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# Traffic-predictive QoS on-demand routing for multi-channel mobile ad hoc networks

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**Abstract**

Mobile multimedia applications have recently attracted numerous interests in mobile ad hoc networks (MANETs) supporting quality-of-service (QoS) communications. Multiple non-interfering channels are available in 802.11- and 802.15-based wireless networks. Channel assignment depends on the available bandwidth at involved nodes and the bandwidth consumption required by a new flow. Predicting available bandwidth of a node in wireless networks is challenging due to the shared and open nature of the wireless channel. This paper proposes a traffic-predictive QoS on-demand routing(TPQOR) protocol to support QoS bandwidth and delay requirements. A distributed channel assignment scheme and routing discovery process are presented to support multimedia communication and to satisfy QoS bandwidth requirement. The proposed channel assignment and reuse schemes can reduce the channel interference and enhance channel reuse rate. The proposed bandwidth prediction scheme can estimate the bandwidth requirement of each node for future traffic by the history information of its channel usage. Unlike many existing routing protocols, we take the traffic prediction as an important factor in route selection. The simulation results show that TPQOR protocol can effectively increase throughput, reduce loss ratio as well as delay, and avoid the influences of future interference flows, as compared to AODV protocol for a different number of channels.

**Keywords:** Mobile ad hoc network, QoS routing, Bandwidth prediction, Channel assignment

## 1 Introduction

In mobile ad hoc networks (MANETs), the topology of the network can change frequently and the network routing becomes a crucial task [1]; while routing with mobility prediction is well-studied, routing with traffic prediction is still considered as an open, but meaningful problem. This is particularly important for routing with quality-of-service (QoS) constraints, since QoS resource-reservations affect future network traffic. There have been significant progress in using mobility prediction to build a more stable route in MANETs, and some predictive and reliable routing schemes [2, 3] have been reported. These accomplishments inspire us to study further on the design of a routing scheme with traffic prediction. The prediction of future traffic can be a powerful tool in QoS routing. For example, if there are two candidate paths and it is predicted that a new traffic will be produced along one of them right after the QoS route has been builded, thus, with the help of traffic prediction, we can choose the more "peaceful" route for the QoS flow so that resources reserved by QoS route and resources used by that new traffic will not affect with each other. Node mobility is modeled as a time-homogeneous semi-Markov process for disruption-tolerant networks in [2], which predicts the future contacts of two specified nodes at a specified time. It can predict not only whether two nodes would have a contact, but also the time of contact. With this model, a node estimates the future contacts of its neighbors and the destination and then selects a proper neighbor as the next hop to forward the message. In [3], an interference aware metric with a prediction algorithm is proposed to reduce the interference between nodes at the MAC layer and works in an on-demand routing scheme in multichannel vehicular ad hoc networks.

Traffic routing and channel assignment jointly play a critical role in determining the performance of MANETs. The scare wireless channel resource, high dynamic link quality, and the uncertain traffic demands are big challenges for routing in MANETS. There are several approaches for traffic routing. One approach is based on traffic-predictive models, such as the method proposed

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in [4], which has a competitive performance when traffic can be predicated accurately, but may result in unbounded worst-case performance when forecasts go wrong. Traffic prediction by employing multi-layer feeding forward neural network model is proposed in [4], which learns the effect of spatio-temporal-spectral parameters on traffic patterns and predicts future traffic load on each of the channels. It is also hard to choose the parameters of neural network model. In another approach, routing can be made with the focus towards maximally unbalanced demand, such that the worst case is contained (known as oblivious routing) such as [5]. It is an open question how these two approaches would compare with each other in real networks. A weighted average predictive algorithm is presented for mesh networks in [5], which gives detailed simulation studies of predictive and oblivious routing. Their results show that the proposed algorithm can accommodate the changing conditions in the predictability of the traffic and has good performance, but it is difficult to give the accurate weights. One natural approach to address the traffic uncertainty in network routing is predictive routing [6], which infers the traffic demand with maximum probability based on history and optimizes the routing strategy for the predicted traffic demand. Underlying predictive routing is the assumption that past behavior is a good indicator of the future. Many researchers have studied predictive routings in MANETs; for example, in [7], authors proposed an algorithm that utilizes the prediction of vehicle position and navigation information to improve the routing protocol in vehicular ad hoc networks with a cross-layer approach. Paper [8] focuses on link quality prediction and estimation. A routing algorithm based on traffic prediction is proposed for DTN in [9]. Paper [10] investigates the cross-layer optimization problem of congestion and power control in cognitive radio ad hoc networks (CRANETs) under predictable contact constraint; a predictable contact model is presented by deriving the probability distribution of contact via a mathematical statistics theory; they do not adapt to MANETs. A method of the prediction of link residual lifetime using Kalman filter is proposed for vehicular ad hoc networks in [11]; it focuses on route selection; an analytical model for predictable contact between two cognitive users is proposed in the intermittently connected cognitive radio ad hoc networks [12]; it is based on mobility model, which do not consider the bandwidth usage and channel assignment. The scheme of opportunistic routing with autonomic forwarding angle adjustment (FAOR) is proposed for cognitive radio ad hoc networks in [13], which is a different network model from this paper.

QoS applications are usually sensitive to available bandwidth. The available bandwidth of each node is directly affected by the existing traffic, which makes traffic prediction very meaningful in QoS routing. The suitability of linear predictors for traffic prediction is discussed in packet and burst switching networks [14], where both the prediction method and the prediction interval are considered in traffic prediction. However, the performance of the network is limited by the packet arrival distribution. A priority aware dynamic source routing protocol is proposed in order to enhance QoS for MANETs in [15]; it assigns the priority for different flows in accordance with their data rates in dynamic source routing. As far as we have known, there is no QoS routing scheme based on the traffic prediction in ad hoc networks.

For channel assignment, a fully distributed channel assignment algorithm is proposed in [16], which can adapt to traffic loads dynamically for wireless mesh networks. The mentioned scheme can improve the utilization of network resource, but does not supply any solution of QoS routing. In [17], a QoS-aware routing mechanism to support real-time multimedia communication is proposed for ad hoc networks. A node estimates the usage of its wireless channels and disseminates the information about its available bandwidth to other nodes in the whole network. Thus, each node obtains a view of topology and bandwidth information of the whole network. Based on the obtained information, a source node determines a logical path with the maximum available bandwidth to satisfy the QoS requirements of applications. However, the above two papers do not take channel reuse into consideration.

The main goal of this paper is to design a routing scheme that can meet QoS bandwidth and delay requirements by taking traffic variations into account. We propose a traffic predictive QoS on-demand routing(TPQOR) protocol to pursue a better network performance. Particularly, TPQOR protocol uses channel reuse mechanism described in our previous work [18], in which we present a cross-layer protocol that solves channel assignment, reuse, and routing problem jointly. In TPQOR protocol, future traffic is predicted according to nodes' history traffic patterns, based on an assumption that the traffic of network nodes has a certain pattern. Such assumption is reasonable in reality considering the device utilization and routing characteristics. Different devices produce different traffic for their use, such as a video monitor usually produces higher traffic than those "light-weight" counterparts such as humidity or temperature sensors, since a node acts as a terminal as well as a router in ad hoc networks, which makes traffic of a node include not only the traffic it produces, but also the traffic it forwards. The shortest path routing has been simulated in a distributed $9 \times 9$ grid [19] , where the routing characteristic of the network is that nodes in the center area have much higher traffic load than nodes in other areas.

