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# Joint Routing and Channel Assignment in Multi-rate Wireless Mesh Networks

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## Abstract

To mitigate the performance degradation caused by performance anomaly, a number of channel assignment algorithms have been proposed for multi-rate wireless mesh networks. However, network conditions have not been fully considered for routing process in these algorithms. In this paper, a joint scheme called Multi-rate Dijkstra's Shortest path - Rate Separated (MDSRS) is proposed, combining routing metrics and channel assignment algorithm. In MDSRS, the routing metric are determined through the synthesized deliberations of link costs and rate matches; then the rate separated channel assignment is operated based on the determined routing metric. In this way, the competitions between high and low rate links are avoided, and performance anomaly problem is settled, and the network capacity is efficiently improved. Theoretical analysis and NS-3 simulation results indicate that, the proposed MDSRS can significantly improve the network throughput, and decrease the average end-to-end delay as well as packet loss probability. Performance improvements could be achieved even in the heavy load network conditions.

**Keywords:** Wireless mesh networks, IEEE 802.11, Multi-rate, Routing, Channel assignment

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## 1. Introduction

Wireless mesh networks (WMNs) are deployed increasingly to provide seamless internet access for the next generation broadband wireless networks. Because of the feasibility of dynamic reconfigurations on a large scale, WMNs can solve "the last mile problem" efficiently, flexibly, and economically. Initially, the IEEE 802.11 standards only support single transmission rate in the physical layer. This limitation has been overcome gradually with the development of wireless transmission techniques as well as more advanced hardware. At present, the support of multi-rate transmission in wireless communication networks has been standardized in the current IEEE 802.11 standards [1]. Benefiting from this multi-rate mechanism, multi-rate WMNs can effectively increase the network capacity and enhance the assurance of the network's quality of service (QoS). Hence, it's essential to make full and reasonable use of multi-rate transmission and the available rate resources in the multi-rate WMNs to enhance the overall network performance. However, the performance of multi-rate WMNs degrades seriously because of the performance anomaly phenomenon, which is pointed out by Heusse in 2003 in multi-rate networks [2]. In multi-rate WMNs networks, links are allowed to transmit in different rates. It is inevitable that some neighboring interference links transmit in the same channel with different rates. Constrained by the CSMA/CA mechanism of 802.11 MAC layer, all links compete channels fairly, thus every link has an equal probability for channel access, regardless of their transmit rates. Compared with the higher rate links, the lower rate links are much more time-costing when transmitting the same amount of data information. The phenomenon, that higher rate links are influenced seriously by lower rate links when they share common public channels, is called performance anomaly. Consequently, even though current IEEE 802.11 protocols support multi-rate transmissions, high rate nodes and links can't take full advantages. The overall network performance degrades seriously because of performance anomaly.

Nowadays, studies generally believe that, only through time equitable principle rather than throughput fairness principle can reach the true fair competitions [3]. It is because just with one-sided throughput fairness pursuit, the lower-rate nodes will occupy channels for much more time than the higher-rate nodes, which is not fair for higher-rate nodes and will greatly reduce overall system throughput [4,5]. The main task of IEEE 802.11 optimization is to achieve the time-based fairness in order to eliminate performance anomalies. It means that the accessing time for different rate links should tend to be equal. The single-channel network is powerless when facing performance anomaly, while the multi-radio multi-channel network has the potential ability to fix it. In the multi-radio multi-channel network, every node is equipped with multiple interfaces, and each interface is tuned to a specific channel. However, the number of non-overlapping channels provided by IEEE 802.11 is limited, so it is important to employ appropriate channel assignment strategies.

Kinds of channel assignment protocols have been proposed for WMNs. Niranjan et al. assign the links with the same or comparable data rates to the same channel to minimize the wastage of channel resources for multi-radio multi-rate single-hop network [6]. Lin et al. present a distributed channel assignment which enables each router to select proper channels to suffer the slightest performance anomaly for the network [7]. Kim et al. separate the high-rate and low-rate links into different channels in [8,9] and seek the high link-rate paths in [10] in their proposed channel assignments for multi-rate networks. A survey and comparison are taken in [11] for existing multichannel protocols proposed to mitigate the performance anomaly problem. The overview works [12,13] summarize and review various channel assignment schemes for multi-radio multi-channel WMNs. Hasan et al. present a network selection and channel allocation mechanism for spectrum sharing, in order to increase revenue by accommodating more secondary users and catering to their preferences, channel assignment can be simultaneously considered with network selection [14].

In static WMNs constituted with fixed mesh routers, transmission rate has an inverse proportion relationship with the distance between two routers. When the distance between two routers increases, a lower rate should be chose for data transmission. The rate selection problems in routing schemes and protocols for multi-rate networks have been discussed in some works. Yun et al. investigate the relationship between physical transmission rate and network capacity in multi-radio multi-channel WMNs, and formulate the joint problem of routing and channel assignment [15]. Rafael et al. present an opportunistic routing in WMNs to jointly optimize both the set of next hops and transmission rates [16]. Liu et al. propose an on-demand bandwidth-constrained routing protocol to discover paths that can meet the end-to-end bandwidth requirements of flows in multi-radio multi-rate multi-channel WMNs [17]. Hu et al. propose a scheme which guarantees that nodes with different transmit rates can access wireless channel fairly by adjusting packet sizes according to their transmission rates [18].In [19], an integrated framework is proposed for joint routing and rate adaptation in multi-rate multi-hop wireless networks. In [20], Rated Window and Packet Size Differentiation schemes are proposed to provide fair proportional throughput for TCP flows of competing stations.

