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An Efficient Bow-Based On-Demand QoS Routing Protocol for MIMO Ad Hoc Networks

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Abstract

The multiple inputs multiple output (MIMO) architecture supports smart antennas and MIMO links is now a popular technique for exploiting the multi-path, spatial multiplexing, and diversity gain to provide high spectral efficiencies and performance improvement in wireless ad hoc networks. In this work, we propose a new multi-path on demand quality-of-service (QoS) routing architecture, looked like a bow and called as *bow*, in MIMO ad hoc networks. A bow-based MIMO ad hoc networks routing protocol, named as BowQR, is also proposed to support QoS requirement and to improve the transmission efficiency. Each *bow* structure is composed of rate-links and/or range-links on demand to provide multi-path routing and satisfy the bandwidth requirement. Two types of transmission links, the rate-link and range-link, exploit the spatial multiplexing and spatial diversity to provide extremely high spectral efficiencies and increase the transmission range. Finally, the simulation results show that our BowQR protocol achieves the performance improvements in throughput, success rate, and average latency.

Key words: Quality-of-service, MIMO, ad hoc network, rate-link, range-link.

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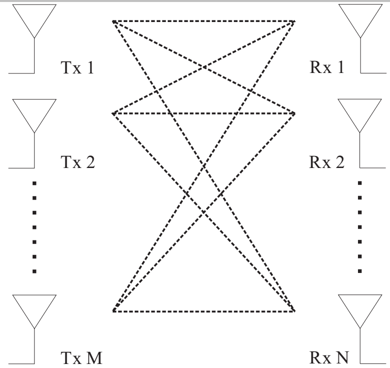


Fig. 1. MIMO illustration.

1 Introduction

In recent years, the multiple inputs multiple output (MIMO) system is a rapid growth technology in wireless communications [1][7][8][9][14][18]. MIMO systems contain multiple antennas for both transmitter and receiver, as shown in Fig.1. The usage of the MIMO mechanism increases the transmission data rates of wireless systems without any additional power consumption and bandwidth usage. A MIMO link employs multiple element arrays (MEAs) at both ends of the end-to-end communication. Such links provide two types of gain, the diversity gain and multiplexing gain, which are two options for the operating mode in the MIMO system [11][23]. In the operation of spatial multiplexing, the transmission link is denoted as the rate-link [20] and the incoming data is demultiplexed into some distinct streams on the same number independent antennas. Each stream is simultaneously transmitted out of an independent antenna in the same channel. Specially, the usages of multiple parallel streams achieve higher capacity on each point-to-point link. In the operation of diversity, the transmission link is denoted as range-link [20] and the data streams of the link are transmitted by multiple antennas simultaneously. The characteristics of multiple antennas contain the increase of the transmission range, the decrease of the bit-error rate (BER), and the decrement of the signal to noise ratio (SNR) or multi-path fading of the link. The usages of MIMO links are exploited in the WLAN and WiMAX standards, such as IEEE 802.11n and 802.16 standards, and become more extremely popular in many currently researches [2][10][17][19][20][21].

In this work, we focus on the QoS supporting and performance enhancing for the MIMO links furnished the MIMO ad hoc network. The MIMO ad hoc network is different from the traditional ad hoc network that each mobile node equips multiple antennas and operates in the same channel. Specially, the QoS routing problem in MIMO ad hoc networks is also an important issue [4][5][6][14]. The QoS routing protocol supports mobile applications to guarantee their bandwidth requirement. A QoS routing protocol with bow-based architecture, namely BowQR, is developed in our MIMO ad hoc networks to enhance the transmission efficiency. A QoS satisfied the bow-path will be constructed after our BowQR protocol executed. It simultaneously takes two operations of MIMO link into consideration, that are spatial multiplexing and spatial diversity, to guarantee the QoS and improve the performance. In addition, a special multi-path structure, looked like a bow and called as *bow* structure, is identified in our MIMO ad hoc networks. Each *bow* composes of rate-links and/or range-links on demand and is identified to satisfy the QoS requirement.

The rest of this paper is organized as follows. Some related works are discussed in Section 2. Section 3 presents the system model and basic idea of our QoS routing protocol. Section 4 gives the performance analysis of our work, which has higher throughput and better success rate but with more overhead. Finally, Section 5 concludes this paper.

2 Related works

The usage of MIMO mechanism can increase the data rates of wireless systems without any additional power consumption and bandwidth usage. The usage of MIMO system grows rapidly in wireless communications. Some medium access control (MAC) and routing protocol for MIMO ad hoc networks are developed in[1][7][8][9][14][17][18][20].

In [17], Karthikeyan *et al.* present a MAC protocol for MIMO ad hoc networks that leverages the physical layer capabilities of MIMO links with the focus being predominantly on the spatial multiplexing capability of MIMO links. They identify several advantages of MIMO links and discuss several key optimization considerations to realize an effective MAC protocol for such an environment. Contiguously, Karthikeyan *et al.* present a first routing protocol in ad hoc network with MIMO links in [20]. They make three following works. First, they identify the capabilities of MIMO links and capture the relevance to their routing protocols.

Then, they analyze the relative tradeoffs of exploiting the different capabilities of MIMO links. Finally, they propose a reactive routing protocol with MIMO links, namely MIR, whose components are built on the insights gained from the analysis results, and hence leverage the characteristics of MIMO links in their operations to improve the network performance[20]. The MIR protocol proposed by Karthikeyan *et al.* [20] is the first proposed routing protocol in MIMO ad hoc networks, but it is only an uni-path (they choose the best one from several available routing paths by their definition) result. Each transmission in the MIR protocol considers only the uni-path rate-link or range-link. The high latency transmission problem occurred on the condition that the rate of one link in the path is too slow. To overcome this problem, our work focuses on developing an multi-path QoS routing protocol for MIMO ad hoc networks. Several QoS routing protocol in ad hoc networks are developed in [3][4][5][13][14]. In [14], Lin *et al.* calculate the end-to-end path bandwidth to develop an on demand QoS routing protocol in a mobile ad hoc network (MANET). Under their routing protocol, the source sends the calculated message and QoS available to the destination in the mobile network. Further, W.-H. Liao *et al.* [13] propose an on demand protocol for searching a multi-path QoS route from a source host to a destination host. Their basic idea is distributing a number of tickets from a source and allowing a ticket to be further partitioned/split into sub-tickets to search for a satisfactory multi-path.

More recently, Chen *et al.* [5] develop an on demand link-state multi-path QoS routing protocol on the wireless mobile ad hoc network. Their protocol collects the bandwidth information of whole links from the source to the destination in order to construct a network topology with the information of each link bandwidth. They offer a multi-path route when the single route of the network contains insufficient bandwidth and offer a uni-path route when the network contains sufficient bandwidth. The destination eventually determines the QoS multi-path routes and replies the source host to perform the bandwidth reservation. Besides, Chen *et al.* propose a lantern-tree-based QoS multicast protocol with a reliable mechanism for MANETs in [4]. They identify a lantern-tree in a MANET to provide an on demand QoS multicast protocol to satisfy the certain bandwidth requirements from a source to a group of destination nodes. The lantern-tree is a tree whose sub-path is constituted by the lantern-path, where the lantern-path is a kind of multi-path structure.

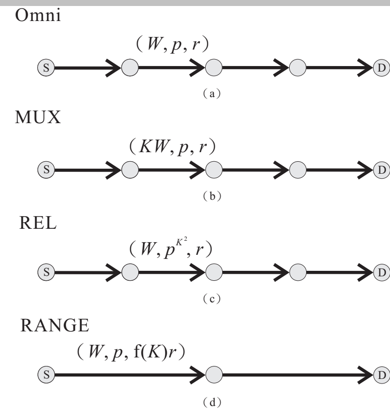


Fig. 2. Strategies of MIMO Operation: (a) one omni-antenna, (b) spatial multiplexing (c) reliability, and (d) transmission range .

To summarize above, several QoS routing protocols in ad hoc networks under time division multiple access (TDMA) model are developed [3][4][5][12][13][15][16]. Our approach simultaneously takes the rate-link and range-link into consideration so as to maintain a QoS multi-path route in MIMO ad hoc networks and utilizes the concept of multi-path route to develop a new multi-path structure, named as the *bow* structure. Further, we propose a bow-based QoS routing protocol to enhance the MIR protocol [20] in MIMO ad hoc networks. The simulation results show that our work improves the success rate, the average latency, and the throughput when the QoS routes are constructed. Nevertheless, the high success rate causes some overheads in our work. In the following section, we will propose our system model and basic idea under the time division multiple access (TDMA) model.

3 System model and basic idea

In this section, we discuss the definitions of our system model and basic idea. Our system model works on the ad hoc network with MIMO links and the MAC sub-layer is implemented by the TDMA channel model. We introduce the enhancements by using different operations of MIMO links. Our basic idea contains some various operations of the MIMO link in each TDMA cycle and is described as follows.

3.1 System model

Our works base on two operations of MIMO link, rate-links for spatial multiplexing and range-links for spatial diversity. In the following, we introduce the enhancements between two operations of MIMO link and omni-antenna link [1][8][20], as shown in Fig. 2. Figure 2 (a) illustrates the MIMO operations of the omni-antenna that contains the values of the transmission rate W, the bit error rate (BER) p, and the communication range r. By the way, the notation tuple of each link on omni-antenna is denoted as (W, p, r). Further, we focus on the strategies of the other three MIMO operations, spatial multiplexing (MUX), diversity to increase reliability (REL), and transmission range (RANGE). In the operation of spatial multiplexing, the incoming data is demultiplexed into K distinct streams on K independent antennas and each stream is simultaneously transmitted out of an independent antenna in the same channel. The transmission link of spatial multiplexing is denoted as the rate-link. The use of multiple parallel streams can achieve higher capacity on a single point to point link. That is, the operation usage of spatial multiplexing can linearly increase the link rate from the value of the rate W to KW. The notation tuple of MIMO link that using spatial multiplexing operation is denoted as (KW, p, r), as shown in Fig. 2(b). In the operation of diversity, the same data stream of the link is transmitted by multiple antennas simultaneously. The use of multiple antennas, which transmit the same data stream, can increase the transmission range or the link reliability and enhances the signal to noise ratio (SNR) or multi-path fading of the link. Using the operation of diversity can decerease the BER from the value p to p^K, where $0 \leq p \leq 1$, and thus increases the reliability.

The notation tuple of MIMO link that using diversity operation to increase link reliability is denoted as (W, p^K, r), as shown in Fig. 2(c). Using the operation of spatial diversity can increase communication range from the value r to $f(K)r$. The transmission link of spatial diversity is denoted as range-link. The notation tuple of MIMO link that using spatial diversity operation to increase communication range is denoted as (W, p, $f(K)r$), as shown in Fig. 2(d). In our system model, we only focus on the issues of the rate-link and range-link for MIMO ad hoc networks. In the following section, we will introduce the usages of the rate-link and range-link in one TDMA cycle.

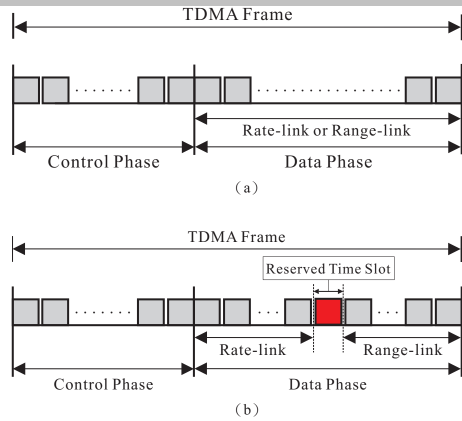
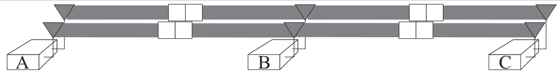


Fig. 3. TDMA frame structure (a) original structure and (b) our approach for MIMO links.

3.2 Basic idea

Our scheme mainly proposes a bow-based on-demand QoS routing protocol to satisfy the QoS requirement in multiple input multiple output (MIMO) ad hoc networks. The QoS satisfied routing path is decided when all the available pre-reserved messages gathered at the destination node. The destination node choose the best routing path which contains low overhead shortest path, and then sends the real reserving message back to the source node along the chosen path. The other pre-reserved routing paths will be dropped when the waiting time passed. For the presentation purpose, we only take one of the available multi-paths to illustrate our approach in the following sections. Two mode of operations with MIMO links in a data phase at one TDMA cycle are adopted to serve the network transmission. The first one is the rate-link which is known as the spatial multiplexing mode, and the other is the range-link which is known as the diversity mode. The network model is described as follows. The MAC sub-layer in our bow-based model is implemented by using the TDMA channel model. The active phases of each TDMA frame are divided into a control phase and a data phase as shown in Fig. 3(a). The bandwidth requirement is realized by reserving time slots on each link. The data phase of each TDMA cycle is either a rate-link or a range-link. In the control phase, the mode of the following data phase, which is either a rate-link or a range-link, will be decided. Our assumption is that the data phase of each TDMA cycle is composed of both the rate-link period and the range-link period. Specially, there is one reserved time slot, denoted as RTS, between the rate-link period and range-link periods as shown in Fig. 3(b). This RTS is reserved for changing the operations between the spatial multiplexing



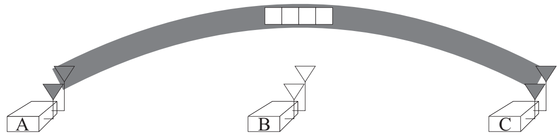


Fig. 4. Examples of (a) rate-link and (b) range-link on 2x2 MIMO links for $B_r = 4$ time slots.