The remainder of this paper is structured as follows: we firstly describe network model as research basement in Sections 2, 3, and 4, depicting our proposed channel reuse scheme and traffic prediction mechanism respectively; Section 5 describes TPQOR routing procedure; Section 6 shows simulation results; at last, we make conclusions for this paper in Section 7.

## 2 Network model

We first present the network model used throughout this paper. An ad hoc network can be modelled as a graph $G = (V, E)$, where $V$ is the set of nodes and $E$ is the set of edges that represent wireless links. A link is assumed to exist between two nodes if and only if the two nodes are within each other's transmission range. For each link $e = (u, v) \in E$, $u$ is the transmitter and $v$ is the receiver. Each node $n$ has a transmission range $R_t(n)$, which allows only those nodes within distance $R_t(n)$ to receive the signal from node $n$ correctly. We assume that each terminal $n$ also has an interference range $R_i(n)$ such that every unintended receiver would be interfered by the signal from node $n$ when it is using the same channel as node $n$ does simultaneously. For simplicity, it is assumed that all nodes have the same transmission range $R_t$ and the same interference range $R_i$, and the interference range of nodes is two times of their transmission range, that is, $R_i = 2R_t$. We define that two distinct links $(u_1, u_2)$ and $(v_1, v_2)$ are interference links if one of two pairs $(u_1, v_2)$ and $(v_1, u_2)$ is less than $R_i$ apart. In order to transmit simultaneously, two interference links need to be assigned with different channels.

In our network model, each node can operate on one common control channel for control information and other several data channels for data packets, each channel can be switched among the network interface cards (NIC) of each node. Let $CT = \{ch1, ch2, ..., chk\}$ denote the set of $K$ orthogonal data channels that can be used by all nodes. We assume that every channel in $CT$ has its unique serial number and has the same bandwidth $Bw_{ch}$. The set of available channels of node $n$ is $A(n)$, which are free channels and can be assigned for future use at node $n$. $C_t(n)$ denotes the set of active transmitting channels of node $n$, and $C_r(n)$ denotes the set of active receiving channels of node $n$.

Interference neighbors of each node $n$ are those nodes locating in the interference range of node $n$. Let $N_i(n)$ denote the set of interference neighbors of node $n$. To reach an interference-free channel assignment for link $e = (u, v)$, both the active transmitting channels of $N_i(v)$ and the active receiving channels of $N_i(u)$ should be excluded. The active transmitting channels of $N_i(v)$ is $C_t(N_i(v)) = \cup_{\forall x \in N_i(v)} C_t(x)$, and the active receiving channels of $N_i(u)$ is $C_r(N_i(u)) = \cup_{\forall x \in N_i(u)} C_r(x)$. That is, in order to avoid conflicts, link $e = (u, v)$ should not be assigned any channel in the set of $C_t(N_i(v)) \cup C_r(N_i(u))$. The notations used in this paper are as shown in Table 1.

**Table 1** Notation used in the paper

| Symbol | Comments |
|---|---|
| $V$ | The set of nodes |
| $E$ | The set of edges that represents wireless links |
| $R_t(n)$ | The transmission range of node $n$ |
| $R_i(n)$ | The interfernce range of node $n$ |
| $CT$ | $K$ orthogonal data channel set $\{ch1, ch2, ..., chk\}$ |
| $N_i(v)$ | Interference node set of node $v$ |
| $C_t(v)$ | Active transmitting channel set of node $v$ |
| $C_r(v)$ | Active receiving channel set of node $v$ |
| $C_r(X(v))$ | Active receiving channel set of node set $X(v)$ |
| $C_t(X(v))$ | Active transmitting channel set of node set $X(v)$ |
| $Bw_{req}$ | QoS request bandwidth for the flow |
| $Bw_{ch}$ | Bandwidth of a channel |
| $A(u)$ | Available channel set of node $u$ |
| $AL(l)$ | Available channel set of link $l$ |

## 3 Channel assignment scheme

In multichannel ad hoc networks, channel assignment is a real hot topic. A good channel assignment scheme should decrease collisions and enhance the network throughput as much as possible. Channel reuse scheme is to economize the number of assigned channels on the precondition of avoiding conflicts as much as possible. In other words, a distinct advantage of channel reuse scheme is that it can leave more available channels for other use. An example for channel assignment with the channel reuse scheme is shown in Fig. 1, where we assume that data channel set $CT = \{ch1, ch2, ch3, ch4, ch5\}$ and $R_i = 2R_t$. The channels are assigned from source node $u1$ to destination node $u6$, where the first four adjacent links from $u1$ to $u5$ must be assigned with different channels to avoid conflicts. We assume that links $(u1, u2), (u2, u3), (u3, u4), (u4, u5)$ are assigned channels $ch1, ch2, ch3, ch4$ respectively. If the channel $ch5$ is assigned to link $(u5, u6)$ for interference-free assignment, it will leave no available

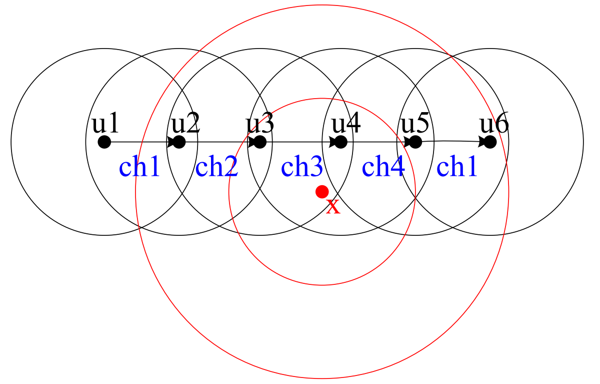


**Fig. 1** The example of channel reuse

channel for other use. For example, there is no available channels for node $x$ to transmit signals. If $ch1$ is reused by links $(u1, u2)$ and $(u5, u6)$ as shown in Fig. 1, $ch5$ will be available for the transmission channel of node $x$. The channel reuse can leave more free channels for other use, and this can enhance the throughput of the network.

In order to implement the channel reuse scheme, we should obtain the information of every node's channel assignment. Obtaining the information from the whole network produces too much traffic and acts against to network scalability. We design a distributed scheme that solves the problem of channel reuse elegantly. In our proposed mechanism, each channel is assigned to an unique serial number. The interference-free channel with the minimum number is firstly assigned. The lower a channel's number is, the higher probability it is reused.

The available channel set $AL(l)$ for a link $l = (u, v)$ is calculated as follows: let $C_t(N_i(v))$ the active transmitting channel set of $v$'s interference neighbors and $C_r(N_i(u))$ the active receiving channel set of $u$'s interference neighbors; $AL(l)$ can be represented as $AL(l) = CT - (C_t(N_i(v)) \cup C_r(N_i(u)))$. The proposed channel assignment scheme selects channels by sequence from $AL(l)$ for channel reuse. Let $Bw_{req}$ represent the minimum bandwidth requirement of a QoS flow, and $Bw_{ch}$ represent the physical maximum bandwidth of each channel. The ceiling integer of quotient of $Bw_{req}$ divided by $Bw_{ch}$ is the number of channels that need to be assigned for the QoS flow. The channel assignment algorithm is given in Algorithm 1.

