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Load Balanced Coding Aware Multipath Routing for Wireless Mesh Networks*

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Abstract — The growth of network coding opportunities is considered the unique optimization goal by most current network coding based routing algorithms for wireless mesh networks. This usually results in flows aggregation problem in areas with coding opportunities, and degrades the network performance. This paper proposes a Load balanced coding aware multipath routing (LCMR) for wireless mesh networks. To facilitate the evaluation of discovered multiple paths and the tradeoffs between coding opportunity and load balancing, a novel routing metric, Load balanced coding aware routing metric (LCRM) is presented, which considers the load degree of nodes when detects coding opportunities. LCMR could spread traffic over multipath to further balance load. Simulation results demonstrate that LCMR could evenly spread the traffic over the network with increasing network throughput in a heavy load at the expense of some coding opportunities.

Key words — Load balanced, Coding aware, Multipath, Routing, Wireless mesh networks.

I. Introduction

Recently, Wireless mesh networks (WMNs)[1] have emerged as a promising solution for next-generation wireless networking to provide better services, and received increasing attention from both industrial and academic community due to their attractive advantages, *e.g.*, low cost, ease of deployment and wide range of application scenarios. Routing algorithm[2] supporting efficient packets delivery is critical to WMN.

Network coding, first presented in Ref.[3], could reduce the number of transmissions, improve network throughput significantly, and save bandwidth consumption[4,5]. The excellent quality of network coding motivates the advances of network coding based routing for WMNs[6].

Current network coding based routing algorithms mainly focus on the increase of network coding opportunities[7−15]. Coding practical routing (COPE)[7] is the first network coding based routing for wireless network. Distributed coding aware routing (DCAR)[11] extends the coding topology scope to increase coding opportunities. Indeed, the increase of coding opportunities means more bandwidth saving and the improvement of throughput. However, according to the basic coding topologies in COPE, coded flows should be partially opposite overlapped or crossed. Therefore, current proposed coding aware routings favor paths, partially overlapped or crossed with existing flows, which lead to routes assembling in the area with coding opportunities. The imbalanced traffic distribution will eventually result in hot spots in the network, which degrades the performance of network coding aware routing for WMNs.Another major disadvantage of these proposed algorithms stems from their design consists in neglecting the interference influence from neighbor nodes.

To cope with the aforementioned limitation of current coding aware routing protocols, this paper proposes LCMR for WMNs. The primary aim of LCMR is to achieve better load balancing over the entire wireless mesh networks with low time and space overhead, while exploiting network coding. For this propose, a novel routing metric, LCRM, is proposed to evaluate discovered multiple routes. In LCRM, the network coding benefits, degree of node load and interference from neighbors are considered jointly.

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The remainder of this paper is organized as follows: Section II introduces the definition of novel routing metric LCRM used in this paper. In Section III, the new routing scheme called LCMR is described in details. The performance evaluation of LCMR is presented in Section IV. Finally, Section V concludes this paper.

II. LCRM Definition

In wireless mesh networks, wireless channel is open and node captures medium through contention. The interference from neighbors substantially degrades the performance of routing. Actually, the interfering influence is dependent on the amount of traffic of interfering nodes. Therefore, the novel routing metric should consider the interference traffic amount.

Besides, the routes accumulation in the area with coding opportunities due to coding aware mechanism, could lead to traffic imbalance throughout the network. Therefore, the new routing metric should reflect the load degree of nodes itself as well as its neighbors. On the other hand, the benefit of network coding in bandwidth resource saving should also be taken into account.

1. Network coding gain (NCG)

The parameter NCG is to reflect the contribution of network coding. Due to the use of network coding, original multiple packets could be coded and transmitted in one packet form. Therefore, the more flows participating in network coding, the more bandwidth savings. On the other side, the NCG should be limited within suitable range to avoid the sharp fluctuations of the path cost. Assume a route r at node i could be coded with other m_i ($m \geq 0$) routes, then the network coding gain for r at i is defined as follows:

$$NCG_i = e^{-m_i} \tag{1}$$

2. Load and interference factor (LIF)

According to the analysis aforementioned, node load and interference are critical to the performance of routing algorithms. LIF aims to take the traffic load of the current node as well as its interfering neighbors into account. Inter-flow and intra-flow interference prone to happens in a wireless mesh network due to its shared nature of the wireless medium. The inter-flow interference occurs when neighbors of adjacent flows contend for the wireless medium, while the intra-flow interference occurs when adjacent nodes of the same route contend for the wireless channel. In addition, the influence of inter-flow and intra-flow interference lies on the amount of traffic on the interfering nodes.

