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PARMA: A PHY/MAC Aware Routing Metric for Ad-Hoc Wireless Networks with Multi-Rate Radios

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PARMA: A PHY/MAC Aware Routing Metric for Ad-Hoc Wireless Networks with Multi-Rate Radios

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***Abstract*— Ad-hoc wireless networks with multi-rate radios (such as 802.11a, b, g) require a new class of MAC/PHY aware metrics that take into account factors such as physical-layer link speed and MAC-layer channel congestion. Conventional "layer 3" ad-hoc routing algorithms typically make routing decisions based on the minimum hop-count (MH). Use of the MH metric leads to selection of paths with few hops but one or more of these hops may turn out to be low-speed radio links due to adaptive rate selection at the physical layer. In this paper, we investigate a new cross-layer routing metric that takes into account both physical layer link speed as well as estimated channel congestion, thus aiming to minimize end-to-end delay that includes both transmission and access times. The proposed "PARMA" routing metric will thus help spread the traffic across the "good links and nodes" in the network, thus increasing network capacity and reducing packet loss and delay. This paper presents the design and implementation of the proposed PARMA metric for proactive ad-hoc routing protocols such as DSDV. DSDV modifications for incorporating the MAC/PHY aware metric into an *ns*-2 simulation model are given. Simulation results for typical multi-rate 802.11 ad-hoc network scenarios show that the proposed cross-layer PHY/MAC aware metric achieves significantly higher network throughput and decreases network congestion by selecting paths with high bit-rate links while also avoiding areas of MAC congestion.**

***Index Terms*— Wireless ad-hoc networks, routing, MAC, multi-hop, mutli-rate, cross-layer design.**

I. Introduction

Ad-hoc networks in which radio nodes communicate via multi-hop routing have long been considered for tactical military communications without wired infrastructure. More recently, ad hoc radio techniques have migrated to dual-use and commercial scenarios such as sensor networks, home computing and public wireless LAN. Wireless mesh networks are being deployed in cities to provide ubiquitous wireless coverage for the general population or in many instances, as a network for common use by the different first responder agencies such as the police, fire-fighters or emergency medical services.

Ad-hoc networks generally use short-range radios such as 802.11a, b, g [1], Bluetooth [2] or Zigbee [3] as the basic building block. Most of these radios are designed to adapt the physical layer (PHY) bit-rate as a function of channel quality, for example, the raw transmission speed of an 802.11a radio may vary from 6 Mbps to 54 Mbps depending on received signal strength (RSSI) measurements. Since the PHY bit-rate of each radio link varies with time and node location, it is important to design ad-hoc routing algorithms that take into account dynamic variations in link-speed to avoid selecting routes with potential transmission bottlenecks. The problem of designing routing algorithms to incorporate multi-rate PHY has been investigated in [4], which proposed Medium Time Metric (MTM) to find paths such that the total transmission time is minimized. And an algorithm which uses the expected transmission count metric (ETX) was proposed and shown to offer certain advantages over conventional routing approaches [5].

Most conventional ad-hoc routing protocols use minimum number of hops (MH) as the metric to make routing decisions. This is primarily a carry-over from routing metrics in wired networks where the transmission rate of a link does not dynamically change and the link rate is independent of the physical transmission range. However, in case of multi-hop wireless networks, the MH metric tends to choose paths with fewer hops. Since longer the transmission range, the lower the date rate possible in a wireless link, each of these hops will tend

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to have a longer physical span and hence will also be associated with lower physical layer bit-rates than an alternative path with more number of hops. In order to take advantage of the multi-rate capability and make better use of available network capacity, it is clear that transmission rate/time needs to be incorporated into the routing metric.

In addition to the transmission rate, we observe that it is also possible to provide an awareness of congestion at each node in order to avoid bottleneck regions with high link utilizations. It makes sense to devise metrics that account for both congestion and rate in a combined manner since both are a function of the medium access layer. For example, a link may provide for a high transmission rate, but could appear congested because neighboring links have a high link utilization. Thus, if we account for only the link rate, this link would show up as a "good" link but when combined with a congestion metric, it may turn out to be just the reverse, which is a more accurate reflection of the PHY/MAC layer. Thus, we attempt to study both these effects in this paper.