**Algorithm 1** Channel Assignment Algorithm(CA) for a link $l = (u, v)$

```
initial: for each link $l = (u, v)$, $AL(l)$ is set to empty
$AL(l) = CT - C_t(N_i(v)) \cup C_r(N_i(u))$
if the flow is not a QoS flow then
    if $AL(l)$ is empty then
        return a FAIL
    else
        return the channel with the minimum number in $AL(l)$ for link $l$
    end if
else
    $Req_{ch} = \lceil Bw_{req}/Bw_{ch} \rceil$
    /*$Req_{ch}$ is the number of the QoS flow required channels */
    if $|AL(l)| < Req_{ch}$ then
        return a FAIL
    else
        return $Req_{ch}$ channels with the minimum number in $AL(l)$ for link $l$
    end if
end if
```

## 4 Traffic prediction scheme

Traffic is an abstract concept referring to data flows which are shuttling to and from in the network, and can be described as various ways, such as consumed bandwidth. Since every new traffic would be assigned one or more interference-free channels in this paper and each channel denotes a certain value of bandwidth, we can use the number of active channels to represent the amount of traffic. When no enough channels in $A(n)$ are available for node $n$ to communicate, it is called traffic overflowing. If a node occurs traffic overflowing, it will not be able to assign enough channels for new QoS flows. The traffic prediction scheme is designed to reduce such a situation in this paper. After receiving a QoS routing request, TPQOR protocol would predict the probability of the traffic overflowing in the networks. When a node receives a QoS routing request, the future probability of its traffic overflowing is estimated by the history of its bandwidth use.

Traffic history of a node is periodically recorded in an FIFO (first in first out) queue $T_{his}$. Let $his\_length$ be the length of the queue. Each element in $T_{his}$ denotes the number of channels in $A(n)$ at one past time. The minimum request channel number $Req_{ch}$ is calculated for a QoS flow in one channel assignment. Let $ovflw\_time$ be the number of times of overflowing. The value of $ovflw\_time$ will be increased by one each time when the number of available channels is not enough for QoS flows. The probability $P_{ovflw}(n)$ for node $n$ to occur traffic overflowing can be represented as:

$$P_{ovflw}(n) = ovflw\_time/his\_length \qquad (1)$$

We define a route with one or more traffic overflowing nodes as traffic overflowing route. According to the definition, the probability $PR_{ovflw}(R)$ of traffic overflowing for a route can be deduced as Eq. 2, where $R$ is a route and $v$ represents each node along the route, and $\bar{R}$ denotes the set of all nodes on the route $R$.

$$PR_{ovflw}(R) = 1 - \prod_{v \in \bar{R}} (1 - P_{ovflw}(v)) \qquad (2)$$

In TPQOR protocol, $PR_{ovflw}(R)$ is an important element to be considered in selecting routes. A good route should not only pass through fewer hops, but also has less probability of traffic overflowing. Therefore, a variable $rt\_pri(R)$ is defined to denote the priority of each candidate route $R$ in Eq. 3, where $MAX\_HOP$ denotes the maximum hops of routes in the network and $TTL$ is the time to live of QRREQ packet. The value of $TTL$ is set to $MAX\_HOP$ initially and decreased by one each time the packet is forwarded. When $Ttl = 0$, the packet will be dropped. As we know, $TTL \in [0, MAX\_HOP]$ and $rt\_pri \in [0, 2MAX\_HOP]$. TPQOR protocol tends to select a route

$R$ with the maximum $rt\_pri(R)$ among all candidate routes for a QoS flow.

$$rt\_pri(R) = 2MAX\_HOP - (PR_{ovflw}(R) \cdot MAX\_HOP + TTL) \quad (3)$$

## 5 Traffic-predictive QoS on-demand routing protocol

In this section, we propose a traffic-predictive QoS on-demand routing (TPQOR) protocol for multi-channel mobile ad hoc networks. TPQOR protocol is a reactive routing protocol, which operates in two phases: route discovery and route reply. Its route discovery process depends on the flooding of QoS Routing REQuest (QRREQ) packets from the source until one of them reaches the destination. In the route reply process, a QoS Routing REPly(QRREP) packet is forwarded back from the destination to the source along a reverse path which has been built in route discovery process. In the process of route discovery, each node maintains itself a route table *rt*. This table is a set of rules that are used to determine where data packets will be directed. A routing table is maintained to keep the next hop information to all possible destination nodes and the previous hop information to their sources for all flows. The format of the routing table is shown in Table 2; four status {ONBUILDING, BUILT, ONREPAIRING, ERROR} are defined for a route, which are explained in Section 5.4.

**Table 2** Routing table

| *Sid* | *Did* | *Fid* | *prev_hop* | *next_hop* | *rt_pri* | *status* |
|---|---|---|---|---|---|---|

*Sid* source node, *Did* destination node, *Fid* flow id, *prev_hop* the previous hop of the current node, *next_hop* the next hop of the current node, *rt_pri* route priority, *status* status of the route

### 5.1 Neighboring maintenance

We propose a multichannel QoS-aware routing protocol that permits a flow with the requested bandwidth and delay. The admission scheme requires the channel usage information of all interference neighbors of a node. In the proposed TPQOR protocol, a node will maintain three lists, *nb_list* (neighboring node list), *intf_list*(interference node list except neighboring nodes), and *CUT* (channel usage table), to record the required information of channel assignment. Each node maintains its own *CUT*, which records the two end nodes of each assigned channel and the communication direction (receiving or transmitting) and whether the channel is reserved for a QoS flow such as shown in Fig. 2. The "Hello" detection method is used to collect the available channels of nodes in the networks. We need to find the neighboring nodes before we execute the route discovery process; the purpose of the HELLO messages is to find the neighboring nodes and to create the neighboring node list, interference node list, and channel usage table for each node. HELLO messages are broadcasted periodically among node's one-hop neighbors. When a node $v$ receives HELLO from its active neighbors, it updates its neighboring nodes, interference nodes, and corresponding channel usage information.