For multi-rate WMNs, there is seldom research working on joint schemes for routing and channel assignment. Kate et al. propose an optimization model to solve the joint problem by considering the dynamic link capacities [21]. A fast heuristic algorithm is proposed in [22] to balance the instantaneous traffics in network. In the algorithm, link-channel assignment is optimized and flow rates are allocated to achieve proportional fairness. The joint problem is also discussed in [23] with the goal to improve spatial reuse by allocating link rates. Different from those previous researches, we first present a joint routing and channel assignment to mitigate performance anomaly for multi-rate multi-ratio multi-channel WMNs. More specifically and within the new joint scheme, the major contributions of this paper are as follows:

1). To achieve the goal of improving network throughput, a joint algorithm combining routing metric and channel assignment is proposed, fully considering the path cost and avoiding the competitions between links of different rate levels. The proposed joint algorithm can significantly improve the network performance, and is fully validated by simulations results with ns-3 using 802.11b.

2). The rate separated method is properly used in channel assignment to avoid the competitions between high rate and low rate links. Thus the negative effects of performance anomaly are significantly decreased, and the overall network performance can be improved.

3). To formulate the performance anomaly problem in multi-rate mechanisms, the multi-ratio multi-channel system model is proposed in this paper, in which different interfaces and orthogonal channels are used to distinguish the high rate and low rate links. This model is practical and complies with the multi-interface multi-channel development trend for WMNs.

# 2. Multi-rate Dijkstra's Shortest path (MDS) routing

## 2.1 Multi-rate system model

Most researches of routing metrics are standing in the unique-rate network environment. The unique-rate assumption does not take the full advantage of the multi-rate capacity of IEEE 802.11 networks. We adopt the multi-rate system model, in which multiple data rates are available. Some links are transmitting in low data rates, while some links can undertake higher rates under the favorable channel conditions. Every node not only selects the next-hop forwarding node, but also chooses a proper transmission rate from the available rate set. Thus, any two nodes in the network can be connected through a chosen path, and the transmission rates for each link along the path can be different from each other. Different transmission rates have different delivery probabilities and link costs. We assume that in the available transmission rate set $R$, every transmission rate $r \in R$ is associated with the specific delivery probability $p_{ij}^{r}$ and link cost $w_{ij}^{r}$ for the link from node $i$ to node $j$.

## 2.2 MDS routing

We modify the Dijkstra's Shortest-Path algorithm to find the minimum-cost paths for multi-rate networks. Dijkstra's algorithm is a famous shortest-path search algorithm in graph theory [24]. It is a classical single-source shortest-path algorithm to find the shortest path from any node to all the other nodes. The expanding search patter is adopted that taking the starting point as the center to expand outwards until reach the destination node. We modify the Dijkstra's Shortest-Path algorithm and propose Multi-rate Dijkstra's Shortest-Path (MDS) routing to search the minimum-cost paths for multi-rate WMNs. In this routing algorithm, both the forwarding nodes and transmission rates are determined for minimizing the overall path cost. Besides, we adopt the "backward" search pattern that paths are built from destination node backward to the other nodes until the source nodes. This search pattern can reduce workload and improve routing efficiency. Using MDS algorithm, we can find the minimum-cost paths not only between any two nodes, but also from any one node to all the other nodes in the network.

In the multi-rate system, the minimum path cost $W_i$ from node $i$ to destination node $d$ is defined as :

$$W_i = \min_{r \in R, j \in G_p} \left\{ W_{ij}^{r} \right\} \tag{1}$$

$$W_{ij}^{r} = w_{ij}^{r} + W_j \tag{2}$$

where $W_{ij}^{r}$ is the overall path cost from node $i$ to destination node $d$, and node $j$ is the forwarding node, and $w_{ij}^{r}$ is the link cost between node $i$ to forwarding node $j$ in transmission rate $r \in R$ , and $W_j$ represents the remaining path cost from forwarding node $j$ to the destination node $d$.

We choose the expected transmission time (ETT) as routing metric [25]. In ETT, the expected transmission time is adopted as the metric index for routing, which means link weights are set by the expected transmission time of data packets. In another words, the link cost is determined by the expected transmission time. Thus, the link cost $w_{ij}^{r}$ is defined as :

