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On Separating Route Control and Data Flows in Multi-radio Multi-hop Ad Hoc Network

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Abstract

Ad hoc networks typically require a significant amount of routing and control information to be distributed in a timely and reliable manner throughout the network, particularly in dynamic environments. As traffic levels increase and the network becomes more heavily congested, there is an increased probability that these critical packets are lost, resulting in obsolete control information being used to make important decisions. This would further compound the problem of network congestion and lead to a very rapid loss of connectivity and throughput. Given this, we argue the solutions to these problems should not rely on putting extra bandwidth on a radio interface. Instead, we should exploit the use of multiple radios to ensure the route can be firmly established. In this paper, we propose a multiradio solution which reserves one radio channel exclusively for routing. Our simulation results have demonstrated that using a separate radio for routing protocol would dramatically improve reliability in heavily loaded ad hoc wireless networks, thereby effectively alleviating the impact of network congestion.

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On Separating Route Control and Data Flows in Multi-radio Multi-hop Ad Hoc Network

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***Abstract*—Ad hoc networks typically require a significant amount of routing and control information to be distributed in a timely and reliable manner throughout the network, particularly in dynamic environments. As traffic levels increase and the network becomes more heavily congested, there is an increased probability that these critical packets are lost, resulting in obsolete control information being used to make important decisions. This would further compound the problem of network congestion and lead to a very rapid loss of connectivity and throughput. Given this, we argue the solutions to these problems should *not* rely on putting extra bandwidth on a radio interface. Instead, we should exploit the use of multiple radios to ensure the route can be firmly established. In this paper, we propose a multi-radio solution which reserves one radio channel exclusively for routing. Our simulation results have demonstrated that using a separate radio for routing protocol would dramatically improve reliability in heavily loaded ad hoc wireless networks, thereby effectively alleviating the impact of network congestion.**

I. Introduction

A mobile ad hoc network (MANET) is a dynamic multi-hop wireless network established by a collection of mobile nodes on a shared wireless channel. Unlike the traditional wireless infrastructure, the ad hoc network features no centralized access point or pre-existing infrastructure. It is an emerging technology that can rapidly expand the wireless coverage through multi-hop transmission. However, such networks are decentralized and all network activities including route discovery and message delivery have to be done by the nodes themselves. Each node within the network is functioning as a self-contained router. Therefore, the routing protocol plays a vital part in interconnecting multiple mobile nodes together via multiple hops.

In the past decade, a significant amount of work has been performed by the ad hoc network research community to propose many different routing protocols for ad hoc networks, these routing protocols have evolved over the years with improved routing performance. However, the ad hoc networks still remain unscalable, and system suffers severe degradation and the performance drops drastically when the network traffic load increases. Hence, there will be little or no chance for the route control packet to be propagated through multiple hops. As a result, the node will lack up-to-date topology information, and gives incorrect indication on where the data packet should be forwarded to. The system becomes unstable, and data packets are most likely dropped due to destinations becoming unreachable even if actual physical connection existed.

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Recently, due to the significant reduction in the cost of commodity wireless hardware, it has become feasible to equip nodes with multiple wireless interfaces. Since then, the focus of wireless multi-hop network is gradually shifting from single radio to multiple radios. Providing multiple radios to each node offers a promising avenue. It could be used as one solution to alleviate the misbehavior of routing protocol due to high control collision - that is, to use separate radios for control and data transmission. This, in effect, would protect route control packets to collide with overwhelmingly large number of data packets and allow both transmissions to flow simultaneously in different space and time.

In this paper, we propose a multi-channel packet separation scheme, reffered to as *Separate Route Control* (or *SRC*). Under SRC scheme, each node manages two interfaces - one for data transmission and the other one for route control. Based on the concept of separating route control, we propose an *Abstract Packet Separation Layer* (*APSL*) which is a shim layer located in between network and link layers. APSL is used to identify route control and data packets and send them to the appropriate interface. It allows SRC to be integrated in the conventional wireless hardware with least amount of modifications.

