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Cross-layer MAC Enabling Virtual Link for Multi-hop Routing in Wireless Ad Hoc Networks

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***Abstract*—Efficient routing is a fundamental issue in multi-hop wireless ad hoc networks. In this paper, we study the limitation of traditional routing structure in multi-hop wireless ad hoc networks due to (a) the layered structure of a wireless protocol stack and (b) the lack of coordination between medium access control (MAC) and routing protocols. These limitations result in long processing delays in a relay/forwarding node. In order to alleviate these issues, we propose a solution based on cross-layer MAC design, which improves the coordination between MAC and routing layers using an idea we call "virtual link". The virtual link idea was implemented and tested in an ad hoc wireless network testbed. Experimental results show that the proposed cross-layer design significantly improves the performance in terms of reduced round trip time (RTT), reduced processing time in the intermediate relay/forwarding nodes and increased throughput compared to a legacy architecture.**

I. Introduction

With the advances in wireless & mobile technologies and the ever increasing demand from the *first responders (e.g., fire-fighters, police and emergency medical rescue team)* and *commercial users* for ubiquitous connectivity, wireless ad-hoc and mesh networks are gaining prominence and playing a major role in many applications. For example, during a natural disaster in a region, while it will be inconvenient or even impossible to create an infrastructure-based network, a multi-hop wireless ad-hoc network for first responder communications could be established quickly with the help of low–cost, low–power, multi–functional radio nodes. Unlike infrastructure based networking, multi-hop ad hoc architecture can create wide-area back-haul networks where traffic can flow among the peers directly using relay/forwarding via multiple hops resulting in higher capacity, ubiquitous connectivity and increased coverage.

Efficient routing in multi-hop wireless ad hoc networks is a fundamental issue to be addressed. Within multi-hop ad-hoc network, a data packet must traverse through multiple hops from source node to destination node. Additionally, such wireless ad hoc networks differ from their wired counterparts in that their topologies are highly dynamic because of node mobility. Thus efficient route discovery/maintenance is critical. Even though there has been major focus on routing protocols based on finding efficient shortest route discovery/maintenance or developing link metrics, there is another key issue that has mostly been not addressed. Due to the highly complicated nature of medium access control (MAC) layer in wireless networks, MAC has to be implemented as software. This is different from a wired network situation where MAC is implemented in hardware. Due to the software MAC implementation, the traditional routing structure in wireless networks results in long processing delays for packet forwarding packet in every intermediate/relay node. Additionally, due to resource-limitations, unwanted delays will make the network system lifetime much shorter and inefficient to operate. Therefore, we address the issue of the cross-layer MAC and routing design.

To date, a great deal of literature has focused on routing issues for multi-hop ad-hoc network, primarily in two directions: (i) shortest route discovery/maintenance and (ii) developing link metrics to analyze a wide variety of performance objectives. At the very beginning, proactive routing protocols like Dynamic Destination-Sequenced Distance Vector (DSDV) and reactive routing protocols such as Ad hoc On-Demand Distance Vector Routing (AODV), were designed for solving routing issues. When these were implemented in real wireless networks several issues were encountered, such as: the destination never learns of a route to the source node, the manner in which RREP packets are forwarded and a rebooted node will lead to routing loops, etc. These issues have been discussed in [1] and [2]. In [3], a performance comparison between AODV and Dynamic Source Routing Protocol (DSR) is discussed. Here, "doodput" and "routing efficiency" are used for evaluating the performance of these routing protocols. In [4], the energy overhead of DSDV, AODV and DSR are evaluated. This work shows that with different transmission ranges there are significant differences in energy overhead between the ad-hoc routing protocols. In [5], researchers compare energy consumption between different routing protocols including AODV, Flooding Protocol and Low-Energy Adaptive Clustering Hierarchy (LEACH). AODV is observed to be not feasible for low energy-limited environment. In [6], a novel routing protocol is proposed to improve energy efficiency. The main idea of this protocol is to reduce message transmissions for routing information update. Cluster-based infrastructure creation are proposed for saving energy in [7] . There have also been few cross-layer attempts. In [8],[9],[10], and [11] the researchers investigate reducing handshaking/control frames before data transmission and reserving channel resource beyond more than one hop.

