Cross-Layer QoS Routing Framework For Wireless Mesh Networks

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Abstract

Wireless mesh networks have recently gained a lot of popularity due to their rapid deployment and instant communication capabilities. Special routing protocols are employed, which facilitate routing between the Mesh Routers as well as between the Mesh Routers and the Mobile Nodes. This work addresses a framework of packet routing in the wireless mesh network. We investigate a cross-layer solution to enable a good application delivery. In addition, we present an IPv6 addressing scheme and new procedures to handle mobility. Another feature of our work, is that we use a modified Multi Protocol Label Switching (MPLS) scheme to introduce a new hierarchical QoS routing.

1 Introduction

The Wireless mesh networks (WMNs) consist of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of WMNs. They provide network access for both mesh and conventional clients. The integration of WMNs with other networks such as the Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks, etc., can be accomplished through the gateway and bridging functions in the mesh routers. Mesh clients can be either stationary or mobile, and can form a mesh network among themselves and with mesh routers. WMNs are anticipated to resolve the limitations and to significantly improve the performance of ad hoc networks, wireless local area networks (WLANs), wireless personal area networks (WPANs), and wireless metropolitan area networks (WMANs). They are undergoing rapid progress and inspiring numerous deployments. WMNs will deliver wireless services for a large variety of applications in personal, local, campus, and metropolitan areas. Despite recent advances in wireless mesh networking, many research challenges remain in all protocol layers. Indeed, the traditional routing protocols described for ad-hoc networks, were actually developed for single-radio nodes. Thus, they frequently lack the ability to exploit the potential offered by the Mesh Routers and, hence, sub-optimal routing has to be addressed in a mesh environment.

This paper presents a detailed framework of a cross-layer hierarchical routing protocol for WMN. This new protocol combines label concept and cross-layer routing algorithm. Indeed, The Cluster Heads (CH) are responsible to select the QoS routes between end routers taking into account QoS requested by the source node. Moreover, The CH gives labels to characterize the selected path. Thus, the routers update their local layer 2.5 label table by incorporating the Label-in and the Label-out values specified by the CH for each established route. By this way, the intermediate mesh routers can provide fast and efficient data packet forwarding without checking the IP address and accessing a large routing table of all nodes in the wireless mesh network. Thus, our work inherits features from MPLS and moreover from Hierarchical Mobile IP (HMIP) [8, 4].

The remainder of this paper is organized as follows. In Section 2, we introduce the motivations behind our work by stressing the necessity of optimizing data forwarding in WMN. In Section 3, we present a detailed description of our cross-layer routing framework. Methodology of the simulation and performance evaluation are presented in Section 6. Section 7 concludes this paper by summarizing the outcomes and outlining future works.

2 Motivations

Today, several companies have already realized the potential of WMN technology and offer wireless mesh networking products. A few testbeds have been established in university research labs. However, for a WMN to be all it can be, considerable research efforts are still needed. For example, the available MAC and routing protocols are not scalable; throughput drops significantly as the number of nodes or hops in WMNs increases. Thus, existing protocols need to be enhanced , revised or re-invented for WMNs. Regarding to these remarks, we invent a new routing and MAC layer protocols that aim to improve WMN application delivery.

3 Our proposal

We focus on QoS routing in wireless mesh networks. In this section, we describe the architecture that we consider in our framework. Then, we detail the different routing procedures that we used to ensure QoS communications between wireless mobile nodes in the wireless mesh network. Our work inherents new features from HMIP and MPLS [4, 8].

3.1 Network architecture

In our work, we consider the wireless mesh architecture shown in Figure 1:

This architecture contains a collection of Cluster-Headers (CH), Mesh Routers (MR), and Mobile Terminals (MT). Each CH can view all the MRs under its coverage. Each MR is attached to a CH; in some cases a router can be
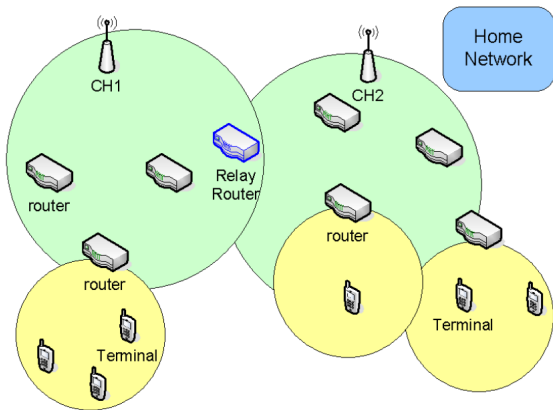
Figure 1: The wireless mesh architecture