Past works on separating control and data traffics have been emphasizing on dividing control and data portion of MAC protocol into separate channels [1]–[4]. However, these techniques require at least some form of hardware modifications. Conversely, our approach features minor modification within the system kernel, which makes it simple yet practical to implement. Here, we will demonstrate that the use of a separate radio for transmitting route control packets would bring substantial improvement in terms of data delivery on a congested network.

The rest of this paper is organized as follows: Section II covers the related work, and we provide an overview of proposed SRC scheme and APSL in Section III. In Section

VI, we present our simulation results, and finally this paper concludes in Section V.

II. Motivation & Related Work

The recent proliferation of wireless system has prompted the commoditization of RF transceivers whose prices have rapidly diminished in the past decade. As a result, it becomes a trend to consider the use of multiple inexpensive radios per node, and such tendency can be manifested by the recent development of multi-channel multi-radio ad hoc/mesh networks. For instance, Tropos Networks developed a dual-radio *MetroMesh^{TM}* architecture in which one radio provides service to the clients, while the other creates the mesh network for backhaul. Similarly, MeshDynamic provides a three-radio *Structured Mesh^{TM}* router that further uses two radios for up and down link backhaul functionality.

Moreover, Balh et. al. [5] have pinpointed that the future solutions to achieve robust wireless system should not rely on requiring major breakthrough in radio technology, but instead combining the existing radio technologies in a way that uses their strengths constructively. Thus, they proposed a multi-radio framework that employs multiple radios in an integrated manner to accomplish a common task. Within this integrated multi-radio framework, Bahl et. al. have identified three specific design guidelines of employing those radios: *Design for Choice*, *Design for Flexibility* and *Design for Separation*. Of these, we are particularly interested in the "Design for Separation" - a framework in which, the control and data traffic are assigned to different radios and operate in separate space and time.

Separating control and data traffic in different channels has been studied extensively in the multi-channel MAC. These schemes typically assume that the total bandwidth can be split into multiple sub-channels where one particular sub-channel is dedicated for control. Each node in the network equips with two more interfaces - one interface has to be assigned to a fixed control channel, while the other interfaces can be dynamically assigned to other data channels. Some of the multi-channel MAC protocols use the control channel to exchange control message for the purpose of negotiating a common channel to rendezvous with other nodes [1], [2]. There are also few proposals that feature the use of separate control channel for exchanging MAC control messages (eg. RTS, CTS, ACK) [3], [4]. These protocols in general reduce the collision rate of control messages and allow the transmission of next packet to be reserved ahead while the current packet is transmitting on data channel.

One problem with the aforementioned techniques is that some assume the total available bandwidth will be split for the control channel, which often require changes in the existing standards, making it difficult to implement. Thus, Tantra et. al. [6] explored the use of a separate low-rate control channel to improve the performance of a high rate-data channel in an infrastructure-based wireless network. Subsequently, Kyasanur et. al. followed this guideline and [7] proposed to assign the control channel in the lower frequency bands, and use the control channel for RTS-CTS exchange. Pathmasuntharam et. al. [8] proposed a Primary Channel Assignment based MAC (PCAM) which provide one dedicated interface for sending and receiving broadcast messages, however, large part of this work is concerned with the evaluation of MAC protocol rather than routing protocol.

Adya et. al. [9] proposed the Multi-radio Unification Protocol (MUP) that coordinates multiple IEEE 802.11 radios operating at different channels. MUP aggregates multiple physical MAC address as used by the wireless Network Interface Cards (NICs) together, and provides it with a single virtual MAC address. This effectively hides the complexity of multiple NICs and makes no modification to the upper layer of the network protocol stacks.

From the above discussion, it is clear that using a separate control channel has been widely used in MAC protocols. In contrast, such techniques have not been applied to routing protocol. The conventional multi-radio routing protocols [10], [11] often consider all channels as means of data transmission, thereby exploiting channel diversity and concurrent transmission of data. That is to say, to the best of our knowledge, none of these routing protocols uses a dedicate radio for exchanging route control, and the impact of contention on routing protocol due to high traffic volume is often omitted. Therefore, it is our objective to substantiate that the use of a dedicated radio for exchanging route control would significantly improve the performance of routing protocol. We demonstrate that our proposed technique would address contention issues and ensure routing protocol functioning well under high network load. As a result, reliability of the network could be improved without the need to introduce any sophisticated routing mechanism.