$$w_{ij}^{r} = \frac{1}{p_{ij}^{r}} \times T \tag{3}$$

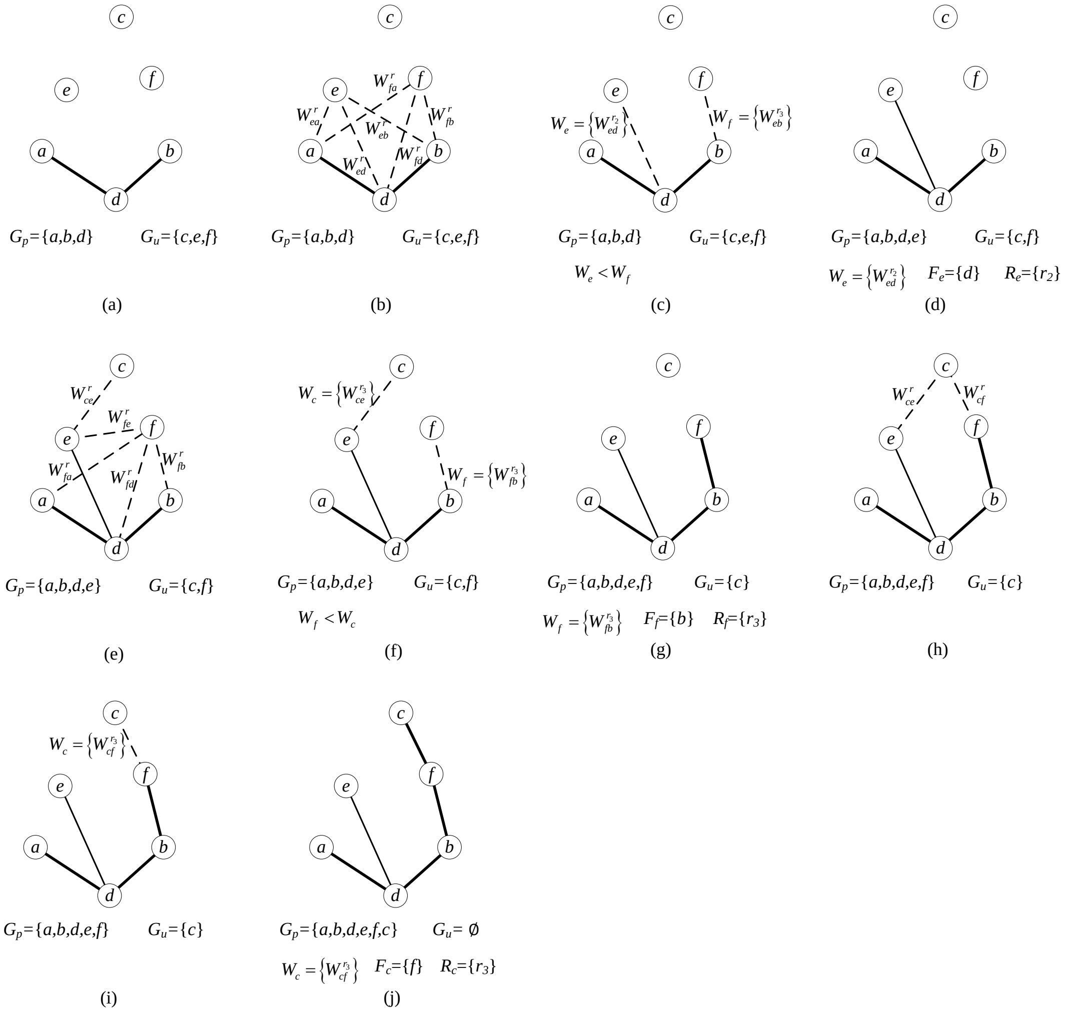
$$T = \frac{s}{r} \tag{4}$$

where $p_{ij}^{r}$ is the delivery probability transmitted in rate $r$ from node $i$ to forwarding node $j$, and $s$ is the packet size. The parameter $w_{ij}^{r}$ represents the time cost of the packet with size $s$ successfully delivered in rate $r$ with probability $p_{ij}^{r}$, and is a reasonable reflection of the time cost of channel usage for link $l_{ij}$. The value of $w_{ij}^{r}$ is affected by transmission rate $r$. Specifically, in (3) $w_{ij}^{r}$ is the function of delivery probability $p_{ij}^{r}$ and transmission time $T$, and rate $r$ has an inverse proportional relationship with transmission time $T$, and the delivery probability $p_{ij}^{r}$ decreases along with the increase of rate $r$. The higher transmission rate means less transmission time cost, but means more retransmission times for successful delivery. Similarly, the remaining path cost $W_j$ is also affected by the link rates along the remaining path.

For a given network graph $G = (V, E)$, $V$ is the set of nodes; $E$ is the set of links between node pairs. The nodes is divided into two groups: the placed-node group $G_p$ and unplaced-node group $G_u$（$G_u$=$G$ -$G_p$）. The placed-node group $G_p$ is the node set within which all nodes have already determined with the minimum path costs, while the nodes in group $G_u$ haven't been checked. Initially, $G_p$={$d$}. Then for every node in $G_u$, its minimum path cost can be found and consequently the node is transferred into group $G_p$. When the group $G_u$ becomes null ($G_p = G$), the minimum-cost paths from all the other nodes to the destination node $d$ are finally built. The process of building minimum-cost paths for all the other nodes to destination node $d$ operates as follows:

1) Step 1: For node $i$ ( $i \in G_u$ ）, taking every node $j$ ( $j \in G_p$ ) as the forwarding node, the cost $W_{ij}^{r}$ of path ($d$, $i$) are calculated for all available rates $r$ ( $r \in R$ ). (Set $W_{ij}^{r} = \infty$ if node $i$ and destination node $d$ are not connected directly, in addition there is no available forwarding node in placed-node group $G_p$.) The minimum $W_{ij}^{r}$ of the calculating results is recorded as the path cost $W_i$ for node $i$.
2) Step 2: Repeat the step 1 for every node in $G_u$. Then find the node $k$ which has the minimum path cost $W_k$ in group $G_u$. The corresponding forwarding node and transmission rate for node $k$ are recorded as $F_k$ and $R_k$.
3) Step 3: Transfer node $k$ into group $G_p$.
4) Step 4: Repeat the given three-step process until $G_u$ = Null ($G_p = G$).

