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大规模移动自主网络中基于簇的 **QoS** 多路径路由*

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A Cluster-Based QoS Multipath Routing Protocol for Large-Scale MANET

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Abstract: To support QoS routing in MANET (mobile ad hoc networks) is a core issue in the research of MANET. Numerous studies have shown the difficulty for provision of quality-of-service (QoS) guarantee in Mobile Ad hoc networks. This paper proposes a scheme referred to a cluster-based QoS multipath routing protocol (CQMRP) that provides QoS-sensitive routes in a scalable and flexible way in mobile Ad Hoc networks. In the strategy, each local node just only maintains local routing information of other clusters instead of any global ad hoc network states information. It supports multiple QoS constraints. The performance of the protocol is evaluated by using the OPNET simulator and the result shows that this protocol can provide an available approach to QoS multipath routing for mobile Ad Hoc networks.

Key words: QoS routing; clustering; multipath routing; mobile ad hoc networks

摘　要: 在移动自主网络中,提供服务质量支持是一个核心研究问题.大量研究表明,在移动自主网络中提供服务质量保障具有很大的挑战性.提出一个基于簇的 QoS 多路径路由协议(CQMRP),通过一种可扩展、灵活的方式为移动自主网络提供服务质量保证.在这个策略中,每个节点只维持局部路由信息而不是整个网络的全局状态信息.它支持多个服务质量约束.采用 OPNET 模拟器对协议性能进行了评估,结果表明,这个协议能够为移动自主网络提供一个可靠的多路径服务质量保证.

关键词: QoS 路由;分簇;多路径路由;移动自主网络
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1 Introduction

An Ad Hoc Networks is a peer-to-peer mobile network consisting of large number of mobile nodes. These nodes create an instant network on demand and may communicate with each other via intermediate nodes in a multi-hop mode, i.e., every node can be a router. Ad hoc networks may be the only solution in many situations where instant infrastructure is needed and no central backbone system and administration (like base stations and wired backbone in a cellular system) exist. Some of the applications include mobile computing in areas where other infrastructure is unavailable, law enforcement operations, as well as disaster recovery situations. However, node mobility and limited communication resources make QoS provision in MANETs routing very difficult. Mobility causes frequent topology changes and may break the existing paths[1]. The advantage and inherent nature of MANETs have led to research interest in routing.

Many routing protocols have been proposed in the literature for ad hoc networks,such as DSR[2], AODV[3], AODV-BR[4],MSR[5], APR[6], SMR[7], TORA[8] and so on. However, they assume that all the nodes have special protocol stacks and are in ad hoc networks isolated from the Internet. All the previous routing solutions only deal with the best-effort data traffic. Connections with quality of service (QoS) requirements, such as voice channel with delay and bandwidth constraints, are not supported. Furthermore, MANETs function under severe constraints such as limited bandwidth and energy, group communications should be performed efficiently and at low control overhead cost.

Otherwise, most of the proposed routing protocol for MANETs[2−4] do not take fairness into account. They tend to have a heavy burden on the hosts along the shortest path from a source to a destination. As a result, heavily loaded hosts may deplete power energy quickly, which will lead to networks partitions and failure of application sessions. The structure of MANET is plane. In other words, all the nodes in the networks are equity, and function as terminal as well router. There is difference in performance instead of function. The main advantage of the structure is that there are multiple paths between source-destination pairs. So it can distribute traffic into multiple paths, decrease congestion and eliminate possible “bottleneck”. To solve the question, there are many research works[3−15] on multipath routing in ad hoc networks. They use multiple paths to take the route task. The multipath routing is proposed as an alternative to single shortest path routing to distribute load and alleviate congestion in the network. In multipath routing, traffic bound to a destination is split across multiple paths to that destination. In other words, multipath routing uses multiple “good” paths instead of a single “best” path for routing. Data load is distributed over multiple paths in order to minimize the packet drop rate, achieve load balancing, and improve end-to-end-delay. However, these schemes require periodic or event-driven control packet updates for each member. Those protocols work effectively with small-scale mobile Ad Hoc network (e.g., less than 100 nodes). These routing schemes don’t take into consideration that the routing control overhead and communications overhead will increase quickly when the number of the networks node increases, due to the attribute of bandwidth constrains and power limitation in MANET with the plane structure. These lead to scalability problem and reliability problem. Such overhead would be unsustainable in a battlefield scenario. On the one hand, most of the routing protocols focus on fault-tolerant problems, and the traffic is distributed mainly on the primary route. It is only when this route is broken that the traffic is diverted to alternate routes. Clearly, they can not meet requirements for throughput and load-balancing of application. Thus, a new architecture and protocols need to be proposed.