III. Design Overview

In this section, we provide an overview of our proposed SRC scheme. The use of SRC schemes for routing does not lend itself to conventional ad hoc routing protocols. Thus, we also propose Abstract Packet Separation Layer (APSL) to address this issue by hiding the complexity of multiple radios from the network layer.

A. Route Control Separation

In this paper, we propose SRC protocol that employs two radios where one radio is assigned to data transmission while the other radio is allocated for route control. The use of our proposed SRC scheme holds a threefold advantage. The first advantage is ***prioritization of route control messages***. Given that the routing protocol plays a vital role in interconnecting multiple nodes in an ad hoc environment, and each data transmission is dependent on the state of the routing table. Therefore, it is natural to consider the routing messages should take precedence over data transmission. However, due to the distributive nature of multi-hop network, the priority of route control messages can only be guaranteed within the node, and route control messages are still competing with data packets coming from neighboring nodes. Thus, by separating route control message, it will ensure control messages to be transmitted in less contention channel, thereby achieving some form of priority. Further, if higher priority given to the route control messages within single channel, it would cause the starvation of data packets as route control messages may need to be continuously exchanged between neighboring nodes.

The second advantage of SRC scheme is to provide mutual benefits for both data and route control packets through ***simultaneous control and data transmission***. As the routing protocol is operated independently, the route discovery and maintenance can be done while data channel is used by other nodes. As a result of parallelism, the route information could be more up-to-date, and the chance of data delivery could be greatly improved.

Interestingly, the operation of route control message which predominately uses broadcast for route discovery and maintenance is in fact imposing a serious "broadcast storm" problem [12] - a problem in which a message that has been broadcast across a network results in even more responses in the subsequent re-broadcast and each response results in still more responses in a snowball effect. This would adversely affect the data transmission as the control messages may dominate the channel. Hence, the use of SRC scheme could allow us to exploit the third advantage which is ***broadcast and unicast separation***. This would immediately keep route control messages from contending with data and further simplify the future development of MAC protocol whereby each traffic can be addressed separately, rather than provide one-for-all MAC for both broadcast and unicast traffics at same time.

On the other hand, using our SRC scheme may impose a problem given different transmission range of multiple radios: if the transmission range of route control channel is longer than data channel, data packet could be dropped since the next hop destination can not be reached by data interface, compromising the performance of data transmission. Thus, in order to ensure the destinations are reachable, the coverage of the route control interface *must* be smaller or equal to the coverage of data interface. This may be achieved through power control, or other suitable mechanism taking different propagation paths of the radios into account. For the purpose of this paper, we assume if the destination is reachable by the route control radio then it is reachable by the data radio and vice versa.

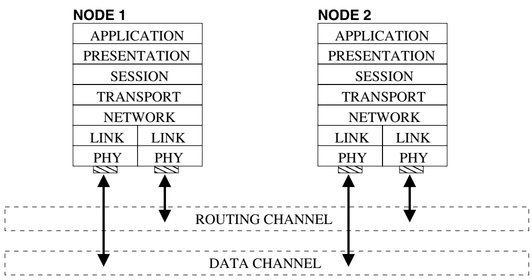

Fig. 1. Architecture of Separate Route Control

Figure 1 illustrates the layer structure of SRC. SRC is envisioned as the route control and data packets operating in different channels using different interfaces. Thus, the layers above the network layer remain the same, while two embedded interfaces provide two independent link and physical layers on each node. One of the interfaces will be dedicated to data transmission and the other one is used for exchanging route control. We assume CSMA/CA is used for access control in both link layers. Since the data and route control channels are spatially separated using different antennas, we assume each interface can be operated independently from each other with least amount of interference by two adjacent antennas.