In the whole updating process, it is required that the minimum path costs from node $d$ to every node in group $G_p$ are always not larger than the minimum costs from node $d$ to each node in group $G_u$.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

**Fig. 1.** Demonstration of the process of finding minimum-cost paths using MDS algorithm

An example of MDS algorithm is shown in **Fig. 1**. Node $d$ is the destination node, node $a$, $b$ and $d$ are belong to the placed-node set $G_p$ ($G_p = \{a,b,d\}$), node $c$, $e$ and $f$ are belong to the unplaced-node set $G_u$ ($G_u = \{c,e,f\}$). $R$ is the set of available transmission rates ($R = \{r_1,r_2,r_3\}$, $r_1<r_2<r_3$). The process of finding minimum-cost paths using MDS algorithm is demonstrated in **Fig. 1**.

The pseudocode of MDS algorithm is listed as follows:

**Algorithm 1.** MDS algorithm

```
function MDS$(G, w, s, R, F)$
  $G_p = \varnothing$
  $G_u = V[G]$
  $W_d = 0$
  for each vertex $i$ in $V[G]$
      $W_i = \infty$
      $F_i = \varnothing$
      $R_i = 1$
  while $G_u \neq \varnothing$
      $W_k = \infty$
      for each vertex $i$ in $G_u$
          for each vertex $j$ in $G_p$
              for each rate $r$ in $R$
                  $W_{ij}^r = w_{ij}^r + W_j$
                  if $W_i > W_{ij}^r$
                      $W_i = W_{ij}^r$
                      $F_i = \{j\}$
                      $R_i = \{r\}$
          if $W_k > W_i$
              $W_k = W_i$
              $k = i$
      $G_p = G_p \bigcup \{k\}$
      $G_u = G_u - \{k\}$
```

## 3. MDS-based Rate Separated (RS) channel assignment

The overall network performance is suppressed by performance anomaly in multi-rate networks. To solve the performance anomaly problem, a highly efficient channel assignment protocol is designed in this section. In the proposed channel assignment, a new metric index—Link Rate Variance (LRV) is proposed to measure the influence of performance anomaly on network throughput. Links are separated according to their transmission rates before competitions are built between low rate links and high rate links. The proposed channel assignment scheme is a joint-design with routing metric. Conventional routing metrics assume that channel assignments are performed by external agency and there is no modification and adjustment in channel assignment. But in practical terms, channel conditions are affected greatly by many factors, and this static network assumption can’t meet the real performance requirement. For this reason, we investigate the joint routing metric and channel assignment, and propose the MDS-based rate-separated channel assignment.

To prevent the channel competitions between low rate links and high rate links, mixed allocations of high rate and low rate links in the common channel should be avoided. High rate links and low rate links should be allocated into different channels, so that high rate links will compete with high rate links, and low rate links will compete with low rate links. The minimum cost paths can be built through MDS routing, and both the forwarding hops and link transmission rates of each node can be determined. Then the rate separated channel assignment is operated for the links of each node. In multi-interface multi-channel multi-rate network, links in each node will be separated and assigned to different interfaces according to their rate levels, and then channels are allocated to interfaces. The maximum throughput weight for each node can be achieved in this way.

### 3.1 Link Rate Variance (LRV)

As a result of performance anomaly, network throughput is affected by the competitions among links with various transmission rates. The index LRV is proposed to reflect the effect degree. We assume all links are in saturation state, the LRV of interface *m* is:

$$v_m = 1 / \left( 1 + \left( \frac{1}{L_m} \cdot \sum_{l \in C_m} \left( r_l - \frac{1}{L_m} \cdot \sum_{l \in C_m} r_l \right)^2 \right)^{1/2} \right) \tag{5}$$

The LRV of node *i* is given as:

$$V_i = \sum_{m \in M_i} v_m \tag{6}$$

where $M_i$ represents the interfaces set of node *i*, $L_m$ is the link number of interface *m*, $C_m$ is link set of interface *m*, *l* is a link on interface *m*, $r_l$ is the transmission rate for link *l*. In fact, LRV is the total standard deviation of transmission rates, and it can be used to measure the degree of the effects of competitions among multi-rate links on network throughput or original links.

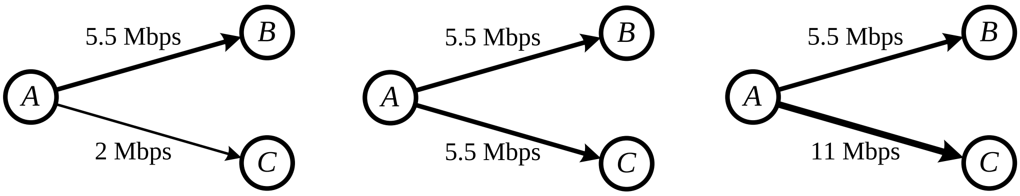


**Fig. 2.** Two links with different rates compete for a common interface.

Three cases are listed in **Fig. 2** to explain the function of LRV. We assume link $l_{AB}$ is the original link with transmission rate $r_{AB}$=5.5Mbps, and link $l_{AC}$ is the new incoming link in three different rates 2Mbps, 5.5Mbps, 11Mbps. Link $l_{AB}$ and $l_{AC}$ share the common interface *m*. Following the fairness principle of IEEE 802.11 MAC layer, the theoretical system throughputs, throughput differentials and LRVs for three cases are respectively calculated. The throughput differential is the absolute value of difference between two theoretical system throughputs that before and after the enrollment of link $l_{AC}$. And the theoretical system throughput *c* is calculated as:

$$c = \frac{1}{\sum_{l \in C_m} r_l^{-1}} \times L \tag{7}$$

where $C_m$ is the set of links competing for common interface $m$, $L$ is the number of these competing links, and $r_l$ represents the rate of link $l$.