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None of the above-mentioned works focuses on the long processing delays in a relay/forwarding node due to the layer structure in wireless communication and the lack of coordination between MAC and routing protocols. In our experiments, for a three hops wireless ad-hoc setup, we observe that 16% of the Round Trip Time (RTT) is spent due to these processing delays; for a four hop ad-hoc network this is around 17% of the total RTT. Moreover, it is also observed that at a routing node, an average of 40-50% of the processing time is used in transferring data packet between MAC layer and routing layer. Clearly, these delays result in battery power wastage, higher latency, reduced system efficiency and data rate.

In this paper, we propose a cross layer MAC design enabling *virtual link* for reducing processing time in routing for forwarding nodes. At the same time, the energy consumption for every data frame is also decreased. This solution has been successfully implemented and tested in a testbed based on the IEEE 802.11 MAC. The testbed consists of Soekris NET5501 [12] devices. With this setup we experimentally evaluate and compare the performances of the proposed virtual link enabled MAC with legacy MAC/routing policy [13].

The rest of the paper is organized as follows. We present the proposed cross layer MAC design enabling virtual link in Section II. A detailed discussion on virtual link is also discussed here. In Section III, we present the test bed setup for performance evaluation and discuss the results. Finally, conclusions are drawn in Section IV.

II. Cross Layer MAC Design Enabling Virtual Link

Figure 1 shows the network layer structure and the entire processing path for **wired networks** like the Ethernet. Here the physical layer and most of the MAC layer functionalities are implemented in network interface card, i.e., in hardware. Such hardware implementation clearly minimizes the impact due to computation-induced delay and power consumption. However, the situation is quite different in a wireless network. Figure 2 shows the same process for a wireless network protocol stack. For example, due to the complexity of the IEEE 802.11 protocol, most parts of MAC are implemented as software. Two type of implementation for 802.11 MAC in [14] discussed are FullMAC and SoftMAC. In SoftMAC most of the MAC layer features are implemented as a module (e.g., in most cases it will be the device driver) in the operating system. Most of the wireless chipsets, especially the wireless chipset from Atheros, Intel, Broadcom and Ralink [15], depend on SoftMAC. In FullMAC chipset, like Prism54 [16], the MAC is implemented in the firmware.

Routing protocols in the conventional wireless layer structure are typically implemented in the network layer. Under this structure, the network layer has three major functions: (i) maintaining the routing table, including route discovery, creating corresponding routing entry in the routing table, modifying or deleting routing entries when a route is broken, etc.; (ii) computing the suitable next hop for the packet and (iii) re-encapsulating the packets according to the corresponding route entry. In the traditional routing structure, packets traversing over multiple hops, experience long unwanted processing

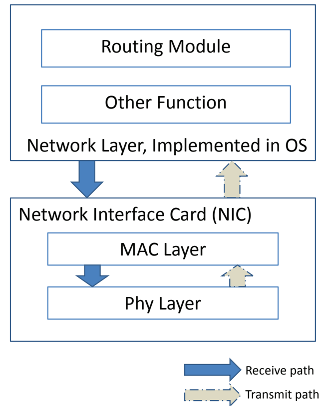

Fig. 1. Three lower layers of a wired network stack.

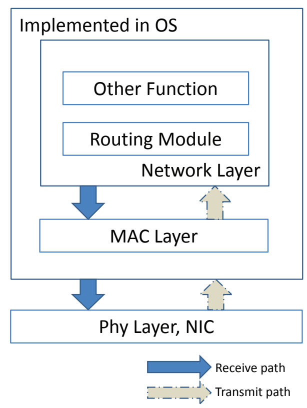

Fig. 2. Three lower layers of a wireless network protocol stack.

delays and energy wastage at intermediate routers. Such delays may not be acceptable, especially in critical wireless applications such as first responders' networks, delay-sensitive real-time media applications etc. Moreover, if devices in a multi-hop wireless ad-hoc network are resource-limited, a traditional routing structure with such unwanted delays will make the system lifetime much shorter and inefficient to operate. In order to break away from such inefficiencies, we introduce a new "virtual link" concept and propose a new cross layer MAC design which makes use of a virtual link to forward data packet much more efficiently. Under this proposal the routing layer implements the first function as mentioned above while the second and third functions are implemented in the data link layer.