Utilizing clustering algorithm to construct hierarchical topology may be a good method to solve these problems. An adaptive mobile cluster algorithm can sustain the mobility perfectly and maintain the stability and robustness of network architecture. Clustering routing has five outstanding advantages over other protocols. First, it uses multiple channels effectively and improves system capacity greatly[17−19,28]. Second, it reduces the exchange overhead of control messages and strengthens node management[17−20]. Third, it is very easy to implement the local synchronization of network[19,20]. Fourth, it provides quality of service (QoS) routing for multimedia services efficiently[21,22,29,30]. Finally, it can support the wireless networks with a large number of nodes[22,23]. Currently the known hierarchical routing protocols for ad hoc networks include CGSR[24],HSR[25],CBRP[16] and LANMAR[26]. They are all unipath routing protocol. CBRP is a typical clustering routing protocol among them. They can not meet the requirement for fault-tolerance and aggregate bandwidth of application.

This paper presents a hierarchical QoS multipath routing protocol for MANET (CQMRP) which uses clustering's hierarchical structure management to search effectively for multiple paths and distributes traffic among diverse multiple paths. It not only ensures fast convergence but also provides multiple guarantees for satisfying multiple QoS constraints. CQMRP also allows that an Ad Hoc group member can join/leave the cluster dynamically. The rest of the paper is organized as follows. Section 2, gives a brief overview of Cluster Architecture. Section 3 introduces the QoS Model, Section 4 introduces the CQMRP algorithm in detail. Section 5 gives the correctness proof of the protocol. We describe the simulation model and present our performance results in Section 6 and conclude the paper in Section 7.

2 Cluster Architecture and Modeling

2.1 Cluster architecture

This paper mainly discusses the type of MANET whose topologies are not changing that fast to make the hierarchical QoS routing meaningless, and it supports the soft QoS without hard guarantees. The CQMRP is based on a multi-level hierarchical scheme, which is given in Fig.1. The proposed mobility-based hierarchical clustering algorithm[18] is used, which can result in variable-size clusters depending on the mobility characteristics of the nodes. As far as multipath routing is concerned, a network is usually represented as a weighted digraph $G=(N,L)$, where N denotes the nodes and L denotes the set of communication links connecting the nodes. $|N|$ and $|L|$ denote the number of nodes and links in the MANET, respectively. Without loss of generality, only digraphs are considered in which there exists at most one link between a pair of the ordered nodes. Associated with each link are parameters that describe the current status of the link.

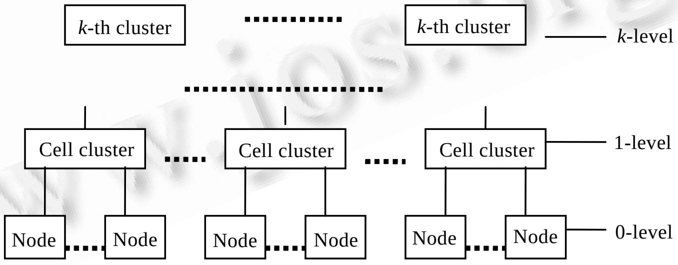

Fig.1 Cluster architecture

2.2 Cluster formation

In MANET, Every node has a unique identifier (ID) number and can be evaluated according to the function and the capacity of the node. *Token*(v_i) is the attribute of the node which can be cluster head, and the value is 0 or 1. If one node has the token ring, then it has the candidacy to be cluster head. *ChooseHead*() is the procedure used to elect the cluster head among the nodes according to OTF (owning token first) and MIF (minimum ID first). That is to say, the node owing the token ring is elected as the cluster head or the node with minimal ID is elected as the cluster head when many nodes own the token ring or no node owns the token ring.

To create the clusters, we use the BFS tree, each node needs to discover its subtree size and the adjacency information of each of its children in the BFS tree. To facilitate the cluster head discovery process, cluster member keeps the IP addresses of other cluster head that can hear. When the former cluster head moves away or a cluster member does not receive three HELLO (as shown in Fig.2) packets continuously from its cluster head, it considers that the wireless link between them is broken (or the cluster head has moved away). Thus, a cluster member chooses the latest refresh cluster head in its routing table as its new cluster head, which is one hop from it, or becomes itself a cluster head if it cannot hear any existing cluster head. After broadcasting its HELLO right next packet, the selected cluster head is informed that a new cluster member has joined its group. The cluster member will obtain the confirmation of its new cluster head when it receives the HELLO packet that carries its IP address.

Message type	Length	Reserved word
IP		
IP (cluster member)		
IP (neighbor cluster heads)		

(a) Cluster head

Message type	Length	Reserved word
IP		
IP (cluster head)		
IP (cluster heads can be heard)		