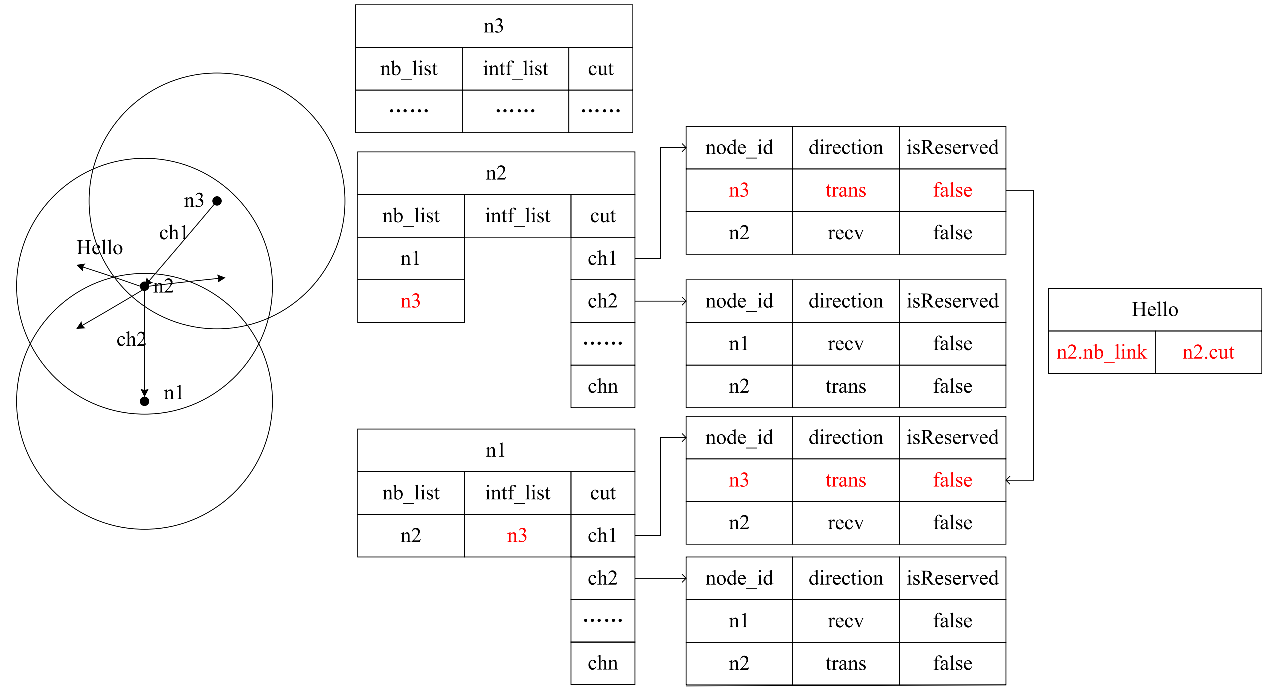
In this paper, we construct the interference node set $N_i(v)$ by discovering two-hop nodes of node $v$, that is, $N_i(v) = \bigcup_{u \in N(v)} N(u)$, where $N(u)$ is the neighboring node set of node $u$. Every Hello packet from node $n$ contains not only information of node $n$ itself, but also its neighbors' information, which is also known through its neighbors' Hello packets. By receiving such Hello packets, a node can indirectly obtain its two-hop neighbors' information. An example of the neighboring maintenance is shown in Fig. 2, where the neighboring node list *nb_list*, interference neighboring node list *intf_list*, and channel usage table *CUT* are shown in its boxes. In this example, node $n3$ is the interference neighboring node of $n1$, but not its neighboring node. Although this makes it difficult for $n1$ to get $n3$'s information directly, $n1$ can get the information through $n2$'s Hello packets because $n1$ and $n3$ are both the neighboring nodes of $n2$.

### 5.2 Route request process

The QoS-aware routing protocol decides to accept or reject an incoming flow in the QRREQ (QoS Route REQuest) packet broadcasting process, which is based on the QoS requirement bandwidth ($Bw_{req}$) and delay ($Del_{req}$). When a source node needs to communicate with another node for which it has no route information in its table, it broadcasts a QRREQ packet to its neighboring nodes. The format of the QRREQ packet is shown in Table 3.

In TPQOR protocol, when a node receives a QRREQ packet, it updates $TTL$, calculates the priority of the current route by using Eqs. 2 and 3, and then decides either to rebroadcast it or drop it. A QRREQ packet will not be rebroadcasted under the following conditions: it reaches the destination node; the same packet has already been received and the new one does not have a higher route priority; the live time of the packet is more than $TTL$; the node, which receives the QRREQ packet, can not meet the QoS requirements.

TPQOR protocol provides the minimum bandwidth and the maximum delay guarantees for QoS routing. In a QRREQ packet, the bandwidth requirement is recorded by $Bw_{req}$. Intermediate node $n$ judges whether it can meet the QoS bandwidth requirement by checking its available channel set $A_t(n) = CT - C_r(N_i(n))$ for interference-free transmitting and the available channel set $A_r(n) = CT - C_t(N_i(n))$ for interference-free receiving. Node $n$ can meet the bandwidth requirement only if both $A_t(n)$ and



| n3 | | |
|---|---|---|
| nb_list | intf_list | cut |
| …… | …… | …… |

| n2 | | |
|---|---|---|
| nb_list | intf_list | cut |
| n1 | | ch1 |
| n3 | | ch2 |
| | | …… |
| | | chn |

| n1 | | |
|---|---|---|
| nb_list | intf_list | cut |
| n2 | n3 | ch1 |
| | | ch2 |
| | | …… |
| | | chn |

| node_id | direction | isReserved |
|---|---|---|
| n3 | trans | false |
| n2 | recv | false |

| node_id | direction | isReserved |
|---|---|---|
| n1 | recv | false |
| n2 | trans | false |

| node_id | direction | isReserved |
|---|---|---|
| n3 | trans | false |
| n2 | recv | false |

| node_id | direction | isReserved |
|---|---|---|
| n1 | recv | false |
| n2 | trans | false |

| Hello | |
|---|---|
| n2.nb_link | n2.cut |

**Fig. 2** The example of neighboring maintenance

$A_r(n)$ have enough channels to offer. The minimum number of channels to guarantee the QoS requirement bandwidth $Bw_{req}$ is $\lceil Bw_{req}/Bw_{ch} \rceil$ as shown in Algorithm 1. Timeout QRREQ packets are those packets whose transmission time exceeds the delay requirement $Del_{req}$, that is, $Del_{req} \leq NOW\_TIME - Time$. We claim that if QRREQ packets could reach the destination within $Del_{req}$, so do data packets.

When a node receives a QRREQ packet, it first checks whether the entry is its own DID. If the node is the destination, it sends a QRREP packet back to the source node along the discovered path; otherwise, it broadcasts the QRREQ packet to its neighbor nodes according to Algorithm 2. Any node that receives the QRREQ message updates its neighboring node list, interference node list, and channel usage table (CUT). An example for route request is shown in Fig. 3, where node S initiates a route query to node D to establish a route with 1000 Kbps minimum request bandwidth and 0.3 s maximum delay. Here, we focus on introducing the proposed bandwidth prediction method in the process of route request, we assume that there exist no timeout packets. In Fig. 3, we assume that $P_{ovflw}(E) = 0.7$, overflowing probability of nodes $S, A, B, C$, and $D$ is 0.1 respectively, $MAX\_HOP = 15$, $TTL = MAX\_HOP$ at node $S$. The process of QoS routing request is divided into five stages (stage.0–stage.4); we calculate the overflowing probability of the routes according to Eq. 2 and the priority of the routes according to Eq. 3 along path S-A-B-C-D and path S-E-C-D; the status items of each node are shown in the boxes:

- Stage 0: $PR_{ovflw}(S) = 0.1, rt\_pri(S) = 30 - (0.1 * 15 + 15) = 14.85$;
- Stage 1: $PR_{ovflw}(SA) = 0.19, rt\_pri(SA) = 30 - (0.19 * 15 + 14) = 13.15, PR_{ovflw}(SE) = 0.73, rt\_pri(SE) = 30 - (0.73 * 15 + 14) = 5.05$;
- Stage 2: $PR_{ovflw}(SAB) = 0.271, rt\_pri(SAB) = 30 - (0.271 * 15 + 13) = 12.935, PR_{ovflw}(SEC) = 0.757, rt\_pri(SEC) = 30 - (0.757 * 15 + 13) = 5.645$;
- Stage 3: $PR_{ovflw}(SABC) = 0.3439, rt\_pri(SABC) = 30 - (0.3439 * 15 + 12) = 12.8415$, $PR_{ovflw}(SECD) = 0.7813, rt\_pri(SECD) = 30 - (0.7813 * 15 + 12) = 6.2805$;
- Stage 4: $PR_{ovflw}(SABCD) = 0.40951, rt\_pri(SABCD) = 30 - (0.40951 * 15 + 11) = 12.85735$.