B. Abstract Packet Separation Layer

Based on the concept of Multi-radio Unification Protocol [9] which has been addressed in Section II, we present the design of APSL - a shim layer that is designed specifically for SRC scheme. The design of APSL is illustrated in Fig. 2 which shows that APSL sits in between network and link layers. It acts as a virtual interface and produces an illusion for the network layer that it is connecting to one single NIC. The Address Resolution Function is built in APSL providing the address mapping for multiple interfaces. APSL also provides a uni-directional filter for the outgoing packets. The outgoing packets enter APSL, and will be redirected to the appropriate interface based on the packet type. On the other hand, when there is an incoming packet, APSL will become transparent allowing the packet to be forwarded directly from link layer to network layer.

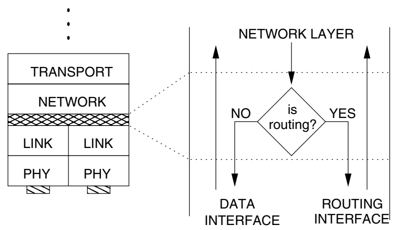

Fig. 2. Abstract Packet Separation Layer

The use of APSL will not only simplify the design of SRC, it also brings a few more advantages. Firstly, APSL does not require any hardware modification. It interoperates with all the legacy hardware, and allows heterogeneous interfaces to work in a cooperative manner. Further, since APSL is able to produce an illusion of the network layer connecting to one single interface, therefore, there is no need to make any change to existing application, transport, or routing protocols if SRC scheme is used.

IV. Simulation Results & Evaluation

In this section, we present our simulation results of the proposed SRC scheme with the comparison to the conventional single channel approach (indicated as SC hereafter). To evaluate the performance, both APSL and SRC have been implemented in the network simulation Qualnet 3.9.5 [13]. The simulation environment consists of 100 nodes uniformly distributed over a 1.5km x 1.5km terrain. In our simulation, we are evaluating the performance of protocols against several different types of network traffic. The network traffic is generated through the random selected pairs with constraint that each pair has to be 3 or more hops away, and each pair is transmitting 1024 bytes of data in a regular interval using Constant Bit Rate (CBR) over the simulation time of 300s. We examine CBR traffic with two different packets rates - 5 packets per second and 10 packets per second. The experiments initially start with 5 CBR flows and gradually increase the number of flows to 60 flows in step of 5 flows at a time.

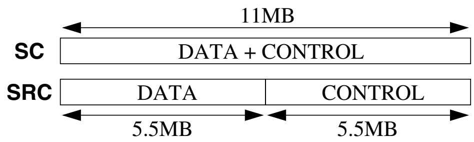

Fig. 3. Bandwidth Allocation for Simulation

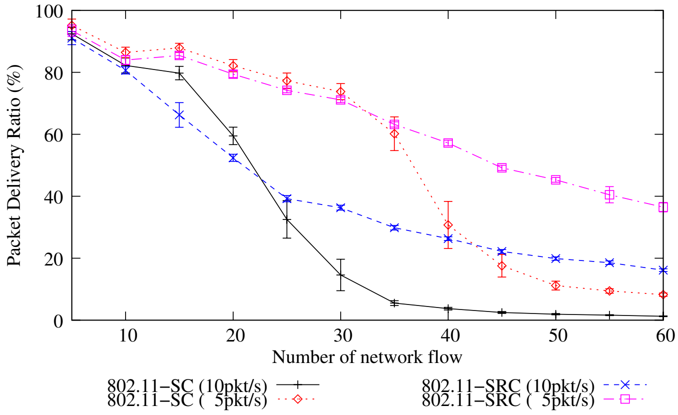

Fig. 4. Average Packet Delivery Ratio - Static Node

In order to provide a fair comparison between SC and SRC schemes, the nodes are configured as in Figure 3. In SC scenario, each node is equipped with one standard IEEE 802.11b compliant interface with the data-rate of 11Mbps for transmitting both data and route control. On the other hand, the nodes under SRC scheme are using two standard IEEE 802.11b compliant interfaces both running at data-rate of 5.5 Mbps for data and route control respectively. This would make the total bit-rate equivalent to 11Mbps, though SRC scheme is using less bit-rate for data transmission. Each interface is operated independently in different channel using Distributed Coordinate Function (DCF), and we assume both data and route control interfaces will not interfere with each other.

