A Simulation-Based Performance Analysis of a Cluster-based Routing Scheme for Wireless Mesh Networks

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Abstract

The cluster-based routing protocol (CBRP) is a grouping mechanism that supports unicast and multicast path discovery for low congestion and packet loss in routing mechanisms for multi-hop wireless mesh networks. No simulation analyses or comparisons with other routing protocols have been reported. In this paper, we have evaluated the performance of the CBRP and compared it to AODV and OLSR through software simulations. The scheme indicates several better performance levels in terms of the channel capacity, path discovery, packet delivery ratio, and end-to-end delay, at the sacrifice of routing overhead degradation.

Keywords: Wireless Mesh Networks, AODV, OLSR, CBRP

1. Introduction

Wireless mesh networks (WMNs) are emerging as a low cost and flexible wireless network technology that has a self-organizing infrastructure. WMNs are flexible, cost effective, and have light infrastructures based on wireless technology. Industry and academia place very high demands on WMNs because of their advantages, such as the network range extension, resilience, fault tolerance and high bandwidth capabilities. Wireless mesh networks extend the coverage of wireless local area network (WLAN) technology to a wider area with multi-hop routing functionality [1]. WLAN technology has a standard name of IEEE 802.11, and wireless mesh networks are known as IEEE 802.11s. WMNs are the latest technology that has a substantial amount in common with mobile ad hoc network (MANET) [2].

The architecture of WMNs has been classified into three categories based on the node functionality in the networks:

Infrastructure WMNs,

Infrastructure-less WMNs,

Hybrid WMNs.

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In infrastructure WMNs, mesh routers provide connectivity to mesh nodes in the infrastructure form. In infrastructure-less WMNs, nodes make the mesh networks and perform mesh functions, such as routing and self-configuration. Hybrid WMNs are a combination of infrastructure and infrastructure-less WMNs [3-4]. In this type of network, mesh clients access the networks via mesh routers and other mesh clients. The current infrastructure WMN is the most popular network because of its stability and management ease.

WMNs are associated with many research fields, one of which concerns routing. Many routing protocols have been proposed, and a substantial amount of work has been performed by researchers; however, much more research could be conducted in this field. The exiting routing protocol has path discovery with the help of a broadcast method [5]. For this reason, a node requires a substantial amount of power, and there are message collisions when congestion occurs in networks. Toward addressing these concerns, one report [6] proposed a cluster-based routing protocol (CBRP) in which all of the nodes in mesh networks were grouped into different clusters, and each cluster has a cluster head (CH). Because this protocol sets up a path between nodes using unicast and multicast methods, the networks produce less congestion and data loss. In a previous work [6], only one protocol was proposed, and some expected effects were analyzed heuristically. This approach requires further performance investigation.

In this paper, we present further research on the CBRP. We defined a pseudo-code for the CBRP and conducted a performance analysis in a simulation environment. We made a performance comparison with Ad hoc On-Demand Distance Vector (AODV) routing [7] and Optimized Link State Routing (OLSR) [8] in terms of several performance metrics, such as channel capacity, hop count, packet delivery ratio, end-to-end delay, and routing overhead. In Chapter 2, we briefly introduce some background knowledge on the existing routing protocols for WMNs and explain the CBRP. In Chapter 3, we describe the pseudo-code for the CBRP. In Chapter 4, simulation results and performance analyses are given. Finally, in Chapter 5, conclusions are described.

2. Existing routing protocol and the CBRP for WMNs

2.1 The existing routing protocol

International organizations are actively providing specifications for mesh networks, such as IEEE802.11, IEEE802.15, and IEEE802.16 [9]. WMNs can easily maintain networks by adding and deleting nodes over the networks. In this article, we are concentrating on routing protocols of IEEE802.11s networks.

Many researchers have proposed a number of routing techniques for WMNs. Many on-demand routing protocols, such as Dynamic Source Routing (DSR) [10] and AODV, have been presented for wireless networks. These protocols are traditional routing protocols for MANET [11]. This type of routing protocol uses a broadcast method for path setup and communication. After these traditional protocols, researchers propose opportunistic routing protocols [12], such as extremely opportunistic routing (ExOR) [13], resilient opportunistic mesh routing (ROMER) [14], and the routing protocol of Zhong et al. [15], which are also broadcast natured. The existing routing protocols use a broadcast message in an initial stage. Although they have an ability to avoid duplicate transmissions, these protocols consume a substantial amount of energy and induce collisions.