(rate-link) and the spatial diversity (range-link). Each node's reserved time slots can not be its free time slots and is fixed in the network. That is, the length of rate-link and range-link period are fixed when the network is initiated. The time interval of changing operations between spatial multiplexing (rate-link) and diversity (range-link) is not greater than a short interframe space (SIFS) time interval [11]. The time interval of SIFS is about 5μs and the time interval of one time slot in data phase is about 10μs. Therefore, the reserved time slots in data phase are enough to change two operations between the spatial multiplexing (rate-link) and spatial diversity (range-link). Under this assumption, we focus on how to exploit the rate-link and range-link efficiently in our scheme, as shown in Fig. 4(a) and (b) respectively.

Fig. 4(a) displays the two-hop example that there are three nodes, node A, node B, and node C, in the network. Node A and node C are two-hop neighboring nodes. Each of them equips two antennas which operates separately in different spatial. There are two rate-links among them. One rate-link is from node A to node B, the other is from node B to node C. We observe that there are two time slots in each spatial (antenna) separately. That is, if we define the symbol B_r to denote the bandwidth requirement of QoS, then each rate-link has four time slots totally to satisfy the $B_r = 4$ time slots. In addition to the rate-link, Fig. 4(b) shows that there is a range-link between nodes A and C, two antennas of node A need to operate in the same spatial in order to extend the transmission range. It means that one antenna is sacrificed to operate in the other spatial (antenna). Specially, it is known that the collaborative usage of two antennas can extend the transmission range from one-hop to two-hop neighbors. We observe that there are four time slots in one spatial (antenna). That is, the range-link between nodes A and B has four time slots totally to satisfy the bandwidth requirement $B_r = 4$ time slots.

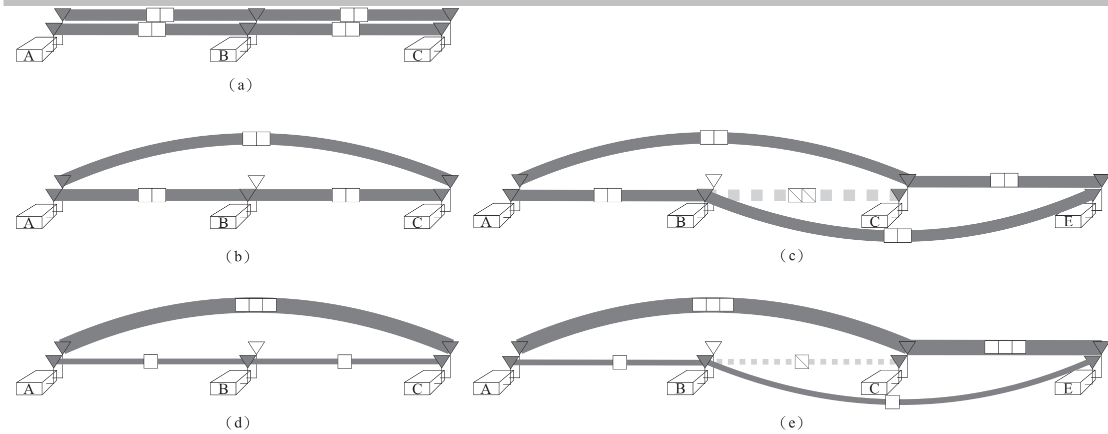


Fig. 5. Example of different bow structures with 2x2 MIMO.

Our scheme identifies a special multi-path structure, named as the *bow* structure. Each *bow* is composed by rate-links and/or range-links on demand to satisfy the bandwidth requirement. In a different bandwidth situation, two *bows* can combine to form one *twin-bow*. Further, we propose a bow-based QoS routing protocol, named as the *BowQR* protocol, to construct a routing path, denoted as *bow-path*, which satisfies a given QoS bandwidth requirement under the TDMA channel model with MIMO links from a source node to a destination node.

In the following, we introduce the terms "bow", "twin-bow" and "bow-path". In this paper, the main concept is using different operations of MIMO links to identify one or more bows/twin-bows to form the routing path from the source to the destination to achieve the QoS requirement, named as the bow-path. We consider four successive neighbor nodes, node A, node B, node C, and node E, as illustrated in Fig. 5(c) and (e). Four successive nodes are formed two pairs of two-hop neighboring nodes, pairs (A, C) and (B, E). A QoS path is requested from source node A to destination node E with a QoS bandwidth requirement B_r. When the network bandwidth is sufficient (greater than the QoS request B_r), our protocol chooses only the rate-link for routing path, as illustrated in Fig. 5(a). If the actual bandwidth (rate-link) B'_r between nodes A and B is less than B_r ($B'_r \leq B_r$), but the range-link B''_r between nodes A and C is sufficient for the bandwidth requirement B_r ($B''_r \geq B_r$), our protocol chooses the range-link for routing path, as shown in Fig. 4(b). Fig. 5(b) and (d) display the multi-path structure, named as the *bow* structure. If the actual bandwidth requirement B'_r between nodes B and C is strictly insufficient ($B'_r \leq B_r$), then node B try to find out the range-link between nodes B and E as illustrated in Fig. 5(c) and (e). Fig. 5(c) and (e) display the multi-path structure, named as the *twin-bow* structure.

Definition 1: Bow structure. Given m-hop successive neighboring nodes α, $n_1 \cdots n_i$, and β, where each node equips with m antennas. Let the multi-path route tuple $\begin{bmatrix} \alpha & \overset{-^*}{} & \beta \\ & n_1 \cdots n_i & \end{bmatrix}$ denotes a *bow* structure from nodes α to node β, where the upper part $\begin{bmatrix} \alpha \ -^* \ \beta \end{bmatrix}$ is a range-link between nodes α and β, the closure star * indicates the number of cross nodes that depending on the available bandwidth of the lower part link $\begin{bmatrix} \alpha \ n_1 \cdots n_i \ \beta \end{bmatrix}$; $\begin{bmatrix} \alpha \ n_1 \cdots n_i \ \beta \end{bmatrix}$ is a path from nodes α to β, and links $\begin{bmatrix} \alpha \ n_1 \end{bmatrix}$, $\begin{bmatrix} n_1 \ n_2 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} n_i \ \beta \end{bmatrix}$, $i \leq m-1$, are either a rate-link or no communication. The total bandwidth between α and β is defined as $B_{\alpha\beta} = \left\| \begin{bmatrix} \alpha & \overset{-^*}{} & \beta \\ & n_1 \cdots n_i & \end{bmatrix} \right\|$, and $B_{\alpha\beta}$ is equal to the bandwidth requirement B_r, that is $B_{\alpha\beta} = B_r$.

Fig. 5 displays that each node equips with two antennas and the bandwidth requirement B_r is 4 time slots. When the rate-link bandwidth is sufficient for the requirement, it only uses a rate-link from node A to node B and a rate-link from node B to node C to construct the QoS routing path $[A\text{-}B\text{-}C]$, as shown in Fig. 5(a). If the available bandwidth between nodes A and B is below the bandwidth requirement B_r, but the sum that added to the available bandwidth between nodes A and C is greater than B_r. Then, the range-link from nodes A to C (cross node B) and the rate-links from nodes A to B and from nodes B to C will be adopted, as illustrated in Fig. 5(b). The available bandwidth between nodes A and B is B_{AB}, and the available bandwidth between nodes A and C is B_{AC}. It is need to satisfy the equation $B_r \leq B_{AB} + B_{AC}$. The $\begin{bmatrix} A & - & C \\ & B & \end{bmatrix}$ is a simplest two-hop *bow* structure, as shown in Fig. 5(b). Fig. 5(c) shows that the bandwidth between nodes B and C is insufficient for the requirement, and the sum of the bandwidth from node A to node B and node A to node C is sufficient for the requirement. The solution will be found if the B_{BE} and B_{CE} are satisfied. Fig. 5(d) shows another simplest two-hop *bow* structure $\begin{bmatrix} B & - & E \\ & C & \end{bmatrix}$.

To simplify this model, we reduce Definition 1 with $m = 2$. Given two-hop counts successive neighboring nodes α, γ and β, and each node equips with two antennas, that is $m = 2$. Let $\begin{bmatrix} & - & \\ \alpha & & \beta \\ & \gamma & \end{bmatrix}$ denotes a reduced *bow* structure, where the upper part $\begin{bmatrix} \alpha & - & \beta \end{bmatrix}$ is a range-link between nodes α and β, the lower part links $\begin{bmatrix} \alpha & \gamma \end{bmatrix}$ and $\begin{bmatrix} \gamma & \beta \end{bmatrix}$ are rate-links. The total bandwidth of the chosen available routing path from node α to β is $B_{\alpha\beta} = \left\| \begin{bmatrix} & - & \\ \alpha & & \beta \\ & \gamma & \end{bmatrix} \right\|$, and $B_{\alpha\beta}$ satisfies the QoS bandwidth requirement B_r to construct the multi-path QoS routing path. The bandwidth needs to satisfy the equation $B_{\alpha\beta} = B_{\alpha\gamma} + B_{\alpha\beta}$, where the lower part $B_{\alpha\gamma} = \left\| \begin{bmatrix} \alpha & \gamma \end{bmatrix} \right\| = B_{\gamma\beta} = \left\| \begin{bmatrix} \gamma & \beta \end{bmatrix} \right\|$ and the upper part $B_{\alpha\beta} = \left\| \begin{bmatrix} \alpha & - & \beta \end{bmatrix} \right\|$. In the following, we define a *twin-bow* structure which is another case that composed of two rate-links and two range-links to satisfy the bandwidth requirement B_r and is extended to three-hop, as shown in Fig. 5(c) and (d) .

Definition 2: Twin-bow structure. Let $\begin{bmatrix} & -^* & l_1 \cdots l_j & \\ \alpha & & & \beta \\ & n_1 \cdots n_i & -^* & \end{bmatrix}$ denotes a *twin-bow* structure between nodes α and β, where the left upper part link $\begin{bmatrix} \alpha & -^* & l_1 \end{bmatrix}$ and right down part link $\begin{bmatrix} n_i & -^* & \beta \end{bmatrix}$ are range-links, other links $\begin{bmatrix} \alpha & n_1 \end{bmatrix}$, $\begin{bmatrix} n_1 & n_2 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} n_{i-1} & n_i \end{bmatrix}$, and links $\begin{bmatrix} l_1 & l_2 \end{bmatrix}$, $\begin{bmatrix} l_2 & l_3 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} l_j & \beta \end{bmatrix}$ are rate-links, $i, j \leq m-1$. The total bandwidth of the chosen routing path from the start node α to the destination node β is $B_{\alpha\beta} = \left\| \begin{bmatrix} & -^* & l_1 \cdots l_j & \\ \alpha & & & \beta \\ & n_1 \cdots n_i & -^* & \end{bmatrix} \right\|$, and $B_{\alpha\beta}$ satisfies the bandwidth requirement B_r. The $\begin{bmatrix} & - & C & \\ A & & & E \\ & B & - & \end{bmatrix}$ is an instance of a three-hop twin-bow structure, as shown in Fig. 5(c) and (e).