LIF is defined as follows:

$$LIF_{ij} = \exp[(LF_i + IF_{ij}) - (1 + |N_{ij}|)] \tag{2}$$

where LF_i (Load factor) is the traffic load of node i, and IF_{ij} (Interference factor) is the total load of interfering nodes of i and j. N_{ij} is the interfering node set of node i and node j, $N_{ij} = N(i) \cup N(j)$. $|N_{ij}|$ is the element number of N_{ij}. Then $(1+|N_{ij}|)$ is to ensure that LIF_{ij} is in [0,1].

The LF_i is defined as follows:

$$LF_i = q_i/Q_i \tag{3}$$

where q_i is the number of packets queuing in node i, and Q_i is the queue length of node i.

Suppose k is one element of N_{ij} and q_k is the number of packets queuing at k, Q_k is the queue length of k. Then IF_{ij} is defined as follows.

$$IF_{ij} = \sum_{k \in N_{ij}}^{N_{ij}} q_k/Q_k \tag{4}$$

3. LCRM

The LCRM value of a link l_{ij} is defined as follows:

$$LCRM_{ij} = ETT_{ij} \times NCG_i \times LIF_{ij} \tag{5}$$

The Expected transmission time (ETT)[16] indicates expected transmission time on link l_{ij}.

The LCRM value for a path P is defined as follows:

$$LCRM_P = \sum_{l_{ij} \in P} LCRM_{ij} \tag{6}$$

According to the definition of LCRM, LCMR prefers path with lower LCRM value,which has more coding opportunities, light load and lower interference.

Theorem 1 LCMR is favor of choosing a neighbor node with coding opportunity, light load and low interference.

Proof When a node i doesn't have coding opportunity, m_i is 0 and the network coding gain of i is 1. When existing coding opportunity, m_i is equal or greater than 1, and the network coding gain of i, NCG_i is less than 1. A node with light load and low interference means that its LF_i and IF_i are low, which lead to small LIF_i. Therefore, the LCRM value of the link from current node to the neighbor node with coding opportunity, light load and low interference is small according to Eq.(5). Since LCMR prefers to choose a path with lower LCRM value, the node with coding opportunities, light load and low interference is more likely chosen.

III. LCMR Details

1. Network coding condition

Before delving into the mechanism of coding opportunity detection, the network coding condition is first analyzed which is the basis of coding opportunity detection. In COPE, the basic coding topologies are summarized and the principle of network coding points out that each receiver of coded packet should be able to decode it. The network coding condition of LCMR based on this principle can be formulated as follows.

Theorem 2 Assume n flows $f_1, f_2, f_3, \ldots, f_n$ traverse through node v. $N(v)$ denotes the set of v's neighbors. Let $next(v, f)$ denotes the next hop of v in flow f and $prev(v, f)$ denotes the last hop of v in flow f. The necessary and sufficient condition that packets from the n flows can be coded at v is as follows:

Take any one of the n flows, f_i, for any other flow f_j ($i \neq j$), the following two items hold.

(i) $next(v, f_i) = prev(v, f_j)$ or $next(v, f_i) \in N(prev(v, f_j))$;

(ii) $next(v, f_j) = prev(v, f_i)$ or $next(v, f_j) \in N(prev(v, f_i))$;

Proof 1) If items (i) and (ii) hold, f_i and f_j form the typical coding topologies (Chain or "X") or hybrid topology with coding opportunity as in COPE, *i.e.* f_i could be coded with f_j at v, which means that $next(v, f_i)$ holds packets of f_j

($i \neq j$). Since f_i denotes anyone of the n flows, it can be found that for any flow, the next-hops of v can decode the received coded packets and get their corresponding native packets. This confirms the sufficiency of the coding condition.

2) On the other hand, if packets from the n flows can be coded at v, it is obvious that for any flow the next-hops of v can decode the received coded packets, *i.e.* they hold packets of any other flow, which leads to the satisfaction of items (i) and (ii). This proves the necessity of the coding condition.

As mentioned earlier, LCMR is a multipath routing algorithm. In the multi-path routing condition, each path of multipath routing in LCMR will be regarded as a normal flow without distinction. Therefore, the network coding condition of multipath routing is the same as Theorem 2.

2. LCMR description

LCMR is based on Dynamic source routing (DSR)[17] and includes two phases: route request process and route reply process. The Route request (RREQ) message in LCMR is appended a Result field to story the coding opportunity detection result of each hop. Besides, the path information in RREQ also includes the NCG and LIF value of corresponding links and nodes.