In this paper, we propose an alternative approach, which is a novel cluster-based routing protocol for wireless mesh networks. We provide extra power and responsibility to the mesh portal point (MPP) and the cluster head of each group.

2.2 The cluster-based routing protocol

In our previous work [6], we proposed a cluster-based routing protocol for WMNs. With this protocol, we provided the solution of the above-mentioned problem regarding existing routing protocols. If networks are partitioned into clusters, then we can reduce the initial broadcast to all of the nodes. Because each cluster has one head that has all of the information on its neighbors, the path request is multicast to different cluster heads only. In this scheme, we divide the mesh networks into groups (Figure 1). The MPP assigns one node to be a cluster head (CH) of each cluster group and stores the cluster head information in its own table, such as CH and CH neighbors. Figure 1 presents cluster groups in WMNs.
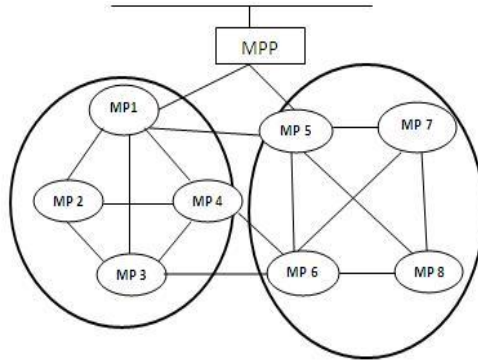
Figure 1. Wireless mesh networks divided into cluster groups

In our routing protocol, the path establishment process is comprised of 4 steps: setup of the cluster head, path creation, path reply, and path setup. The details of the process are as follows.

1) Setup of Cluster Head.

Each cluster head has extra authority compared to other cluster members. Each cluster head has two tables. One table stores information on neighbor cluster heads, and the second table stores information about cluster group members, which is assigned by the MPP. Every cluster member stores the information on its CH.

2) Path creation.

When a normal cluster member wants to communicate with a destination node, it sends a path request (PREQ) message to its cluster head (Figure 2(a)). Then, the cluster head checks its own group member list. If a destination exists in the same group, it quickly sends a path reply with path information, and a source node starts a transmission according to that path. If a destination node belongs to another cluster, the cluster head sends a PREQ message to the mesh portal (Figure 2(b)), and the mesh portal multicasts a PREQ message to all of the cluster heads (Figure 2(c)). Cluster heads then check their own group table, and if any CH finds a destination node in an area, it sends a PREQ message to the destination node (Figure 2(d)). The destination node sends its own status to its cluster head (Figure 2(e)).

3) Path reply.

After receiving the status message from the destination node, the destination cluster head sends a path reply message to the mesh portal (Figure 3(f)). This reply message is intended to be sent to the source node with the destination path information. MPP forwards the PREP,

which is received from destination CH2 to source CH1, as shown in Figure 3(g). CH1 forwards it to the source node.

4) Path setup.

A bidirectional path established between the CH1 and CH2 nodes is shown in (Figure 3(h)), and CH1 forwards the destination information to the source node (Figure 3(i)). Thus, the final path between the source and destination nodes is established, as shown in Figure 3(j).

