Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2022 Page No. 1088– 1098
Article History: Received: 06 April 2022, Revised: 28 April 2022, Accepted: 04 May 2022, Publication: 31 May 2022

Coding-Aware Routing with Shortest Path Based Backpressure Scheme

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Abstract:

Coding-aware routing is an effective method to effectively improve the network coding gain and obtain the maximum network transmission capacity. Different from the traditional coding-aware method, this paper proposes a dynamic coding-aware routing method by integrating network coding-awareness, shortest hop strategy and back-pressure routing. This method gets rid of the dependence of traditional code-aware routing on network topology and spatial distribution of data flows. Taking advantage of the inspiration of load balancing, we realize the dynamic integration of coding perception and data routing by utilizing the data backlog pressure between nodes as the driver of data. The simulation results show that the routing method of this paper can effectively improve the network transmission capacity and increase the network throughput in a grid wireless network.

***Keywords**: Network coding, Backpressure routing, Coding-aware routing.*

I. INTRODUCTION

Network coding is a network transmission method that leverages information coding during network transmission to maximize network capacity. But unlike traditional information coding, network coding pursuits the maximum network transmission capacity of network information theory. The gain of network coding relies on network topology and spatial distribution of data flows. For dynamic time-varying networks (such as adhoc networks), the network topology and spatial distribution of data flows are usually time-varying. This leads to a huge challenge in building network coding opportunities [1-3].

Designing a network coding opportunity-aware routing method, named coding-aware routing, is one of the important ways to create coding opportunities actively. The current research on network coding opportunistic perception mainly focuses on three aspects: 1. Coding perception of fixed topology. For this kind of network coding methods, there is no need for coding awareness and information listening during the network coding process since the topology is fixed. Encoding and decoding are performed on fixed nodes in the network [4-7]. 2. Coding awareness based on on-demand routing. Lei et al. proposed some network coding-aware routing methods based on on-demand routing [8, 9]. This type of coding-aware routing discovers network coding opportunities proactively and finds routes by maximizing network coding opportunities. However, maximizing network coding opportunities is not always maximizing network throughput. Some research found that coding perception based on on-demand routing strategy is very sensitive to topology changes, which is prone to inefficient routing problems [10]. 3. Encoding awareness based on opportunistic routing. Hai et al. propose the schemes that combine code-awareness with opportunistic routing [11, 12] [3]. Using the characteristics of opportunism and multi-path, the dependence of coding-aware routing on topology is reduced, so as to realize dynamic coding-awareness. However, there is a situation in which the set of forwarding nodes is reduced when coding awareness is considered in opportunistic routing. This shrinkage of forwarding nodes set reduces the gain of opportunistic transmission. This may lead to a reduction in the transmission capacity of the entire network [11].

In recent years, some scholars have studied coding-aware routing methods based on queuing strategies and dynamic structures [13-17]. These methods enable encoding opportunity awareness without any knowledge of network topology and packet flows. At the same time, it also gets rid of the dependence of the encoding perception on the path, such as methods based on on-demand routing. However, the queuing strategy based methods have a certain delay defect and cannot quickly establish a route. In order to solve this problem, this paper introduces a shortest path-based back-pressure coding-aware routing method, which can effectively solve the dynamic fusion of coding-awareness and data routing.

II. DYNAMIC CODING-AWARE ROUTING

2.1 System Model

We consider a multi-hop network model $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of nodes and $\mathcal{L}$ is the set of edges. A node $n \in \mathcal{N}$ represents a network node that has a routing function and operates in time slot $t \in \{0,1,2,3 \dots\}$. Each node has an independent buffer queue and transmits fixed-length packets on the time-varying link channel. An edge $(a,b) \in \mathcal{L}$ represents a link linking node a and node b. To simplify the model, we assume that the edge (a,b) is a symmetric link, ie $(a,b) = (b,a)$. Transmission rate of link (a,b) is defined by $\mu_{ab}(t)$ in time slot t. Let $(\mu_{ab}(t))$ denote the transmission rate matrix of (a,b) in time slot t. Define $\mu_{ab}^{(c)}(\mathrm{t})$ as the routing variable of the link (a,b) about the destination node c in the time slot t, which obeys the following constraints:

$$\big(\mu_{ab}(t)\big) \in \Gamma_{S(t)} \tag{1}$$

$$\mu_{ab}^{(c)}(t) \geq 0 \tag{2}$$

where $\Gamma_{S(t)}$ represents the network transmission rate matrix set in time slot t. In this paper, we use (c) to denote the data flows destined for node c.