(b) Cluster member

Fig.2 HELLO message format

3 QoS Model

A node is assumed to keep the up-to-date local state about all outgoing link. The state information of link $e(i,j)$ includes 1) $DL_{e(i,j)}$, the delay of link $e(i,j)$ including the radio propagation delay, the queue delay, and the protocol-processing time; 2) $BW_{e(i,j)}$, the residual (unused) bandwidth of the link; and 3) $CO_{e(i,j)}$, which can be simply one as a hop count or a function of the link utilization. In order to make a preference of stationary links over transient links, the cost of a transient link should be set much higher than that of a stationary link. Let $s\in N$ be the source node of a MANET, and $d\in\{V-\{s\}\}$ be a set of destination nodes. For any link $e(i,j)\in L$, we can define some QoS metrics: delay function $DL_{e(i,j)}$, cost function $CO_{e(i,j)}$, and bandwidth function $BW_{e(i,j)}$. Similarly, for any node $i\in N$, one can also define some metrics: delay function $DL_{n(i)}$, cost function $CO_{n(i)}$, and delay-jitter function $DJ_{n(i)}$. The delay, bandwidth, and cost of a path $p_k=\{s,i,j,\ldots,m,t\}$ are defined as follows:

$$DL(p_k)=\sum_{l\in pk} DL_{e(i,j)}+\sum_{i\in pk} DL_{n(i)}\ ,$$

$$BW(p_k)=\min\{BW_{e(i,j)},BW_{e(i,j)},\ldots,BW_{e(i,j)}\},$$

$$CO(p_k)=\sum_{l\in pk} CO_{e(i,j)}+\sum_{i\in pk} CO_{n(i)}\ .$$

The QoS-based multipath routing problem is to find a solution that satisfies some QoS constraints:

Delay constraint:

$$DL(p_k)\le DL \tag{1}$$

Bandwidth constraint:

$$BW(p_k)\ge BW \tag{2}$$

Cost constraint:

$$CO(p_k)\le CO \tag{3}$$

where DL is delay constraint, BW is bandwidth constraint, CO is delay cost constraint, and PL is packet loss constraint. In the above QoS constraints, the bandwidth is concave metric, the delay and cost are additive metrics, and packet loss constraint is multiplicative metrics. For simplicity, we assume that all nodes have enough resource, i.e., they can satisfy the above QoS constraints. Therefore, we only consider the link's or edges' QoS constraints, because the links and the nodes have equifinality to the routing issue in question. The characteristics of edge can be described by a three-tuple (DL,BW,CO), where DL, BW and CO denote delay, bandwidth and cost, respectively. For simplicity, we also mainly consider the former two QoS constraints of the above QoS constraints (Eqs.(1)~(3)).

4 CQMRP

4.1 Virtual route discovery

The protocol CQMRP is an *N*-stage routing decision process, as explained below. A cluster is denoted by $C_i=\{N_i^j\}$, where N_i^j is the member of cluster C_i. Let CH_i be the cluster head of C_i. CQMRP defines the successor set of node N_i^j in cluster C_i as S_i^j and the predecessor set as D_i^j.

```
1  Set VirtualRouteSet∈{}
2  Set CandidateRouteSet∈{}
3  int VirtualRouteDiscovery(ID,CandidateRouteSet){
4  if ($s\in C_i$, and $d\in C_i$){
5        setup multiple path $r_k=\{s,V_{i1},V_{i2},\ldots,d\}$;
6        insert path $r_k$ into CandidateRouteSet;
7        VirtualRouteSelection(ID,VirtualRouteSet);}
8  if   ($s\in C_i$, and $d\notin C_i$){
9      search for a stable and optimal route as a directional
   guideline$\{s,C_2,\ldots,C_{n-1},d\}$;
10     setup multiple path $r_k=\{s,V_{i1},\ldots,d\}$;
11     insert path $r_k$ into CandidateRouteSet;
12     VirtualRouteSelection(ID,VirtualRouteSet);}
13         return failure; /* Unable to find a set so far */}
14  int VirtualRouteSelection(ID,VirtualRouteSet){
15  For each path $r_k\in$CandidateRouteSet
16       Compute path-quality P;
17       if ($P\geq p_{lower}$){
18           insert path $r_k$ into VirtualRouteSet(VR);
19       }
20 }
```

Fig.3 Virtual route discovery procedure

When a source node *s* ($s\in C_i$) seeks to set up a connection to a destination *d*, *s* sends a route request message (RREQ) to its cluster head CH_i. The RREQ message includes the following fields {*source-address*(*s*), *estination-address*(*d*),*Session-ID*,$P_{lower}(DL,BW,CO)$,*virtul-route*(*VR*),*path-quality* $(P_{p_k}(DL(p_k),BW(p_k),CO(p_k)))$ }. The route discovery procedure is shown in Fig.3.

If d is a member of cluster C_1 as well and hears the request message, then it sets up multiple paths from source node s to d (lines 4~6);

If destination node d is not in the same cluster as source node s, then (lines 8~13);

Finally (lines 14~18), when all complete paths to destination node have been established, it will choose all maximal disjoint, loop-freedom reliable paths that satisfy Eqs.(1)~(3) QoS constraints·

The above paths just are possible routes, we call them ***virtual route***.

4.2 Reverse link labeling

The reverse link labeling algorithm tries to find as many as possible real routes that are along the virtual path with loop-freedom and satisfy the QoS requirement for this particular session as well. The destination d generates a one-hop broadcast, sending the reverse labeling message. The reverse labeling message includes the following fields:

{*source-address*(*s*),*Labeling Source Address*(*l*),*Session-ID*,$P_{lower}(DL,BW,CO)$,
virtul-route(*VR*),*Hop*(*H*),*path-quality* $(P_{p_k}(DL(p_k),BW(p_k),CO(p_k)))$ }.