To simplify this model, we reduce Definition 2 to form $\begin{bmatrix} & - & \delta & \\ \alpha & & & \beta \\ & \gamma & - & \end{bmatrix}$, where cross links $\begin{bmatrix} \alpha & - & \delta \end{bmatrix}$ and $\begin{bmatrix} \gamma & - & \beta \end{bmatrix}$ are rate-links; neighboring links $\begin{bmatrix} \alpha & \gamma \end{bmatrix}$ and $\begin{bmatrix} \delta & \beta \end{bmatrix}$ are rate-links, and the number of antennas m equals 2. The total bandwidth between α and β equals $B_{\alpha\beta} = \left\| \begin{bmatrix} & - & \delta & \\ \alpha & & & \beta \\ & \gamma & - & \end{bmatrix} \right\|$, $B_{\alpha\beta}$ satisfies the bandwidth requirement B_r, and the equation $B_{\alpha\beta} = B_{\alpha\delta} + B_{\alpha\gamma} = B_{\delta\beta} + B_{\gamma\beta}$, where $B_{\alpha\delta} = \left\| \begin{bmatrix} \alpha & - & \delta \end{bmatrix} \right\|$,

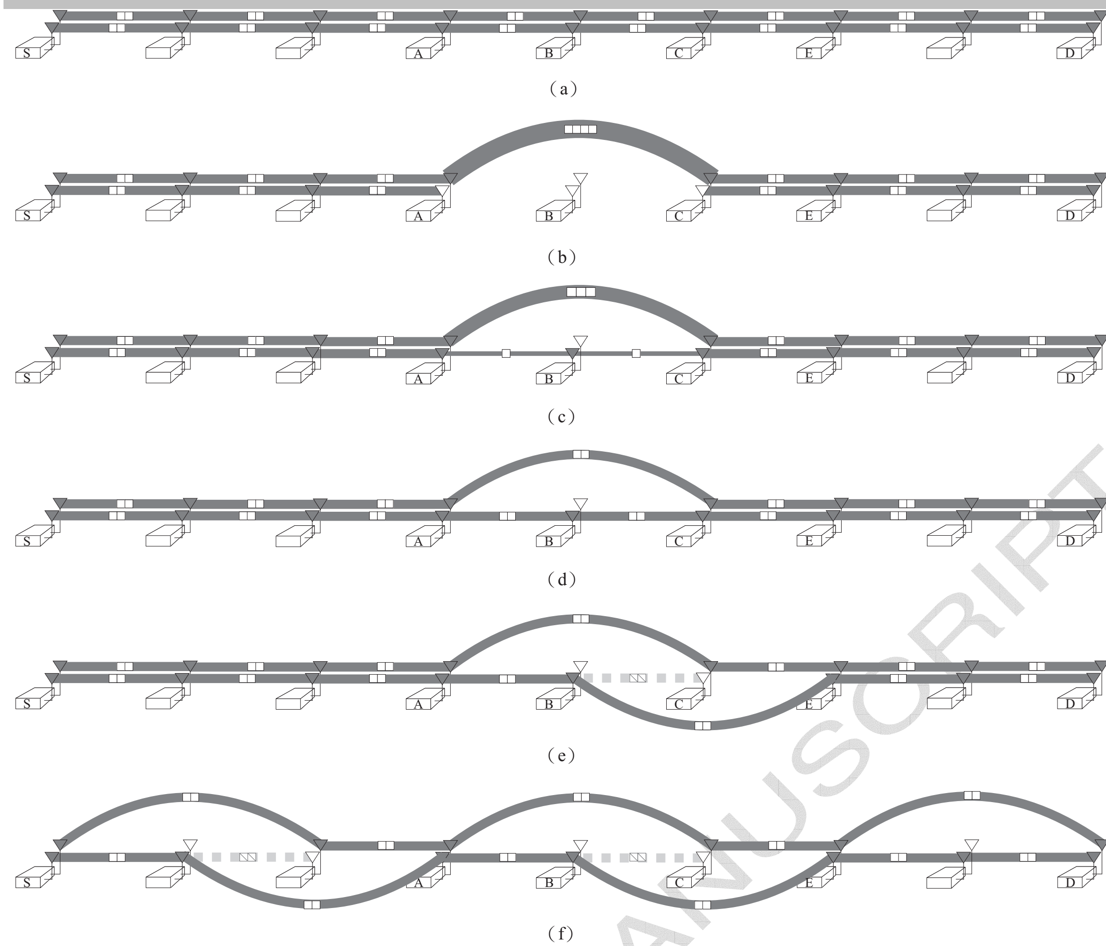


Fig. 6. Examples of the bow-path construction.

$B_{\alpha\gamma} = \left|\left[\alpha \ \gamma\right]\right|$, $B_{\delta\beta} = \left|\left[\delta \ \beta\right]\right|$ and $B_{\gamma\beta} = \left|\left[\gamma - \beta\right]\right|$.

Definition 3: Bow-path. A path is said to be a *bow-path* if and only if one or more bows/twin-bows exist in the path.

In the following, we illustrate that each bow structure can combine both transmission operations of MIMO link to fit the sub-bandwidth requirements as shown in Fig. 6. The number of sub-paths, which construct the multi-path routing path, depends on the network bandwidth. We first consider a QoS routing path from the source node S to the destination node D, which satisfies the bandwidth requirement B_r, exists only in rate-links of the path, as shown in Fig. 6(a). An alternative path from node S to node D is constructed with various sub-path in different situation, as illustrated in Fig. 6. Fig. 6(b) displays that the sub-path from nodes A to C is chosen using the range-link from nodes A to C, and the time slots tuple (range-link, rate-link) = (4, 0). Fig. 6(c) illustrates the sub-path from nodes A to C is replaced by the *bow* structure, where the time slots tuple

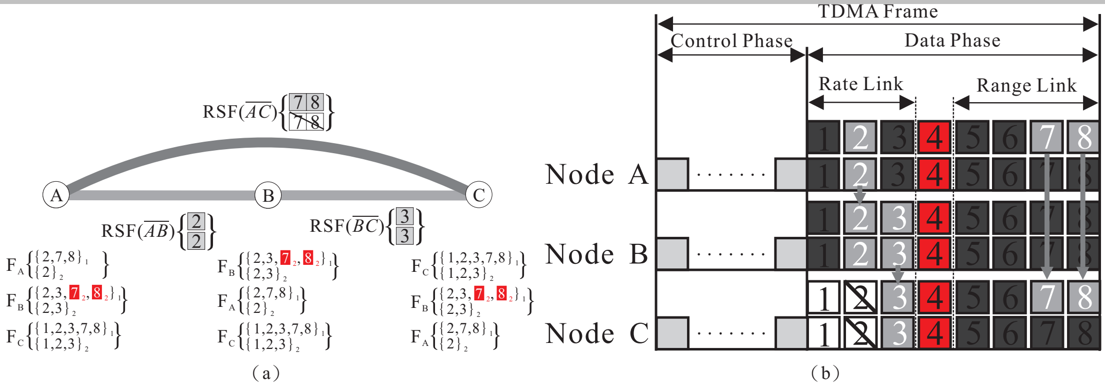


Fig. 7. Time slots reservation on a bow structure.

(range-link, rate-link) = (3, 1). Fig. 6(d) illustrates the sub-path from nodes A to C is also replaced by the multi-path *bow* structure, and the time slots tuple (range-link, rate-link) = (2, 2). In this instance, if the bandwidth of the rate-link between nodes B and C is strictly insufficient, then node B must try to identify a two-hop *bow* structure to the node E. If all the one-hop and two-hop requests are rejected then the QoS request will be failed. Fig. 6(e) displays that the sub-path from nodes A to E is replaced by the *twin-bow* structure, which is the sub-path from nodes A to E as shown in Fig. 5(c), to satisfy the bandwidth requirement B_r from the source node S. In the most complex case, several bows and twin-bows are combined to identify the QoS route path from the source node S to the destination node D, as shown in Fig. 6(f).

Fig. 7(a) shows that a two-hop example of the time slot allocation in a *bow* structure, and the bandwidth requirement $B_r = 4$ time slots. In this instance, the main issue is that the available bandwidth of link $\overline{AB}$ is insufficient. By the way, node A needs to find the available bandwidth of link $\overline{AC}$ and the total bandwidth from nodes A to C must satisfy the bandwidth requirement B_r. Fig. 7(b) illustrates that the time slot allocation of nodes A, B, and C. The darkest time slots are reserved for the hardware of antennas changing MIMO transmission model from rate-link (multiplexing) to range-link (diversity). When using rate-link, its interference region is two-hop neighboring links and the usage of each time slot for a normal connected link is only dependent on the status of its two-hop neighboring links. In addition to the rate-link, the interference region is three-hop neighboring link and the usage of each time slot for a normal connected link only depends on the status of its three-hop neighboring links. Fig. 8(a) illustrates an example of time slots allocation in a twin-bow structure, the bandwidth requirement B_r is also 4 time slots. Similarly, the main issue is that the available bandwidth of

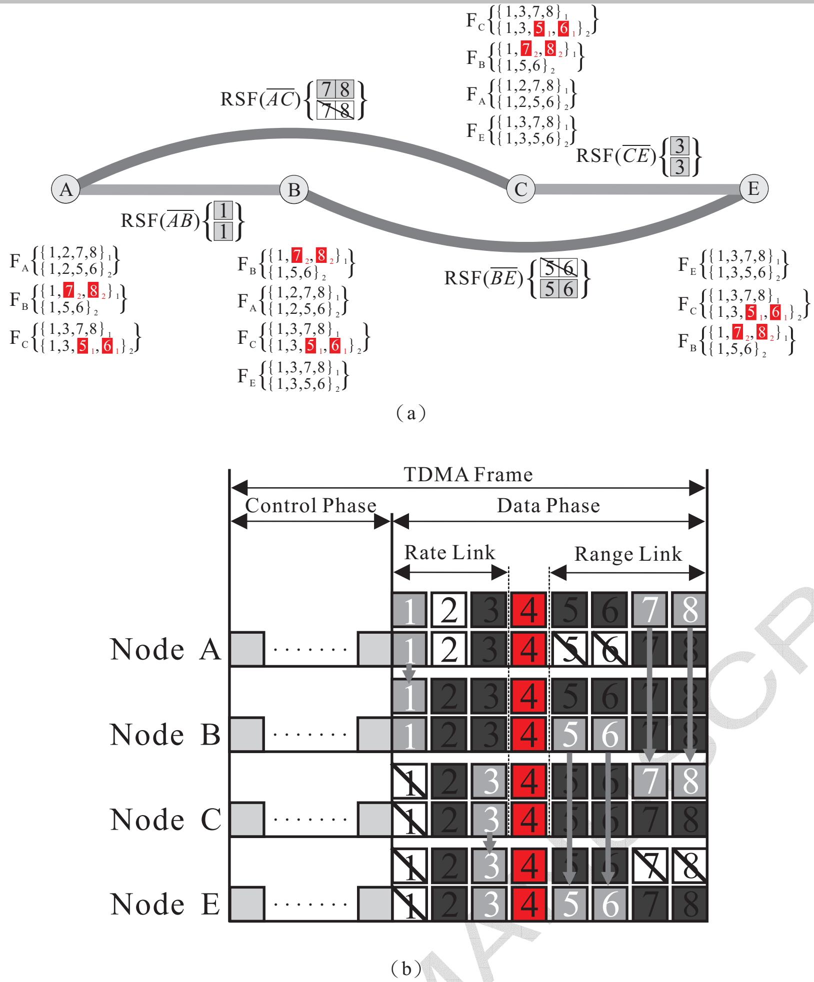


Fig. 8. Time slots reservation on a twin-bow structure.

link $\overline{BC}$ is insufficient. By the way, node B needs to find the available bandwidth of link $\overline{BE}$ and the total bandwidth from nodes A to E must satisfy the bandwidth requirement B_r. The main concept of identifying bows or twin-bows in one bow-path to achieve QoS requirement is mentioned above.

4 BowQR: Bow-based QoS routing protocol

In the following, we propose our QoS routing protocol using our bow-based routing structure on the MIMO ad hoc network. We name our bow-based QoS routing protocol as *BowQR* protocol. The BowQR protocol mainly constructs one or more bows to accomplish the QoS routing path. The BowQR protocol is achieved by three phases that are *bow identification* phase, *bow-path construction* phase, and *bow-path maintenance* phase. The *bow identification* phase identifies the bow structure for each node in MIMO ad hoc network. The *bow-path construction* phase constructs the bow-based QoS routing path by merging the bow-paths from the source node to the designated destination. The *bow-path maintenance* phase maintains the the bow structure for the sake of enhancing the robustness and preserving its stability.

4.1 Phase 1: bow identification

In order to identify the bow structure, local link-state information is first collected for each node by periodically maintaining the beacon message, where the beacon lifetime is two-hop counts. Then, the beacon message will be flooded into MIMO ad hoc network within two-hop transmission, each node acquires local link-state information from all two-hop neighboring nodes before identifying the bow structure. The free slots of node A are denoted as $\{\{\alpha_1,\alpha_2,\cdots,\alpha_{a_1}\}_1, \{\alpha_1,\alpha_2,\cdots,\alpha_{a_2}\}_2, \cdots, \{\alpha_1,\alpha_2,\cdots,\alpha_{a_m}\}_m\}$, where $\{\alpha_1, \alpha_2, \cdots, \alpha_{a_i}\}_i$ denotes the set of free time slots in the i-th antenna, $0 \leq i, a_i \leq m$, and a_i is the number of free time slots. In our assumption, there exists a fixed reserved time slot (RTS) between the rate-link and range-link period in each TDMA frame. The fixed reserved time slot is excluded from the free time slots of any node in the network. For instance as shown in Fig. 7, the free time slots list of node A is $\{\{2,7,8\}_1, \{2\}_2\}$ with two antennas. The fixed reserved time slot (RTS) is at the fourth time slot. That is, the rate-link period includes the first, second, and third time slots. The range-link period includes the fifth, sixth, seventh, and eighth time slots. The link-state information includes all one-hop and two-hop neighboring nodes and all corresponding free time slots list of these nodes. For instance as shown in Fig. 7(a), each node equips with two antennas, one-hop neighboring node of A is B and the free time slots list of B is $\{\{2,3\}_1,\{2,3\}_2\}$, while the two-hop neighboring node of A is C and the free time slots list of C is $\{\{1,2,3,7,8\}_1,\{1,2,3\}_2\}$. Let the free time slots list of one or two-hop neighboring nodes A and B are $\{\{\alpha_1, \alpha_2, \cdots, \alpha_{a_1}\}_1, \{\alpha_1, \alpha_2, \cdots, \alpha_{a_2}\}_2, \cdots, \{\alpha_1, \alpha_2, \cdots, \alpha_{a_m}\}_m\}$ and $\{\{\beta_1, \beta_2, \cdots, \beta_{b_1}\}_1, \{\beta_1, \beta_2, \cdots, \beta_{b_2}\}_2, \cdots, \{\beta_1, \beta_2, \cdots, \beta_{b_m}\}_m\}$, then we have an intersection function $\cap$ ($\{\alpha_1, \alpha_2, \cdots, \alpha_{a_i}\}_i, \{\beta_1, \beta_2, \cdots, \beta_{b_i}\}_i$) $=$ $(\{\gamma_1, \gamma_2, \cdots, \gamma_{n_i}\}_i)$, where $i = 1, 2, \cdots, m$ and $n_i \leq \min\{a_i, b_i\}$.