Figure 2: Similarity with HMIP

Figure 3: Similarity with MPLS

attached to 2 CHs (Relay Router in Figure 1). It is assumed that mesh routers are not moving frequently. They can appear (switch on) or disappear but not move as end user nodes. No assumptions are made on the mobility of the end user wireless nodes. In this structure, the mesh routers are equipped with 2 different interfaces. The first interface is servicing the access of the end user terminals: it can be through any kind of radio access technology (IEEE 802.11 for example). The second interface is connecting the routers to the Mesh network; it is implementing the openairinterface transmission and protocols. The nodes are grouped in clusters under the responsibility of a cluster head (CH).
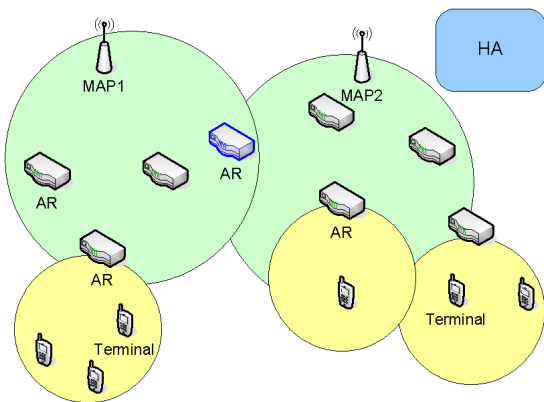
Naming and routing are proposed to be designed according to IPv6 and HMIP philosophy. In this framework, terminals are keeping their IPv6 addresses from their home network and will allocate local addresses when moving under the mesh network coverage. In order to let terminals be joinable via their home address, it is proposed to use schemes similar to HMIP based protocols. CH will play the role of MAP (Mobile Anchor Point), and mesh routers the role of AR (Access Routers). A terminal will use a local registration scheme when attaching to a router, while CH will take care of propagating the actual binding to the Home Agent. The proposed solution will restrict the needed signalling of terminals to a dialogue with Access Routers. As far as routing to outside the mesh is concerned, a gateway function (GW) is needed. For simplicity, this document assumes that the GW function is located at each cluster head.
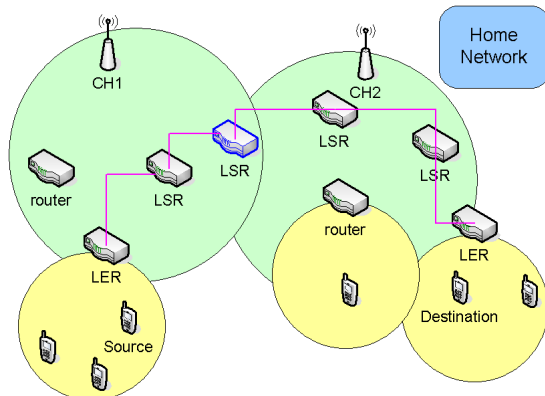
Furthermore, routing will rely on a scheme derived from MPLS. IP packets generated from a source will reach the first access router which will act as a Label Edge Router (LER) as shown in Figure 3. All intermediate routers will serve as Label Switching Routers (LSR) and finally the destination will be reached via its LER of attachment. Labels assignment and distribution are performed by CH: the Label Distribution Protocol (LDP) is replaced by specific mechanisms described in subsequent sections.

3.2 Description of QoS routing protocol for WMN

3.2.1 Short Overview

We describe a hierarchical QoS routing mesh protocol. This new protocol combines label concept and cross-layer routing algorithm. Indeed, the CHs are responsible to select the QoS routes between end routers taking into account the QoS requested by the source node. Moreover, each CH gives labels to characterize the selected path inside its domain. Thus, the routers update their local routing table by incorporating the Label-in and the Label-out values specified by the CH for the established route. The intermediate mesh routers can provide fast and efficient forwarding without checking the IP address and accessing a large routing table of all nodes in the wireless mesh network.