Throughout the simulation, the reactive routing protocol - Ad hoc On-Demand Distance Vector Routing (AODV) is used as the routing protocol, and two-ray pathloss is applied as the propagation model. The mobility model used in this experiment is the random waypoint with the minimum speed of 0 meter per second and maximum speed of 20 meters per second. We ran our simulation against several different sets of pause times, and compared their performance.

In order to collect accurate simulation results, our simulations follow Monte-Carlo Simulation approach [14]. The data presented in this paper is the estimation obtained by running at least 20 independent simulations with different random seeds. Finally, the results are calculated and plotted with 95% confidence interval.

A. Static Network

In the simulation studies, we first evaluate the performance of SRC using static topology. In this experiment, we characterize the performance of the SRC scheme by examining its packet delivery ratio, normalized control overhead, and the number of packet dropped due to route not found.

Figure 4 plots the packet delivery ratio (PDR), which indicates the percentage of successful packet delivery. As we can see from the figure, SRC scheme has performed slightly less than SC scheme when the amount of traffic is low. This is because the capacity of the network is still able to cope with the number of contenting flows. Interestingly, as the number of flows increases, the PDR of SC scheme drops drastically when it reaches a certain threshold (20 flows for 10 pkt/s and 35 flows for 5 pkt/s). The entire network became extremely unstable as both route control and data packets are contending for the channel. The route control packets cannot correctly specify the route to the destination, and neither the data packets can be delivered to the designated receiver. Consequently, the contention between route control and data packets results in only a few packets being able to propagate through multiple hops.

On the contrary, when SRC scheme is applied, it can stabilize the performance of SC scheme, and rate of PDR drop is presented in a steady manner. The introduction of SRC would immediately take route control packets away from the contentious channel, and allow routing protocol to function normal. From the figure, there is a substantial performance improvement when number of flows increases. SRC scheme starts to show its improvement when its SC counterpart reached the threshold. In the scenario with 60 flows and the packet rate of 5 packets per second, the PDR obtained in SRC scheme is almost 4 times higher than the one obtained by SC scheme despite the fact that the available bit-rate for data transmission is lower. Thus, using SRC scheme in general provides much better capability of handling large traffic than its single channel approach.

The normalized control overhead is depicted in Figure 5. This value is a ratio of the number of route control packets transmitted to the number of data packets delivered to the receiver. By examining Figure 5, it is clear that SC scheme is generating a large amount of route control packets once it has reached a certain amount of flows (eg. 20 and 35 flows for packet rate of 10 pkt/s and 5 pkt/s respectively). In the extreme case, SC scheme produces almost 200 times as much route control packets as SRC scheme produces in order to successfully transmit a data packet. The congested network causes the loss of the route control packets due to the collision, and forces routing protocol to generate more route control packets in order to find the route to destination. This exacerbates the

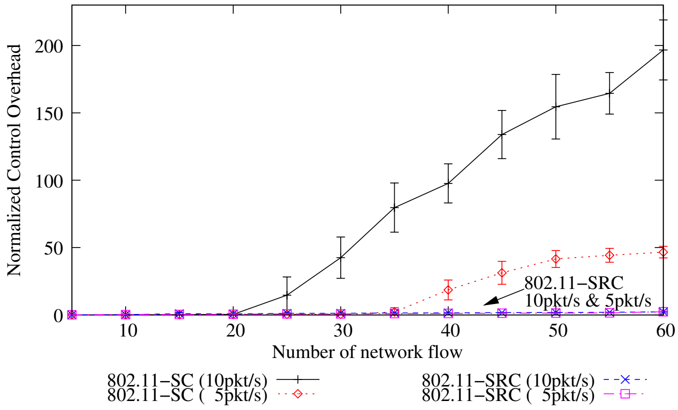

Fig. 5. Normalized Control/Data Ratio - Static Node

contention problem in the already congested network, and creates network instability. On the other hand, SRC scheme is able to keep the normalized control overhead low at all times. This would maximize the functionality of routing protocol by effectively reducing the number of redundant packets, leaving more capacity for topology maintenance.