Let $\{\gamma_1, \gamma_2, \cdots, \gamma_{n_i}\}_i$ represents the shared free time slots between nodes A and B, the link $\overline{AB}$ is either a rate-link or a range-link, where $i = 1, 2, \cdots, m$ and $n_i \leq \min\{a_i, b_i\}$. If the link $\overline{AB}$ is a rate-link then communication between nodes A and

B should be selected from shared time slots $\{\gamma_1, \gamma_2, \cdots, \gamma_{n_i}\}_i$ in the range-link period. Otherwise, if the link $\overline{AB}$ is a range-link then the communication between nodes A and B should be selected from shared time slots $\{\gamma_1, \gamma_2, \cdots, \gamma_{n_i}\}_i$ in the rate-link period. For example as shown in Fig. 7(a), the free time slots of nodes A and B are $\{\{2,7,8\}_1, \{2\}_2\}$ and $\{\{2,3,\{7\}_2,\{8\}_2\}_1, \{2,3\}_2\}$ respectively, and the intersection function $\cap$ ($\{\{2,7,8\}_1, \{2\}_2\}$, $\{\{2,3,\{7\}_2,\{8\}_2\}_1, \{2,3\}_2\}$) $= (\{2\}_1, \{2\}_2)$. Observe that, for the purpose of enhancing transmission range, if node B communicates with other node using time slots $\{7,8\}_2$ for range-link on antenna (spatial) 1, then time slots $\{7,8\}_1$ on antenna (spatial) 2 need to be reserved for supporting time slots $\{7,8\}_2$ on antenna (spatial) 1. We use the notation of $\{\{7\}_2,\{8\}_2\}_1$ to show that time slots $\{7,8\}_1$ are reserved to support $\{7,8\}_2$ for range-link, as shown in Fig. 7(a) and 8(b). The same rule can be applied to the selection of the two-hop neighboring node between nodes A and C. For example as shown in Fig. 7(a), the free time slots of nodes A and C are $\{\{2,7,8\}_1, \{2\}_2\}$ and $\{\{1,2,3,7,8\}_1, \{1,2,3\}_2\}$ respectively, and the intersection function $\cap$ ($\{\{2,7,8\}_1, \{2\}_2\}$, $\{\{1,2,3,7,8\}_1, \{1,2,3\}_2\}$) $= (\{2,7,8\}_1, \{2\}_2)$. The slots $(\{2\}_1, \{2\}_2)$ are reserved for rate-link $\overline{AB}$, and then the slots $\{7,8\}$ are chosen for the shared free time slots between nodes A and C using antenna 1. The identification of twin-bow structure and the identification of bow structure are the same, as illustrated in Fig. 8(a). Similarly, we assume that node B communicates with other node using time slots $\{7,8\}$ for range-link on antenna (spatial) 1, and node C communicates with other node using time slots $\{5,6\}$ for range-link on antenna (spatial) 2. That is, the notation for the lists of free time slots of nodes B and C are $\{\ \{1,\{7\}_2,\{8\}_2\}_1, \{1,5,6\}_2\ \}$ and $\{\ \{1,3,7,8\}_1, \{1,3,\{5\}_1,\{6\}_1\}_2\ \}$, respectively.

Further, if the free time slots are calculated in each link, then the chosen time slots in the corresponding antennas will be reserved. In the following, we define three kinds of representation, $SF(\overline{AB})$ for total shared free time slots, $ASF(\overline{AB})$ for available shared free time slots, and $RSF(\overline{AB})$ for reserved shared free time slots between nodes A and B.

- Let $SF(\overline{AB}) = (\{\gamma_1,\gamma_2,\cdots,\gamma_{n_1}\}_1, \{\gamma_1,\gamma_2,\cdots,\gamma_{n_2}\}_2, \cdots, \{\gamma_1,\gamma_2,\cdots, \gamma_{n_m}\}_m)$ represents the total shared free time slots between nodes A and B from antenna (spatial) 1 to antenna (spatial) m, respectively.
- Let $ASF(\overline{AB}) = SF(\overline{AB}) - RSF(\overline{AX})$ represents the available shared free time slots between nodes A and B ,where $X \in$ all the two-hop neighbors

of node A and $RSF(\overline{AX})$ denotes those time slots that have been used (reserved) on the same link $\overline{AX}$ with different antenna (spatial).

- Let $RSF(\overline{AB}) = ((\{\gamma_1, \gamma_2, \cdots, \gamma_{p_1}\}_1, \{\gamma_1, \gamma_2, \cdots, \gamma_{p_2}\}_2, \cdots, \{\gamma_1, \gamma_2, \cdots, \gamma_{p_m}\}_m)$ represents the chosen reserved shared free time slots between nodes A and B, where $p_i \leq n_i$, $i = 1, 2, \cdots, m$.

For instance as shown in Fig. 7(a), the total shared free time slots $SF(\overline{BC}) = \{\{2, 3, \{7\}_2, \{8\}_2\}_1, \{2, 3\}_2\}$ is calculated from the free time slots of nodes B and C. The available shared free time slots $ASF(\overline{BC}) = \{\{2, 3\}_1, \{2, 3\}_2\}$, and the reserved shared free time slots, $RSF(\overline{BC}) = \{\{3\}_1, \{3\}_2\}$.

Recall that, we denote $\begin{bmatrix} & -^* & \\ \alpha & & \beta \\ & n_1 \cdots n_i & \end{bmatrix}$ as a *bow* structure in Definition 1, where the upper part $\begin{bmatrix} \alpha & -^* & \beta \end{bmatrix}$ is a range-link, links $\begin{bmatrix} \alpha & n_1 \end{bmatrix}$, $\begin{bmatrix} n_1 & n_2 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} n_i & \beta \end{bmatrix}$ are either a rate-link communication or no communication, $i \leq m-1$. As $m = 2$, we can simplify this model and denote $\begin{bmatrix} & - & \\ \alpha & & \beta \\ & \gamma & \end{bmatrix}$ as the simplest *bow* structure, where $\begin{bmatrix} \alpha & - & \beta \end{bmatrix}$ is a range-link and $\begin{bmatrix} \alpha & \gamma & \beta \end{bmatrix}$ is a two-hop rate-link path. For this simple model, the time-slot reservation of $\begin{bmatrix} & - & \\ \alpha & & \beta \\ & \gamma & \end{bmatrix}$ is constructed as the following steps.

A1. First, the QoS supported BowQ_REQ packet is generated from the source node. If node α receives a BowQ_REQ packet, then checks whether the $ASF(\overline{\alpha\gamma})$ of the lower part in the rate-link period is sufficient or not for the bandwidth requirement B_r. If the bandwidth is sufficient to fit the QoS request then node α forwards the BowQ_REQ packet to node γ and jumps to A4, else jumps to A2.

A2. Node α checks the bandwidth information of its two-hop neighboring node β. If $ASF(\overline{\alpha\beta})$ in the range-link period is sufficient for the residual of B_r, then node α forwards the BowQ_REQ packet to node β and jumps to A3, else the QoS request failed and the protocol finished.

A3. Node β receives the BowQ_REQ packet from node α, and reserves $RSF(\overline{\alpha\beta})$ in the range-link period between nodes α and β. And then, the protocol finished.

A4. Node γ receives the BowQ_REQ packet from node α. Then, node γ checks the bandwidth information of its neighboring node β. If $ASF(\overline{\gamma\beta})$ in the rate-link period is sufficient for B_r, then node γ forwards the BowQ_REQ packet to node β. And then, nodes α, γ, and β reserve $RSF(\overline{\alpha\gamma})$ and $RSF(\overline{\gamma\beta})$ in the rate-link period among them and the protocol finished, else jumps to A2.

Based on the above steps to identify a bow structure, we conclude the following rules for the time-slot reservation.

(Rule 1) The reserved time slots of the range-link $\begin{bmatrix} \alpha - \beta \end{bmatrix}$ are chosen from $ASF(\overline{\alpha\beta})$ at the range-link period of each time slot frame.

(Rule 2) The reserved time slots of the rate-links $\begin{bmatrix} \alpha \ \gamma \end{bmatrix}$ and $\begin{bmatrix} \gamma \ \beta \end{bmatrix}$ are chosen from $ASF(\overline{\alpha\gamma})$ and $ASF(\overline{\gamma\beta})$ at the rate-link period in each time slot frame. $RSF(\overline{\alpha\gamma})$ must be different from $RSF(\overline{\gamma\beta})$ in the same rate-link period.

For instance as shown in Fig. 7(a), $\begin{bmatrix} A & - & C \\ & B & \end{bmatrix}$ is a bow structure and it follows the above rules. The reserved shared free time slots $RSF(\overline{AC}) = \{\{7, 8\}_1\}$ on the range-link $\begin{bmatrix} A - C \end{bmatrix}$ from $ASF(\overline{AC}) = \{\{2, 7, 8\}_1\}$ in the range-link period satisfies Rule 1. The reserved shared time slots $RSF(\overline{AB}) = \{\{2\}_1, \{2\}_2\}$ on the rate-link $\begin{bmatrix} A \ B \end{bmatrix}$ which is different from the reserved shared time slots $RSF(\overline{BC}) = \{\{3\}_1, \{3\}_2\}$ on the rate-link $\begin{bmatrix} B \ C \end{bmatrix}$ satisfies Rule 2.

We define $\begin{bmatrix} & -^* & l_1 \cdots l_j & \\ \alpha & & & \beta \\ & n_1 \cdots n_i & -^* & \end{bmatrix}$ as a twin-bow structure in Definition 2, where $\begin{bmatrix} \alpha -^* l_1 \end{bmatrix}$ and $\begin{bmatrix} n_i -^* \beta \end{bmatrix}$ are range-links, links $\begin{bmatrix} \alpha \ n_1 \end{bmatrix}$, $\begin{bmatrix} n_1 \ n_2 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} n_{i-1} \ n_i \end{bmatrix}$ and links $\begin{bmatrix} l_1 \ l_2 \end{bmatrix}$, $\begin{bmatrix} l_2 \ l_3 \end{bmatrix}$, $\cdots$, and $\begin{bmatrix} l_{i-1} \ l_i \end{bmatrix}$ are rate-links, $i \leq m - 1$. We further denote $\begin{bmatrix} & - & \delta & \\ \alpha & & & \beta \\ & \gamma & - & \end{bmatrix}$ as a twin-bow structure for our simple model with the number of antennas $m = 2$. Specially, $\begin{bmatrix} & \delta & \\ \gamma & & \beta \\ & - & \end{bmatrix}$ forms a bow structure when the rate-link $\begin{bmatrix} \alpha \ \gamma \end{bmatrix}$ exists and the range-link $\begin{bmatrix} \alpha - \delta \end{bmatrix}$ doesn't exist. On the other hand, $\begin{bmatrix} & - & \\ \alpha & & \delta \\ & \gamma & \end{bmatrix}$ forms a bow structure when the the rate-link $\begin{bmatrix} \delta \ \beta \end{bmatrix}$ exists and the range-link $\begin{bmatrix} \gamma - \beta \end{bmatrix}$ doesn't exist. $\begin{bmatrix} & - & \delta & \\ \alpha & & & \beta \\ & \gamma & - & \end{bmatrix}$ can also be defined as a bow structure in a sub-path of a twin-bow structure. For this simple model, the time slot reservation steps of $\begin{bmatrix} & - & \delta & \\ \alpha & & & \beta \\ & \gamma & - & \end{bmatrix}$ can be described as follows.

B1. If node α receives a BowQ_REQ packet then checks whether the $ASF(\overline{\alpha\gamma})$ in the rate-link period is sufficient or not for the bandwidth requirement B_r. And then, if $ASF(\overline{\alpha\gamma})$ is sufficient then node α forwards the BowQ_REQ packet to node γ and jumps to B4, else jumps to B2.

B2. Node α checks its two-hop neighbor information, and then finds out one node δ where the $ASF(\overline{\alpha\delta})$ in the range-link period is sufficient for the residual of B_r. Node α forwards the BowQ_REQ packet to node δ and jumps to B3. If no available node found, then the QoS request failed and the protocol finished.