A. Virtual Link

Consider an ad-hoc network example as shown in Figure 3. Nodes S and C in this example are within the communication range of each other, i.e., a physical link between nodes S and C exists. Then, these two nodes can communicate with each other over this physical link by using legacy IEEE 802.11 MAC or any other MAC protocol. In contrast to the physical link between node S and C, the nodes S and D are not within the communication range of each other as shown in the Figure 3. However, note that physical links exist between S-C and C-D. If these two physical links could be combined to obtain

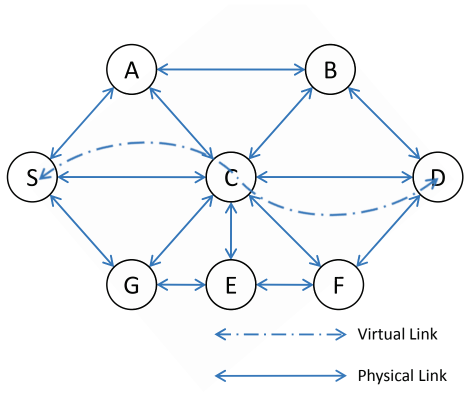

Fig. 3. A multi-hop ad-hoc network example

a "virtual link" then we obtain a logical link between S and D. It is then possible for nodes S and D to communicate with each other directly minimizing intermediate router processing thereby reducing the delays discussed before. By extending this idea of virtual links, any two nodes in Figure 3 could communicate with each other. The proposed MAC protocol will establish and maintain virtual links automatically and efficiently. With the proposed method, the routing layer will be responsible for the task of maintaining the routing table; however, the task for data frame re-encapsulation will be done by the virtual link enabled MAC. In the following subsection, we present the details of this system.

B. Proposed System Architecture

In the proposed cross-layer MAC architecture, we introduce two extra modules: *Inbound Monitor* module (as shown in the workflow of Figure 4) and *Self-Learning* module (as shown in the workflow of Figure 5). The steps for creating a virtual link are then as follows. When the wireless MAC starts to run in a node, its IP address is noted and the Inbound Monitor also starts to run. The Inbound Monitor of this node checks for the destination IP address on each frame. If the destination IP is equal to its own IP address, this is treated as a normal frame. Otherwise, the Inbound Monitor will look up the corresponding virtual link entry for this frame. If a suitable virtual link is located successfully, this frame will be re-encapsulated according to this virtual link entry and sent to the physical layer immediately for relay/forwarding purpose. If no corresponding virtual link is found, the self-learning module will be triggered. From now on, this monitor module will work on the outbound direction of the IEEE 802.11 MAC. After routing layer re-encapsulate the frame, which triggers the self-learning module, this frame will be shown again on the outbound direction. The self-learning module will create a suitable virtual link according to the new MAC header of this frame. When other data frames arrive at this node, the Inbound Monitor will re-encapsulate the MAC header according to corresponding Virtual Link entry. Figure 4 shows the work flow of Inbound Monitor module. Figure 5 describes the work flow for the Self-Learning module.

We introduce two new parameters: an integer value T_e and a boolean value MRU. T_e is used to decide the expiry time

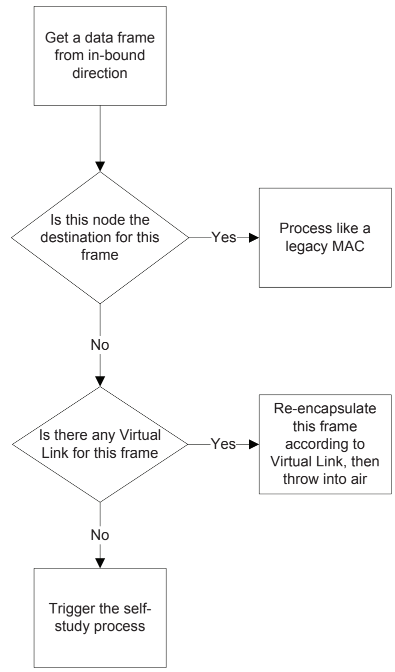

Fig. 4. Work flow of Inbound Monitor module.