In this scheme, MPP multicasts during path discovery only once, and the remaining transmission uses unicast messaging. Hence, this scheme reduces the power consumption and improves the network performance at the mesh portal. The cluster head periodically updates its own table, which helps to detect any change that occurs in networks. Furthermore, in the case of link-failure retransmits to the mesh portal by the CH, error message (RERR) broadcasting is eliminated. However, when the cluster head fails, then broadcasting is required.
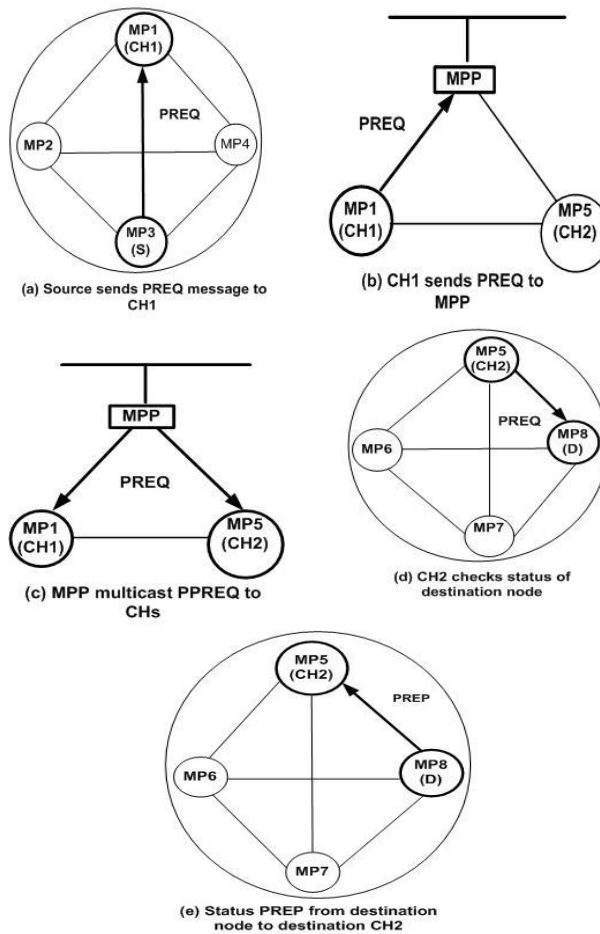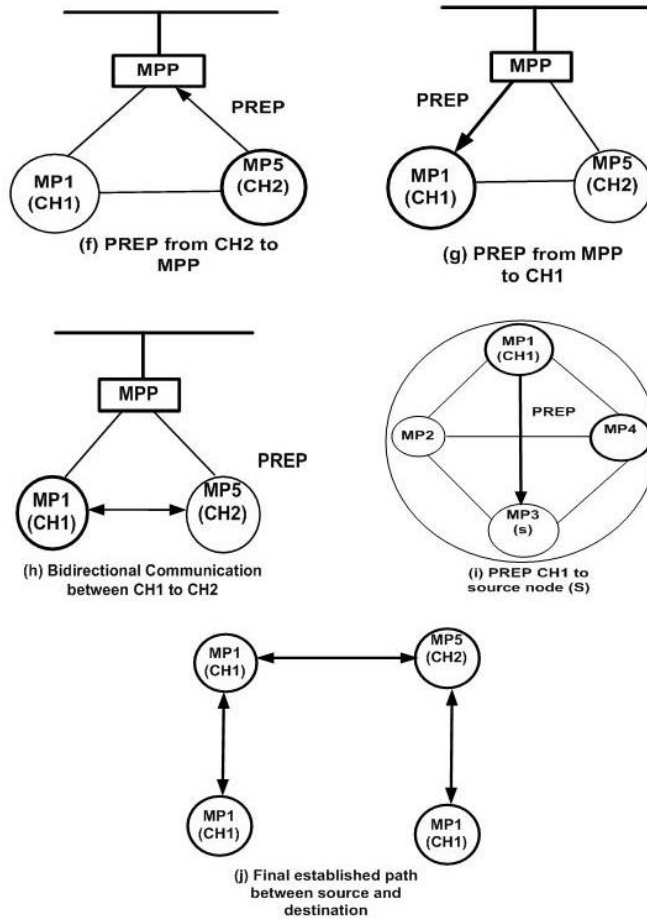

Figure 2. Path request (PREQ) process in the CBRP

Figure 3. Path reply (PREP) process in the CBRP

3. Pseudo-code for the CBRP

3.1 The Basic Process of CBRP

There are 5 main basic processes of the CBRP, as follows:

(a) Partitioning of the network graph,

(b) Distribution of cluster connectivity messages to CH,

(c) Distribution of routing information to the individual nodes by each CH,

(d) Intra cluster route made via MPP,

(e) Inter cluster route made through the calculation of neighbors between the source and the destination.