B3. If node δ receives the BowQ_REQ packet from node α, then reserves the $RSF(\overline{\alpha\delta})$ in the range-link period for the range-link between α and δ. And then, node δ checks its one-hop neighboring information from node β. If $ASF(\overline{\delta\beta})$ in the rate-link period is sufficient for the bandwidth $B_{\alpha\delta}$, then δforwards the BowQ_REQ packet to β and jumps to B5, else the QoS request failed and the protocol finished.

B4. if node γ receives the BowQ_REQ packet from node α, then reserves $RSF(\overline{\alpha\gamma})$ in the rate-link period between nodes α and γ. Node γ checks whether $ASF(\overline{\gamma\beta})$ in the range-link period is insufficient or not for the bandwidth $B_{\alpha\gamma}$, then it find out one node β from its two-hop neighboring information where $ASF(\overline{\gamma\beta})$ in the range-link period is sufficient for the bandwidth $B_{\alpha\gamma}$. Then, node γ forwards the BowQ_REQ packet to node β and jumps to B6. If no available node found, then the QoS request failed and the protocol finished.

B5. Node β receives the BowQ_REQ packet from node δ, and reserves $RSF(\overline{\delta\beta})$ in the rate-link period between nodes δ and β, and then jumps to B6.

B6. Node β receives the BowQ_REQ packet from node γ, and reserves $RSF(\overline{\gamma\beta})$ in the range-link period between nodes γ and β and the protocol finished.

Similarly, based on the above steps to identify a twin-bow structure, we conclude the following rules for the time-slot reservation.

(Rule 3) Time slots reserve on the range-links $\begin{bmatrix} \alpha - \delta \end{bmatrix}$ and $\begin{bmatrix} \gamma - \beta \end{bmatrix}$ are $RSF(\overline{\gamma\beta})$ and $RSF(\overline{\alpha\delta})$ respectively, and their values must be different from each other in the range-link period.

(Rule 4) Time slots reserve on the rate-links $\left[\alpha\ \gamma\right]$ and $\left[\delta\ \beta\right]$ are $RSF(\overline{\delta\beta})$ and $RSF(\overline{\alpha\gamma})$ respectively, and their values must be different from each other in the rate-link period.

For instance as illustrated in Fig. 8(a), $\begin{bmatrix} & - & C & \\ A & & & E \\ & B & - & \end{bmatrix}$ is a twin-bow structure. To follow the above rules, the reserved shared time slots $RSF(\overline{AC}) = \{\{7,8\}_1\}$ are on the range-link $\left[A - C\right]$. The reserved shared time slots $RSF(\overline{BE}) = \{\{5,6\}_2\}$ are on the range-link $\left[B - E\right]$. $RSF(\overline{AC}) = \{\{7,8\}_1\}$ is different from $RSF(\overline{BE}) = \{\{5,6\}_2\}$, that satisfies Rule 3. The reserved shared time slots $RSF(\overline{AB}) = \{\{1\}_1,\ \{1\}_2\}$ are on the rate-link $\left[A\ B\right]$ which is different from time slots $RSF(\overline{CE}) = \{\{3\}_1,\ \{3\}_2\}$ on the rate-link $\left[C\ E\right]$, that satisfies Rule 4.

In the following, we illustrate how to construct a bow-path using one or more bows and twin-bows structures, and show the detail descriptions of BowQ_REQ packets which are mentioned above.

4.2 Phase 2: bow-based QoS routing path construction

Based on the identified bows, several bow-paths, which conisit of several bows and twin-bows, are constructed and finally satisfy the bandwidth requirement B_r from the source node to the destination node. To identify a bow structure, the local link-state information is collected for each node in the MIMO ad hoc network. This work is achieved by periodically maintaining the beacon messages, where the lifetime of the beacon is two-hop count. Since the lifetime of the beacon is two-hop, each node acquires two-hop neighboring information. Employing the information, each node can collect local link-state information from all two-hop neighboring nodes.

Each node employs the RTS/CTS to find the locations and free time slots of its neighboring nodes' range-links, and then decides the reserved time slots of the links between them. Each node maintains two-hop neighbors' information by the message exchanging of RTS/CTS. The source node initiates a bandwidth requirement packet BowQ_REQ and transmits this packet to its neighbors. Each packet records the bandwidth requirement B_r and link-state information. For each bandwidth request, the source node must creates a designated BowQ_REQ. A BowQ_REQ packet tuple is denoted as BowQ_REQ(S_ADDR, D_ADDR, $next\_hop$, $node\_list$, $reserved\_time\_slot$, B, B_r), where the detailed description is given in Table 1.

Packet field	Field description
S_ADDR	The source node
D_ADDR	The destination node
$next\_hop$	The one or two-hop neighbor of the current node which has received the BowQ_REQ packet.
$node\_list$	A list of nodes which denotes all the chosen nodes from the source to the current traversed node.
$reserved\_time\_slot$	A list of reserved time slots including two antennas dividedly among next hop node, current node and previous node.
B	The needed bandwidth from the current node to the next.
B_r	The bandwidth requirement from the source to the destination.

Table1: Detailed description of a BowQ_REQ packet

When a QoS connection with the bandwidth requirement B_r from the source to the destination is issued. Let node S be the source node, node D be the destination node. Then, the source node S prepares a QoS request packet BowQ_REQ(S_ADDR, D_ADDR, $next\_hop$, $node\_list$, $reserved\_time\_slot$, B, B_r) = (S, D, S, { }, { }, B_r, B_r) and jumps to C1 to start the routing protocol. The formal algorithm of the bow-path construction is given below.

C1. Let node e denotes the current node of the current state. When node e receives a BowQ_REQ packet from the MIMO ad hoc network, then node e checks whether node e equals the parameter $next\_hop$ or D_ADDR or not. If node e equals D_ADDR then jump to C4. If node e equals $next\_hop$ then jump to C2, else drops this packet.

C2. If the current node is node e then node e checks the values of $ASF(\overline{ee'})$, which is the current needed bandwidth B, and bandwidth requirement B_r from its neighbor node e'. And then, four cases are considered as follows.

Case I. If $B_{ee'} = \left|ASF(\overline{ee'})\right| \geq B$, then nodes e and e' reserve the needed bandwidth, B time slots, for the rate-link between them. Then, node e forwards BowQ_REQ (S, D, e', $current\_node\_list$+$\{e\}$, $\{T_1 \sim T_B\}$, B_r, B_r) packet to the one-hop neighbor e,where TS_i means the i-th chosen time slot, and then jump to C3.

Case II. If $B_{ee'} = \left|ASF(\overline{ee'})\right| < B$, then node e checks its two-hop neighboring information and finds out the node e'' from *node_list* field which is the one-hop neighbor of e' and two-hop neighbor of e. If there exists a node e'' such that $B_{ee''} = \left|ASF(\overline{ee''})\right| \geq B$. Then, node e forwards BowQ_REQ (S, D, e'', $current\_node\_list$+$\{e\}$, $\{TS_1 \sim TS_{B_{ee''}}\}$, B_r, B_r) packet to the one-hop neighbor e'', and then jump to C3.

Case III. If $B_{ee'} = \left|ASF(\overline{ee'})\right| < B$, then node e checks its two-hop neighboring information and finds out the node e'' from *node_list* field which is the one-hop neighbor of e' and two-hop neighbor of e. If there exists a node e'' such that $B_{ee'} + B_{ee''} = \left|ASF(\overline{ee'})\right| + \left|ASF(\overline{ee''})\right| \geq B$. Then, node e forwards BowQ_REQ (S, D, e'', $current\_node\_list$+$\{e\}$, $\{TS_1 \sim TS_{B_{ee''}}\}$, B_r, B_r) packet to the one-hop neighbors e' and e'', forwards BowQ_REQ (S, D, e', $current\_node\_list$+$\{e\}$, $\{TS_1 \sim TS_{B_{ee'}}\}$, B_r, B_r) packet to the neighbor e', where all the TS_i are different in both packets and then jump to C3.

Case IV. If $B_{ee'} = \left|ASF(\overline{ee'})\right| < B$, then node e checks its two-hop neighboring information and finds out the node e'' from *node_list* field which is the one-hop neighbor of e' and two-hop neighbor of e. If node e'' is mismatched then the QoS request is failed and the routing protocol is finished.

C3. Let node x be the current node. If node x receives multiple packets and these packets contain the same source node, the same destination node, and the same bandwidth requirement B_r from the same MIMO ad hoc network. Then, node x combines the same properties packets to form the new designated packet, and then jumps back to C2.

C4. If node e is equal to *D_ADDR* then node e sends a route reply message BowQ_RREP for BowQ_REQ back to the source node *S_ADDR*. Then, the Bow-Based QoS routing path construction is finished.

Let $\left[\begin{bmatrix} & -^* & \delta_1 & \\ \alpha_1 & & & \beta_1 \\ & \gamma_1 & -^* & \end{bmatrix}, \cdots, \begin{bmatrix} & -^* & \delta_t & \\ \alpha_t & & & \beta_t \\ & \gamma_t & -^* & \end{bmatrix}\right]$ denotes a bow-path, where

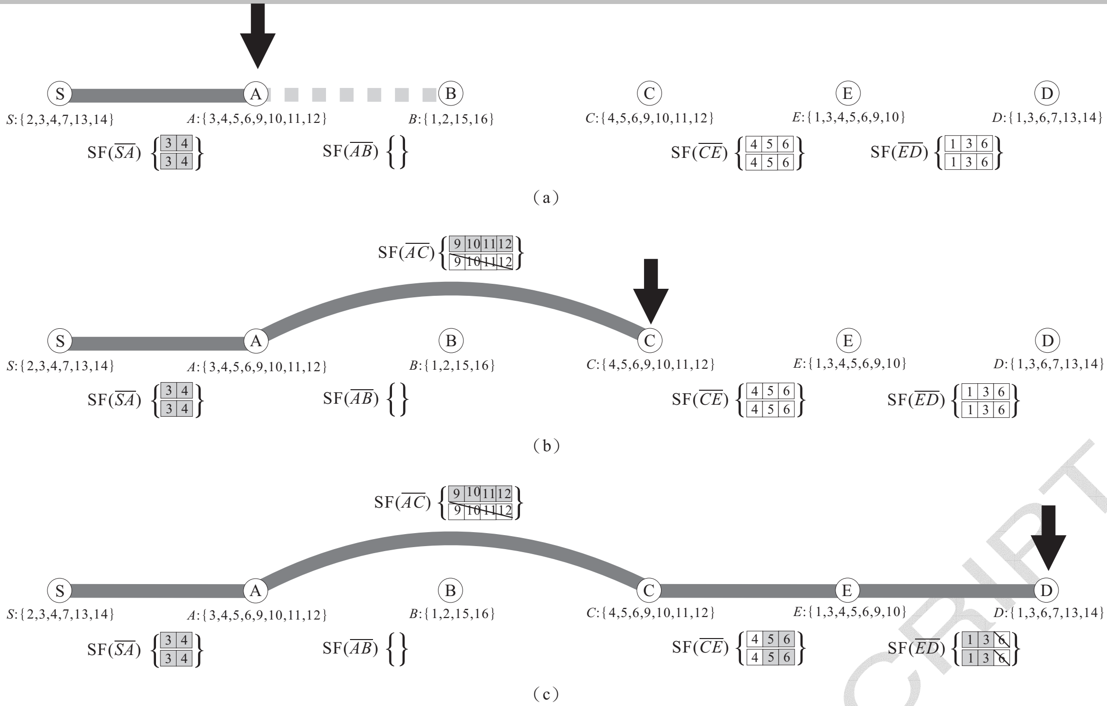


Fig. 9. Example for a uni-path result if the network bandwidth is sufficient.

$\begin{bmatrix} & -^* & \delta_i & \\ \alpha_i & & & \beta_i \\ & \gamma_i & -^* & \end{bmatrix}$ is the i-th twin-bow of the bow-path, $\beta_{k_5} = \alpha_{k_5+1}$, $1 \leq k_5 \leq t-1$, and $m = 2$, where m is the number of antennas. In the following cases, the number of time slots in the data phase of a frame contains 16 time slots and the reserved time slot is the 8th time slot. Some instances of the bow-based QoS routing path construction are given as follows.

(Instance I): Fig. 9 illustrates the instance of a uni-link uni-path bow structure, where the bandwidth requirement B_r equals 4, the number of antenna m equals 2, and the fixed reserved time slot is at the eighth time slot of the 16 time slots in each time frame. Fig. 9(a) shows that node S sends RREQ route request packet to node A firstly and reserves the time slots $RSF(\overline{SA}) = \{\{3,4\}_1, \{3,4\}_2\}$. Because of $ASF(\overline{AB}) = \{\ \}$ and node A finds out $ASF(\overline{AC}) = \{\{9,10,11,12\}_1, \{9,10,11,12\}_2\}$, and then the time slots $RSF(\overline{AC}) = \{\{9,10,11,12\}_1\}$ are reserved, as shown in Fig. 9(b). Fig. 9(c) displays that the links $\overline{CE}$ and $\overline{ED}$ reserve the time slots $RSF(\overline{CE}) = \{\{5,6\}_1, \{5,6\}_2\}$ and $RSF(\overline{ED}) = \{\{1,3\}_1, \{1,3\}_2\}$ respectively. Finally, the uni-path $\Big[\big[S\ A\big]\big[A - C\big]\big[C\ E\ D\big]\Big]$ is constructed from the source node S to the destination node D.