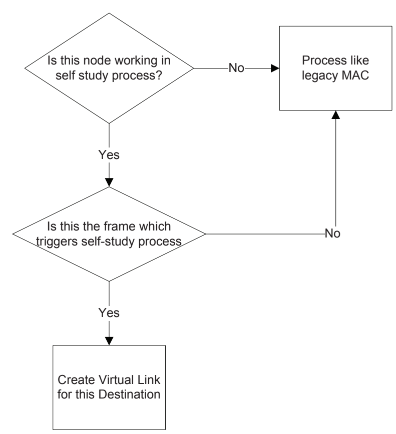

Fig. 5. Work flow of Self-Learning module.

for a virtual link entry. If a virtual link entry is not activated by a data frame for T_e, this entry will be removed from Virtual Link Table. The Boolean value MRU is used for maintaining the Virtual Link table. With MRU set to TRUE, MAC will monitor the Routing Protocol Data Unit (RPDU) on both inbound and outbound directions; when a non-Hello RPDU is found, the whole Virtual Link Table will be cleared. If this boolean value is set to FALSE, Virtual Link entry will be removed only when the expired timer is triggered. In the following section, we demonstrate the performance improvement with this proposed cross-layer MAC design.

III. Testbed Setup and Experiment Results

To evaluate the proposed cross-layer design we conducted extensive experiments and present the results in this section. We primarily focus on three metrics — processing time in MAC layer and routing layer, round trip time (RTT) for data packets with different length and hop counts and throughput which is measured at the destination node.

A. Testbed Setup

In order to setup a testbed, we use Soekris NET5501 [12] for the network nodes. We setup the multi-hop ad hoc networks in a region of 20 m× 20m area with wireless nodes scattered randomly in the region at a distance of 5–20 meters from each other. NET5501 is equipped with a 433MHz AMD Geode LX (X86 architecture) CPU, 512MB DDR-SDRAM. Compact Flash card is used for software and data storage purpose. A customized Linux 2.6.24.6 is deployed in these nodes. IPTABLE is applied for blocking the communication to emulate the designed topology. The wireless transceivers for the nodes are Atheros AR5414 chipset based wireless network interface cards (WNIC). The MAC implementation is based on open source Madwifi driver. ICMP and IPERF are used for measuring the performance.

B. Experiment Result

In order to find out the processing time consumed in coordinated MAC/Routing Layer, we create monitors on both inbound and outbound direction of MAC. With the time difference in these two monitors, the time consumption for MAC and Routing layer are obtained. Figure 6 shows the result, X-axis for different packet sizes and Y-axis for time consumption. As observed from the Figure 6, with the proposed approach, we get a 45% improvement with 100 byte long packets compared to legacy routing mechanism; while with the packet sizes going up to 20,000 bytes, we get a 55% improvement. This clearly demonstrates that cross-layer MAC design enabled virtual link increases the efficiency of multi-hop routing by sufficiently reducing the processing time consumption at the intermediate relay nodes.

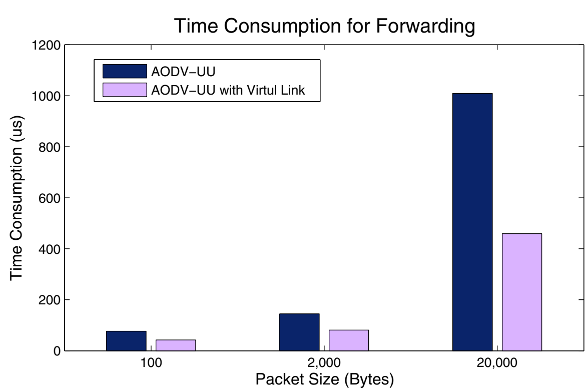

Fig. 6. Time Consumption for Forwarding Different Size of Packet

Next, we focus on the round trip time (RTT) performance comparison for data packets with different length and hop counts. In these experiments, ICMP packets with different size are used for measuring the Round Trip Time(RTT). Figure 7, 8 and 9 show RTT comparison between AODV-UU with legacy MAC and AODV-UU combined with the proposed MAC. As shown in the results, proposed method clearly reduces the round trip time over the legacy approach. Moreover, it is also interesting to note that with the increasing hop counts the performance improvements are also increasing thus indicating that the proposed methodo to be useful for multi-hop wireless ad hoc networks.