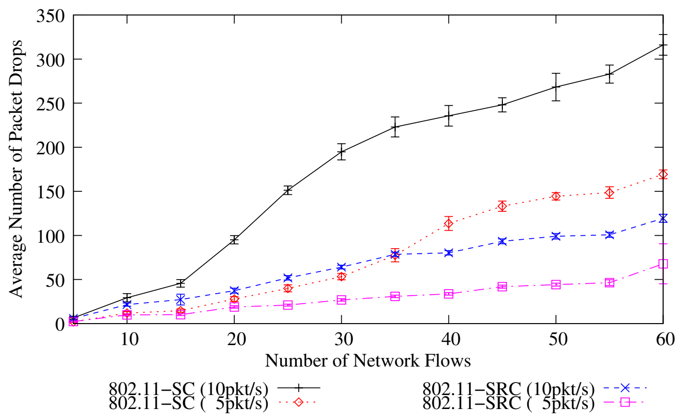

Fig. 6. Average Number of Packet Dropped - Static Nodes

The number of packets dropped is illustrated in Figure 6, this value specifies the average number of packets dropped while waiting for the route to be established. This would also indicate the success of route establishment and maintenance by the route control packets. It is clearly depicted in the figure that SRC scheme maintains lower number of packet drops in most of the scenario. There is around a threefold reduction in number of packet drops in highly loaded networks when SRC is applied. Thus, by examining both Figure 5 and 6, it can be seen that the routing protocol is being used more effectively when SRC is applied, since significantly less route control packets are generated to provide better route establishment and maintenance.

B. Mobile Network

In mobility experiment, we are evaluating the performance of our scheme in the highly contentious environment with several different random waypoint pause times. Based on the previous simulation, we are testing the network against 50 ongoing flows.

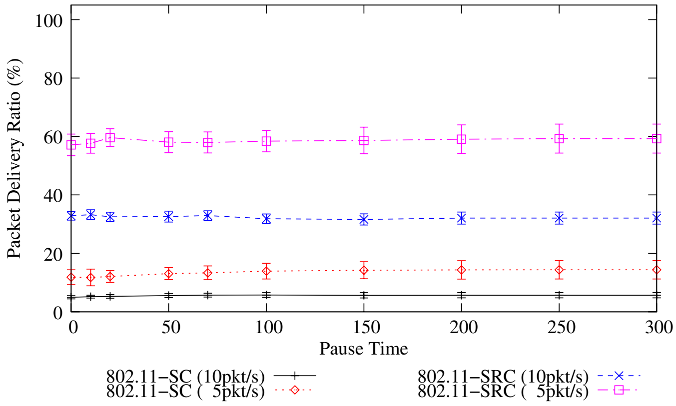

Fig. 7. Average Packet Delivery Ratio - Mobile Nodes

Figure 7 illustrates the packet delivery ratio of the network in various mobility patterns. It can be observed from Figure 7 that the overall packet delivery ratio has improved on SC scheme. This is partly due to the moderate level of mobility would force routing protocol to update its route when the node is out of range. This results in frequent route updates and providing some forms of route diversity, thereby alleviating network bottleneck as some traffic may be diverted to nearby nodes. Although mobility may provide some temporarily relief for congested network. However, our SRC scheme demonstrates at least 4 times higher packet delivery ratio than it SC counterpart. This observation would presents a clear evidence that applying SRC scheme would allow the network to be more adaptable in mobile environment, courtesy of a less contentious control channel.