We explain our method with the aid of pseudo-code. In pseudo-code, CH is the symbol for cluster head, and S and D represent for the source and destination, respectively.

1) Route Assignment Process.

(1) Intra cluster route:

(a) R= Rreq+Rrep,

(b) Req= (S+CHs) + (CHs+MPP) + (MPP+CHd) + (CHd+D),

(c) Rrep= (D+CHd) + (CHd+MPP) + (MPP+ CHs) + (CHs+S),

where R=route, Rreq=route request, Rrep=router reply, S=source, CHs=source cluster head, CHd=destination cluster head, MPP=mesh portal point, and D=destination.

(2) Inter cluster route:

(d) R= Rreq+Rrep,

(e) Rreq= S+CHs,

(f) Rrep= CHs+S.

(3) Pseudo-code for inter cluster.

```
INTER_CLUSTER_COMMUNCATION(S, D)
begin
    S unicast Rreq to CHs
    // check cluster table
    T = Cluster_Table_of_CHs
    if (D in T)
        begin
            //Find path for S
            Find common neighbors of S and D.
            Calculate most common neighbors.
        end
    else
        return//Stop communication
    Unicast path information to S
    S unicasts acknowledgement to path neighbors.
    Receive acknowledgement reply from intermediate nodes.
    Start communication
end
```

(4) Pseudo-code for intra cluster Group:
```
INTRA_CLUSTER_GROUP(S, D)
begin
    S unicast to CHs.
    // CHs review table.
    T = cluster_table_of_CHs
    if (S in T and D in T)
        begin
            INTER_CLUSTER_COMMUNCATION(S, D)
        end
    else
        Unicast RREQ to MPP.
        MPP multicast to all CHs
        for each CH do
            begin
                CH checks its own Table
                CHd finds destination node
                // Chd checks availability of D
```

```
            if ( D is available )
            break
        end
    Chd unicasts RREP to MPP
    MPP unicasts PREQ to CHs
    CHs makes path to CHd through bidirectional.
    CHs unicasts Path information to S.
    S starts communication with D through CH.
    end
end
```

4. Performance analysis of the CBRP

In a WMN environment, we analyzed the performance of the CBRP protocol by performing simulations with OPNET. Table 1 shows the parameters for the simulation in the OPNET simulator. We selected AODV and OLSR for comparing targets because they are typical routing protocols for WMN that work in a reactive and proactive manner, respectively [7, 8].

A different simulation scenario has been studied according to 5 different performance metrics: channel capacity, path discovery, packet delivery ratio, end-to-end delay and routing overhead. The WMN nodes are randomly placed. To analyze the channel capacity of WMNs, ten cluster heads were placed in a 1000x1000 m^2 area. The packet size was set to 512 bytes, and the packet transmission rate was set to 10 packets/sec. The radio range was set to 50 m. The radio bandwidth is 2 Mbps. The total number of nodes is 100.

Table 1. Parameters common to all simulations

Parameter	Value
Simulation area	$1000 * 1000\ m^2$
Total number of nodes	100
Total number of CHs	10
Simulation Time	200s
Packet size	512 bytes
Bandwidth	2 Mbps
Packet rate	10 pkts/s

To evaluate the performance of the CBRP mechanism, we must analyze the capacity of each CH and the capacity of the whole network. We also used a single radio system for wireless mesh networks, which indicates that the same radio is used for both access and wireless backhaul. This option represents the lowest cost entry point in the deployment of a wireless mesh network infrastructure. The actual average channel capacity of a mesh node is between 1/N times the channel capacity and $(1/2)^N$ times the channel capacity, where N is the number of wireless hops in the longest path between a wireless single node and wired networks [16].

4.1 Channel capacity of the CBRP

The channel capacity of each cluster head is measured by the average data transmission rate for each cluster head. The total channel capacity is measured by summing the data transmission rate of all cluster head.