In this network model, we allow the use of low-complexity XOR network coding operations [18]. When a node starts to send data in a XOR network coding based network, multiple data packets are allowed to be encoded with the XOR operation, and broadcast to many receiving nodes at the same time. Opportunistic listening is allowed to detect the data of transmission between neighbors. As mentioned above, network coding opportunities depend on network topology and data flow state. In a time-varying network environment, both network topology and data flow keep changes which depend on the current network state and have time-varying characteristics. Therefore, network coding opportunities are also time-varying. In order to characterize such characteristics, this paper defines $S(t)$ to represent the network state at time t, and let $\Omega_{S(t)}$ represent the set of network coding opportunities in the network state $S(t)$.

2.2 Backpressure Routing

In a queuing network, passing a packet from one node to another is equivalent to removing it from the first node's queue and adding it to the second node's queue. Any packet that is delivered to its destination node is equivalent to be removed from the network. Define $Q_n^{(c)}(t)$ as the queue length of data buffered from data flow (c) at node $n \in \mathcal{N}$ at time t. The data backlog of the link (a, b) with respect to the data flow (c), we named link backlog in this paper, is represented by the difference of the data queue lengths between nodes at both ends of the link for flow (c). Here, it is assumed that for all $c \in \mathcal{N}$, there is always $Q_c^{(c)}(t) = 0$. It means that all nodes in the network do not cache packets destined for themselves. According to the definition of link backlog above, backpressure routing defines the following weights:

$$\mathrm{w}_{\mathrm{ab}}^{(c)}(t) = \max\left[Q_{ab}^{(c)}(t), 0\right] \tag{3}$$

According to this weight, the data pressure weight on the link (a, b) at time t is defined as follows:

$$\mathrm{w}_{\mathrm{ab}}(t) = \max_{c\in\mathcal{N}} \mathrm{w}_{\mathrm{ab}}^{(c)}(t) \tag{4}$$

Equation (4) shows that when the link (a, b) is active, the data transmitted by the link is competed by the data flow with the largest weight. Thus, the routing problem of the entire network can be described by the following optimization problem:

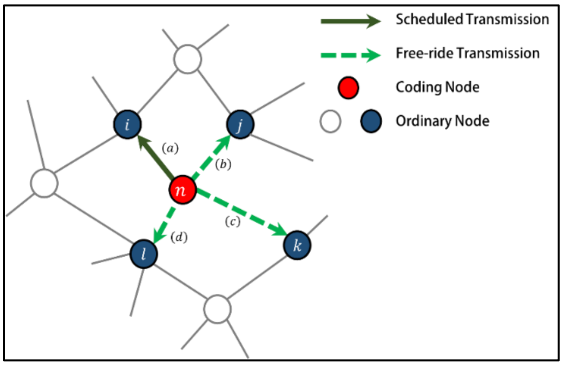
$$\begin{aligned} &\max \sum_{a\in\mathcal{N}} \sum_{b\in\mathcal{N}} \mu_{ab}(t) w_{ab}(t) \\ &\mathrm{s.t.:} \left(\mu_{ab}(t)\right) \in \Gamma_{S(t)} \\ &\qquad \mu_{ab}(t) \geq 0 \end{aligned} \tag{5}$$

This routing strategy has been shown to optimally stabilize network queues [19]. According to Lyapunov stability theory, this routing strategy is also a strategy to maximize network throughput [20].