One way to account for MAC-layer congestion is to introduce a MAC layer congestion parameter into the routing metric, from which access delay at each hop can also be estimated. This parameter is special because the wireless link is usually shared with other links in the same neighborhood, while in a wired network, links operate independently of each other and channel access on one link has no effect on any of the adjacent links. Thus, whether a packet could access the channel immediately is determined not only by the states of two ends of the link, but also by the states of all neighboring nodes of the sender and the receiver.

Based on the above considerations, we are investigating a new integrated MAC/routing policy based on a routing metric related to both the PHY bit-rate and MAC congestion information. Taking DSDV [6] as the routing protocol baseline, we study the distance-vector routing behavior under a multi-rate PHY, and with a MAC-aware metric. The problem is studied in detail with an *ns*-2 simulation model [7]. Our studies provide an understanding of the routing metric in ad-hoc networks with multi-rate and the routing algorithm design when using a MAC-integrated routing metric.

The rest of this paper is organized as follows. In the next section we introduce the wireless multi-rate capability. In Section III we discuss the routing metrics, and propose a routing metric which integrates the MAC information such as the link bandwidth and the medium busy degree. Then we discuss the potential weakness of distance-vector routing algorithms when the integrated routing metric is used. We also present an enhancement to DSDV by which the routing protocol can settle down in a reasonably short time and achieve the best route. The simulation model and the performance results with both the integrated routing metric and the hop-count metric are presented in Section IV. The last section summarizes the main results and outlines our future work.

II. Multi-rate in MAC Layer

A. Overview

The widely used IEEE 802.11x standard uses adaptive selection of physical layer bit-rate as a function of observed channel quality. 802.11b radios can choose different physical rate (1, 2, 5.5, 11 Mbps) while 802.11a/g radios select between 6, 9, 12, 18, 24, 36, 48 or 54 Mbps as the physical channel rate. This automatic PHY bit-rate adaptation feature is considered to be useful in most systems because it permits end-users to take advantage of good-quality short-range links when available. When such multi-rate radios are used to build ad-hoc networks, the network topology and link speed changes more dynamically than in radio networks with a single mode radio with fixed bit rate and range.

Fig. 1 depicts the way in which an 802.11b radio device experiences different bit-rates when connecting to its neighbors at various distances.

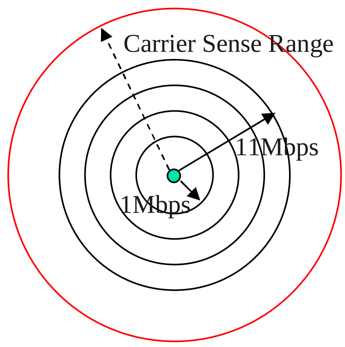

Fig. 1. Transmission Range of Multi-rate

As shown in Fig. 1, if a node wants to use rate 11 Mbps, only nodes in the inner-most circle can decode its frame correctly with sufficient SNR (Signal-to-Noise Ratio). However, if it chooses to use the lower 1 Mbps rate, the transmission range would be much larger. The outer-most circle is used to indicate threshold of carrier sense in 802.11 MAC. It means, if there is a node outside this circle, then the signal level of this radio's transmission heard by this node would not be large enough to let the node sense the channel as "busy". Note that in the above mentioned descriptions a simple path-loss model is assumed and the received signal strength is simply compared to a series of fixed thresholds. From the above, it may be inferred that networks may benefit from connections with multiple short-range, high-speed links relative to a single low-bit rate hop that spans a longer distance. A network example is shown in the 10-node chain topology of

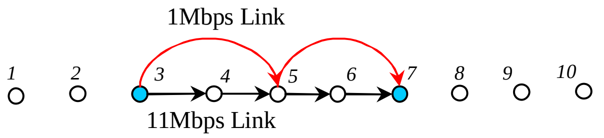

Fig. 2. Chain topology and different links

In the example, 10 stationary nodes are placed in a straight line. Assume each node can reach its immediate neighbor with a fast 11 Mbps link but can only reach the node next to the immediate neighbor with a 1 Mbps link. Therefore, from node 3 to node 7, node 3 can either choose route 3-4-5-6-7 with 11 Mbps data-rate used for each hop, or a 2-hop route 3-5-7 with 1 Mbps rate used for each hop. This diversity of route selection will not occur in single-rate networks. With the simulation in Section IV, it will be demonstrated that short high-speed links are actually better than long-range slow links under certain circumstances.