Although path S-E-C-D passes one hop less than its counterpart path S-A-B-C-D, its intermediate node E

**Table 3** The format of QRREQ packet

| *Sid* | *Did* | *Fid* | *Type* | $Bw_{req}$ | $Del_{req}$ | *Seq* | *Time* | $PR_{ovflw}$ | *TTL* |
|---|---|---|---|---|---|---|---|---|---|

*Sid* source ID; *Did* destination ID; *Fid* flow ID; *Type* the type of packet; $Bw_{req}$ QoS minimum bandwidth requirement; $Del_{req}$ QoS maximum delay requirement; *Seq* request packet broadcasting sequence number; *Time* QRREQ packet time stamp, it records the starting time of QRREQ packet; $Pr_{ovflw}$ the probability of traffic overflowing of the current route; *TTL* the maximum time to live of the packet, whose initial value is the maximum hops of the network

**Algorithm 2** Process of Receiving a QRREQ packet

```
initial: node $u$ has received a QRREQ packet $qrreq$ from node $v$
$qrreq.TTL - -$
calculate overflowing probability $PR_{ovflw}$ and priority $rt\_pri$ of the current route
refresh $qrreq.PR_{ovflw}$
$rt\_item.status$ = ONBUILDING
if $rt\_item.rt\_pri < rt\_pri$ then
    $rt\_item.rt\_pri = rt\_pri$
    $rt\_item.pre\_hop = u$
else
    drop $qrreq$ and return
end if
if $qrreq.TTL = 0$ then
    $rt\_item.status$ = ERROR
    drop $qrreq$ and return
end if
if $|A_t(n)| < \lceil Bw_{req}/Bw_{ch} \rceil$ or $|A_r(n)| < \lceil Bw_{req}/Bw_{ch} \rceil$ or $NOW\_TIME - qrreq.Time < qrreq.del_{req}$ then
    $rt\_item.status$ = ERROR
    drop $qrreq$ and return
end if
if $n! = qrreq.Did$ then
    rebroadcast $qrreq$
else
    send QRREP packet back
end if
```

suffers a high probability of traffic overflow. This makes the path S-E-C-D to have a lower route priority, though it has fewer hops. Therefore, TPQOR changes the pre-hop of node C from E to B in stage 3.

### 5.3 Route reply process

When a suitable path is found from a source node to its destination node, the destination node will send a QoS route reply (QRREP) packet back to the source node. The QRREP packet can be delivered to the source node through the *pre_hop* recorded in route items at nodes along the path. We define the format of the QRREP packet as shown in Table 4.

Not only reconfirming route is the purpose of route reply process, but also conflict-free channels are assigned to each link along the reverse route according to the channel assignment Algorithm 1. During the route reply phase, for a link $l = (u, v)$, QRREP packet is forwarded from downstream $v$ to upstream $u$; channel information, which includes $C_t(N_i(v))$ and $C_r(N_i(v))$, is carried in the QRREP packet of node $v$; and the QRREP packet is forwarded along the reverse path from the destination to its source. Upon receiving a QRREP packet, each node along the route updates its routing table and channel usage table (CUT). When node $u$ receives unicast RREP packet from node $v$, it firstly extracts the interference channel sets of node $v$. Then, if no channel is assigned to the forwarding link $(u, v)$, it calculates the available channel set of link $l = (u, v)$, that is, $AL(l) = CT - (C_t(N_i(v)) \cup C_r(N_i(u)))$. If $|AL(l)| * bw_{ch} \geq bw\_req$, which means there is enough bandwidth for QoS request, $m = \min\{i|i*bw_{ch} \geq bw\_req\}$ channels with the minimum number in $AL(l)$ are assigned to forwarding link $(u, v)$. The information of the assigned channels is sent back to node $v$ for updating the channel usage information. After the route has been established, each node along the route should have enough channels for QoS routing without channel conflicts, and then the route status is changed to *BUILT*. When a node receives a QRREP packet, the processing procedure can be summarized in Algorithm 3. An example of route reply process is shown in Fig. 4, which is according to the route request process in Fig. 3. Here, we assume that the available channel set $CT = \{ch1, ch2, ..., ch8\}$, the bandwidth of each channel is 500 Kbps, so two channels are at least needed to assign each link for 1000 Kbps QoS bandwidth requirement. The QRREP packet is forwarded from destination $D$ to source $S$ in five stages as shown Fig. 4. In each stage, two channels are assigned to the forwarding link. Some route items, CUT, and neighboring table are updated. The change of the related route items and assigned channels are shown in the figure.

**Algorithm 3** Process of node $u$ receiving a QRREP packet from node $v$

```
initial: node $u$ has received a QRREP packet $qrrep$, $rt\_item$ is the related route item
for link $l = (u, v)$, $AL(l) \Leftarrow CT - (C_t(N_i(v)) \cup C_r(N_i(u)))$
let $m = \lceil Bw_{req}/Bw_{ch} \rceil$
if $|AL(l)| \geq m$ then
    select $m$ channels $C_m$ in $AL(l)$ by using channel assignment algorithm Algorithm 1
    $C_t(N_i(u)) = C_t(N_i(u)) \cup C_m, C_r(N_i(u)) = C_r(N_i(u)) \cup C_m$
    $rt\_item.next\_hop = v$
    $rt\_item.status$ = BUILT
else
    $rt\_item.status$ = ERROR
    return "there are no enough channels for QoS requirement"
end if
if $u \neq qrrep.Sid$ then
    forward $qrrep$
end if
```