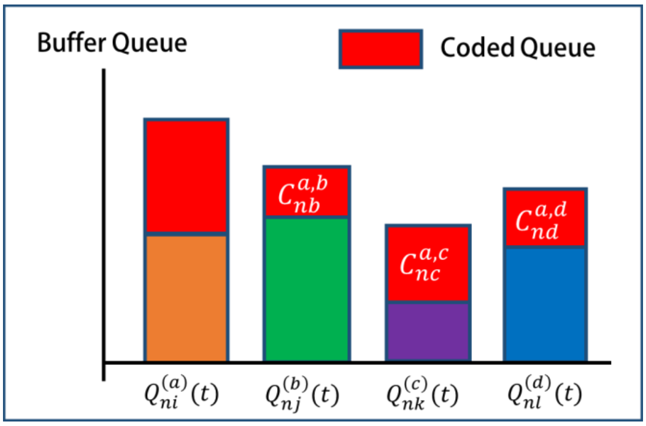
2.3 Code-aware Back-pressure Routing

Network coding gain is achieved by encoding some of unscheduled data with the scheduled data at the currently transmission slot. Thanks to network coding, the encoded unscheduled data can reach its destination "for free" by being transmitted with the aid of scheduled data. SENGUPTA et al. call this process "free rides"[7]. Most of the network coding methods using "free rides" belong to the inter-session network coding. To simplify the problem, this paper uses the simplest XOR network coding in inter-session network coding.

In order to describe the network coding process from a queuing perspective, we give an instance as shown in Fig. 1(a). A scheduled transmission of flow (a) on link (n, i) can offers some free-ride seats for flows (b), (c) and (d). We introduce a notation $C_{nj}^{(ab)}(t)$ shown in Fig. 1(b) to denote the amount of data from flow (b) encoded into flow (a) on link (n, j) in time slot t. Obviously there is $C_{nj}^{(ab)}(t) \leq Q_{nj}^{(b)}(t)$. According to the previous scheduling settings for data flows, for all $a, n, i \in \mathcal{N}$, when flow (a) is scheduled for transmission at time slot t, we have $C_{ni}^{(aa)}(t)=0$. Traditional backpressure routing releases at most $Q_{ni}^{(a)}(t)$ amount of data at node n at time t. However, after using network coding, this transfer can be released at most $Q_{ni}(t)=Q_{ni}^{(a)}(t)+C_{nj}^{(ab)}(t)+C_{nk}^{(ac)}(t)+C_{nl}^{(ad)}(t)$.



(a) Scheduled and free-ride transmission



(b) The backlog released at this scheduled transmission

Fig 1: The benefit of free-ride transmission

Obviously, using network coding after one transfer scheduling can release more data backlog. The amount of encoded data $C_{nj}^{(ab)}(t)$ is time-varying and related to the current network state $S(t)$. Specifically, it can be regarded as the variables related to the current network coding opportunity $\Omega_{S(t)}$, the network transmission rate matrix $\Gamma_{S(t)}$, and data streams (a) and (b).

In order to better describe network coding during backpressure routing, a concept called "network coding rate" is defined. Let $\sigma_{ni}^{(ab)}(t)=C_{nj}^{(ab)}(t)/Q_{ni}^{(a)}(t)$ represent the network coding rate of the flow (b) encoded into flow (a) at node (a) in time slot t. The network coding rate is also additive and constitutes the network coding state of the current network. For example, $\sigma_{ni}^{(a)}(t)=\sum_{b\in\mathcal{N}}\sigma_{ni}^{(ab)}(t)$ indicates the network coding rate of flow (a) on the link (n,j) in time slot t. Notation $\sigma_{ni}(t)=\sum_{a\in\mathcal{N}}\sigma_{ni}^{(a)}(t)$ represents the network coding rate of link (n,j) in time slot t. Notation $\sigma_{n}(t)=\sum_{i\in\mathcal{N}}\sigma_{ni}(t)$ represents the network coding rate at node n in time slot t.