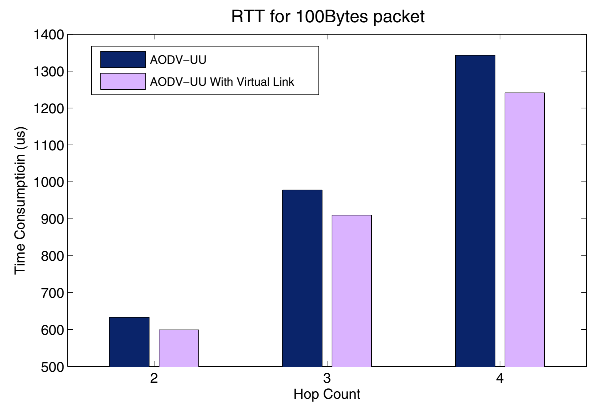

Fig. 7. RTT for 100 Bytes Packet

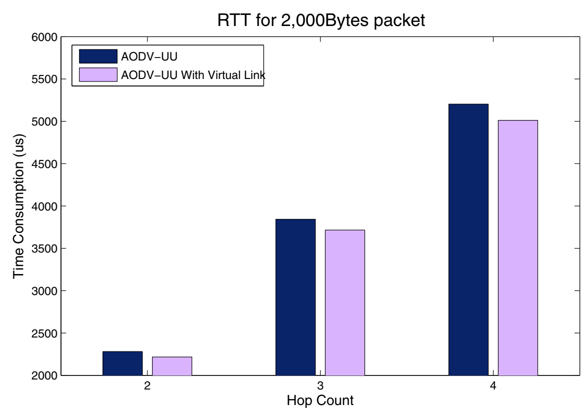

Fig. 8. RTT for 2,000 Bytes Packet

Figure 10 shows throughput difference between AODV-UU with legacy MAC and AODV-UU with the proposed MAC. In this experiment, an iperf server runs in source node. The throughput is measured from the iperf client side which runs in destination node. In this figure, X-axis presents hop counts, and Y-axis shows the throughput, which is measured at destination node. As shown in the Figure 10, the throughput improvement of the proposed approach over the legacy approach is around 7% with 2-hops case and around 10% with 4 hops setup thus clearly justifying the basis of our proposed methodology.

IV. Conclusion

A cross-layer MAC design based on the concept of virtual link is proposed in this paper for improving the routing

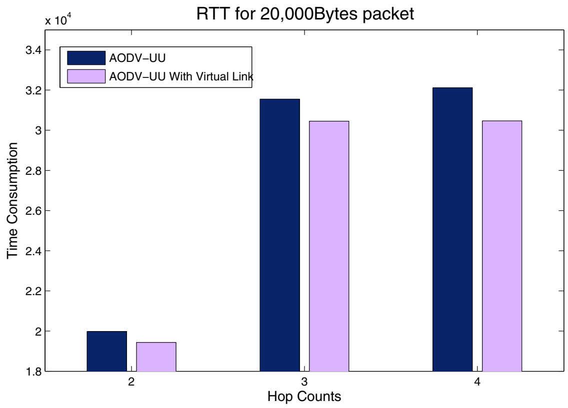

Fig. 9. RTT for 20,000 Bytes Packet

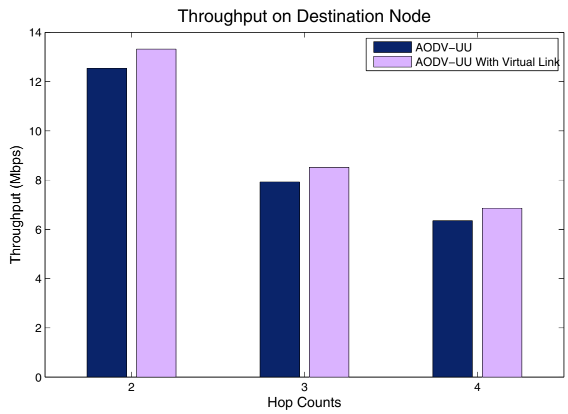

Fig. 10. Throughput under different hop count

efficiency in multi-hop wireless ad hoc networks. We introduce two new modules: *Inbound Monitor* and *Self-Learning* that help in enabling and maintaining the virtual links. To demonstrate the proposed method, we have implemented a wireless ad hoc testbed system and compared its performance with a traditional legacy routing technique. The tests performed in this testbed clearly demonstrate that cross-layer MAC design employing the proposed virtual link concept reduces the processing time at the intermediate nodes by approximate 50% while the throughput increases by 7–10% when compared with the legacy routing algorithm.

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