(Instance II): Fig. 10 illustrates the instance of the multi-path bow structure,

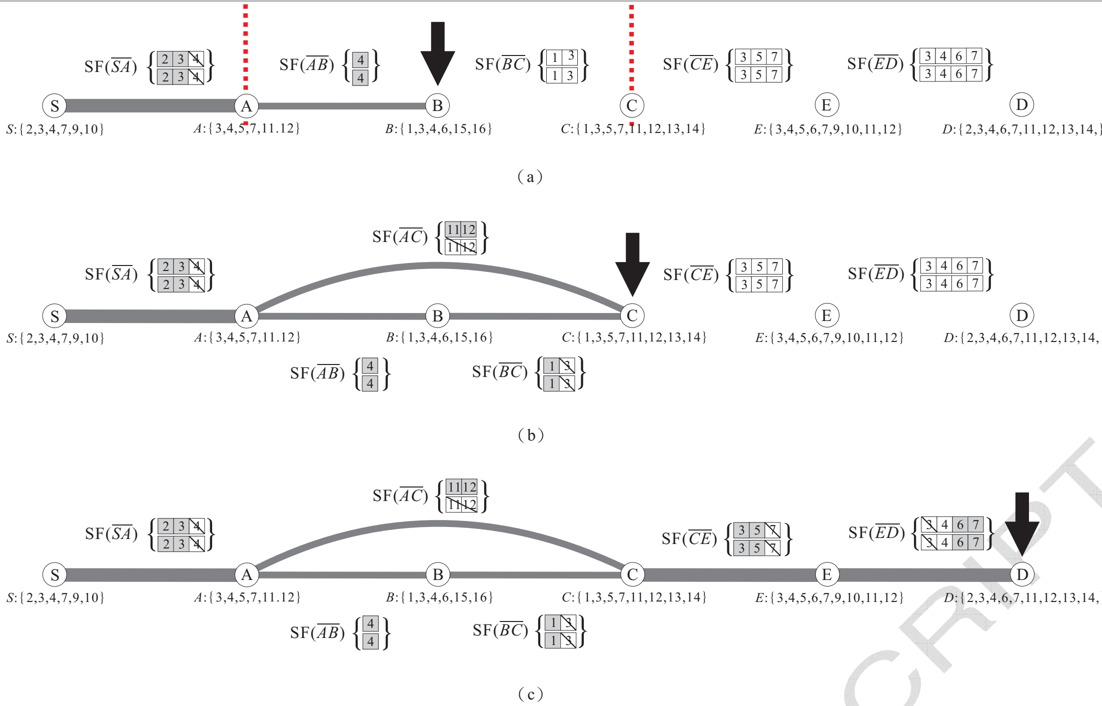


Fig. 10. Example for bow-path construction to identify a bow.

where the bandwidth requirement B_r equals 4, the number of antenna m equals 2. Fig. 10(a) shows that node S sends RREQ route request packet to node A and reserves the $SF(\overline{SA}) = \{\{2,3\}_1, \{2,3\}_2\}$. Fig. 10(b) shows that node A constructs the bow $\begin{bmatrix} & - & \\ A & & C \\ & B & \end{bmatrix}$ with $SF(\overline{AC}) = \{\{11,12\}_1\}$, $SF(\overline{AB}) = \{\{4\}_1, \{4\}_2\}$, and $SF(\overline{BC}) = \{\{1\}_1, \{1\}_2\}$. Fig. 10(c) illustrates that the links $\overline{CE}$ and $\overline{ED}$ are constructed with $RSF(\overline{CE}) = \{\{3,5\}_1, \{3,5\}_2\}$ and $RSF(\overline{ED}) = \{\{6,7\}_1, \{6,7\}_2\}$. Finally, the bow based multi-path bow-path $\left[\begin{bmatrix} S & A \end{bmatrix} \begin{bmatrix} & - & \\ A & & C \\ & B & \end{bmatrix} \begin{bmatrix} C & E & D \end{bmatrix}\right]$ is constructed from the source node S to the destination node D.

(Instance III): Fig. 11 illustrates the instance of a multi-path bow structure, where the bandwidth requirement B_r equals 4, the number of antenna m equals 2. Fig. 11(a) illustrates that node S sends a RREQ route request packet to node A and reserves $SF(\overline{SA}) = \{\{2,3\}_1, \{2,3\}_2\}$. Fig. 11(b) illustrates that node A constructs the bow $\begin{bmatrix} & - & C & \\ A & & & E \\ & B & - & \end{bmatrix}$ with $SF(\overline{AC}) = \{\{11,12\}_1\}$, $SF(\overline{BE}) = \{\{15,16\}_2\}$, $SF(\overline{AB}) = \{\{4\}_1, \{4\}_2\}$, and $SF(\overline{CE}) = \{\{5\}_1, \{5\}_2\}$. Fig. 11(c) illustrates that link $\overline{ED}$ is constructed with $SF(\overline{ED}) = \{\{6,7\}_1, \{6,7\}_2\}$. Finally, the twin-bow based multi-path bow-path

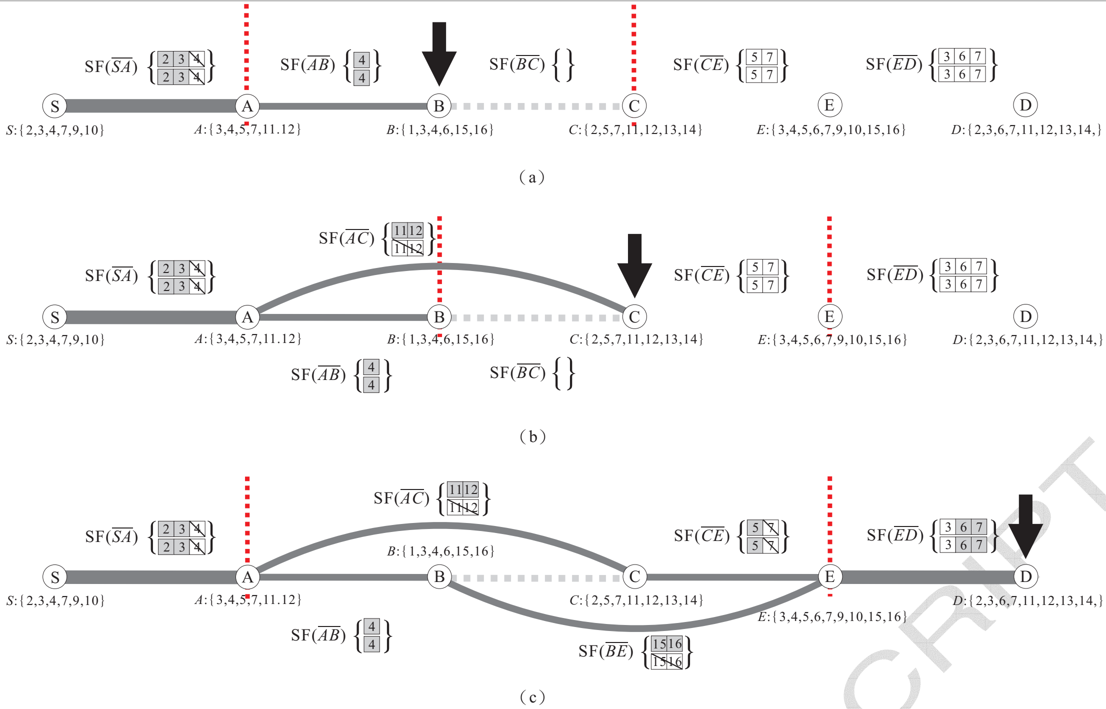


Fig. 11. Example for bow-path construction to identify a twin-bow.

$\left[\left[S\ \ A\right]\left[A\ \begin{matrix} - & C \\ B & - \end{matrix}\ E\right]\left[E\ \ D\right]\right]$ is constructed from the source node S to the destination node D.

4.3 Phase 3: bow-path maintenance

BowQR protocol works in the MIMO ad hoc network. Each node may fail or move at random and thus leads the bow-path to be broken. Under this scenario, our *bow-path maintenance* phase will be triggered to maintain the bandwidth requirement from the source to the destination. Given $\left[\left[\alpha_1\ \begin{matrix} -^* & \delta_1 \\ \gamma_1 & -^* \end{matrix}\ \beta_1\right], \ldots, \left[\alpha_t\ \begin{matrix} -^* & \delta_t \\ \gamma_t & -^* \end{matrix}\ \beta_t\right]\right]$ as a bow-path, where $\left[\alpha_t\ \begin{matrix} -^* & \delta_t \\ \gamma_t & -^* \end{matrix}\ \beta_t\right]$ is the t-th twin-bow of the bow-path. If the structure of $\left[\alpha_t\ \begin{matrix} -^* & \delta_t \\ \gamma_t & -^* \end{matrix}\ \beta_t\right]$ is broken, it means that $B_{\alpha_t\beta_t} = \left|\left[\alpha_t\ \begin{matrix} -^* & \delta_t \\ \gamma_t & -^* \end{matrix}\ \beta_t\right]\right|$ is less than the bandwidth requirement B_r, then the proceeding hop nodes of the failed or moved node try to find out other node to replace the failed or moved

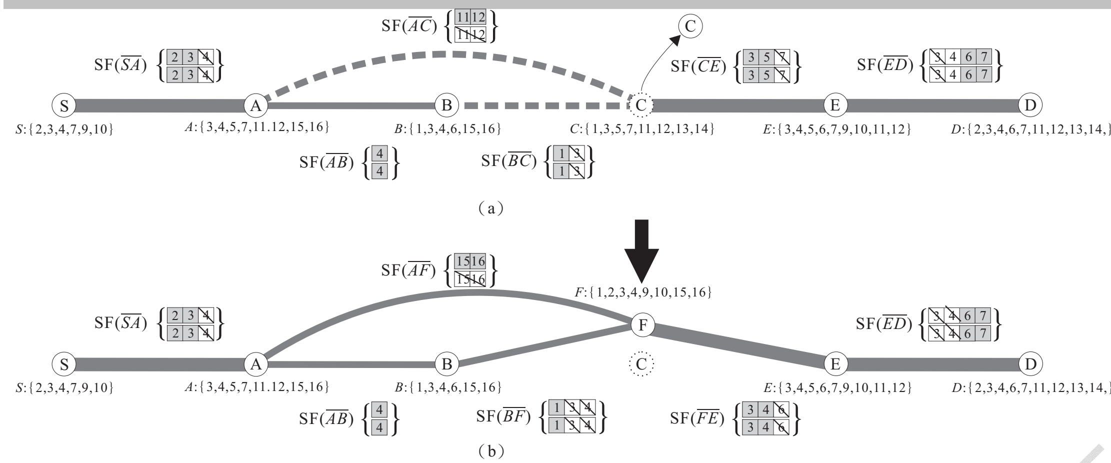


Fig. 12. Example for bow-path maintenance.

node. For instance as illustrated in Fig. 12, $\left[[S\ A] \left[A \begin{array}{c} - \\ B \end{array} C \right] [C\ E\ D] \right]$ is a bow-path. Fig. 12(a) shows that the moving of node C causes the rate-link $\overline{BC}$ and the range-link $\overline{AC}$ to be broken. The bow $\left[A \begin{array}{c} - \\ B \end{array} C \right]$ is broken and the bow-path is also broken. The *bow-path maintenance* phase starts, the proceeding hop nodes of C are nodes A and B. Nodes A and B try to find out another node to replace node C for maintaining the bow structure, as shown in Fig. 12(b).

The bow-path $\left[[S\ A] \left[A \begin{array}{c} - \\ B \end{array} F \right] [C\ E\ D] \right]$ will be constructed after the *bow-path maintenance* phase is executed, where $B_{AF} = \left\| \left[A \begin{array}{c} - \\ B \end{array} F \right] \right\|$ is equal to the bandwidth requirement B_{SD}.

5 Simulation results

Our protocol mainly presents a bow-based QoS routing protocol in the MIMO ad hoc network. In order to evaluate our protocol and Karthikeyan *et al.*s' MIR protocol [20], we have implemented them on the NCTUns 3.0 simulator [22]. To make a fair comparison, we modify the MIR protocol to support the same QoS bandwidth requirement. In the following, we used "BowQR" and "MIR" to denote our protocol and Karthikeyan *et al.*s' routing protocol. The simulation parameters are given below.