The Delay Requirement and Accumulated Delay fields are only for applications that have delay requirements.

Before starting the reverse-link labeling phase, *d* sets *L* as its IP address, *H* as 0 and $DL(p_k)$ as 0 while other fields are the same with those in the route request message. Every node that receives the reverse labeling message checks whether it meets the following conditions in order to broadcast the packet again after:

- increasing *H* by 1;
- adding its delay to $DL(p_k)$;
- recording l, *H* and $DL(p_k)$ into its routing table;
- replacing l with its IP address, l must meet the following requirement:

It belongs to a cluster head that is in the virtual route *VR*.

It has enough bandwidth: $BW(p_k)\geq BW$.

The accumulated delay $DL(p_k)$ does not exceed the delay requirement in QoS: $DL(p_k)\leq DL$.

The hop number H doesn't exceed the maximum hop $H_{\max}$.

It is neither a leaf node nor the source node s.

The intermediate nodes also record the labeling information from other labeling source address L with a bigger H (not 2 hops bigger than the maximum hop number) but do not broadcast it.

Thus, more than one route will be discovered between s and d that comprise of links labeled by session ID.

4.3 Route strategy and traffic distribute

After source node receives the RREP messages, it sets up multiple paths from s to d. These paths are ***real paths***. We classify these paths into optimal path, the shortest path and so on. For some particular requirement application, we classify all data packets (or users) into different service levels. Source node can select the proper path for the different service level applications. For the general applications, it will calculate the path weight value according to path-quality message included in the paths messages and utilize traffic distributing scheme[31] to distribute different size of traffic over the available paths.

4.4 Dynamic route repairing and maintaining

When a cluster member node does not receive three HELLO packets continuously from its cluster head, it considers that the wireless link between them is broken. Thus, it must find a new cluster head, which is one hop from it, or becomes itself a cluster head if it cannot hear any existing cluster head.

If the route used to forward packets is broken due to node mobility or some link can't meet the QoS requirement, the node deletes the entry of this link from its routing table and selects another redundant labeled links that meet the requirement to forward information. The session traffic, QoS requirement and the link label of the link are switched to the new link.

When all paths are broken, some cluster disappears or forms, source node immediately initiates a new route discovery without any examination.

5 Correctness and Complexity

5.1 Proof of correctness

As mentioned above, this paper mainly discusses the type of MANET whose topologies are not changing that fast to make the hierarchical QoS routing meaningless, and it supports the soft QoS without hard guarantees. In the following, we discuss CQMRP's correctness.

We first give the proof of correctness of the routing update correctness, then give the proof of correctness of the routing decision process and loop-free.

Theorem 1. if changes of link delay/topology occur between time τ_0 and τ_1 in MANET, and no changes occur within a transient time slot after time τ_1, then after some finite time, the routing tables (intra-cluster or inter-cluster) stored at the node will be correct and consistent.

Proof: Case of updates for intra-cluster routing tables is first considered, since the changes of network status occur between time τ_0 and τ_1, and there are impacts of the broadcast speed of update messages, computation and modification speed of routing tables for local nodes, thus the intra-cluster routing tables are dynamic and unstable. But there are no changes in MANET within a transient time slot after time τ_1, every update message sent can reach each reachable node. Thus, the routing tables stored at each local node have the most up-to-date information about network status after time τ_1 (some finite time, say τ_2 and $\tau_2>\tau_1$). The value of τ_2 is relative to the transportation delay of update messages between a pair of the remotest nodes after receiving the update messages, i.e., the intracluster routing tables is correct. Meanwhile, since routing tables stored at each local node contain identical routing information with the same network status, the routing table is considered to be consistent. Then, case of updates for intercluster routing tables is considered. The intercluster routing tables would contain routing information with optimal link delay estimates at each bridge node of first-level (second-level or third-level) cluster in MANET. It can be implemented by the update procedure of intercluster routing information. Intercluster updates can broadcast an intracluster updates to other clusters via the bridge node. Thus, routing tables stored at each bridge node will have the most up-to-date information about intercluster network status after time τ_2 (some finite time, say $\tau_3>\tau_2$) i.e., the intercluster routing table is considered correct. Meanwhile, since routing tables stored at each bridge node contain identical routing information with the same intercluster network status, the intercluster routing table can be considered to be consistent.

Now we prove the correctness of the above routing decision process. In routing decision process, some principles of the following theorem are used. Thus, the key to proof of correctness for routing decision process lies in the proof of correctness for the following theorem.

Theorem 2. If in the N-stage routing decision process at the initial state $x(0)$, optimal routing sequence is $u^*(0),u^*(1), u^*(2),\ldots,u^*(N-1)$, then in the $(N-1)$ stage routing decision process at the initial state $x(1)$, sequence $u^*(1),u^*(2),u^*(3), u^*(N-1)$ is also optimal routing sequence.