The theoretical system throughput in the case of Fig. 2 is calculated as:

$$c' = \frac{1}{r_{AB}^{-1} + r_{AC}^{-1}} \times 2 \tag{8}$$

The calculation results for the cases of **Fig. 2** are shown in **Table 1**.

For the first case $r_{AC}$=2Mbps, the system throughput becomes larger than 2Mbps but smaller than original system throughput 5.5Mbps; for the second case, the later system throughput is 5.5Mbps and remains the same with the original system throughput; for the third case, the system throughput with new incoming link becomes larger than original system throughout but smaller than the incoming link throughput 11Mbps. We can see that system throughput inevitably changes when there are new incoming links competing for channels. The system throughput is driven down by the lower rate links and driven up by the higher rate links; system throughput would remain unchanged when the new incoming links have the same rates with pre-existing links. The values of LRVs reflect the degrees of system throughput changes. If the incoming link has a rate that has relatively small effects on system, LRV will remain relatively large ($\mathrm{LRV} \leq 1$).

**Table 1.** Calculation results of theoretical system throughputs, throughput differentials and LRVs

| $r_{AC}$ | Theoretical system throughput | Throughput differential | LRV |
|---|---|---|---|
| 2 Mbps | 2.9 Mbps | 1.7 Mbps | 0.36 |
| 5.5 Mbps | 5.5 Mbps | 0 Mbps | 1 |
| 11 Mbps | 7.3 Mbps | 1.9 Mbps | 0.27 |

### 3.2 Rate Separated (RS) channel assignment algorithm

Only using LRV to make channel assignment, links in the same or similar rates are likely allocated together. The link numbers on interfaces could have an uneven distribution. Some interfaces could suffer a heavy load, while some are relatively vacant. For example, there are one link in 11Mbps, 6 links in 5.5Mbps, and two links in 2Mbps. To achieve the maximum LRV, the only one link in rate 11Mbps will be allocated to interface $m_0$, 6 links in rate 5.5Mbps will be allocated to interface $m_1$, and the two links in rate 2Mbps will be allocated to interface $m_2$. Obviously, $m_1$ is overloaded, but $m_0$ and $m_2$ have relatively light loads. Although the performance anomaly is avoided, the throughput would decrease because of the uneven distribution of link number on every interface. To solve this uneven link distribution problem, another index called Jain's fairness indices [26] is introduced. The Jain's fairness indices of node $i$ is expressed as:

$$J_i = \frac{(\sum_{m=1}^{D} L_m)^2}{D \times \sum_{m=1}^{D} L_m^2} \tag{9}$$

where $L_m$ is the link number of interface $m$, and $D$ is total interface number of node $i$. The $J_i$ is an efficient measurement of the proportionality of channel assignment. The value of $J_i$ approaches $1/D$ when links are allocated extremely biasedly, while $J_i$ approaches 1 when there is an absolutely even distribution of links for every interface. Combing LRV and fairness indices $J_i$, the throughput weight of node $i$ can be defined as:

$$S_i = V_i \times J_i \tag{10}$$

We design the Rate Separated channel assignment (RS) algorithm based upon the throughput weight $S_i$. The RS algorithm has the ability to avoid performance anomaly through separating links into different interfaces according to their transmission rates for every multi-interface multi-channel node, and to improve the network throughput. The RS algorithm is performed in two phrases. For the first phase links are allocated to interfaces, and then for the second phase channels are assigned to interfaces for every node.

The process of allocating links to interfaces for node $i$ is operated as follows:

1) Step 1: There are three interfaces respectively $m_0$, $m_1$, $m_2$ and $k$ links for node $i$. The $k$ links are ranked in a descending order of their transmission rates $l_1,l_2,l_3\ldots\ldots l_k$. And they are divided into two group, $G_1=\{l_1,l_2,l_3\ldots\ldots l_{\lfloor k/2\rfloor}\}$and $G_2=\{l_{\lfloor k/2\rfloor+1}, l_{\lfloor k/2\rfloor+2},\ldots\ldots l_k\}$. Obviously, the link $l_{\lfloor k/2\rfloor}$ is the lowest rate link in group $G_1$, and the link $l_{\lfloor k/2\rfloor+1}$ is the highest rate link in group $G_2$. All of the links in group $G_1$ are temporally allocated to interface $m_0$. And all of the links in group $G_2$ are temporally allocated to interface $m_2$. The interface $m_1$ is temporally empty. Then the current throughput weight $S_i$ for node $i$ is calculated.
2) Step 2: Move the link with the lowest rate in group $G_1$ to interface $m_1$, and calculate the new node throughput weight $S_i'$. If $S_i' > S_i$, allocate this link to the interface $m_1$ permanently and the node throughput weight is updated to $S_i'$, then proceed to step 3; if $S_i' \le S_i$, return this link to interface $m_0$, the node throughput weight remains unchanged as $S_i$, the link assignment for interface $m_0$ is over, then proceed to step 4.
3) Step 3: Repeat the step 2 for the next lowest rate link in group $G_1$.
4) Step 4: Move the link with the highest rate in group $G_2$ to interface $m_1$, and calculate the new node throughput weight $S_i'$. If $S_i' > S_i$, allocate this link to the interface $m_1$ permanently and the node throughput weight is updated to $S_i'$, then proceed to step 5; if $S_i' \le S_i$, return this link to interface $m_2$, the node throughput weight remains unchanged as $S_i$, the link assignment for interface $m_2$ is over, then proceed to step 6.
5) Step 5: Repeat the step 4 for the next highest rate link in group $G_2$.
6) Step 6: The link allocations for node $i$ comes to the end.