B. Auto Multi-rate Mechanism

With the capabilities to choose PHY rate from multiple values, it is still unclear how a device makes its decision on which rate to choose. The IEEE 802.11 standard does not specify this, leaving it as an implementation detail. Lucent [8] proposed an ARF (Auto Rate Fallback) scheme which simply steps up to a new rate whenever 10 consecutive transmissions succeed or no failure occurs during a time interval. Also, a node will step down to a lower rate if one or more ACK is missing. The problem with ARF is that the scheme only works when a sender communicates with one single receiver. Otherwise, the ARF fallback would make wrong judgments of rates to different receivers. Thus, ARF would only be useful in a scenario where a client station is associated with one AP and talks with it consistently. Another study [9] proposed RBAR (Receiver-Based Auto Rate) to solve this problem. Basically, a node first uses the lowest rate to send an RTS frame to a receiver. Based on a measurement of signal strength, the receiver chooses an appropriate rate for the sender and piggybacks this information to the sender with a CTS frame. Then the sender could send the DATA frame with the selected bit-rate. The RBAR scheme avoids the problem of ARF, but has the drawback of requiring an RTS/CTS exchange before every DATA transmission.

When constructing an ad-hoc network with muti-rate 802.11x or other similar radios, PHY adaptation can be applied on a packet-by-packet basis depending on the communicating neighbor. This can be implemented with a small table within the MAC layer for recording the selected PHY rate for each neighbor (based on SNR measurements of received packet). Then, the device driver can look up the table for the destination address of each outgoing frame and obtain a suitable rate for it. For the purpose of our research, we implement this simple SNR-based Autorate scheme in *ns*-2 [7].

C. Measuring and Estimating Channel Access Delay

The channel access delay is an important metric that correlates to the offered traffic at the MAC layer taking into account both the local traffic and that generated by neighboring nodes. In [10], the authors use measurements in 802.11 MAC to predict channel contention, but details of the prediction method have not been provided. Here we present an estimation method based on physical layer information. Because the wireless medium is shared, suppose a node is transmitting periodically, all its neighbors will have access to a smaller radio resource than the situation when no node is transmitting. To measure this effect, a "virtual access delay" estimation is introduced. One intuitive approach is to send periodic probes but this would introduce unnecessary overhead. Here we propose a passive estimation method to avoid the probe overhead. Every node records every channel event sensed from physical channel and makes an estimation of the "expected delay if a packet has to be sent". Suppose all nodes in a neighborhood which have a packet to access the common channel in a time instant are modeled as in an M/M/1 queue, with delay given by:

$$T_q = T_s \frac{\rho}{1-\rho}$$

ρ represents the utilization of server(channel). Each node can estimate ρ, by sensing the occupancy of channel. If it uses an average time cost for one channel event to represent service time T_s of a packet, it could calculate T_q, and give this estimation to routing protocol for use in the routing metric.

To evaluate the above channel access delay estimation method, we use a grid topology having 154 nodes with spacing of 350 meters between adjacent nodes. The carrier sense range is 1783 meters (slightly greater than 5 node distances), according to the propagation model used in *ns*-2 and using the parameters shown in Table I in Section IV. The topology is shown in Fig. 3. We have a 3-hop CBR flow running in the center of the grid. The data rate used for each hop is 11Mbps. The channel occupancy estimates when simulated with saturated load is shown in Fig. 4. Obviously, the congested area is much larger than the specific region through which the flows pass in this example. Nodes with highest occupancy levels actually lose the ability to support any flows further. This particular phenomenon shows that in wireless medium, routing metrics commonly used in wired networks cannot be applied directly to the wireless mesh network. Discreteness is necessary to select a "good" path with the consideration of load. Note that the maximum channel occupancy level shown in the figure is only around 77%. This will be explained later. With different offered load, we also plot the estimated access delay of one specific node (shown as the hollow node in the center of Fig. 3) in Fig. 5.