Proof: Suppose $v^*(0),v^*(1),v^*(2),\ldots,v^*(N-1)$ is optimal routing sequence and $u^*(0),u^*(1), u^*(2),\ldots,u^*(N-1)$ is not optimal routing sequence, then we have

$$D[x(1),v^*(1),\ldots,v^*(N-1)]<D_{N-1}[x(1),u^*(1),\ldots,u^*(N-1)] \tag{4}$$

Using routing sequence $u^*(0),v^*(1),\ldots,v^*(N-1)$ to routing region, we get:

$$D_N[x(0),u^*(0),v^*(1),\ldots,v^*(N-1)]=D[x(0),u(0)]+D[x(1),u(1)]+\ldots+D[x(N-1),v^*(N-1)].$$

From Eq.(10), we have:

$$\begin{aligned}D_N[x(0),u^*(0),v^*(1),\ldots,v^*(N-1)]&=D[x(0),u(0)]+D[x(1),u(1)]+\ldots+D[x(N-1),v^*(N-1)]\\&=D[x(0),u(0)]+D_{N-1}[x(1),v^*(1),v^*(N-1)]<D[x(0),u(0)]+D_{N-1}[x(1),v^*(1),v^*(N-1)]\\&=D_N[x(0),u^*(0),u^*(1),\ldots,u^*(N-1)].\end{aligned}$$

This result is contradicting the assumption that $u(0),u(1),\ldots,u(N-1)$ is optimal routing sequence. Thus $u(1),u(2), u(3),\ldots,u(N-1)$ must be also optimal routing sequence.

5.2 Complexity analysis

Let the time taken by the route directional guideline message and route discovery message to traverse a link including processing and buffering at nodes be one unit of time, then the time taken by these messages together is $O(n_1+n_2)$, where n_1 is the number of links of the path followed by route directional guideline message, and n_2 is that of the route discovery message, $n_1\le n_2$. Therefore, the total connection time for the protocol is $O(2n)$.

Let the number of the nodes of the network be $|N|$. The overhead of the multipath routing with plane structure is $O(|N|^2)$, and the overhead of the multipath with n level cluster structure is $O\left(|N|^2*|N|^{\frac{1}{\sqrt{n}}}\right)=O\left(|N|^{\frac{2}{\sqrt{n}}}\right)$[27], the total overhead of the protocol is $O\left(|N|^{\frac{2}{\sqrt{n}}}\right)$.

6 Simulation

We use OPNET modeler to simulate our proposed algorithm. The goal is to verify the correct operation of

CQMRP and evaluate its performance using discrete event simulation. Two different ways are used to study the CQMRP algorithm. In one method, we compare multipath routing (CQMRP, SMR) and unipath routing (AODV, CBRP). The other method is to compare cluster-based routing algorithm (CQMRP, CBRP) and routing algorithm with plane structure (AODV, SMR). Both of the ways are all under different mobile speeds.

6.1 Simulation parameters and factors

In the simulation, we assume mobile nodes move in a 1500m×500m rectangular region for 900s simulation time and each node moves independently with the same average speed. All nodes have the same transmission range of 250m. The mobility model is the random waypoint model. In this mobility model, a node randomly selects a destination from the physical terrain. It moves in the direction of the destination in a speed uniformly chosen between the minimal speed and maximal speed. After it reaches its destination, the node stays there for a pause time and then moves again. We change the pause time from 0s to 900s to investigate the performance influence of different mobilities. A pause time of 0 second presents continuous motion, and a pause time of 900s corresponds to no motion. We change node number from 50 to 1000 to investigate the performance influence of node number increase. 20 source nodes and 20 destination nodes were chosen randomly with uniform probabilities. The size of all data packets is set to 512 bytes. Simulation time is 4 hours for every session. For each scenario, 10 runs with different random seeds were conducted and the results were averaged. These parameters are summarized in Table 1.

Table 1 Simulation parameters

Parameter	Values	Note
N	50~1000	Number of nodes in the network
DIM	1500m×500m	Terrain dimensions
BW	10 Mbps	Bandwidth shared by adjacent nodes
Td	10 ms	PHY and propagation delays
*H*l	128 bits	Link frame header size
Lq	500 Kbytes	Link layer queue size
MSS	1460 bytes	TCP maximum segment size
LUDP	500 bytes	Fixed UDP data segment size
$v_{\max}/v_{\min}$	30/0 m/s	Node movement speed max/min
$t_{\max}/t_{\min}$	250/0 ms	Interval time to send packets

6.2 Performance metrics

We evaluate mainly the performance according to the following metrics:

Throughput: The aggregate transport throughput is the primary performance metric for routing optimization. The measured TCP or UDP throughput for all transmission sessions averaged over multiple simulation runs is used to compute the aggregate transport throughput for each combination of network topology and traffic pattern.