An example of the link allocation process is shown in **Fig. 3**.

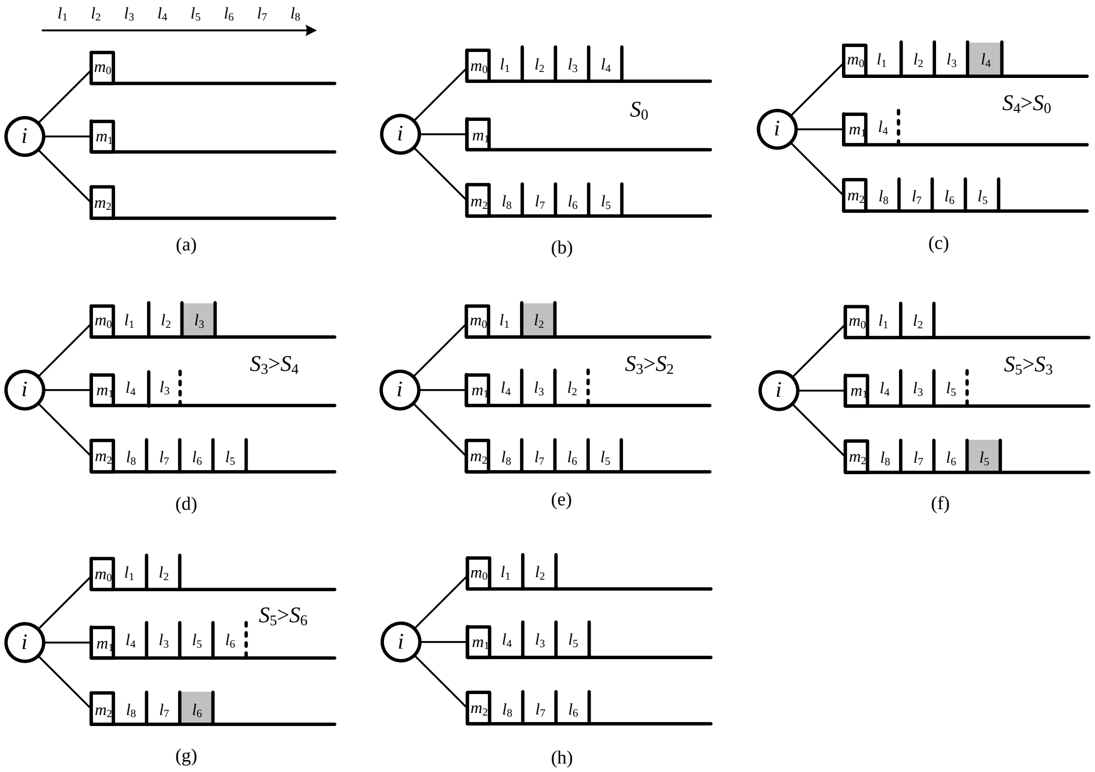


**Fig. 3.** Schematic diagram for link allocations

After allocating links to interfaces for all nodes, the channel assignments are implemented for interfaces starting from the destination node backwards to source nodes. We assume the neighboring nodes within two hops are interference nodes. The total transmission time for all the links using a common channel within the interference range is adopted to reflect the interference status. And it is employed as the main index to perform channel assignment. The total expected transmission time $T_{total}\left(i_m^k\right)$ of interface *m* using channel *k* of node *i* is written as:

$$T_{total}\left(i_m^k\right)=\sum_{l_m\in C_m} T_{l_m}^k+\sum_{l_x\in B} T_{l_x}^k \tag{11}$$

In (11), $T_{l_m}^k$ is the expected transmission time of link $l_m$ on interface *m* using channel *k*, $T_{l_x}^k$ is the expected transmission time of link $l_x$ which is the link using the common channel *k* in the interference neighboring node *x*, *B* is the set of interference neighboring nodes. The first term of (11) stands for the total expected transmission time of the links on interface *m*, and the second term reflects the interference conditions among the links competing for the common channel within interference range.

After calculating the total expected transmission time $T_{total}\left(i_m^k\right)$ for each channel, assign the channel with the minimum $T_{total}\left(i_m^k\right)$ to interface *m*.