Figure 4 shows the channel capacity performance comparison of each node with respect to existing routing protocols AODV, OLSR and CBRP. When the number of nodes is 1, then all three routing protocols have the same channel capacity; however, when the number of nodes in the network is increased, the routing protocols' capacity is decreased because of network congestion and collision. However, the CBRP still has a better performance compared to the AODV and OLSR. When the number of CHs is 3, the largest difference occurs between the CBRP and AODV, which is almost 6 Mbps. The AODV uses a broadcast method for communication that requires a substantial amount of traffic. However, the CBRP and OLSR use the unicast method for communication, which is why their capacity performance is better than AODV. Although the OLSR and CBRP use unicast methods, the CBRP shows better performance than the OLSR. The OLSR is not supportive for large-scale networks.
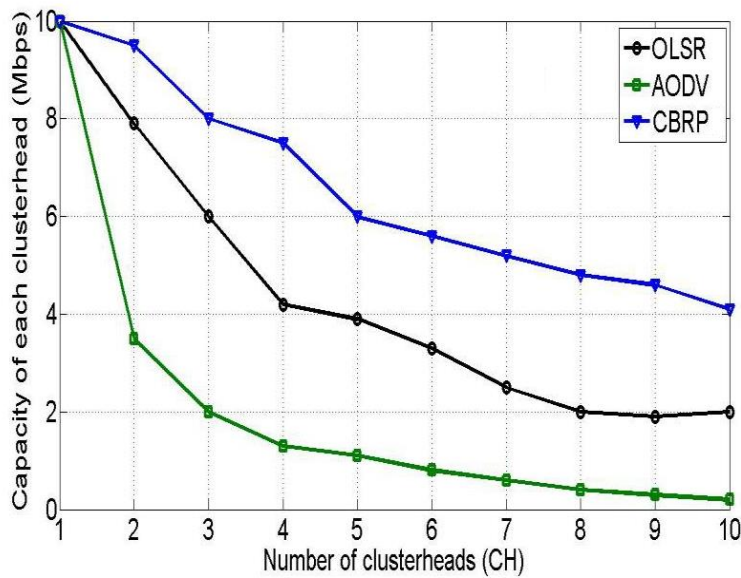

Figure 4. Comparison of each CH capacity

The simulation result in Figure 5 presents a comparison of the total channel capacity of the CBRP and the routing protocols AODV and OLSR. When the number of nodes is 1, then all three routing protocols have the same channel capacity. However, as the number of CHs increased, the AODV performance decreased but the capacities of the OLSR and CBRP increased. In the figure, for up to 4 nodes, the CBRP's performance is less than that of the OLSR's; however, for 5 nodes and higher, the OLSR's performance decreases compared to the CBRP. After 4 nodes, the OLSR and AODV saturate to the values 6 Mbps and 28 Mbps, respectively, but the CBRP still continues an increasing trend. In a large-scale network, the CBRP provides a better capacity performance when compared to the OLSR and AODV.
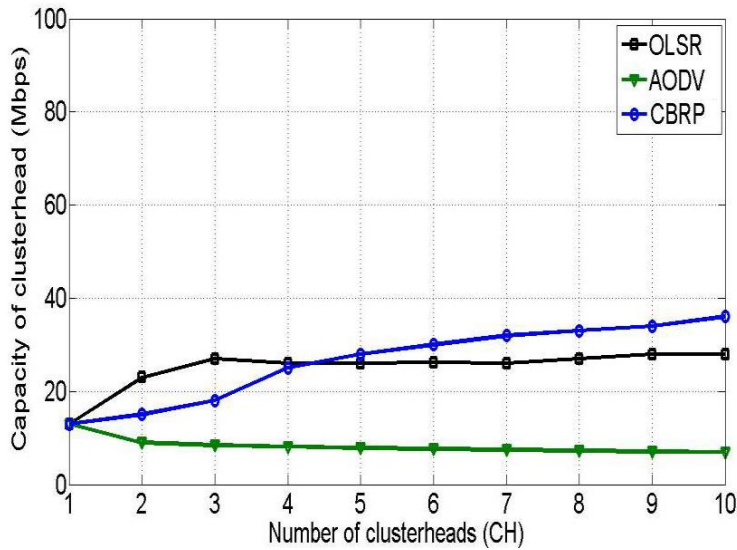
Figure 5. Comparison of the CH capacity in the whole WMN