- The *number of antennas* is 2.
- The *transmission radius* is 50 m.
- The *number of mobile nodes* is 500.
- The *number of time slots* in data phase of a frame is assumed to be 16 slots.
- The *bandwidth requirements* (B_r): The QoS request bandwidth from the source to the destination is denoted as B_r. In our simulation, there are eight different values for B_r, e.g. 1, 2, 3, 4, 5, 6, 7 and 8 time slots,.
- The *mobility* (M_o): M_o is the mean value of the moving speed of the mobile node. Our simulation considers ten different values for M_o, e.g. 0, 5, 10, 15, 20, 30, 35, 40, 45, and 50 km/h.
- The *ratio of the range-link period* (R_{range}): R_{range} is defined as "the number of time slots for the range-link period" divided by "the number of time slots exists in the data phase of each frame". Nine different ratios R_{range}, 100% (16/16), 87.5% (14/16), 75% (12/16), 62.5% (10/16), 50% (8/16), 37.5% (6/16), 25% (4/16), 12.5% (2/16), and 0% (0/16) are take into consideration in our simulations.
- The *network density* (D_n): Our simulation considers five different percentage for D_n: 75%, 60%, 45%, 30%, and 15%, and simulated in five different area sizes: 500×500, 1000×1000, 1500×1500, 2000×2000 and 2500×2500 m^2 with 500 randomly mobile nodes. With the same number of mobile nodes, the *network density* is changed by tuning different area sizes.
- The *average network bandwidth* (B_n): B_n is defined as the average available share free time slots between two-hop neighbors in the network. Our simulation considers ten different percentage for B_n: 6.25% (1/16), 12.5% (2/16), 18.75% (3/16), 25% (4/16), 31.25% (5/16), 37.5% (6/16), 43.75% (7/16), and 50% (8/16).

Each simulation result is obtained by the average of 1000 simulation runs. The data transmission rate is 2Mb/s. The duration of each time slot of a time frame is assumed to be 5 ms, and the duration of a control time slot is assumed to be 0.1 ms. The source and destination are randomly selected. Once, a QoS request is successful , a time slot is reserved for all the subsequence packets. The reservation is released when either the data transmission process is finished or the link is broken. The performance metrics consist of the following.

- *Success Rate* (SR): The number of successful QoS routes divided by the total number of QoS route requests, which are initiated from a source to a destination node.

- *Throughput* (TP): The number of the received data packets for all the destination nodes divided by the total number of the data packets transmitted by the source nodes.
- *Average Latency* (AL): The interval from the ime the bow-path is initialed to the time the transmission of the source node is finished.
- *Overhead* (OH): OH is the total number of transmitted packets, including the control packets.

It is worth to mention that a BowQR protocol is improved by having a high *SR* and *TP*, and a low *AL*, but a higher *OH*. In the following, we illustrate our simulation results of *SR*, *TP*, *AL*, and *OH* from various perspectives.

5.1 Success rate (SR)

The simulation results shown in Fig. 13 illustrates the performance of the success rate. The success rate (*SR*) is obtained by calculating the average value of all estimated *SR* values. In the following, we display the performance of the success rate *SR* versus different parameters.

The simulation results reflect the performance of the success rate vs. density level (D_n), mobility (M_o), bandwidth requirement (B_r), average network bandwidth (B_n), and ratio of the range-link period (R_{range}), respectively. Each simulation result in Fig. 13(a), 13(b), 13(c), 13(d), and 13(e) is obtained by assuming the 5-tuple parameters (B_r, B_n, M_o, R_{range}, D_n) = (4, 31.25%, 30 km/h, 50%, (15%∼75%)), (4, 31%, 50%, 45%, (0∼50) km/h), ((1∼8), 31%, 50%, 45%, 30 km/h), (8, (5%∼50%), 50%, 45%, 30 km/h), ((4, 50%, (0%∼100%), 75%, 0 km/h), (4, 25%, (0%∼100%), 45%, 30 km/h), (4, 6%, (0%∼100%), 15%, 50 km/h), (4, 6%, (0%∼100%), 15%, 50 km/h)), respectively.

The higher the density level is, the shorter the average distance between any two nodes is. The shorter the average distance between any two nodes is, the higher the success rate will be. The lower the mobility is, the higher the success rate will be. The lower the bandwidth requirement is, the higher the success rate will be. A higher bandwidth requirement indicates that each link in the path needs to reserve more available share free time slots. The higher the average network bandwidth is, the higher the success rate will be. A higher network bandwidth

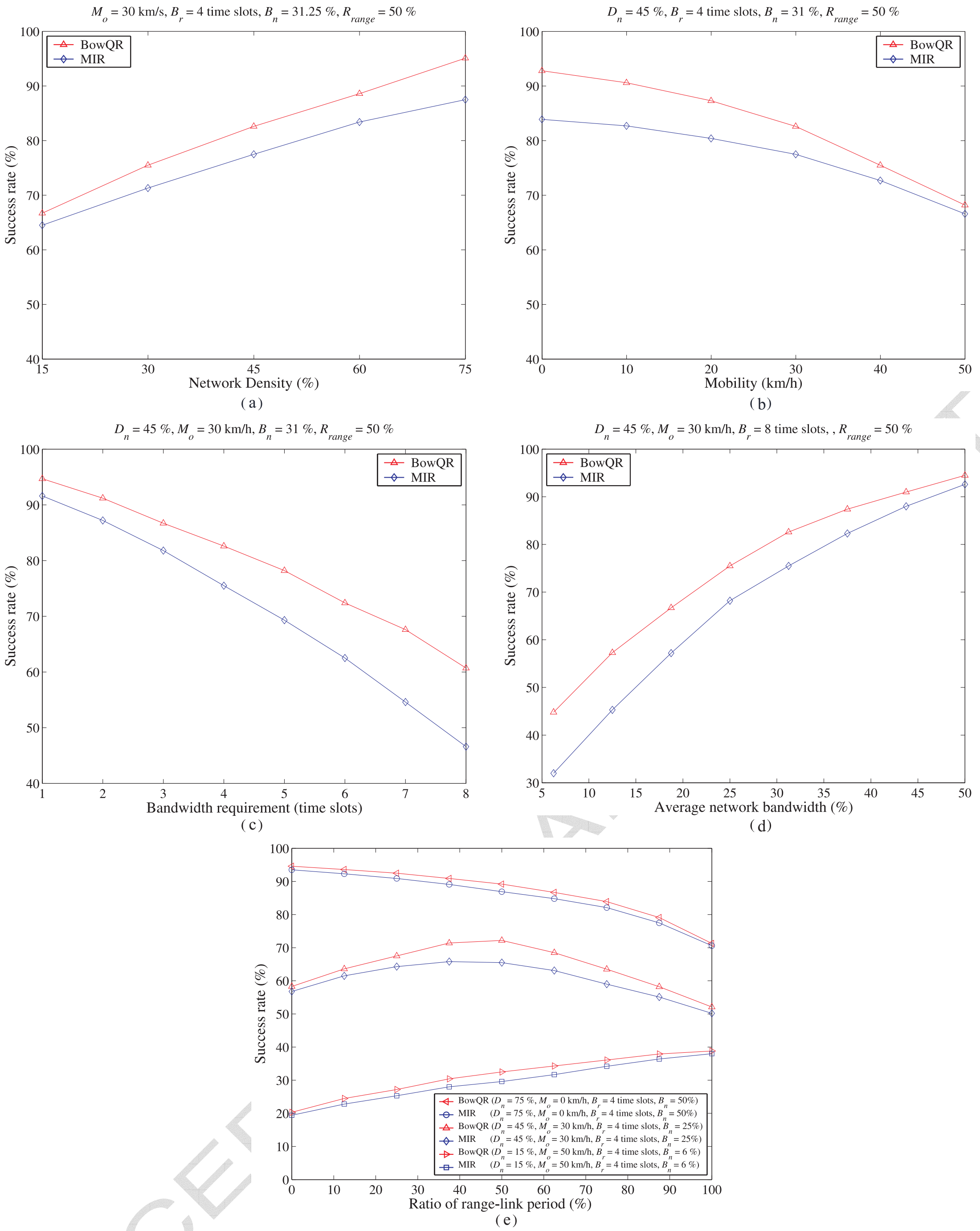


Fig. 13. Performances of success rate vs. (a) density level, (b) mobility, (c) bandwidth requirement, (d) average network bandwidth, and (e) ratio of range-link period.

indicates that two-hop neighbors in the network have more available share free time slots.

Fig. 13 displays that our BowQR protocol has a better performance in success rate than those of MIR protocols with all the different parameters.

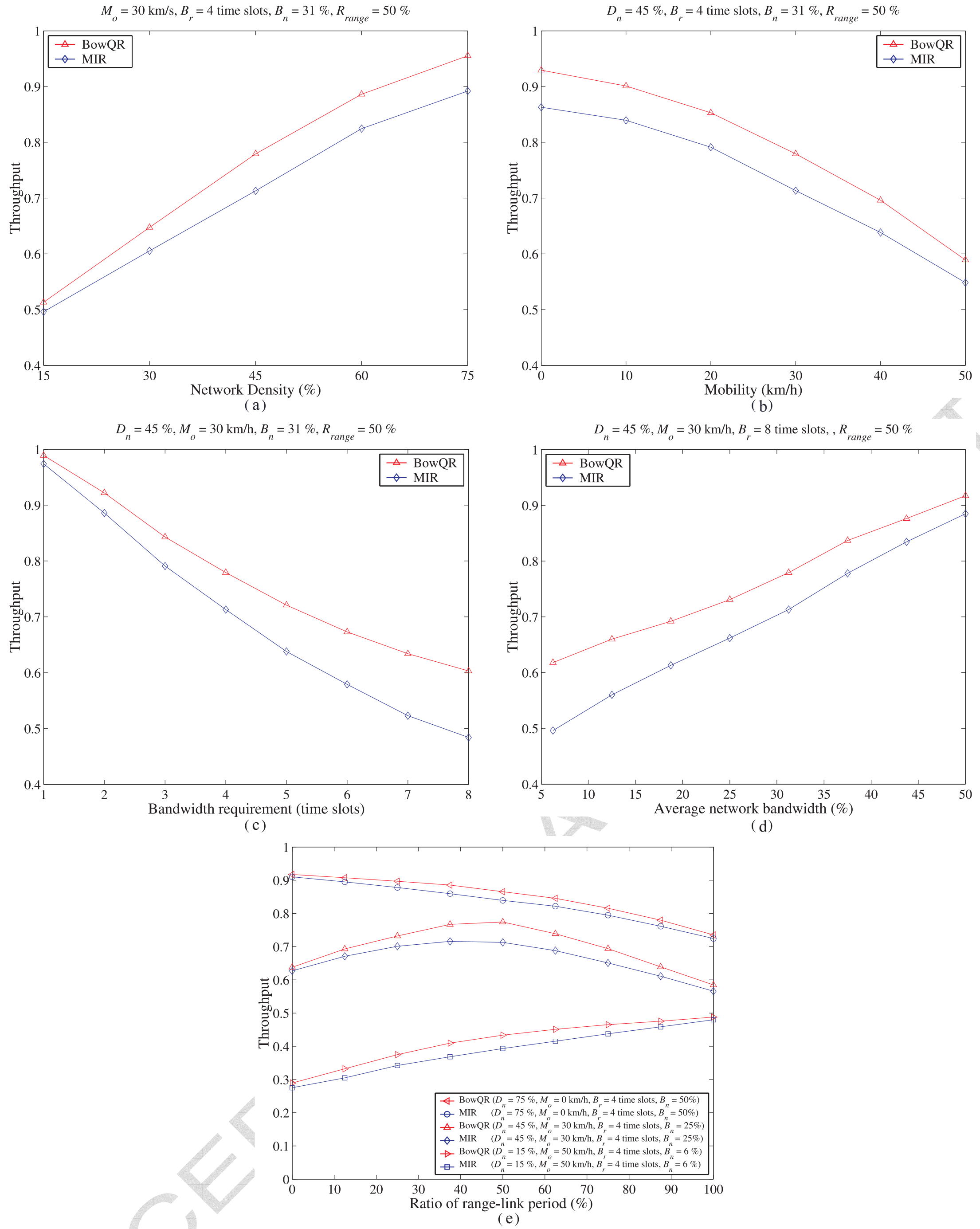


Fig. 14. Performances of throughput vs. (a) density level, (b) mobility, (c) bandwidth requirement, (d) average network bandwidth, and (e) ratio of range-link period.

5.2 Throughput (TP)

The throughput (TP) is obtained by calculating the ratio of the total numbers of received data packets for all the destination nodes to the total number of data packets transmitted by the source nodes, as illustrated in Fig. 14. In the following, we display the performance of the throughput (TP) versus different parameters.

The simulation results reflect the performance of the throughput vs. density level (D_n), mobility (M_o), bandwidth requirement (B_r), average network bandwidth (B_n), and ratio of range-link period (R_{range}), respectively. Each simulation result in Fig. 14(a), 14(b), 14(c), 14(d), and 14(e) is obtained by assuming the 5-tuple parameters (B_r, B_n, M_o, R_{range}, D_n) = (4, 31%, 50%, (15%∼75%), 30 km/h), (4, 31%, 50%, 45%, (0∼50 km/h)), ((1∼8), 31%, 50%, 45%, 30 km/h), (8, (5%∼50%), 50%, 45%, 30 km/h), ((4, 50%, (0%∼100%), 75%, 0 km/h), (4, 25%, (0%∼100%), 45%, 30 km/h), (4, 6%, (0%∼100%), 15%, 50 km/h)), respectively.