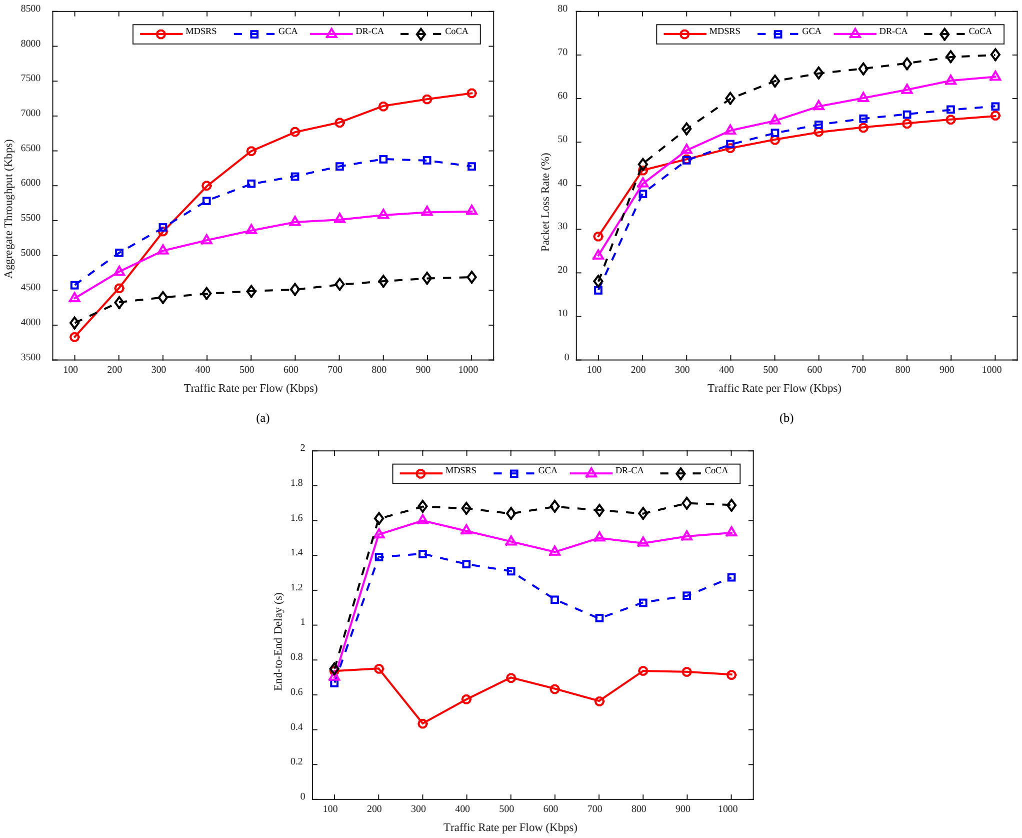
## 4. Simulation Results

In this section, NS-3 is used for simulations to compare the network performance between MDSRS, GCA[8], DR-CA[6] and CoCA[9]. In the simulation scenario of 1500* 1500m WMNs area, 30 routing nodes are distributed randomly, and one node is randomly selected as the gateway. A number of routing nodes are randomly selected to transmit data flows to gateway. All nodes are configured with three IEEE 802.11b interfaces. Three orthogonal channels are available. According to the two-ray ground wireless transmission model, the transmission rate is determined by the distance between two nodes. We choose 1Mbps, 2Mbps, 5.5Mbps and 11Mbps in 802.11b as the available rates, and the corresponding maximum transmission ranges are 300m, 250m, 200m, and 150m respectively. Packet size is set as 1000 bytes. Simulation time is set to be 120s. The system parameter settings of NS-3 simulation for performance evaluations are shown in Table 2.

**Table 2.** Parameters for performance evaluation

| Parameters | Values |
|---|---|
| Simulator | NS-3 |
| Comparison | MDSRS, GCA [8], DR-CA [6], CoCA [9] |
| PHY/MAC technology | 802.11b |
| Network size | 1500 m × 1500 m |
| No. of nodes | 30 (random distribute) |
| No. of channels | 3 |
| No. of interfaces | 3 |
| No. of gateways | 1 |
| Propagation model | The two-ray ground propagation model |
| Data rates | 1 Mbps, 2 Mbps, 5.5 Mbps, 11 Mbps |
| Transmission ranges | 300 m, 250 m, 200 m, 150 m |
| Packet size | 1000 bytes |
| Simulation time | 120 s |

For the first simulation scenario, the number of active nodes in transmitting is fixed to be 30, and the traffic rate for each node increases gradually. Performance evaluations and comparisons between MDSRS, GCA, DR-CA and CoCA are carried out. Network throughputs, average packet loss probabilities and average end-to-end delays are respectively evaluated, and the results are illustrated in **Fig. 4**. In **Fig. 4(a)**, the network throughput increases along with traffic rate both for MDSRS, GCA, DR-CA and CoCA. It is noted that 300 Kbps of traffic rate is the critical point for the throughput competitions of MDSRS. The proposed MDSRS has an obviously better network throughput performance when the traffic rate is beyond 300 Kbps. However, when the traffic rates are below 300 Kbps, our proposed MDSRS has a weaker throughput performance. It is because our proposed joint scheme of routing metric and channel assignment has a certain demand for network costs. And the network costs are not sensitive to traffic rates, so the performance advantages of MDSRS are more remarkable when the network runs with a high rate. It is worth mentioning that current networks services have increasing requirements of network bandwidth, and seldom of them are below 300 Kbps. Similar results for the evaluations of packet loss probability are showed in **Fig. 4(b)**. The packet loss probability with MDSRS is higher than them when the traffic rate is below 300 Kbps, and is lower than GCA when the nodes send packets in the rate beyond 300 Kbps. **Fig. 4(c)** indicates the relationships between network average end-to-end delay and traffic rate for MDSRS, GCA, DR-CA and CoCA. We can find that MDSRS has a consistently better performance of average end-to-end delay than them, showing a significant delay decrease.