Considering the network coding rate, the weight calculation of backpressure routing is modified as:

$$W_{ab}^{(c)}(t) = \max\left[\left(1 + \sum_{d\in\mathcal{N}}\sum_{k\in\mathcal{N}} \sigma_{ak}^{(cd)}(t)\right) Q_{ab}^{(c)}(t), 0\right] \tag{6}$$

It can be seen that, Equation (6) adds the network encoding rate for the calculation of the weights after network encoding is considered compared with Equation (3). The dynamic fusion of data routing and coding perception is realized by introducing the network coding rate variable into the weight calculation. Next, similar to equation (4), the final weight of the link (a, b) at time t is expressed as

$$W_{ab}(t) = \max_{c\in\mathcal{N}} W_{ab}^{(c)}(t)$$

According to this link weight assignment method, the final coding-aware routing strategy can be described by solving the following maximum weight problem:

$$\begin{aligned} &\max \sum_{a\in\mathcal{N}}\sum_{b\in\mathcal{N}} \mu_{ab}(t) W_{ab}(t) \\ &\text{s.t.}: \left(\mu_{ab}(t)\right) \in \Gamma_{S(t)} \\ &\qquad \left(\sigma_a(t)\right) \in \Omega_{S(t)} \\ &\mu_{ab}(t), \sigma_a(t) \geq 0 \end{aligned} \tag{7}$$

2.4 Code-aware Routing Based on Shortest Path Optimization

The traditional back-pressure routing has slow convergence speed, and when the data backlog in the network is not enough, it will cause a large delay [21]. Therefore, this paper considers a method based on the shortest path strategy to optimize the slow convergence problem of backpressure based coding-aware routing in the early stage. We assume that every node in the network knows the minimum number of hops to reach any other node. Let $H_a^c(t)$ denote the minimum number of hops from node a to node c in time slot t. This information is usually obtained during network setup and maintenance. It can also be achieved through periodic communication with neighbor nodes. This shortest path precomputation and neighbor node information maintenance are often used in dynamic path design [22, 23].

In traditional back-pressure routing, if there are multiple data streams that satisfy Equation (4), one is randomly selected as the data to be transmitted on the current link. If there is not much data in the network, this behavior can easily lead to random transmission of packets. This is also the main reason for the large delay. To this end, we use the minimum number of hops $H_a^c(t)$ instead of randomly selecting candidate data streams. Definition $N_{ab}^*(t)$ represents the set of all data streams satisfying Equation (4) on the link (a, b) of time slot t. Then, the flow (c) that is finally scheduled for transmission should satisfy

$$(c) = \operatorname*{argmin}_{c\in N_{ab}^*(t)} H_a^c(t) \tag{8}$$

Considering that most distributed dynamic networks use FIFO for packet scheduling and queuing, we redesigned the packet scheduling process. Here every packet at the head of the queue is forced to be scheduled. And the routing information of the data packet is obtained by the following formula:

$$n = \underset{(a,n)\in\mathcal{L}}{\operatorname{argmin}} \left[H_n^c(t) \middle| W_{an}^{(c)}(t) = \max_a^{(c)}(t) \right], \tag{9}$$

where $\max_a^{(c)}(t) = \max_{b\in\mathcal{N}} W_{ab}(t)$ denotes the maximum backlog of data (c) at node a at time slot t.

The above formulation changes the scheduling strategy of the original back-pressure routing from ‘commodity selection’ to ’link selection’. In the original back-pressure routing, only the optimal commodity can be scheduled in each time slot. In our routing scheduling, a packet must be scheduled if it is buffered at the head of the transmission queue. Therefore, our routing strategy is strong packet-driven, which enables all packets buffered in the transmission queue to be scheduled in sequence.

III. PERFORMANCE EVALUATION

In this section, we evaluate the performance of shortest-path-based back-pressure coding-aware routing in terms of throughput, end-to-end delay, network coding times and buffering status under different network settings, e.g. source rates, network topologies, and a number of traffic flows. We compare the simulation results with some other network coding aware routings including CFCR [13] which is a network coding aware routing based on a connected dominating set, DCAR [9] which is a network coding aware routing based on dynamic source routing [23], and BP [20] which is a traditional backpressure routing without network coding. In the simulations, we use BCAR to denote the results of our method.

In the simulation experiments, we use the 4 x 4 mesh topology network model as shown in Fig. 2. In this network, a total of 16 nodes connected by 24 symmetrical links are included. The capacity of each link is limited to around 500kb/s. All data flows are transmitted using user datagram protocol (UDP) transmission with constant bit rate. All transmitted packets have a fixed length of 512 bytes. The generation rate of each flow is limited to around 300kb/s.