3.2.2 DYNAMIC ADDRESS ALLOCATION SCHEME

In this work, we consider the Address Auto-configuration method described in IPv6 [5] and we propose a modified node registration scheme based on HMIP [4]. Thus, a Mobile Node (MN) learns that it is moving to a new access router of attachment or not, when receiving a Router Advertisement (RA) message from the MR. Indeed, RA message is transmitted periodically, it incorporates the IPv6 address prefix of the attached mesh access router. When joining a new subnet, the MN generates link local address and allocates it to the interface. The MN confirms that the generated link local address is not already used on the same mesh access router subnet using the Neighbor Solicitation (NS) message. Then, it sends Router Solicitation (RS) message on the network. RS message transmission is a must (not an option as in IPv6). It enables the mesh router to learn about the new MNs that join its subnet. The MN

receives the RA and gets the included IPv6 address prefix. If the mesh router detects that the new MN still attached to the same CH domain the MN registration procedure is finished. Else, the mesh router sends, to its attached CH, a Regional Registration Request (RR) message that incorporates both IP address and local assigned address of the MN. The CH sends BU (Binding Update) to the Home Network. Therefore, the Home Network associates the mobile node IP address to the CH IP address.

Note that in the basic HMIP [4], the mesh router only sends fixed prefix allocated to the mobile nodes that are located in its subnet. In other words, the router does not care to whom it sends information. It does not maintain such records. However, in our scheme the mesh router maintains an association list of the mobile nodes that maps their IP address with the new allocated local address and their link layer address. Moreover, the CH maintains a list of the attached routers in its domain IntraCHTable. We will detail later the routing table maintained by each CH.
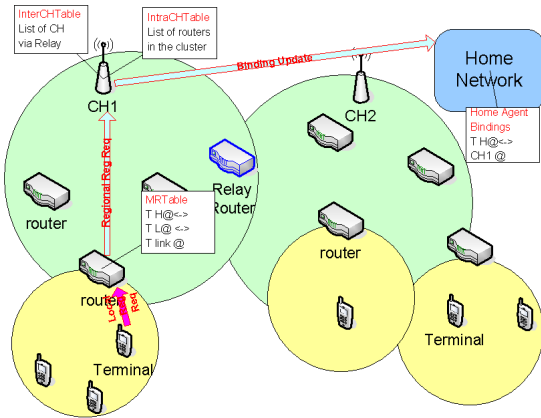

Figure 4: : Terminal attachment

3.3 ROUTE ESTABLISHMENT SCHEME

The route establishment scheme depends on the source and destination locations. In this subsection, we present the different primitives that we follow to set up routes between sources and destination nodes. We distinguish four scenarios of the MN and the CN (Correspondent Node) locations:

1) The MN and the CN are within the same router subnet.

2) The MN and the CN are within the same CH domain but are not in the same subnet.

3) The MN and the CN are within different CH domains.

4) The CN is outside the mesh network.

3.3.1 Intra-router routing

When a MN wants to initiate a communication with another MN it sends the data packet to its attached router. The router verifies if the CN IP address is registered in its attached node list or not. If yes, data packets between the source and destination will be routed though their attached mesh router. In consequence, all traffic between mobile nodes residing under the coverage of a mesh router will pass through it.

3.3.2 Intra-CH routing

Upon receiving the first packet, the mesh router sends a Route Request message (RREQ) to its attached CH. This packet contains ID of this router and the IP address of the destination MN. The CH asks the Home Agent for the binding information of the destination. The CH receives the CH@ of attachment of the destination. Using its Intra-CHTable, CH queries the routers for the destination. Hopefully one mesh router responds. Then, the CH establishes the path between end to end routers. Indeed, it assigns a list of labels for this path and sends it to the mesh routers that will participate in the communication set up. The selected path takes into account the QoS requirements incorporated in the RREQ message.

3.3.3 Inter-CH routing

When the destination node is within a different source CH domain, the inter-CH Routing Table of CHs (inter-CHTable) is used to select the routes between the end to end routers. Indeed, each CH disposes of InterCHTable which identifies the next CH or (CHs) that is (are) able to connect the CH to the different CHs in the mesh network.