When a node s has packets to send, but there is no available route to destination d, s initiates the route request procedure. In route request procedure, the intermediate node initiates coding detection process as shown in Algorithm 1 and obtains the Result.

Algorithm 1 The coding detection algorithm

Input node v, route of RREQ r_d, the neighbors of v (exclude the last hop of RREQ), routes that traverse through v: $r_1, r_2, r_3, \ldots, r_n$.
Output *Result*, whose element is tuples of neighbors set that enable coding opportunity for r_d at v and corresponding number of routes participate in network coding.
$Result = \oslash$;
$Num = 0$;
For v's each neighbor n_i, $i = 1$ to m (m is the number of v's neighbors exclude the last hop of RREQ) do
r_d appended with n_i composing new route r'_d;
$CodeSet = r'_d$;
For r_j, $j = 1$ to n do
If r_j meets the coding conditions with routes in $CodeSet$ then
$CodeSet = CodeSet \cup r_j$;
Endfor;
$Num = |CodeSet|$;
If $Num \neq 1$ then
$Result = Result \cup < n_j, CodeSet, Num >$;
Endfor
return *Result*

Upon receiving m RREPs (Route reply), s updates its route cost matrix and establishes multiple routes to d in routing table based on the paths in RREPs. Assume s gets m paths to d, and the LCRM value of these routes is $r_1, r_2, r_3, \ldots, r_i, \ldots, r_m$. Then the fraction of traffic that assigned on i-th path is as follows:

$$f^i_{s,d} = (1/r_i)/(\sum_{i=1}^{m} 1/r_i) \tag{7}$$

Then the traffic will be distributed over all available paths according to the LCRM value of each path.

IV. Performance evaluation

1. Simulation parameters

Simulations are conducted using Network simulator 2 (NS2)[18] to verify the performance of LCMR. The network topology consists of 40 nodes randomly placed in an area of 1500m×1500m. LCMR is implemented on top of 802.11b MAC with channel bandwidth of 11 Mbps at each node. For the sake of performance analysis, COPE, DCAR and LCMRs are taken as comparison items. LCMRs is the modified version of LCMR without use of LIF.

All flows are of identical traffic characteristics, *i.e.* data rate and packet size in simulation. The offered load is sent as CBR and increases gradually. The source and destination of each flow are randomly selected from the 40 nodes. Each packet is 512 byte. The transmission range of each node is 250m, while its interference range is 550m. The length of the queue at each node is 100.

To investigate how well traffic is distributed over the entire network, the following parameter traffic distribution index in Ref.[19] is utilized.

$$f = (\sum_{i=1}^{n} x_i)^2/n(\sum_{i=1}^{n} x_i^2) \tag{8}$$

where n is the number of links in the network and x_i denotes the number of packets that traversed the ith link. This parameter ranges from zero to one and indicates how well the traffic is distributed over the network.

2. Simulation results analysis

Fig.1 presents the evolution of the routing overhead of four routings considering different offered load. The routing overhead is expressed in terms of packet counts. The routing overhead of LCMR consists of RREQ/RREP messages and periodic Hello messages, which are also indispensable for COPE and DCAR. Therefore, the routing overhead of the four mechanisms is near as shown in Fig.1. However, in case of high traffic load, the routing overhead of LCMR is slight lower than other schemes, since more signaling packets are required in other three methods in case of congestion, while LCMR could evenly distribute the traffic throughout the network and avoid congestion.

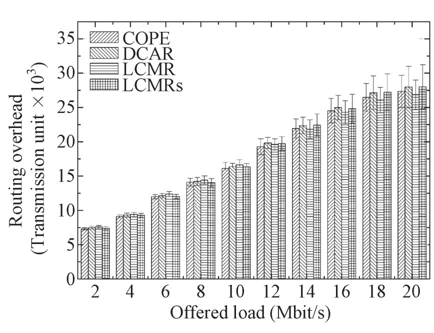

Fig. 1. Routing overhead versus offered load

Fig.2 graphs traffic distribution index comparison among COPE, DCAR, LCMR and LCMRs. The figure indicates that

LCMR and LCMRs outperform COPE and DCAR due to their multipath mechanism, and LCMR exhibits a best distribution of traffic, especially in case of heavy load. Specially, it is interesting from Fig.2 that the traffic distribution index performance of LCMR is higher than that of LCMRs which doesn't use the LIF parameter. The underlying reason beneath this performance consists in the fact the LCMR could be aware of the node load and interference traffic load at neighbors using LIF parameter. Although DCAR considers the total queueing packets number of a route and its traffic distribution index is greater than that of COPE, its traffic distribution index is far lower than that of LCMR and LCMRs, because that single route is used in DCAR. Fig.2 indicates that multipath mechanism and LIF are critical for LCMR to balance the traffic load.