Control overhead: The control overhead is defined as the total number of routing control packets normalized by the total number of the received data packets.

Average end-to-end delay: The end-to-end-delay is averaged over all surviving data packets from the sources to the destinations.

Load balancing: In network graph $G=(N,L)$, We use a state function $CoV(f)=\frac{f(v_i)}{\frac{1}{n}\sum_{i=1}^{n}f(v_i)}$ [13] as a metric to evaluate the load balancing, where I is the set of positive integers, $f(n)$ represents the number of data packets forwarded at node v. The smaller the $CoV(f)$ is, the better the load balancing is.

***Success Delivery Rate* (*SDR*)**:

$$SDR=\frac{\text{Number of data received}}{\text{Number of data originated}}.$$

Route discovery frequency: The total number of route discoveries initiated per second

6.3 Performance analysis

Network topology, routing schemes, and traffic patterns are the factors considered for the simulation. Since the number of multiple paths available depends on the actual network topology and network congestion may be affected by both routing and traffic patterns, we evaluate the performance of each routing scheme using different topologies and different traffic patterns. We divide the topologies into three categories, low, medium, and high connectivity. For each category, we use a total of 10 different random topologies in the simulation experiments. The average number of neighbors in low, medium and high connectivity topologies are approximately 4, 5, and 6 neighbors, respectively. All topologies are generated randomly and only those without partitions are used. The connectivity in terms of average number of neighbors is summarized in Table 2 for different radio ranges R (in meters). The connectivity also affects the system capacity.

Table 2 Connectivity (degree) for generated topologies

Seed	1	2	3	4	5	6	7	8	9	10
R=135m	3.94	4.22	4.24	4.12	3.98	4.38	4.14	3.96	4.08	4.40
R=150m	4.98	5.38	5.30	4.86	5.20	5.22	5.16	5.16	5.34	5.44
R=165m	6.20	6.48	6.48	6.24	6.52	6.32	6.38	6.36	6.46	6.68

For traffic generation, we use three traffic loads, low, medium, and high. The traffic load is adjusted by changing the number of transmitting and receiving pairs. There are 4, 8 and 12 simultaneous data sessions for the low, medium, and high load conditions, respectively. Heuristics are used to ensure that the communicating nodes spread across the network, i.e., that they are not located closely in the network. For each combination of topology and traffic pattern, 5 repetitions with different random seeds are carried out. In each simulation run, all statistics are collected for a duration of at least 100 seconds after a start-up time of 10 seconds.

The simulation results are validated against analytical results. The TCP throughput T is compared with a simple analytic model given in: $T=\frac{0.75\times w\times MSS}{RTT}$, here W is the congestion window size, MSS is the maximumsegment size, and RTT is the roundtrip time. Table 3 compares the simulation and theoretical TCP throughput of a single data session for five different topologies. In these experiments, fast retransmission and fast recovery options for TCP are disabled and unipath routing is used. The simulation results match the theoretical values computed using the average congestion window size $W\cdot MSS$ and measured RTT.

Table 3 Measured and theoretical TCP throughput (Kbytes/s)

Topology	W·MSS (bytes)	RTT (s)	Throughput (Kbytes/s)	
			Simulation	Theoretical
1	55 642	1.53	28.0	27.8
2	55 642	1.45	31.2	29.3
3	55 642	1.49	30.8	28
4	68 286	1.56	35.5	32.8
5	68 286	1.42	35.5	36.1

6.4 Simulation results

Table 4 summarizes the aggregate UDP throughput observed for all topologies with different connectivity under different traffic load conditions. The average (Avg) and standard deviation (Std) are calculated over 10 random topologies with five replications per topology. The table also shows the percentage improvement (Imp) for using multipath schemes over unipath routing. On average, CQMRP outperforms all other schemes for all cases.

In most topologies, CQMRP provides the highest throughput. While SMR also provides performance improvements, their results are more dependent on the actual topology. CQMRP provides approximately 50 to 110 percent throughput improvement for low traffic load conditions. For medium load traffic load conditions, CQMRP again provides consistent improvement in throughput. When the traffic load is high and the network itself becomes congested, the advantages of multipath algorithms become less prominent, but still offer some throughput improvement. Again, all multipath routing algorithms provide performance improvements. It should be noted that CQMRP performs better for medium connectivity topologies than for low connectivity topologies. Fig.4, Fig.5 show respectively the results for low connectivity and low traffic load, and high connectivity and high traffic load.