The CH source sends a RREQ that incorporates the QoS metric requested by the source MN towards the CH destination. The RREQ message is then transmitted though the Mrelay until reaching the destination CH. Each CH that receives the RREQ message forward the message to the next CH based on the interCHTable. When the RREQ arrives at the destination CH, the destination CH sends a RREP message that incorporates the selected link quality towards the CH source. When receiving the RREP message from the different route opportunities that could connect the source to the destination, the CH source selects the route that can satisfy the application QoS requirement. Then, it sends a Route Confirmation (RConfirm) message to the destination CH in order to reserve resources. If any route could satisfy the application requirements, the CH source decides to not establish connection or to choose a route with the higher available quality. When the intermediate CHs receive the RConfirm message, they assign labels to the routers that have to participate in the communication set up.

3.3.4 CN is outside the Mesh network

When the CN is outside the mesh wireless network, we can apply a routing scheme similar to HMIP [1] that is optimized to establish path between source and destination nodes. Thus, packets sent by the CN are firstly routed to the HA of the MN. Then the HA will forward the packets to the registered CH of the MN. The CH asks routers within its domain if their node list contains the destination IP address. Once the CH receives a response from the corresponding router, the packets are tunneled from the CH to the access router.

CH sends a Binding Update (BU) message to the CN. The BU message informs the CN about the CH address to which the MN is attached. Then the CN sends packet directly to the CH (implementing a gateway function).

3.4 MOBILITY MANAGEMENT: PATH MAINTENANCE

Each terminal in communication keeps a list of its correspondent addresses. When moving from a point of attachment to another, the terminal will pass its list to trigger a route updating.

3.4.1 Mobility between Mesh routers

The terminal nodes in our architecture might be highly mobile. So we have to maintain communication even when the nodes move. To this end, when a destination MN discovers that is connected to a new mesh router, it has to inform its new router of attachment about its current CNs. If the router has a routes to CN@, it forwards the data packets. Else, the new access router sends to its attached CH, a RREQ message. This RREQ message incorporates the list of CNs IP addresses. Then, the CH re-establishes the routes using the corresponding label routing table.

This process is initiated only if the destination MN is participating in data communication. Indeed, the MN has to check its CN list when changing a router of attachment.

3.4.2 Mobility between Clusters

In addition to the previous procedure, a Forwarding RREQ message is sent to the CH of attachment via MRelay nodes. Each cluster head is responsible to assign the corresponding labels in their respective clusters.

3.5 LABEL-SWITCHING PROCEDURE

In our framework, the CH uses the label-switching feature to reserve routes between source and destination routers in the wireless mesh network.

3.5.1 Path reserve intra-CH

When the CH receives a RREQ message from the mesh router associated to the source node, it selects the mesh routers that will participate in packet forwarding process. Then, it identifies a list of labels. The assigned labels define a path based-label that describes a connection between two mesh routers for the requested service level. The labels are incorporated in the Label Reservation Messages (LRM) and sent to the corresponding mesh routers. Each router that receives the LRM sends back to the CH a LRM Acknowledgment (LRM ACK) message in order to avoid LRM lost. Then, it updates its local label routing table by including the corresponding parameters describing the established path: label-in, label-out, source, destination, and service level.

3.5.2 Data packet forwarding procedure

The received data packets from the source MNs are classified and routed at the ingress attached router. The mapping between IP packets and a Label Switched Path (LSP) is done by providing a Forwarding Equivalence Class (FEC) specification for each LSP. Thus, the packet is assigned to a FEC, and the FEC is encoded with a label at the Ingress mesh router. When an intermediate mesh router receives a labelled packet, it will use the label as an index to look up the forwarding table. The packet is processed as specified by the forwarding table entry. The incoming label is replaced by the outgoing label, and the packet is switched to the next router. Before a packet arrives at the destination router, the label is removed. The label switching path operation in a sample mesh network is shown in Figure 5.