The higher the density level is, the higher the throughput will be. The higher the mobility is, the lower the throughput will be. The higher the bandwidth requirement is, the less the throughput will be. A higher network bandwidth indicates that one or two-hop neighbors in the network have more available shared free time slots. The higher the average network bandwidth is, the higher the throughput will be. A higher ratio of range-link period indicates that there are more time slots in the range-link period.

Fig. 14 displays that our BowQR protocol can achieve a higher throughput than those of MIR protocols with all the different parameters.

5.3 Average latency (AL)

The simulation results shown in Fig. 15 illustrates the performance of the average latency. The average latency (AL) is obtained by calculating the interval from the ime the bow-path is initialed to the time the transmission of the source node is finished. In the following, we display the performance of the average latency (AL) versus different parameters.

The simulation results reflect the performance of the average latency vs. density level (D_n), mobility (M_o), bandwidth requirement (B_r), average network bandwidth (B_n), and ratio of range-link period (R_{range}), respectively. Each simulation result in Fig. 14(a), 14(b), 14(c), 14(d), and 14(e) is obtained by assuming the 5-tuple parameters (B_r, B_n, M_o, R_{range}, D_n) = ((4, 31%, 50%, (15%∼75%), 30 km/h), (4, 31%, 50%, 45%, (0∼50 km/h)), ((1∼8), 31%, 50%, 45%, 30 km/h), (8, (5%∼50%), 50%, 45%, 30 km/h), ((4, 50%, (0%∼100%), 75%, 0 km/h), 4, 32%,

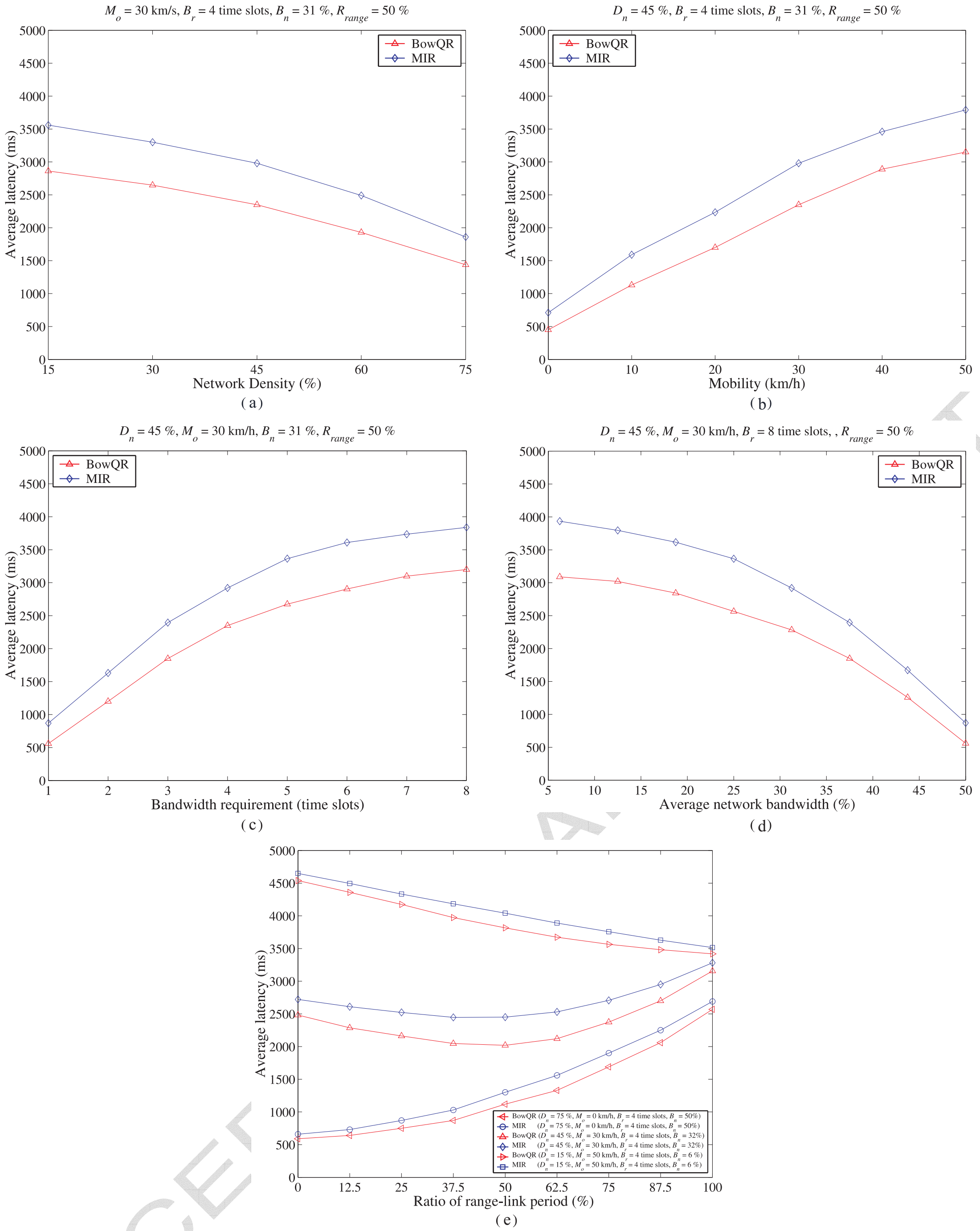


Fig. 15. Performances of average latency vs. (a) density level, (b) mobility, (c) bandwidth requirement, (d) average network bandwidth, and (e) ratio of range-link period.

((0%∼100%), 45%, 30 km/h), (4, 6%, (0%∼100%), 15%, 50 km/h))), respectively.

The higher the density level is, the lower the average latency will be. The higher the mobility is, the higher the average latency will be. The higher the bandwidth requirement is, the higher the average latency will be. A higher network bandwidth indicates that one or two-hop neighbors in the network have more available shared free time slots. The higher the average network bandwidth is, the lower the average latency will be. A lower AL indicates that a better scheme is achieved. A higher ratio of the range-link period indicates that there are more time slots in the range-link period.

Fig. 15 displays that our BowQR protocol has a better performance in average latency than those of MIR protocols with all the different parameters.

5.4 Overhead (OH)

The simulation results shown in Fig. 16 illustrates the performance of the overhead. The overhead (OH) is obtained by calculating the total number of transmitted packets, including the control packets. Our approach aims to obtain a more stable QoS routing result, by causing the extra overhead cost. That is, our approach increases the amount of the extra control message to offer the best results of the success rate, throughput, and average latency. In the following, we display the performance of the overhead (OH) versus different parameters.

The simulation results reflect the performance of the average latency vs. density level (D_n), mobility (M_o), bandwidth requirement (B_r), average network bandwidth (B_n), and ratio of range-link period (R_{range}), respectively. Each simulation result in Fig. 16(a), 16(b), 16(c), 16(d), and 16(e) is obtained by assuming the 5-tuple parameters (B_r, B_n, M_o, R_{range}, D_n) = ((4, 31%, 50%, (15%∼75%), 30 km/h), (4, 31%, 50%, 45%, (0∼50 km/h)), ((1∼8), 31%, 50%, 45%, 30 km/h), (8, (5%∼50%), 50%, 45%, 30 km/h), ((4, 50%, (0%∼100%), 75%, 0 km/h), (4, 25%, (0%∼100%), 45%, 30 km/h), (4, 6%, (0%∼100%), 15%, 50 km/h))), respectively.

The higher the density level is, the higher the overhead will be. The higher the mobility is, the higher the overhead will be. In the ad hoc network, network topologies frequently change when there are more mobile nodes with mobility. The higher the bandwidth requirement is, the higher the overhead will be. Observe that our protocol acquires a more number of OH than that of MIR protocol. The higher the average network bandwidth is, the lower the overhead will be. A higher network bandwidth indicates that one or two-hop neighbors in the network have more available shared free time slots. Observe that our protocol acquires more number of OH than that of MIR protocol. A higher ratio of the range-link period indicates that there are more time slots in the range-link period. Both protocols

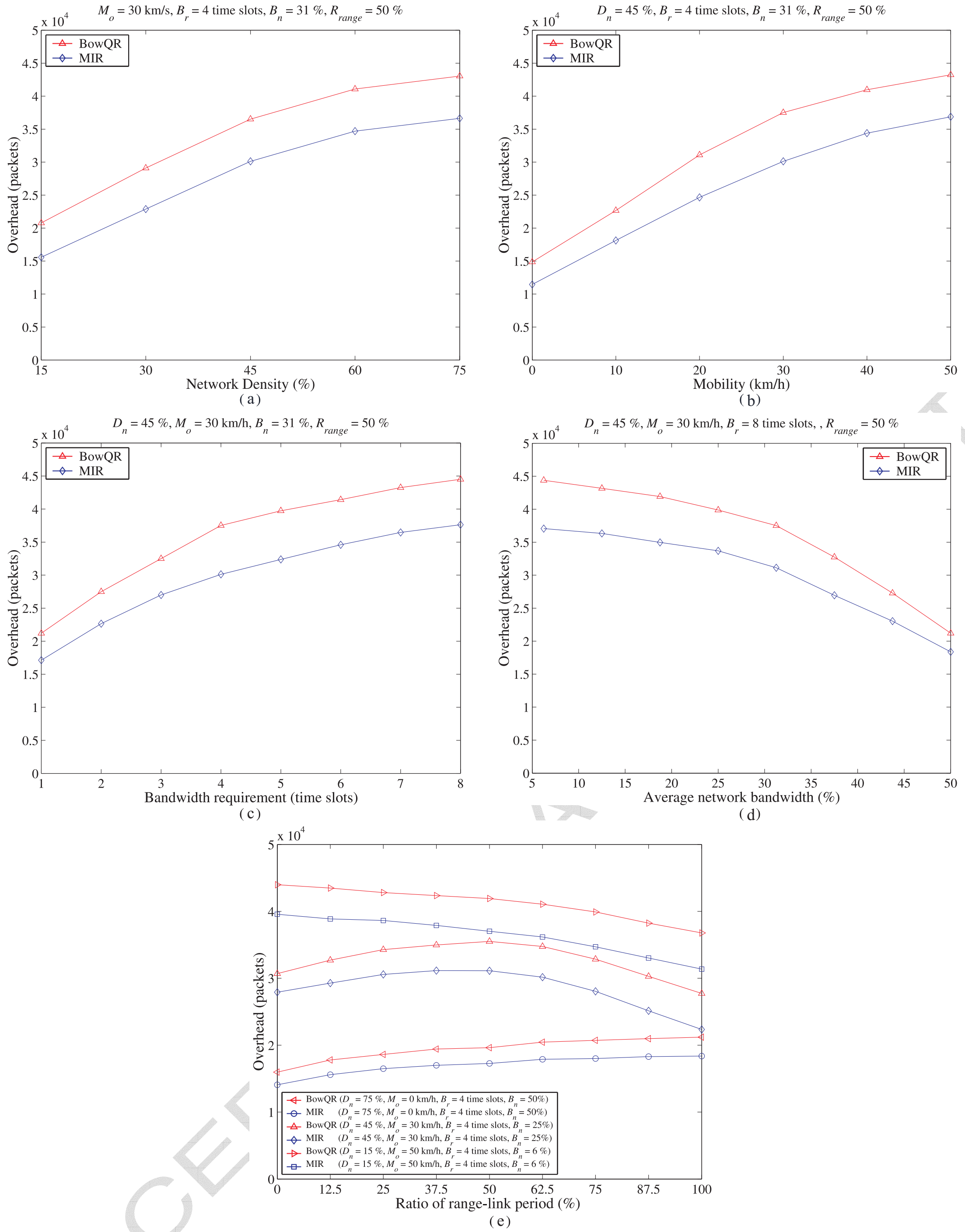


Fig. 16. Performances of overhead vs. (a) density level, (b) mobility, (c) bandwidth requirement, (d) average network bandwidth, and (e) ratio of range-link period.

have lower AL value at any ratio of the range-link period.

6 Conclusion

In this work, we propose a multi-path bow-based on-demand MIMO ad hoc networks routing protocol, called BowQR. Our BowQR protocol is proposed to support the QoS requirement and improve the transmission efficiency of MIMO ad hoc networks. Each TDMA cycle is composed of the rate-link period and the range-link period in a data phase, and is adopted in MAC sub-layer to support the QoS routing. Specially, there is one reserved time slot between the rate-link period and the range-link periods in each time slot frame. Two types of transmission links, the rate-link and the range-link, exploit the spatial multiplexing and spatial diversity to provide extremely high spectral efficiencies and increase the transmission range. Our associated bow structure is composed of the rate-links and/or the range-links on demand to provide the multi-path route and accomplish the bandwidth requirement. Finally, the simulation results show that our BowQR protocol achieves the performance improvements in terms of the throughput, success rate, and average latency.

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