The load balancing capability of LCMR results in the throughput enhancement, as can be seen in Figs.3 and 4.

Fig.3 depicts the network throughput versus offered load. It becomes evident from this figure that LCMR outperform other three routings. A stunning amelioration is observed for high offered load. It appears that LCMRs should outperform DCAR, since it exploits multipath mechanism. However, it is clear for Fig.3 that the throughput of LCMRs is lower than that of DCAR in case of heavy load. This occurs for the reason that LCMRs doesn't use LIF in route discovery and discovered multiple paths congregate in coding areas without use of LIF, which further aggravates the congestion.

Fig.4 plots the Cumulative distribution function (CDF) versus throughput. From Fig.4, it can be seen that for LCMR, 80 percent of time the throughput is above 6 Mbit/s, whereas for COPE is below 6 Mbit/s. For LCMRs, 60 percent of time the throughput is less than 7 Mbit/s. The CDF of DCAR is close to that of LCMR. However, flows in LCMR generally obtain higher throughput compared with DCAR. This confirms the load balancing capability of LCMR in enhancing the network throughput.

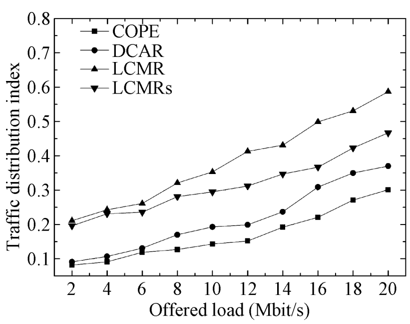

Fig. 2. Traffic distribution index versus offered load

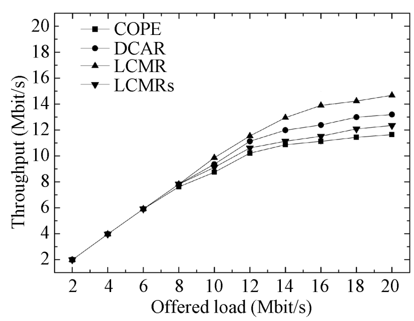

Fig. 3. Throughput versus offered load

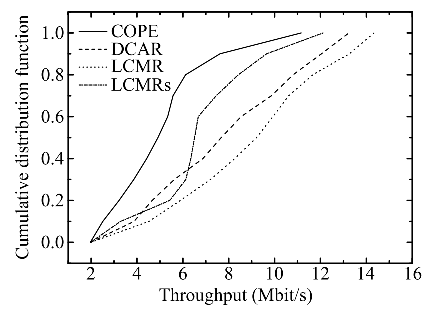

Fig. 4. Cumulative distribution function versus throughput

Fig.5 illustrates the coded packets percentage versus offered load. It is evident from this figure that the coded packets percentage of COPE is far lower than other schemes. The coded packets percentage of DCAR, LCMR and LCMRs is close in light load. Fluctuation of the DCAR and LCMRs is little with the increase of offered load. When the offered load is between 2 and 8 Mbit/s, the coded packets percentage of LCMR increase gradually and get maximum at 8 Mbit/s. When the offered load is larger than 8 Mbit/s. The coded packets percent of LCMR decreases gradually. It should be noted that the capability of LCMR in load balancing is at the expense of reduction in network coding opportunities.

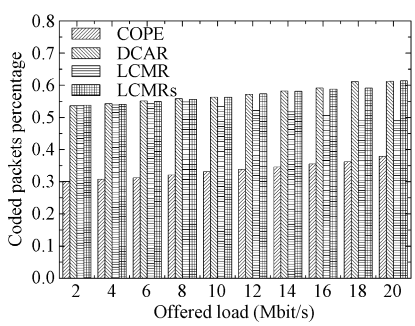

Fig. 5. Coded packets percentage versus offered load

V. Conclusion

In this paper, we proposed a distributed routing scheme, LCMR for wireless mesh networks. To balance the network traffic, LCMR exploits a novel routing metric, LCRM. LCRM considers not only the benefit of network coding, but also the node load degree and negative influence of interference. Through simulations on NS2, LCMR can achieve better load balancing at some expense in coding opportunities reduction. In other words, LCMR has a desirable trade-off between coding opportunity and traffic load balancing.

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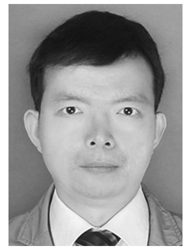

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