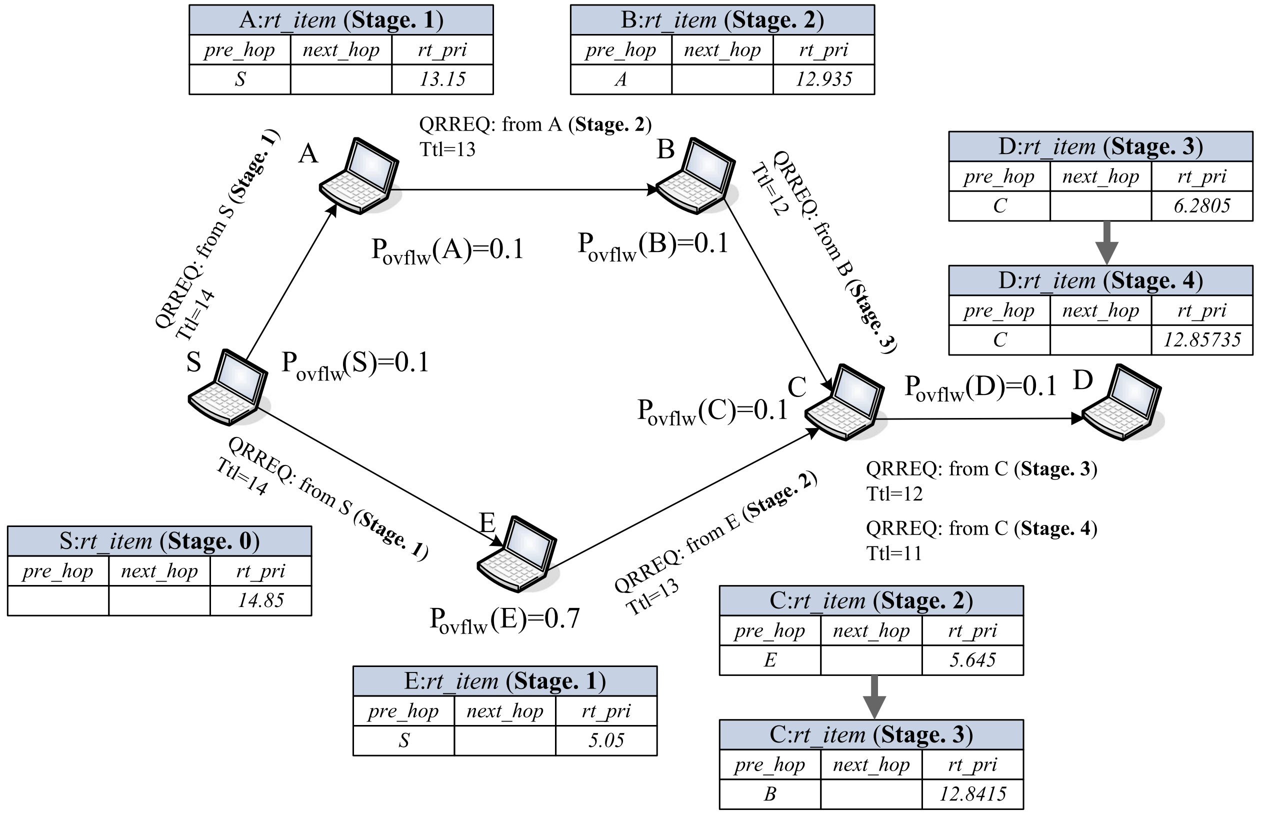


**Fig. 3** The example of QoS route request process

### 5.4 Route maintenance

During the life cycle of each TPQOR route item, it may experience different situations. Four status, {ONBUILDING, BUILT, ONREPAIRING, ERROR}, are defined for a route in this paper. An ONBUILDING status denotes that a route is being built, but has not yet been confirmed through the route reply process; a BUILT status denotes a mature route for delivering data packets; an ONREPAIRING route is a route under rebuilding; ERROR means an invalid route and it should be abandoned. Every route item starts with ONBUILDING and ends up with ERROR. The state machine of route maintenance is indicated in Fig. 5, where the meanings of event set {A, B, C, D, E, F, G} is explained as follows: A, receiving a QRREP packet; B, destination node initiates a route reply process; C, status timed out; D, next hop is out of the transmission range; E, destination node applies for rebuilding the route; F, receiving a route error packet QERROR; G, timed out for not receiving data packet; H, status timed out; I, source node receives a route error packet QERROR; J, receiving a fresher QRREQ packet.

**Table 4** The format of QRREP packet

| *Sid* | *Did* | *Fid* | *Type* | *Bw_req* | *TTL* |
|---|---|---|---|---|---|

*Sid* source ID, *Did* destination ID, *Fid* flow ID, *Bw_req* QoS minimum bandwidth requirement, *Type* the type of packet, *TTL* the maximum time to live of the packet

A route may be broken with node mobility or unsatisfied QoS requirements. In this case, a QoS route ERROR (QERROR) packet would be initiated for informing source node to rebuild a route. QERROR can be initiated either by the destination or intermediate node and will be forwarded to the source node. When a node receives QERROR, it should release the occupied resources. Route rebuilding process is as same as the process of building a new route. After the source receives QERROR, it will start a route rebuilding process. The format of QERROR is shown in Table 5.

## 6 Results and discussion

In the numerical simulation, NS-2 simulator is used to evaluate the performance of the proposed TPQOR protocol and IEEE 802.11 amendment standard is used to MAC and PHY layers to support static and dynamic multi-channel access. In our design of network model, 25 static nodes are uniformly distributed in a scenario of 1000 m × 1000 m, all of which are equipped with multiple interfaces and the same number of non-overlapping

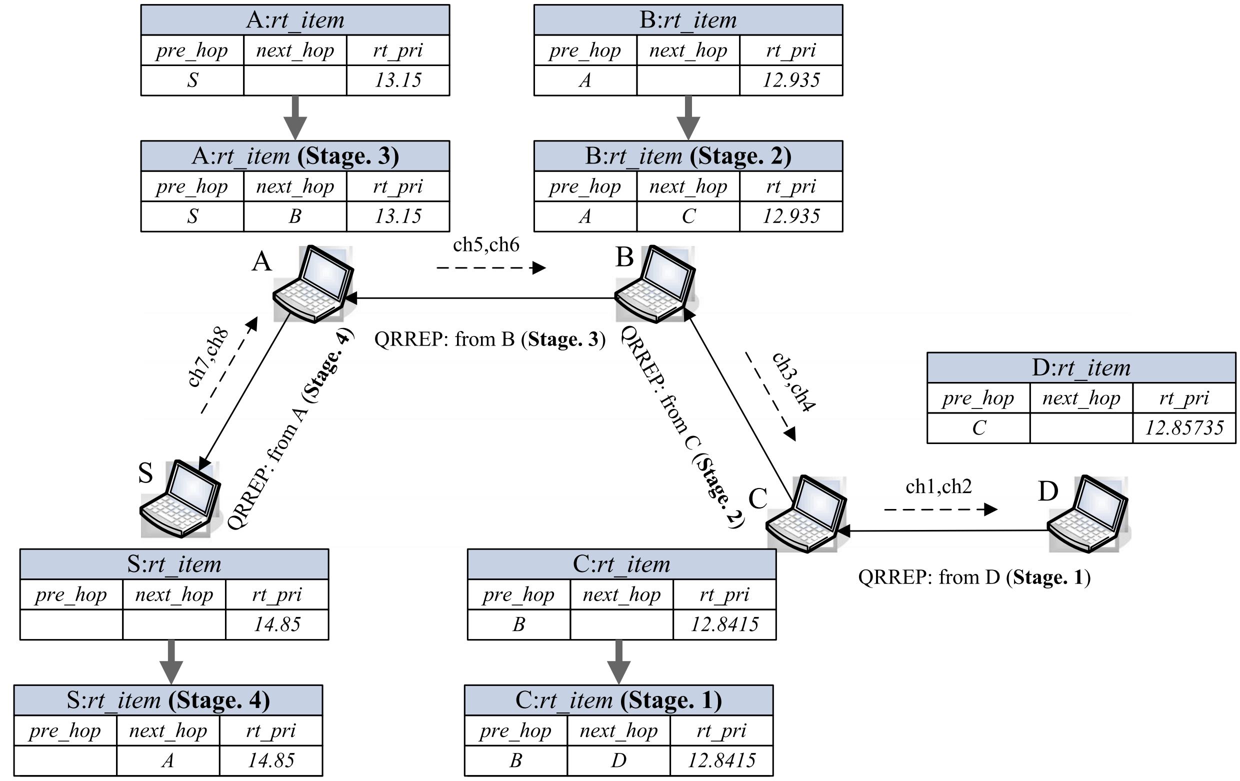


**Fig. 4** The example of QoS route reply process

wireless channels. The channel maximum transmission rate is set to 1.5 Mbps. The transmission range of each node is set to 100 m, and the interference range is set to 200 m. During the simulation time of 100 s, one QoS CBR flow and other nine ordinary CBR flows with different sources and destinations are randomly chosen. We use different loads, 100 kbps, 200 kpbs, 500 kbps, 1000 kbps, and 1500 kbps, to test the performance of evaluated protocols respectively. Average network throughput and average end-to-end delay are the average value of three times simulation. In the simulation, the following metrics are used for our performance evaluation:

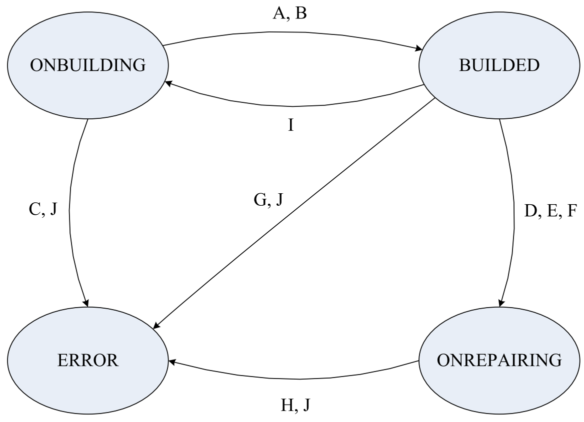


**Fig. 5** The state machine of route maintenance

*Average network throughput*: the average successful packet delivery over all the existing flows in the network, that is, the average number of received packets for all flows.

*Packet loss ratio*: the percentage that packet loss occupies over all sending packets, which is $\frac{\text{the number of lost packets}}{\text{the number of all sending packets}} \times 100\%$.

*Average end-to-end delay*: the average time between transmission of data packets at sources and successful reception at their receivers, which is $\frac{\sum(\text{receiving packet time}-\text{sending packet time})}{\text{the number of all received packets}}$.

### 6.1 Results of performance evaluation

We firstly evaluate the performance of single channel AODV protocol [20] and the proposed TPQOR protocol with different channel sets. Figure 6 compares

**Table 5** The format of QERROR packet

| *Sid* | *Did* | *Type* | *Fid* | *Seq* |
|---|---|---|---|---|

*Sid* source ID, *Did* destination ID, *Type* the type of packet, *Fid* flow ID, *Seq* request packet broadcasting sequence number

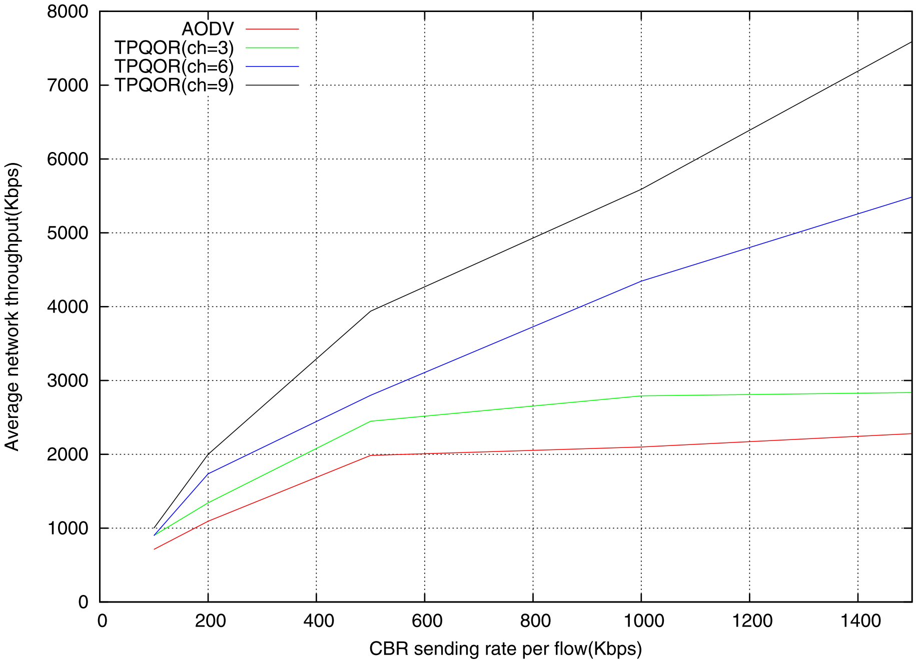


**Fig. 6** Average network throughput at different loads

the average network throughput of AODV protocol to TPQOR protocol with different number of channels at different loads. It shows that the average network throughput will increase when the transmission rate of CBR flows increases. The characteristic of multi-channel makes the network throughput of TPQOR protocol increase faster than AODV when the transmission rate of CBR flows increases. Furthermore, the more channels it has, the more obvious superiority it performs. As shown in Fig. 7, the single channel AODV protocol has more packet loss rate than multi-channel TPQOR protocol, because multi-channel can decrease the packet conflict, and when CBR

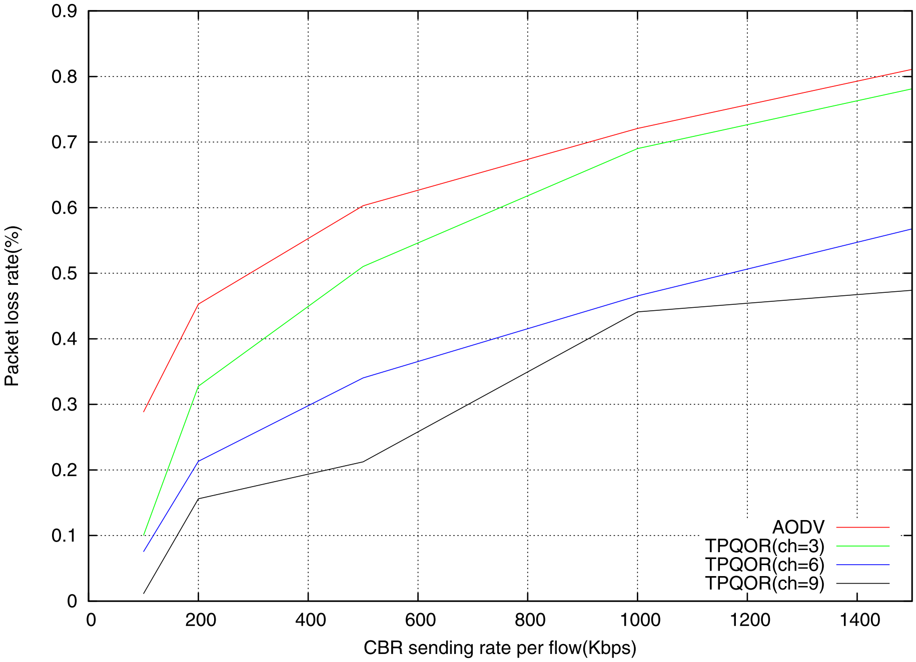


**Fig. 7** Packet loss ratio at different loads

rate increases, higher load brings more conflicts and causes the packet loss ratio to increase. Figure 8 indicates that TPQOR protocol performs better than AODV protocol especially when the number of data channels increases, and as CBR rate increases, the average end-to-end delay increases as well. In Fig. 8, data does not seem as regular as data in Figs. 6 and 7. The reason is that when the packet loss ratio increases, lots of packets are dropped on the halfway, which makes the measured average end-to-end delay irregular.