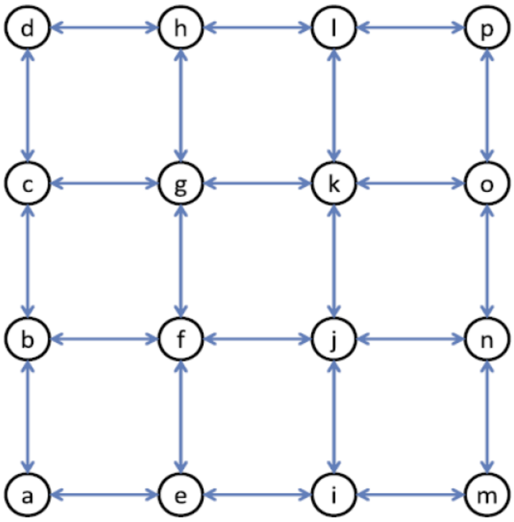


Fig 2: Grid network with 4 x 4 mesh topology

3.1 Throughput Results

We first compare and analyz the throughput performance. As shown in the Fig. 3, our method significantly outperforms other methods in throughput performance. The maximum throughput of this method is 35% higher than that of BR and CFCR. In addition, the maximum throughput of BCAR occurs when the load is around 150kb/s, which is nearly 50% higher than that of BR and CFCR. The DCAR scheme uses a single-path routing strategy based on DSR. So its throughput performance is significantly weaker than that of BCAR and CFCR, and even inferior to the traditional BP routing algorithm. The above comparison of throughput performance shows that BCAR can make good use of the characteristics of network coding to accelerate the release of data backlog, and improve network throughput under dynamic time-varying networks.

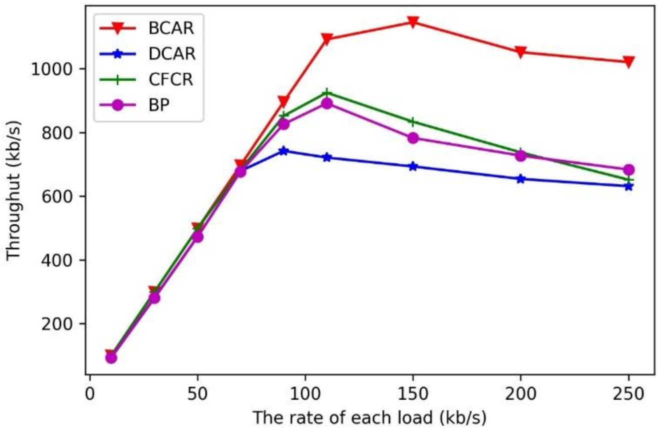


Fig 3: Throughput performance in the grid network

3.2 End-to-end Delay Results

Next, we compare the simulation results of above routing algorithms in terms of network delay as shown in Fig. 4. The network delay increases with the increase of the load rate. Overall, BR has highest delay than other algorithms. CFCR has the minimal delay. But it is worth noting that the network delay will increase rapidly when the load rate exceeds a certain value. We call this value the "saturation point" of the load rate. The saturation point represents the maximum access rate that the network can hold in a stable state. It indicates the point of the maximum network transmission capacity. Obviously, the saturation points of BCAR, CFCR and DCAR are all larger than that of BP algorithm. This shows that network coding expands the maximum transmission capacity. However, because DCAR uses a single-path strategy, the delay is easily affected by the queuing problem which results in a rapid increase of the delay. Therefore, the saturation point of DCAR is smaller than that of BCAR and CFCR. Furthermore, CFCR may produce high saturation points differently than BCAR. The former is due to the use of a specific dominating set, so that the data flow can be quickly transmitted between nodes in the set with an orderly manner. The latter relies on the rapid release of data backlog, which drives more data flows to paths containing more network coding opportunities. Thereby, BCAR prevents some data flows from flowing into longer paths to reduce network latency and increase network transmission capacity. Next, the comparison of network coding opportunities also confirms this.