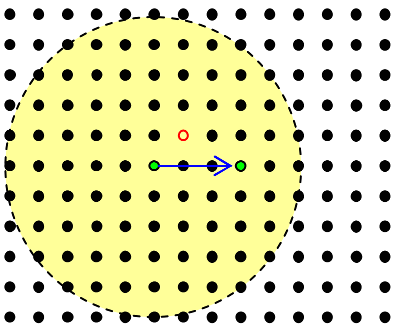

Fig. 3. A 14 by 11 grid

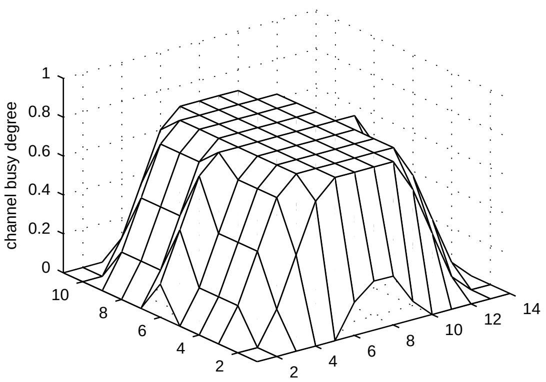

Fig. 4. Distribution of Channel Busy Degree

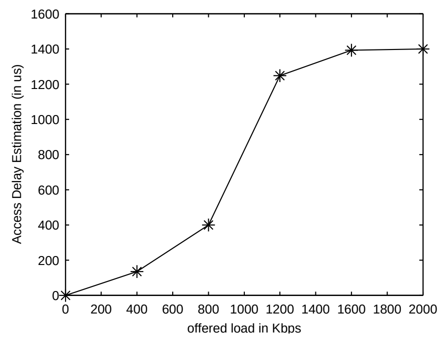

Fig. 5. Access delay estimation with varying load

Fig. 5 shows that the estimated delay increases monotonically when load is increased. However when the network is congested, the access delay estimation does not increase any further but holds at a steady level. This is because queuing effects cannot be monitored by PHY layer. Although those queuing delays will increase dramatically if the congestion is not eased, it cannot be estimated from channel access delay alone. We compared measurements of access delay with the corresponding estimates and found that the estimate is faithful. The only difference is that estimation of access delay is usually smaller than the actual measurements. There are some additional delays introduced by IEEE 802.11 MAC, such as SIFS, DIFS and backoff intervals. As those delays cannot be monitored, the delay estimation is expected to be an underestimate using the proposed simple method.

III. Route Selection

A. Routing Metric

Most ad-hoc routing protocols, including DSDV, AODV [14] and DSR [15], use the number of hops as the metric to make routing decisions. In wired networks, minimizing the number of hops can achieve both routing optimization goals: to minimize the mean packet delay, and to maximize the total network throughput. But in wireless networks, the minimum hop-count (MH) metric is most unlikely to achieve these two optimization goals. Previous work showed that in a wireless ad-hoc networks with different link qualities, the MH metric would choose routes with a small number of links with relatively long physical span and hence lower bit-rate and link quality in terms of packet error rate [11]. Even when the link quality is uniform, the MH metric is not suitable for wireless ad-hoc networks with different link bandwidths. Because it tends to choose paths with long range links which have low effective throughput [12].

This motivates investigation of routing metrics which take into account the physical layer bit-rate on each link, as mentioned earlier.

We propose a routing metric which aims to optimize the average packet end-to-end delay. The end-to-end delay of a data packet of size $Packet\_Size$ transversing a path p_i is calculated as follows.

$$Delay\ _{p_i} = \sum_{\forall links \in p_i} (T_{transmit} + T_{access} + T_{queuing}) \quad (1)$$

where $T_{transmit}$ denotes the packet transmission time in the link, T_{access} the medium access time spent by the packet getting access to this link, and $T_{queuing}$ the queuing time required for the packet waiting before trying to access the channel.