Table 4 Aggregate UDP throughput results (Mbps)

Connectivity	Traffic	AODV	CBRP		SMR		CQMRP	
		Avg	Avg	Imp(%)	Avg	Imp(%)	Avg	Imp(%)
Low	L	2.08	2.2	5.77	2.74	31.73	3.35	61.06
	M	2.54	2.72	7.1	3.29	29.53	4.4	73.22
	H	3.82	3.79	–0.79	4.22	10.47	5.35	40.05
Medium	L	1.65	1.7	3.03	2.65	60.61	2.96	79.39
	M	2.47	2.78	12.55	4.05	46.21	5.19	110.1
	H	3.96	4.04	2.02	5.22	31.82	6.42	62.12
High	L	1.98	1.95	–1.51	2.71	36.87	3.32	67.68
	M	2.85	2.97	4.21	4.11	44.21	5.3	85.97
	H	4.53	4.65	2.65	5.53	22.08	6.35	40.18

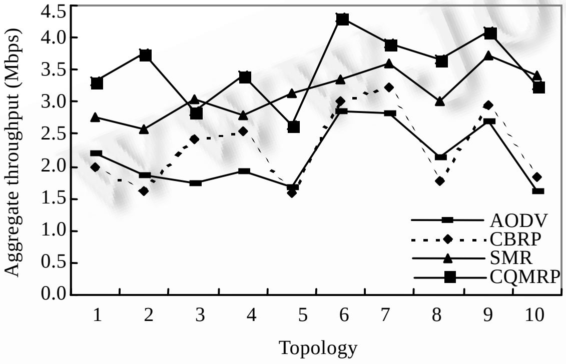

Fig.4 UDP throughput for low connectivity and low traffic load

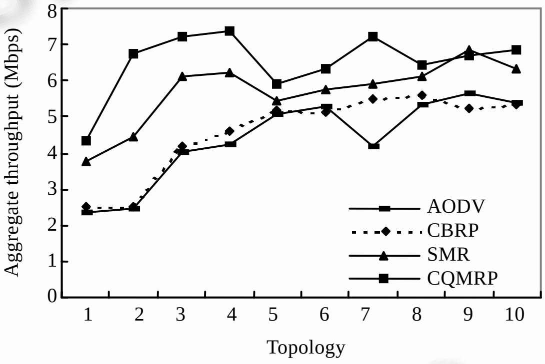

Fig.5 UDP throughput for high connectivity and high traffic load

Figures 6 and 7 show that the control overhead for unipath routing (AODV, CBRP) is less than multipath routing (SMR, CQMRP). This is due to the fact searching for diverse multiple paths in our method could be more costly than searching for a single path using on-demand routing approaches. The control overhead of CQMRP is lower than that of SMR, especially when the node number increases large enough. The reason for that is searching for multiple paths with hierarchical structure management could be lower costly than searching for multiple paths at large network using the general approaches. The bigger the size of the network is, the lower the cost of CQMRP is relative to SMR. Similarly, the control overhead of CBRP is less than that of AODV.

Figures 8 shows the results of average end-to-end delay. The end-to-end delay includes the queue delay in every host and the propagation delay from the source to the destination. Multipath routing will reduce the queue delay because the traffic is distributed along multiple paths. On the other hand, it will increase the propagation delay since some data packets may be forwarded along the sub-optimal paths. From Fig.8, the unipath routing has slightly higher average end-to-end delay compared to multipath routing and the average end-to-end delay of CQMRP is slightly lower than that of SMR. This demonstrates that the multipath routing could distribute the traffic and improve the end-to-end delay, the smaller the number of the paths, the higher the average end-end delay, but the improvement is limited below pause time of 300 seconds. With the decrease of pause time, the average end-to-end delay for both multipath routing and unipath routing increases, because the network topology changes more frequently at smaller pause time. More route discoveries will be promoted and thus the queuing delay of the data packets in the source nodes increases, which leads to the increase of the average end-to-end delay.

Figure 9 gives the results of load balancing. The CoV of network load for the unipath routing is higher than that for the multipath routing. This is because the multipath routing can distribute the network traffic along different paths. The unipath routing always uses the shortest paths between the sources and the destinations, which will unfairly assign more duties to the nodes along the shortest paths. The CoV of network load for CQMRP is lower than that for SMR, this is because that the load of SMR is distributed in two routes per session and the load of CQMRP is distributed in all the available routes per session. With the decrease of pause time, the CoV of network load for the unipath routing and the multipath routing also decreases. This shows that the increase in mobility could result in better load balancing of the traffic among the nodes. “Hot spots” are likely removed due to mobility.