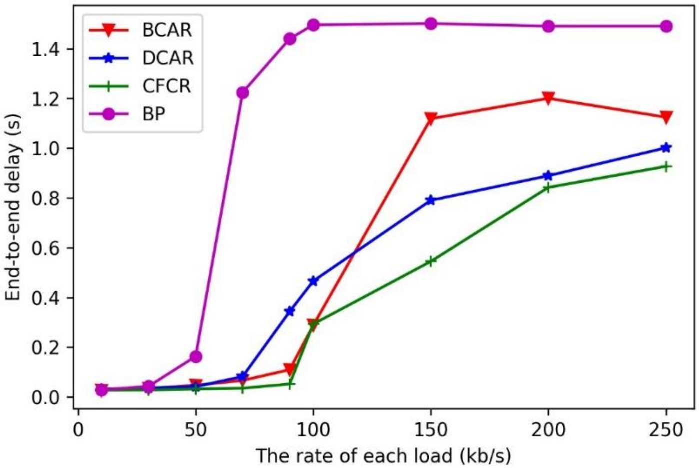


Fig 4: End-to-end delay performance in the grid network

3.3 Sensing of Network Coding Opportunities

The number of occurrences of network coding in the network can illustrate the ability of coding-aware routing to sense network coding opportunities. To this end, we compare the number of times of network encoding for BCAR, CFCR and DCAR in this section. In the Fig. 5, we give the comparison results of the network encoding times in the grid network. It can be seen that the network coding opportunities collected by BCAR are significantly more than those of CFCR and DCAR. When the load is relatively light, the number of network coding of DCAR is slightly higher than that of CFCR. As the load increases, the single-path strategy limits the generation and collection of network coding opportunities. As a result, the number of network encodings for DCAR is gradually less than that for CFCR. The above results indicate that BCAR has better network coding opportunistic sensing than other two coding-aware routing algorithms. This also indirectly explains why BCAR has a high network transmission capacity.

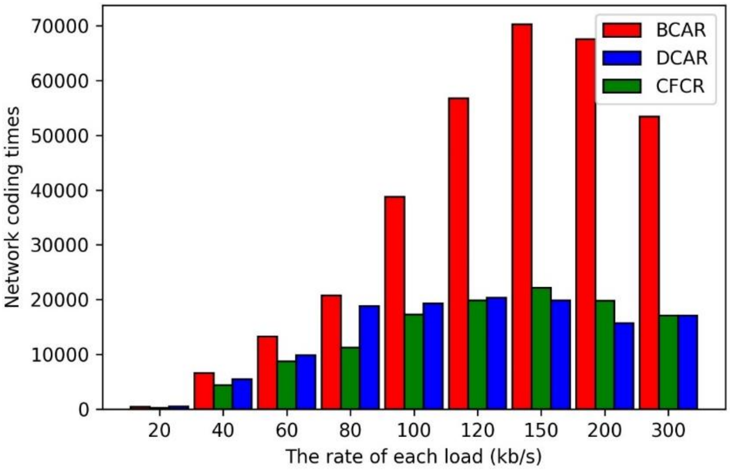


Fig 5: The number of times of network coding

3.4 Network Queuing Results

In this section, we start from the network queuing states to study the ability of compared methods in network balancing which reflects the impact of network transmission capacity. We compare and analyze the two network queuing states respectively. The first is the number of nodes at full cache queuing. It indicates the number of nodes suffering from the overflow state. This network queuing state represents the overload degree of the current network. The second is the number of buffering nodes, which is the number of nodes buffering one packet at least at the current time. This network queuing state represents the load balancing capability of the network. Fig. 6 shows the comparison results of the number of buffering nodes. Since we fixed link capacity and buffer-queue length, the network transmission capacity is limited. As the network load rate increases, the number of buffering nodes reaches a peak. For BCAR and BP, this peak is close to the total number of nodes of the network. For CFCR and DCAR, this peak is only about 50% of the total number of nodes. This indicates that the load balancing ability of BCAR and BP is stronger than those of CFCR and DCAR. Fig. 7 shows the comparison results of the number of overflow nodes in the network. As shown that before the load rate reaches a certain value, the number of overflow nodes is always 0. When this value is exceeded, the number of overflow nodes increases rapidly in the network. This critical value represents the maximum access rate of network and indicates the network capacity. Therefore, BCAR has the largest network capacity. It's nearly 25% higher than the second-highest CFCR. The method using network coding is obviously higher than the traditional BP algorithm. This shows that network coding does improve the transmission capacity of the network. Combining these two results, BCAR can not only carry a higher network access rate, but also balance network transmission well. So it stabilizes the network effectively and presents high network throughput.