4.2 Number of Paths discovered

Figure 6 represents the average path that is discovered in the CBRP, AODV and OLSR routing protocols. While the AODV can discover the highest number of paths, the OLSR and CBRP discover a smaller number because of their proactive mechanism. The AODV uses a broadcast message, and the OLSR has a predefined path discovery method. However, the CBRP routing uses a unicast and multicast method for path discovery. For this reason, it has a lower number of path discovery features. Each routing protocol has its own pros and cons, depending on the network conditions and requirements.
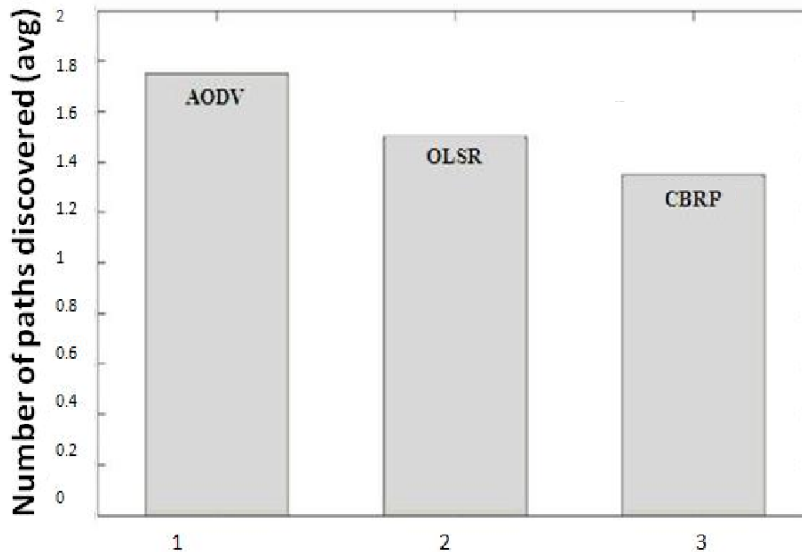

Figure 6. Average numbers of paths discovered by each protocol.

4.3 Packet delivery ratio

The packet delivery ratio (PDR) denotes the ratio of the total packets received by the destination to the total packets sent by the source during the whole simulation, which reflects the routing efficiency. For every 1 second, we measured the number of packet that have been sent and received during 200 second. The PDR is used to determine the optimal number of delivery paths under different circumstances and is also used to determine the suitability of different clustering algorithms for supporting multi-path routing. The more packets are received, the better the performance is.

In other words,

$$PDR = \frac{\Sigma\, Pr_i}{\Sigma\, Ps_i} \ , \tag{1}$$

where PDR denotes the packet delivery ratio during the whole simulation, Pr_i denotes the number of packets received during the i-th time frame by the destination, and Ps_i denotes the number of packets sent during the i-th time frame by the source.

Figure 7 shows the PDR for the AODV, OLSR and CBRP with respect to the number of nodes. The CBRP performs better than the OLSR and AODV for a high and low network size. The AODV performs better than the OLSR in terms of the number of nodes. CBRP delivers almost 40~60% packets in 20 to 100 nodes. Because CBRP's 40% performance is much better that OLSR's 20% and AODV's 28% even when number of node is 100, our protocol is better than the other in a large network.
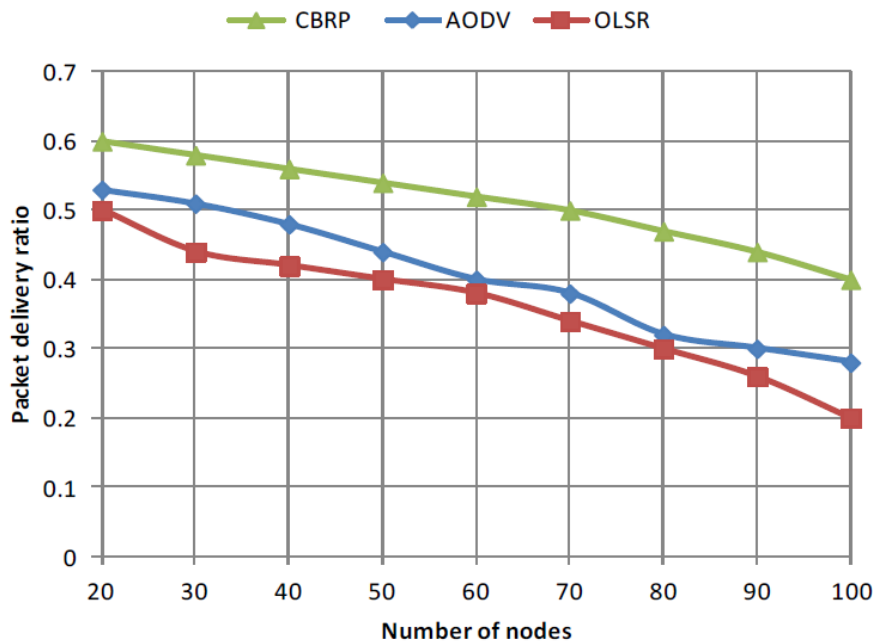