(a) (b)

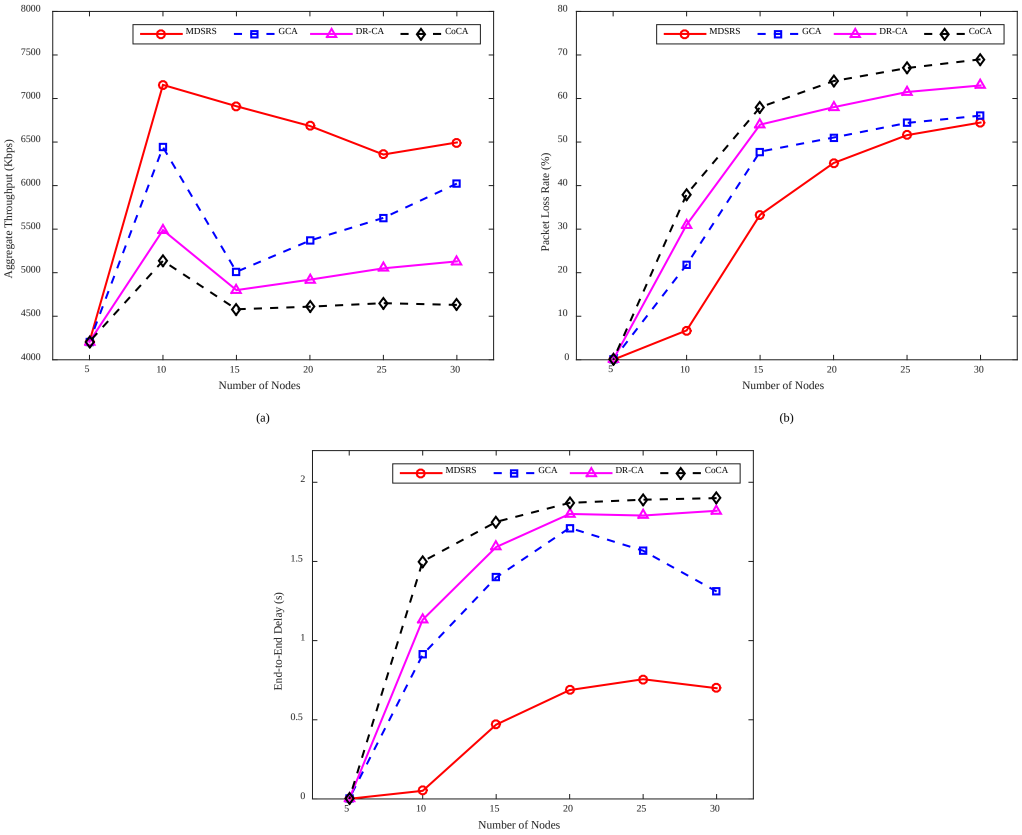
(c)

**Fig. 4.** Performance evaluations and comparisons when the traffic rate varies

For the second simulation scenario, the nodes' traffic rate is fixed as 500 Kbps, and the range of active routing node number is set from 5 to 30. In the simulation process, the number of data flow increases gradually. Network throughputs, average packet loss probabilities and average end-to-end delays for MDSRS, GCA, DR-CA and CoCA are evaluated and compared. The results are illustrated in **Fig. 5**. In **Fig. 5(a)**, MDSRS has a better performance in network aggregate throughput than GCA, DR-CA and CoCA. For instance, when nodes number is 25, the aggregate throughput by MDSRS is 12.9% higher than that by GCA, 25.8% higher than DR-CA, 36.7% higher than CoCA. **Fig. 5(b)** shows that the MDSRS implemented network has a lower average packet loss probability than the network implemented with GCA. For instance, when the nodes number is 25, the packet loss rate by MDSRS is 5.2% lower than that by GCA, 16.1% lower than DR-CA, 23.1% lower than CoCA. Average delay evaluations are illustrated in **Fig. 5(c)**, and MDSRS has consistently less average end-to-end delay than GCA. When the nodes number is 25, the end-to-end delays by MDSRS is 51.7% lower than that by GCA, 57.5% lower than DR-CA, 60.3% lower than CoCA.

The performance improvement of MDSRS can be explained as follows. MDSRS can take full account of network conditions by combining the routing metric and channel assignment. So it can make a better selection of paths, transmission rates and available channels for nodes according to different network status, and transmit data packets quickly and effectively.

Therefore, the network throughput is improved and average packet loss rate and average end to end delay are decreased.



(a)

(b)

(c)

**Fig. 5.** Performance evaluations and comparisons when the number of nodes varies

## 5. Conclusions

A joint routing and channel assignment called MDSRS is proposed in this paper to mitigate performance anomaly for multi-rate WMNs. In the proposed scheme, routing metric is carried out through effective measurements for link rates and path costs; channel assignment is performed based on the determined routing metric. By combining the routing metric and channel assignment, the network conditions are fully considered, and the performance anomaly is avoided. Our proposed MDSRS not only helps choose the suitable rates for different links, but also has the better network load balance capacity in the assignment of links and channels. MDSRS allows the network achieve a significantly reduction in end-to-end delay and at the same time maintain relatively high throughput and low packet loss probability. The performance of MDSRS algorithm is verified by simulations using NS-3. Simulation results indicate that, by using MDSRS, network throughput has a remarkable improvement and the network delay and packet loss probability are both reduced. Especially in the heavy load network, there are obvious performance advantages, which reflect MDSRS's robust capacity in the end-to-end performance improvement and network capacity optimization.

In the future research, considering the real-time and diversity characters for realistic network, we will develop MDSRS into a dynamic joint algorithm for channel assignment and routing metric. The partially overlapped channels will be adopted. We will also study how to reduce the additional overhead caused by the joint algorithm, so that the algorithm can meet the needs of various types of business. In addition, the algorithms will be tested and polished through the implementations of the experimental networks.

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