In order to reveal the effectiveness of TPQOR traffic prediction scheme, a new simulation scenario is constructed: there are two paths between a source and its destination, a Pareto [21] distributed interference flow is produced along the shorter route, while no interference flow is produced along the longer one. The QoS flow throughput of our proposed TPQOR protocol with traffic prediction are shown in Fig. 9; the QoS flow with 100-Kbps bandwidth requirement starts at the simulation time 50 s. The interference flow rate is quite low at that time, TPQOR protocol chooses another path for the QoS flow at the beginning by using traffic prediction with the history traffic utilization of the interference flow, and TPQOR protocol maintains 100 Kbps end-to-end throughput for the QoS flow during the whole simulation time. The simulation results show that TPQOR protocol with bandwidth prediction can reduce the route rebuilding process and enhance the throughput of the network.

## 6.2 Discussion

In MANETS, nodes can communicate with each other without infrastructures and nodes are expected to forward packets for other nodes in spite of limitation of their resources. Traffic routing and channel assignment jointly play a critical role in determining the performance of MANETs. Traffic predictive has a competitive performance when traffic can be predicated accurately; a traffic-predictive QoS on-demand routing (TPQOR) protocol is proposed to support bandwidth and delay requirement for MANETs in the paper; the future traffic is predicted according to nodes' history traffic patterns. In real situation, different devices may produce different traffic and may influence each other, especially burst interference flows will affect the bandwidth requirement of the QoS flow, so the more accurate predictive scheme is needed for future research direction.

The study has the following limitations:

(1) All channels are assumed to have the same bandwidth, transmission, and interference range.

(2) The variations of wireless channels is not considered in the simulation, and the transmission data rate of all channels may change, when the wireless channel is in deep fade.

(3) The traffic prediction with the only nodes' history traffic information is not accurate, the more predictive factors are needed to be considered.

The accurate traffic prediction is a considerably different and challenging problem in MANETs, traffic

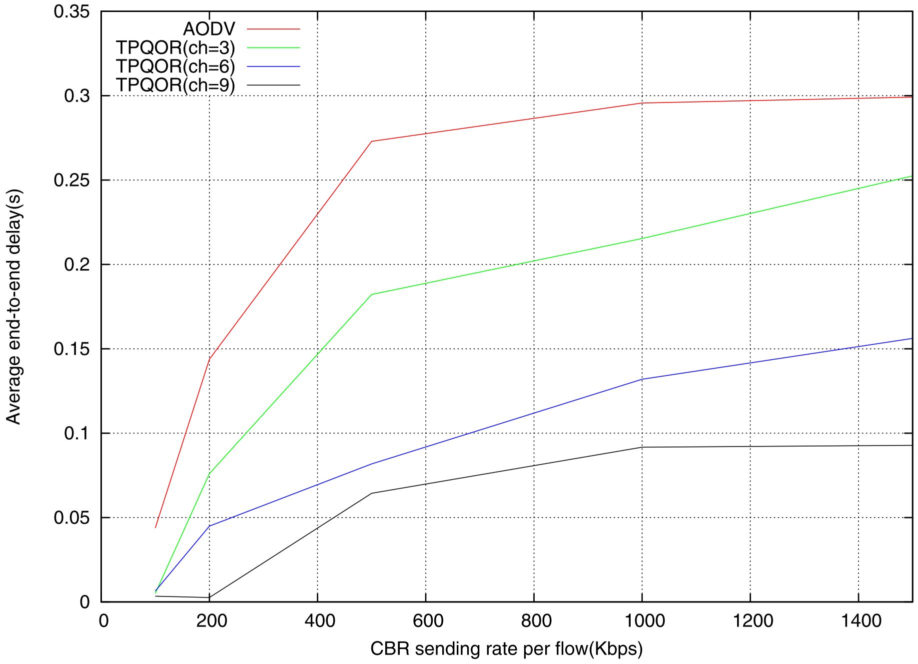


**Fig. 8** Average end-to-end delay at different loads

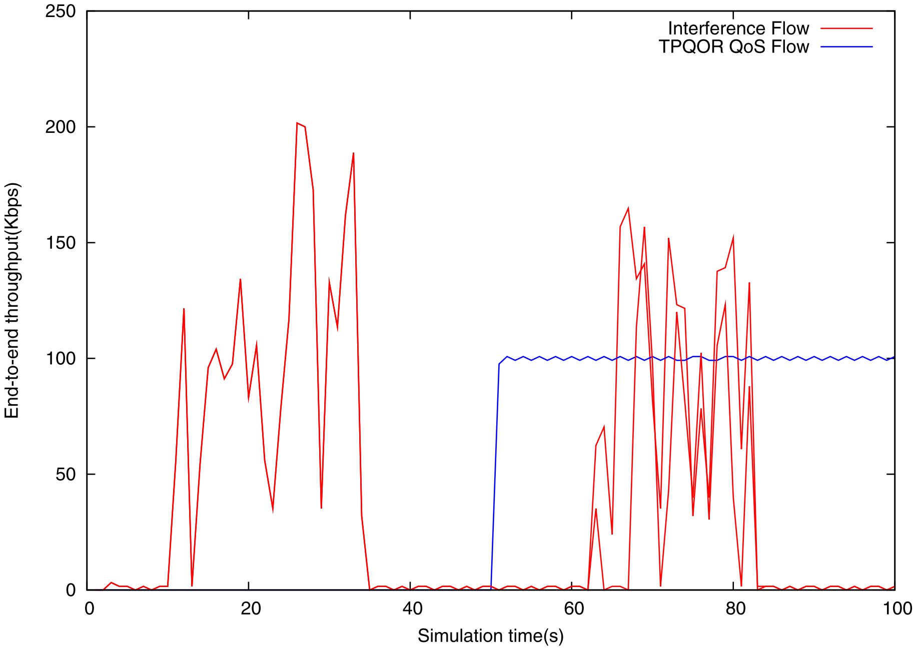


**Fig. 9** QoS flow end-to-end throughput of TPQOR as interference flow end-to-end throughput changes

variations are caused by different network states at different timescales, and there are additional research opportunities to improve the proposed traffic-predictive scheme to adapt the network variations.

## 7 Conclusions

This paper proposes a traffic-predictive QoS on-demand routing (TPQOR) protocol to support QoS bandwidth and delay requirements. The main contributions of this work include a proposed novel channel assignment scheme and a proposed traffic prediction scheme. The proposed channel assignment scheme can efficiently express the channel usage and interference information within a certain range, which reduces interference and enhances channel reuse rate. Unlike some existing routing protocols, TPQOR protocol takes the traffic prediction as an important factor in selecting route. The simulation results show that TPQOR protocol can effectively increase throughput, reduce loss ratio as well as delay, and avoid the influences of future interference flows, as compared to AODV protocol.

### Abbreviations

AODV: Ah hoc on-demand distance vector routing; CRANET: Cognitive radio ah hoc network; CUT: Channel usage table; DTN: Delay-tolerant networks; FIFO: First in first out; MANETs: Mobile ad hoc networks; NIC: Network interface card; QERROR: QoS route error; QoS: Quality-of-service; QRREP: QoS routing reply; QRREQ: QoS routing request; TPQOR: Traffic-predictive QoS on-demand routing; TTL: Time to live

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### Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

### Authors' contributions

JZ and LL propose the TPQOR protocol cooperatively, JZ writes the manuscript, and LL contributes to the implementation of the simulation programs and collects the simulation results. HT helps to check the simulation and result analysis. All authors read and approved the final manuscript.

### Competing interests

The authors declare that they have no competing interests.

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