The packet transmission time can be calculated as:

$$T_{transmit} = N_{transmit} \times \frac{Packet\_Size}{Speed} \quad (2)$$

where $Speed$ is the link speed, which would be one of the data rates the multi-rate devices provide. And $N_{transmit}$ is the number of transmissions, including retransmissions, needed for the packet to be received correctly. When the link quality is poor, packet retransmissions might be carried out by the MAC protocol. $N_{transmit}$ reflects the link quality which can be predicted by measuring the delivery ratios of the probe messages sent periodically in each link. In this paper, we focus on networks with uniform link quality. Under this assumption, the Eq.(2) is simplified as [1]:

$$T_{transmit} = \frac{Packet\_Size}{Speed} \quad (3)$$

The medium access time, T_{access}, is used to indicate the medium busy level around the sending node of the link. When the medium is busy, it takes a relatively long time for a packet to get the chance to transmit. Incorporating the medium access time to the routing metric, the routing algorithm can choose a route with light traffic load in addition to the high speed links, spread the traffic over all the links to achieve load balance, increase the effective bandwidth and further avoid congestion. Note that when estimating the medium access time in the MAC layer, a smoothing window is used to get the average value over a time duration. This window is used with a technique which will be described latter to smooth the link layer changes and make the routing metric not change so rapidly.

[1]There may be multiple transmissions to get a packet across. Since it is a metric, it is an approximation of the actual time that may be needed for a transmission.

In addition, a large access delay also reflects a growing interface queue length when the network is congested. When we consider the system below saturation, the queuing delay, $T_{queuing}$, can be omitted.

With the above assumptions and simplifications, the routing metric calculation can be summarized as Eq.(4).

$$Delay\ _{p_i} = \sum_{\forall links \in p_i} \left(\frac{Packet\_Size}{Speed} + T_{access} \right) \quad (4)$$

It is clear that this routing metric is both PHY rate-aware and MAC traffic-aware as discussed in the introduction. In the following, we study this kind of routing metric, in conjunction with the class of distance-vector routing algorithms, taking DSDV as a specific example. Our study also reveals potential problems in the cross-layer design of ad-hoc wireless networks.

B. Implementations

Our rationale for choosing DSDV as the routing protocol to study our PHY/MAC-aware delay-based metric is as follows. The periodic routing updates in DV protocols can exchange the PHY/MAC information via the metric, so that the dynamic network condition can be known by all the nodes in the network. Thus nodes can switch their routes if there are better routes to the same destination available before the current routes are broken. With on-demand routing protocols, routes continue to be used until they are broken. So in order to make the on-demand routing protocols work with other metrics than the MH metric, extra control messages have to be added in order to initiate route discovery procedures before routes are broken, which would increase the routing overhead. Another reason for using DSDV is that the periodic advertisements provide a way to adjust the data rate according to the received SNR. We can also measure the MAC channel occupancy through transmission of existing control messages in DSDV. [5] uses probe messages to measure the link quality which introduces extra overhead to the routing protocol. With our implementations, extra overhead to the routing protocol is minimized.

1) DSDV Operations: DSDV uses a sequence number which is originated by the destination to indicate the freshness of the routing information and prevent routing loops. In addition to the sequence number, another important technique in DSDV is the use of the weighted average settling time. Since the routing information broadcasts are asynchronous, some fluctuation of routing updates could occur. To solve this problem, and also reduce the number of rebroadcasts, advertisement of routes is delayed until the route has stabilized. In particular, each entry in the routing table is associated with the average settling time, which is the length of time between the arrivals of the first and the best route to a particular destination with the same sequence number. The route is advertised after twice the average settling time has passed since the first route is received.

With these two techniques implemented, the best routes are easy to achieve when the MH metric is used. But problems arise when the best route is not the shortest one. This is because, in DSDV, the time for a route from the destination to reach the other end depends on the settling time at each intermediate node in the path. The more the number of hops transversed, the greater the total settling time required. If the best route is not the shortest one, it is likely to arrive late, and even worse, it may arrive later than some routes with a new sequence number. Without the correct settling time, it is difficult to get the best routes and use them to forward packets.

2) Enhancement: As discussed in Section III-B.1, DSDV uses the delay-advertisement approach. Another approach, called the delay-use, is proposed in [5]. In the delay-use approach, two routing tables are used at each node. A route is not used until it is allowed to be advertised. Before the route can be used and advertised, if there is a route to the same destination with the new sequence number arrived, the old route is moved to the second table and the new route is stored in the current table. We use this modification in our implementation. However, the correct settling time for each entry of the routing tables is critical for both the delay-advertisement and the delay-use approaches.