Note that a mesh router could at the same time ingress, egress and Label Switch Router LSR). Indeed, in Figure 5 we can see that the mesh router B is an ingress and LSR at the same time.
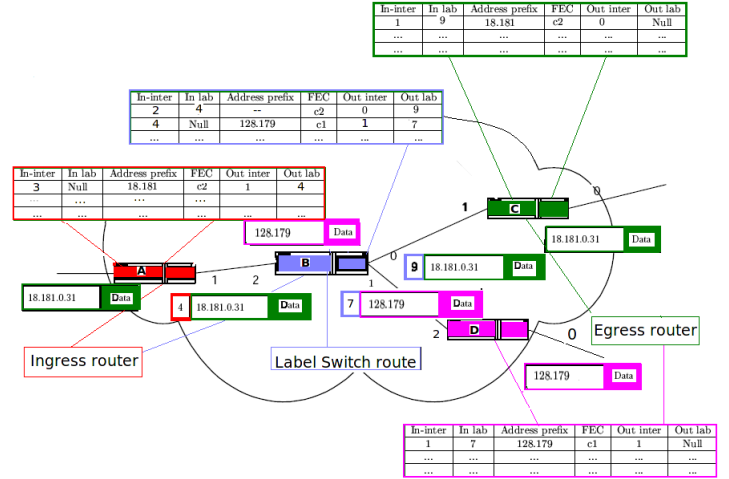

In-inter	In lab	Address prefix	FEC	Out inter	Out lab
1	9	18.181	c2	0	Null
...	...	...	...	...	...

In-inter	In lab	Address prefix	FEC	Out inter	Out lab
2	4	--	c2	0	9
4	Null	128.179	c1	1	7
...	...	...	...	...	...

In-inter	In lab	Address prefix	FEC	Out inter	Out lab
3	Null	18.181	c2	1	4
...	...	...	...	...	...

In-inter	In lab	Address prefix	FEC	Out inter	Out lab
1	7	128.179	c1	1	Null
...	...	...	...	...	...

Figure 5: : Label-based routing tables

3.5.3 Path reserve inter-CHs

The CHs that will communicate between each other have to define together the list of label-in and label-out of the relay routers in order to avoid redundancy of label assignment. Since we consider stable mesh routers, the label could be shared between non-adjacent routers in the mesh network.

3.6 CROSS-LAYER QOS ROUTING

The co-operation between layers to enable performance enhancement is very important and useful in wireless networks. The global objective of such interaction is to achieve a reliable communication-on-the-move in highly dynamic environments as well as QoS provisioning. Numerous works have been presented in the open literature that introduce several coupling ways and solutions between different communication layers as we discussed in [3]. Much prior research has recognized the shortcomings of shortest-path routing in wireless networks due to the varying channel characteristics.

3.6.1 Role of CH in the QoS routing

In our work, we present a new metrics for routing in multi-radio, mesh wireless network. We aim to select a high-quality path between a source and a destination attached routers. These metrics are computed based on physical statistical measures at each wireless mesh router. Then, they are transmitted periodically to the associated CH. The CH updates both local CH and inter-CHs routing tables including the new QoS metric values corresponding to each mesh router. Based on these collected parameters the CH selects the "best" available route that takes into account the QoS application requirements specified within the RREQ message.

3.6.2 QoS metrics

Each mesh router measures periodically the following QoS metrics:

Metric 1: RSSI (dBm) on physical resources corresponding to logical channel.

Metric 2: Average SINR (dB) on physical resources corresponding to logical channel.

Metric 3: Average number of transmission rounds (times 10) on transport channel associated with logical channel.

Metric 4: Average residual block error rate (times 1000) on transport channel associated with logical channel (after HARQ!).

Metric 5: Actual Spectral efficiency (bits/symbol times 10) of transport channel associated with logical channel.

We define four classes of services and we map for each category a minimum tolerated level of each QoS metric. Thus, the selected path takes into account the QoS requirement of the class of service incorporated in the RREQ message. If no route could be established considering the application requirements, we have to choose between considering the available paths even the QoS are not satisfied or not establishing the route because the application performance will be very poor.

4 ROUTING TABLES

The SINR has been concerned for providing potential performance improvements and more responsive systems. The higher the value of SINR, the better the performance of networks is. The mesh routers transmit periodically to their attached CH the SINR of their neighbors. To deal with rapid SINR variations, we use an estimator of Exponentially Weighted Moving Average (EWMA) to smooth the estimated SINR values. We propose a modified link-state based table-driven routing protocol that captures the approximate network status periodically without generating lot of control traffic. It uses the SINR information captured by the mesh routers to address a QoS routing in the WMN.

4.1 INTRA-CH ROUTING TABLE CALCULATION

To calculate the intra-CH routing table, the CH collects the list of neighbors for each mesh router in its domain. Indeed, each CH in the WMN maintains a table that associates each router to its neighbor list.