Figure 7. The packet delivery ratios as a function of the number of nodes

4.4 End-to-end (ETE) delay

The data transmission time from a source to a destination is known as the 'end-to-end (ETE) delay' and includes the delay time induced by the cache during the discovery phase, the queue waiting time, and the transmission time over the links. For every 1 sec during 200 seconds, we measured the number of packet that have been sent and the time difference between sender and receiver.

A lower ETE delay signifies a better performance. The ETE delay is defined as follows:

$$ETE\ delay = \frac{\Sigma(T_{R_i} - T_{S_i})}{\Sigma N_{P_i}} \tag{2}$$

where T_{R_i} denotes the time of receiving packets, T_{S_i} represents the time of sending packets, and N_{pi} denotes the number of packets at the i-th time frame. The delay time increases as the number of nodes increases.

In Figure 8, we can see that the CBRP has a low ETE delay when compared to the OLSR and AODV. The OLSR and AODV almost have more than a 2 sec delay time, but for the CBRP, the delay is < 1.5 sec at 100 nodes. The average ETE delay difference between the CBRP and AODV is almost 1.2 seconds, and between the CBRP and OLSL it is almost 0.6 seconds. These results ensure better performance for the CBRP when compared to the AODV and OLSR.
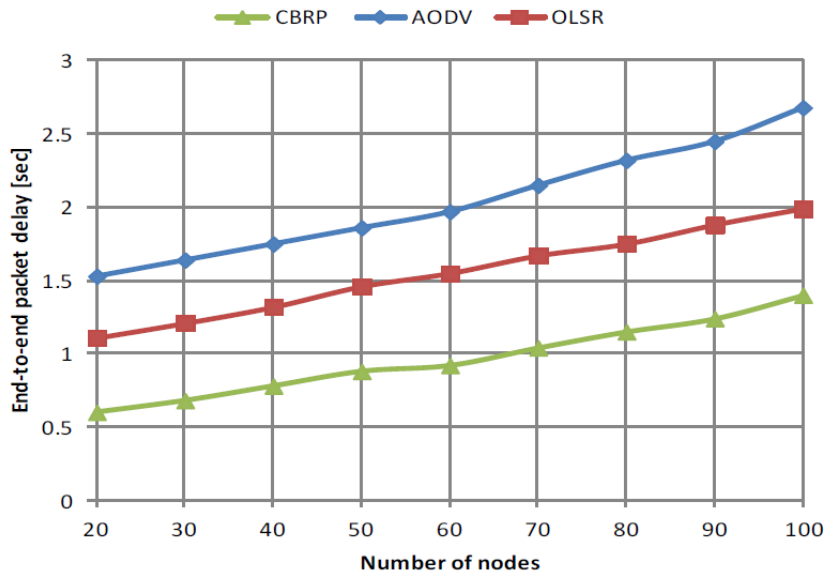