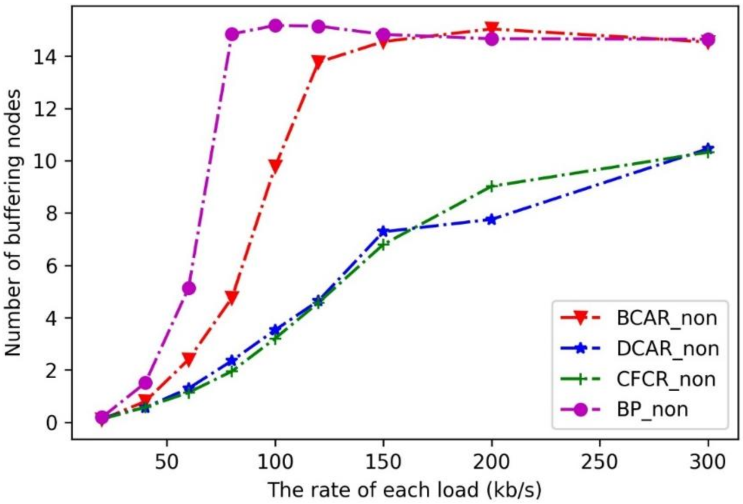


Fig 6: The comparison of number of buffering nodes

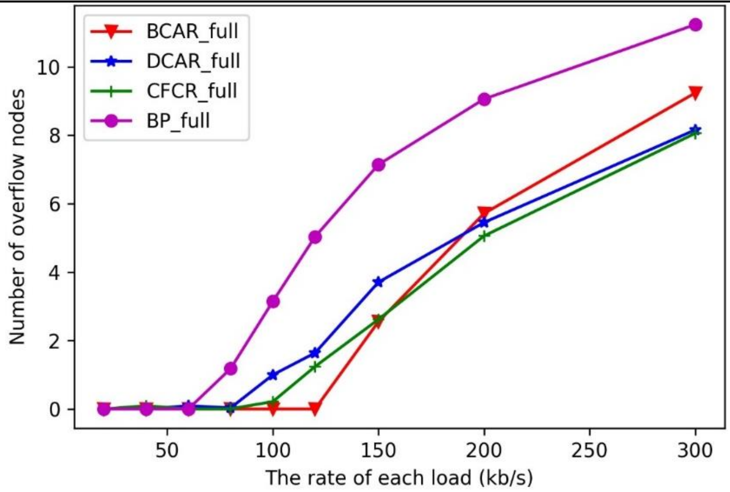


Fig 7: The comparison of number of overflow nodes

III. CONCLUSION

In this paper, we propose a dynamic network coding-aware routing with shortest-path based backpressure routing. This network coding-aware routing integrates network coding sensing, shortest hop strategy and back-pressure routing. Taking advantage of the load balancing, the proposed routing scheme realizes the dynamic integration of coding sensing and data routing by utilizing the data backlog pressure between nodes. It makes the coding sensing free from dependence on network topology and spatial distribution of data flows. Taking advantage of the fast convergence of shortest-paths strategy, the proposed method achieves a good delay performance. The simulation results show that, compared with some traditional coding-aware routing methods, the proposed method improves the throughput performance by nearly 70%, expands the network capacity by 50% and reduces the network delay by 30%. The sensing of coding opportunities is also improved by nearly 150%. Therefore, our proposed routing scheme is suitable for multi-hop time-varying network with network coding enabled.

ACKNOWLEDGEMENTS

This work is financially supported by Guangdong Rural Science and Technology Commissioner Project (KTP20200226).

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Article History: Received: 06 April 2022, Revised: 28 April 2022, Accepted: 04 May 2022, Publication: 31 May 2022

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