4.1.1 Intra-domain route selection algorithm

In this sub-section we describe the algorithm used by the CH to select route between the source and the destination router. Indeed, for each mesh router the CH constructs routes to all the routers in the domain using the neighbor table described above.

Based on the received SINR metric values from the routers, the CH calculates a cost function (f(SINR)) that describes the QoS of a given link. Then, it updates the intra-domain routing table. Using this table the CH constructs the local topology. Thus, it is able to establish a route between any two routers under its domain. The algorithm of routing table calculation used is similar to that used by OLSR. However, we use the SINR metric instead of

the shortest path to construct the routing table of a mesh router X. The algorithm is run on the directed graph containing the arcs X¬ -> Y where Y is any symmetric (SYM) mesh router neighbor of X(see Table 1).

The following procedure is given as an example to calculate (or recalculate) the routing table of a router R1 (R_source):

1. All the entries from the routing table are removed.

2. The new routing entries are added starting with the symmetric neighbors (h=1) as the destination router. Thus, for each router in the neighbor set where: R_status = SYM (there is a symmetric link to the neighbor), and for each associated value of f(sinr) such that f(sinr) >= f(sinr_thresh) (sinr_thresh: minimum tolerated value of sinr defined according to application requirement) a new routing entry is recorded in the routing table for (h=1) with:

   R_dest_addr = address of the neighbor;

   R_next_addr = address of the neighbor;

   QoS_metric (R_dest, R_next) = f(sinr) (R_source, R_next) R_distance = 1;

   The new route entries for the destination nodes h+1 hops away are recorded in the routing table. The following procedure MUST be executed for each value of h, starting with h=2 and incrementing it by 1 each time. The execution will stop if no new entry is recorded in an iteration.

3. For each topology entry in the topology table, if its T_dest_addr (in the neighbor list) does not correspond to R_dest_addr of any route entry in the routing table AND its T_last_addr corresponds to R_dest_addr of a route entry whose R_distance is equal to h, then a new route entry MUST be recorded in the routing table (if it does not already exist) where:

   R_dest_addr = T_dest_addr;

   R_next_addr = R_next_addr of the recorded route entry where:

   R_dest_addr == T_last_addr ;

   (R_dest, R_next) QoS_metric = (R_source, R_dest_addr) f(sinr) ;

   R_dist = h+1;

4. Several topology entries may be used to select a next router R_next_addr for reaching the mesh router R_dest_addr. When h=1, ties should be broken such that nodes with highest f(sinr) are preferred as next hop.

We can describe several routing tables that correspond to different priority classes of service. We have to define the QoS cost function that identify a route between routers Rx and Ry: (Rx,Ry) f(sinr). In the OLSR route establishment scheme, the routes are selected based on the short hop count metric.

4.2 INTER-CH ROUTING TABLE

Each CH identifies the list of its CH neighbors. Any CH which has more than one neighbor, extracts from the intra-CH table the different relay route possibilities that could

connect these CH neighbors. The CH associates the computed QoS metric for each selected route. This information is incorporated in the Inter-CHTable. Each CH announces in the mesh network the list of its neighbors. Based on the exchanged information, each CH can compute a route or many routes to any CH in the WMN with different QoS metrics.
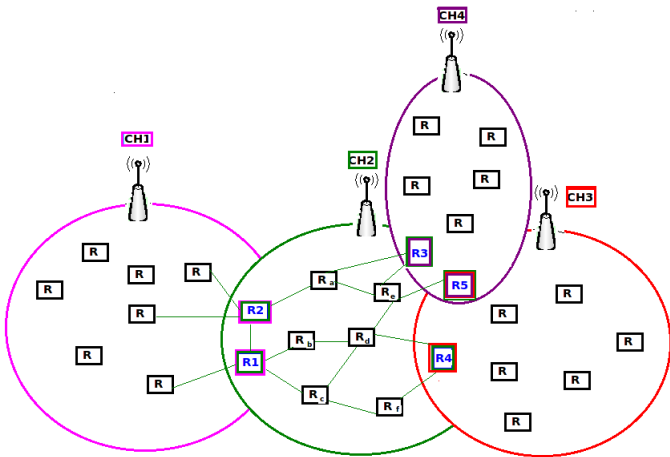

Figure 6: : Example of relay routes

4.3   Algorithm of inter-CH routing

Each CH announces in the mesh network the list of its neighbors. Based on the exchanged information, each CH can compute a route or many routes to any CH in the WMN using the modified OLSR algorithm described above. Thus, the CH has a global view of the CH topology in the WMN. Indeed, in its Inter-CHTable, it disposes of the list of other CH destinations in the mesh network. Each entry in the table describes the relay routers (for the CH neighbors) constructed based on the modified OLSR described for intra-CHTable. Moreover, the QoS metric that connect next CH hop that corresponds to the relay routes and the number of CHs to be traversed to reach the destination CH is recorded.