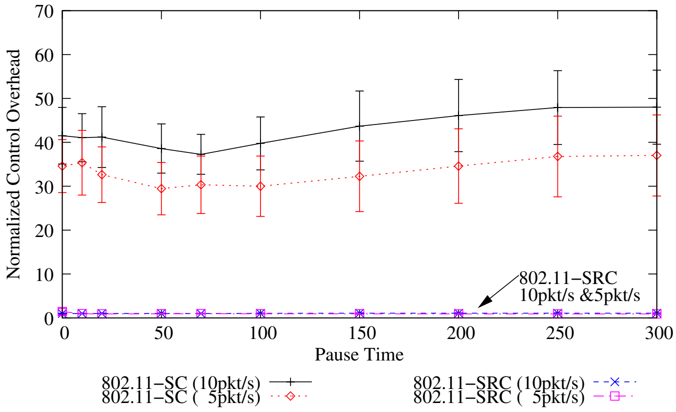

Fig. 8. Normalized Control/Data Ratio - Mobile Nodes

Figure 8 depicts the normalized control overhead in mobile scenario. Here, it can be seen that the SRC scheme is the direct beneficiary of less contentious control channel. It allows the routing protocol to generate fewer number of route control packets, while keeping the routing protocol away from misbehavior. On the contrary, although SC scheme has a significant drop in its normalized control overhead, it can not match the performance obtained when SRC scheme is applied. The moderate mobility indeed helps SC to keep routing protocol generating less control overhead, however, it is still not able to avoid the route instability.

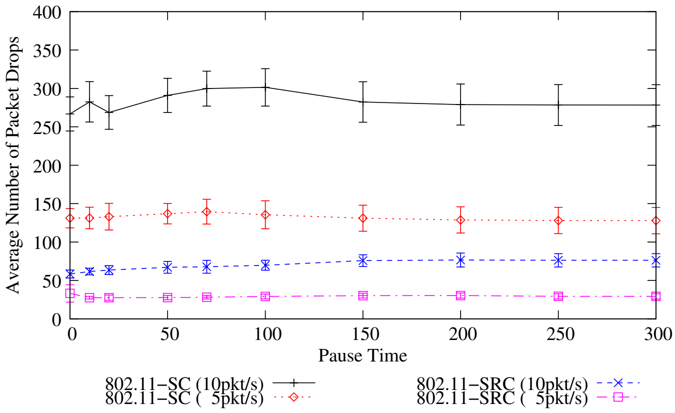

Fig. 9. Average Number of Packet Dropped - Mobile Nodes

Figure 9 examines the effectiveness of routing protocol by evaluating number of packet dropped due the routes not being found. When comparing to the results in the static model, it can be seen that SC scheme achieves less than 10% of reduction in the number of packet drops, while SRC scheme obtains more than 40% of reduction. Thus, this result would indicate the routing protocol is more effective with SRC scheme when mobility is applied, and it further strengthen the benefits of using SRC scheme.

V. Conclusion

In this paper, we have investigated the potential of route control and data separation utilizing a separate interface. By studying several MAC layer approaches on separating control and data into different channels, we argued that separating control and data could also be done on route control and data packets. We thus proposed the Separate Route Control (SRC) scheme, which enables the separation of route control packets and data packets in different radio channels. Based on the design of SRC scheme, we also proposed an Abstract Packet Separation Layer (APSL) which co-ordinates both route control and data interfaces, and allows packets to be forwarded to the designated interface.

Our simulation results demonstrate that there can be a significant boost in terms of packet delivery in a heavily loaded network by using this separation even when the total bit rate is the same. In general, our proposed SRC scheme is capable of improving the reliability of ad hoc networks by providing substantial performance boost to its single channel counterpart. Moreover, it stabilizes the performance of the routing protocol, and alleviates the misbehavior of routing protocol in heavily loaded network.

This study has identified the first insight of potential future research in employing additional interface for routing. By removing other external influential factors from the routing protocol such as contention with data packets, much of the work can be emphasized on improving the delivery of route control packets or the functionalities of routing protocol. For instance, a reliable broadcast mechanism could be implemented as most of the conventional routing protocols use broadcast for the route discovery. Furthermore, since two radios are being used, the condition of route control channel may not reflect on the condition of data channel. Consequently, multiple traffics would flow into the same intermediate node, thereby causing bottleneck. Thus, the co-ordination between control and data interface is also crucial. Future research could also focus on incorporating new features of routing protocols, such as topology control, alternative route reservation, and load balancing. As for our future work, we intend to follow these guidelines in the hope to further maximize the reliability of multi-hop networks.

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