yeung, N . Cai, "Linear network coding," *IEEE Trans Information Theory*, 49(2),pp. 371-381,2003.

[10] R . Koetter, M . Medard,"An algebraic approach to network coding," *IEEE/ACM Trans. Networking,* 11, pp.782-795, 2003.

[11] T. Ho,M. Medard, R. Koetter, D. Karger, M. Effros J. Shi，and B. Leong, "A random linear network coding approach to multicast," *IEEE Transactions on Information Theory*, vol. 52,no.10, pp.4413–4430, 2006.

[12] S. Deb, M. Effros, T. Ho, D. R. Karger, R. Koetter, D. S. Lun, M. M´edard, and N. Ratnakar, "Network coding for wireless applications[R]," *A brief tutorial,* In IWWAN, 2005.

[13] A. Ramamoorthy, J. Shi, and R. Wesel,"On the capacity of network coding for wireless networks[R]," *In 41st Annual Allerton Conference on Communication Control and Computing, Oct.* 2003.

[14] S. Katti,H. Rahul,W. Hu,D. Katabi,M. Medard and J. Crowcroft,"XORs in the air：practical wireless network coding," *IEEE/ACM Transactions on Networking(TON),* vol. 16, no.3, pp.497–510, 2008.

[15] T. Nage, F. Richard Yu and M. St-Hilaire," Adaptive Control of Packet Overhead in XOR Network Coding," *Proceedings of Conference on IEEE International Conference on Communications (ICC'2010)*, pp.1-5, 2010.

[16] J. Le, J. C. S. Lui, and D. M. Chiu, "DCAR: Distributed coding-aware routing in wireless networks," *IEEE Transactions on Mobile Computing*, vol. 9, no. 4, pp.596-608, 2010.

[17] B. Guo, H. K. Li, C. Zhou, Y. Cheng,"Analysis of General Network Coding Conditions and Design of a Free-Ride-Oriented Routing Metric,"*IEEE Transactions on Vehicular Technology*, 60(4), pp.1714-1726, 2011.

[18] S. Wang, A. Vasilakos, H. B. Jiang, X. Q. Ma,"Energy Efficient Broadcasting Using Network Coding Aware Protocol in Wireless Ad Hoc Network[R]," *2011 IEEE International Conference on Communications(ICC)*,pp.1-5,2011.

[19] B. Ni, N. Santhapuri, Z. Zhong, and S. Nelakuditi. "Routing with opportunistically coded exchanges in wireless mesh networks," *Proc. IEEE WiMesh*, pp. 157–159, 2006.

[20] Z. Yu, Y. W. Wei, B. Ramkumar, Y. Guan,"An Efficient Signature-Based Scheme for Securing Network Coding Against Pollution Attacks," *Proceeding of the IEEE International Conference on Computer Communications (INFOCOM)*, pp.1409-1417, 2008.

[21] D. Johnson, Y. Hu, and D. Maltz,"The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4," *IETF RFC 4728*, http:/ / www.ietf.org/ rfc/ rfc4728.txt, 2009.

[22] J. Wu, "Extended Dominating-Set-Based Routing in Ad Hoc Wireless Networks with Unidirectional Links," *IEEE Trans. Parallel and Distributed Systems*, 9(3),pp. 189-200, 2002.

[23] S. Sengupta, S. Rayanchu, and S. Banerjee, "An Analysis of Wireless Network Coding for Unicast Sessions: The Case for Coding-Aware Routing," *Proceeding of the IEEE INFOCOM*. Anchorage, AK, pp. 1028 – 1036, 2007.

[24] P. Chaporkar and A. Proutiere, "Adaptive network coding and scheduling for maximizing throughput in wireless networks," *in Proceeding of the Annual ACM Int'l. Conference on Mobile Computing & Networking(MobiCom)*. Montr´eal, Canada, pp. 315–146, 2007

[25] A. Khreishah, C.-C. Wang, and N.B. Shroff, "Cross-layer Optimization for Wireless Multihop Networks with Pairwise Intersession Network Coding," *IEEE Journal on Selected Areas in Communications,* 27(5), pp. 606 – 621, 2009

[26] T. Cui, L. Chen, and T. Ho, "Energy Efficient Opportunistic Network Coding for Wireless Networks," *Proceeding of the IEEE International Conference on Computer Communications (INFOCOM)*. pp. 1022-1030, 2008

[27] S. H. Yang, J. Wu, and C. Mihaela, "Efficient broadcast in MANETs using network coding and directional antennas," *Proceeding of the IEEE International Conference on Computer Communications (INFOCOM)*. pp.1499 – 1507, 2008.

[28] L. Li, et al. "Network coding-based broadcast in mobile ad-hoc networks," *Proceeding of the IEEE International Conference on Computer Communications (INFOCOM)*. pp.1739 – 1747, 2007.

[29] A. Khreishah, et al. "Flow-based xor network coding for lossy wireless networks," *IEEE Transactions on Wireless Communications,* 11(6), pp. 2321-2329, 2012.

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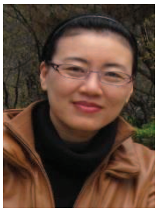

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