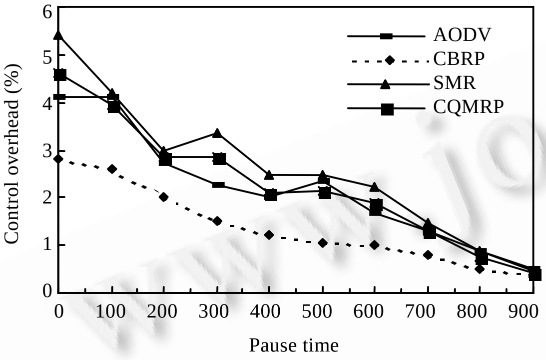

Fig.6 Control overhead with varying speed

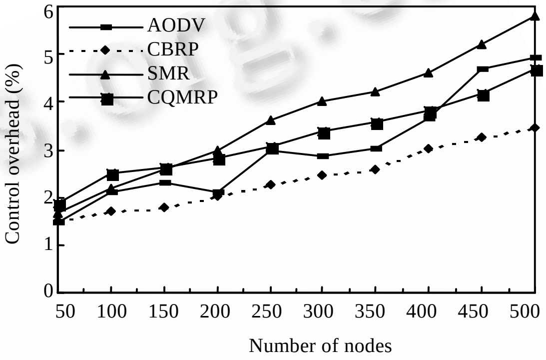

Fig.7 Control overhead with varying network nodes

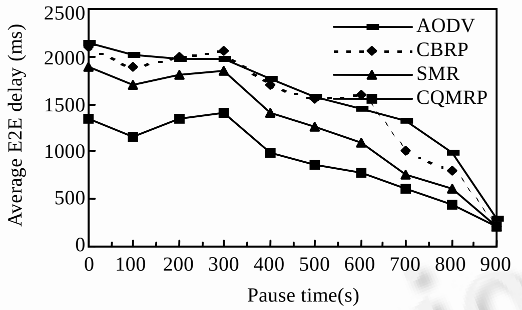

Fig.8 Average end-to-end delay with varying speed

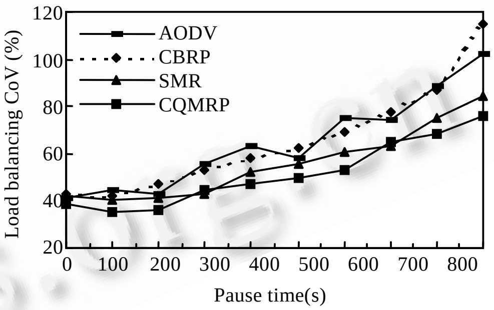

Fig.9 CoV of the network load with varying speed

Figure 10 shows the success delivery ratio for CQMRP, AODV, CBRP and SMR. It illustrates that the proposed CQMRP outperforms the others at any mobility speed ranging from 1 to 30 meters/second. We notice that at low mobility speeds, CQMRP performs similarly to the other three routing scheme due to the relative stationary node movement. In addition, the simulation results demonstrate the ability of multipath routing (CQMRP and SMR) to obtain consistent success delivery ratio regardless of the change in node mobility speed. In contrast, unipath routing (AODV and CBRP) suffers in its success delivery ratio when the maximum mobility speed increases.

Figure 11 shows the result of total number of routing discovery phases versus the mobility. The frequency of routing discovery for multipath routing (CQMRP and SMR) is less than that for the unipath routing approach (AODV and CBRP). This result is coincident with the theoretical analysis in Ref.[13]. The frequency of routing discovery for multipath routing CQMRP and SMR is almost the same since the number of routing discovery mainly depends on the link breakage of the selected multiple paths instead of the method of using multiple paths.

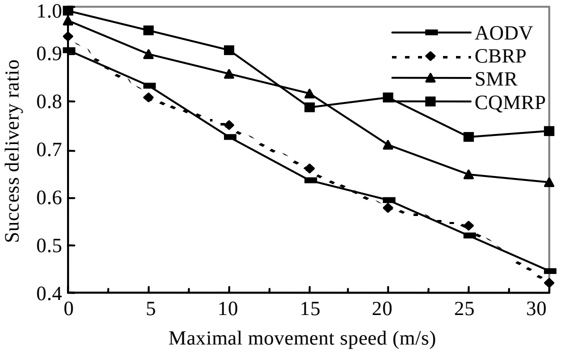

Fig.10 Success delivery rate with varying speed

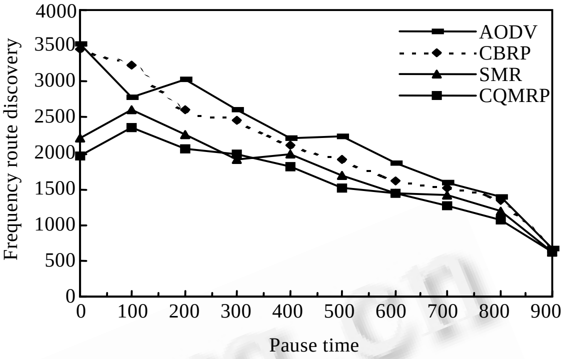

Fig.11 Number of route discovery with varying speed

7 Conclusions and Future Work

CQMRP distributes traffic among diverse multiple paths to the sharing rate of channel. It not only ensures fast convergence but also provides multiple guarantees for satisfying multiple QoS constraints. It decreases routing control overhead and improves the networks scalability using clustering’s hierarchical structure diverse. It improves performance as aggregate bandwidth, throughput and load balancing using multipath routing. In other words, it improves the reliability of the network. These benefits make it appear to be an ideal routing approach for MANETs. However, these benefits are not easily explored because the data packet that is fragmented into smaller blocks must be reassembled at the destination node, it may lead to error and increase control overhead. In the future, we will do some work on the dynamical distribution of traffic into multiple paths algorithm and error correction packet segmentation algorithm to improve the performance of CQMRP.

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