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4.4   ROUTING   TABLE   AT   MESH ROUTER

The mesh router maintains two tables. The first one records the list of MNs in the router subnet. The second table is the label-based routing table that is described in Figure 5. This table is used to route packets. The labels are assigned by the CH.

5   LABEL DISTRIBUTION PROTOCOL (LDP)

When the CH selects a route between source and destination mesh routers, it has to assign labels to enable data packet forwarding process. We define a label assignment procedure that is used by each CH to label the selected path. The selection of the routers and process of label assignment are similar to an explicitly routed LSP.

5.1   INTRA-DOMAIN LABEL ASSIGN-MENT SCHEME

The CH uses LDP to assign label/FEC bindings to the mesh router. We speak about LDP session that allows each mesh router to learn the label mapping and send an ACK of the received label reservation message.

5.1.1   Labels for a selected path

When the CH selects a route to set up resource reservation for a particular priority flow, it informs the MRs participating in this path of the assigned labels to be considered in the packet forwarding process. As an example, each CH considers the range of [100, 1000] values as labels, to be assigned to the MR in its domain and that are not relay routers. The labels could be maintained for all communication set up or re-allocated if the communication terminates.

5.1.2   LDP Message Exchange

We define the following list to be used by LDP: Label Reservation Message (LRM), ACK of LRM, Path Error Message (PEM), Path Repair Message (PRM), and ACK of PRM. These messages are used for: 1- Session messages, used to establish, maintain, and terminate sessions between LDP peers (MRs). 2- Advertisement messages, used to create, change, and delete label mappings for FECs. 3- Notification messages, used to provide advisory information and to signal path error.

5.1.3   Packet formats

In this subsection, we identify the different required fields for each control message:

1. Label Reservation Message (LRM)

2. ACK of LRM

3. Path Error Message: if a MR "E" detects some problems on the active link to a next MR "D", the MR "E" will send a Path Error Message (PEM) to its attached CH to tell that the link to D is failed. The CH looks at its intra-table and repairs the path if an alternative route exists by sending a LRM to "E". The MR "E" buffers the data packet received during the path-repair process. After creating a new path, "E" will forward all buffered data packets to the new created label. The other MRs participating to the packet forwarding process do not need to know the modification of this path.

4. Path Repair Message:when the MR notifies an error to its attached CH, the CH sends a Path Repair Message (PRM) to re-establish the broken link.

5. ACK of Path Repair Message: the MR send an ACK to confirm the reception of the PRM.

5.2 INTER-DOMAIN LABEL ASSIGNMENT SCHEME

The CHs reserve a range of label values between [1, 99] to be assigned only to the relay mesh routers. For each communication set up using relay routers, the CH notifies the used labels. When a new path is select using relay routers, the CH avoids the used labels for the routers that are neighbors of the used relay routers participating in packet forwarding.

6 Performance evaluation Methodology

Our framework proposal is being implemented on a real platform using a new Eurecom MAC layer architecture that is able to capture the medium behavior and send reports to high levels. These reports describe the QoS of the links. The experimentation network contains at least 3 CH, 7 MR, and 10 mobile nodes. All mobiles nodes in the network are configured to have mobility by configuring trajectories. Since there are many factors that can be used to evaluate network performance, we will focus on several of the most important factors in the evaluation tests such as throughput and end-to-end delay.

7 Conclusion and Future Works

In this paper, we provide a framework for cross-layer QoS routing in wireless mesh networks. Our proposal inherits features from OLSR, HMIP, and MPLS. The Label Switching approach allows more flexible routing decisions, under the control of CHs. QoS is naturally managed by the CHs using the QoS metrics computed at MAC layer.

For the future work, we will implement the different described protocols of this framework in real plate-form and investigate the application performance.

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