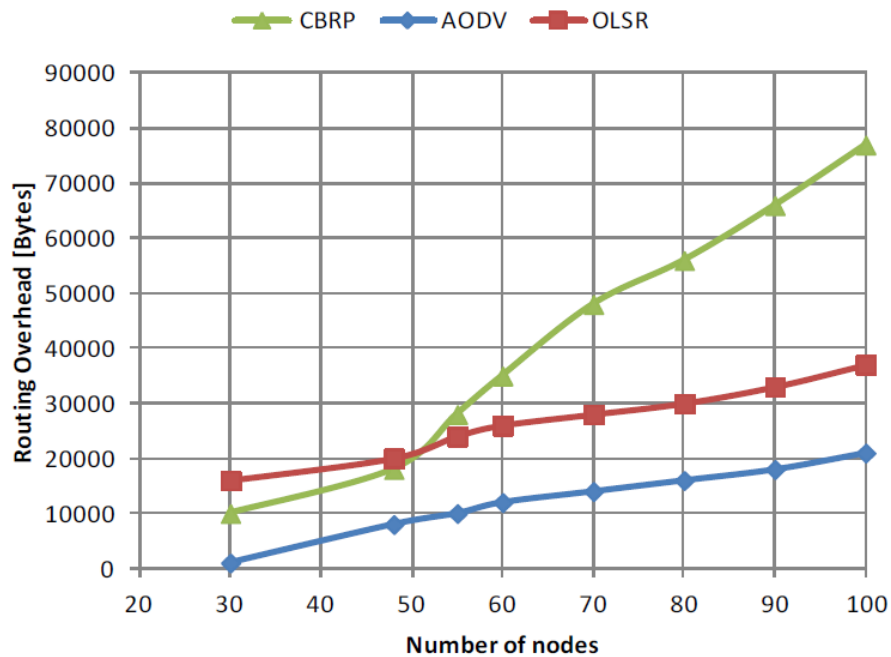**Figure 8. The end-to-end delay as a function of the number of nodes**

Figure 9. The routing overhead as a function of the number of nodes

4.5 Routing Overhead

Routing overhead is the total number of routing packets that are transmitted over a network during a simulation time of 200 s. Figure 9 indicates that the routing overhead of the CBRP is low when compared to the OLSR for ≤ 50 nodes. After 50 nodes, the routing time rises very quickly because of node congestion and traffic collisions. This result is a drawback of our previously proposed routing protocol. The AODV and OLSR have less overhead when compared to the CBRP. When the number of nodes is less, then the CBRP provides a better performance compared to the OLSR. When the number of nodes is increased, the collision and congestion occurrences also increase in the network because of overhead. The CBRP has almost an additional 50,000 bytes of overhead when compared to the OLSR. The CBRP has almost an additional 42,000 bytes of overhead when compared to the OLSR at 100 nodes.

We have compared the performance of the CBRP with respect to the AODV and OLSR. With the exception of the routing overhead, the CBRP outperforms the AODV and OLSR for the channel capacity, path discovery, packet delivery ratio, and end-to-end delay. Thus, the CBRP outperforms the other protocols at the sacrifice of routing overhead degradation.

5. Conclusions

In this paper, we analyzed the performance of a cluster-based routing protocol for wireless mesh networks. This study presented further research for the routing scheme that was proposed earlier by our research team.

The proposed routing scheme divides the network into a number of groups (clusters). If the source and destination are in the same cluster, then the cluster head sends path information to the source as a unicasting message. If the destination node is not a member of the same cluster as a source, then the cluster head sends a route request message to the MPP. The MPP forwards this route request to all of the cluster heads in the form of a multicast message. As a

result, it again does not require the broadcasting of the route request for the path. However, in case of an existing routing protocol, flooding takes place over the whole network even when the destination is very near to the source. As a result, this approach appears to be very costly. As the group size is increased, fewer multicasts and more unicasts exist. However, an overload on the cluster head can occur. A decision on the size of the group and the number of clusters depends on the topology and application of the networks.

Through software simulation, we have evaluated the performance of the proposed CBRP compared to the AODV and OLSR. The scheme shows several better performances in terms of the channel capacity, path discovery, packet delivery ratio, and end-to-end delay at the sacrifice of routing overhead degradation.

A possible future research direction would be to determine the group size and the number of clusters, depending on the topology and application of the networks.

Acknowledgement

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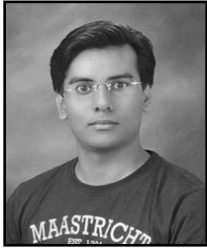
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