We propose an approach to quickly adjust and achieve the correct settling time. Our approach is to handle the received routes with the last old sequence number instead of ignoring them as the current protocol does. This avoids missing the best route when it arrives latter than the first route of the next new sequence number. In particular, a route with the last old sequence number is chosen if it has a better metric than the one stored in the second table (note that these two routes have the same sequence number). Meanwhile, the average settling time of the route to the same destination in the current table is updated accordingly. With this enhancement, the settling time can be converged quickly and the best routes can be guaranteed before twice the settling time has passed. Our simulations show that without this enhancement, only one third of the routes used are the best routes; while 99% of the routes are the best with this enhancement.

We note that DSDV with two routing tables works well in small and medium networks. When the network becomes large and the variations of the route arrival times increase, the overlapping between the routes to the same destination but with the different sequence numbers will increase. More routing tables are required to store the routing states and prevent missing the best routes. In this sense, DSDV suffers from a scalability limitation when used with the PHY/MAC aware metric.

3) Smoothing Link Layer Changes: Because of the contention access nature of 802.11 MAC, the medium access delay is a random variable. We found that the medium access time obtained from the MAC layer cannot directly be used in the routing metric due to convergence problems. In order to solve this problem, in addition to the smoothing window described earlier, a non-linear mapping between the access delay from MAC to the T_{access} in the routing metric calculation Eq. 4 is used in our implementations. A time threshold τ is defined according to the network conditions. If the access delay is less than τ, it is used directly for T_{access}; if the access delay is greater than τ, it is enlarged (e.g., ten times of its value) and then used for T_{access}. In addition, only significant changes, such as a delay having 20% increase, can trigger routing updates; non-significant changes are advertised by periodic updates. With this design, the triggered updates are reduced while the significant link changes can be advertised over the network.

Moreover, due to the different time scales of the network layer and the PHY/MAC layer variations, we must be careful not to degrade the network routing protocol when incorporating the PHY/MAC aware routing metric. This is a trade-off: if the routing advertisements are too frequent, the routing overhead is large; if the routing advertisements are too slow, the route exchanges can not trace the link changes which would degrade the routing performance. An on-demand mode might be helpful to reflect the link condition in time. As stated in [13], a cautious approach is required for this type of cross layer design in order to balance factors such as settling time, overhead and routing performance.

IV. Simulation Results

The system performance with the proposed PARMA metric is compared with the MH and MTM metrics using the *ns*-2 network simulator [7]. We use two ad hoc network scenarios: line and grid networks. We present simulation results after describing each scenario.

A. Simulation Parameters

In our simulations with DSDV, the time period between the periodic updates is 15 seconds, the minimum time between the triggered updates is 1 second. An update must be heard from a neighbor in 45 seconds, otherwise the neighbor is regarded as unreachable.

Our simulation study considers constant bit rate (CBR) as the traffic generation model [7]. Packets have a constant size and are sent at a deterministic rate. We choose the packet size of 512 bytes, and vary the sending rate as an input parameter in order to gradually increase the offered load to the network as a whole.

Multi-rate 802.11b is used with four rates: 1, 2, 5.5 and 11 Mbps. The transmission power is fixed at 15 dbm. The carrier sense threshold is -108 dbm. RTS/CTS is disabled. ACKs are transmitted using the basic rate of 1 Mbps. The receiver thresholds and the corresponding effective distances are shown in Table I.

TABLE I

RATE, RECEIVING THRESHOLD, AND EFFECTIVE DISTANCE

	Receiver threshold	Distance
Carrier sense	-108 dbm	1783 m
1 Mbps rate	-94 dbm	796 m
2 Mbps rate	-91 dbm	669 m
5.5 Mbps rate	-87 dbm	532 m
11 Mbps rate	-82 dbm	399 m

Three important performance metrics are evaluated:

- System throughput: measured as the total number of useful data received at traffic destinations (in bps).
- Packet delivery ratio: measured as a ratio of the number of data packets delivered to their eventual destinations and the number of data packets generated by sources.
- Average end-to-end delay: total time elapsed between generation of a packet at source and its receipt at the destination.

B. Scenario I

First we try a simple topology with 10 stationary nodes placed in a straight line with a distance of 350 meters between the neighboring nodes, as shown in Fig. 2. In this linear scenario, a short link with distance of 350 meters can provide 11 Mbps data rate, while a longer link with distance of 700 meters only gives 1 Mbps. There is one flow, originated from one node to the destination which is 1400 meters away. As observed, the hop-count metric tends to choose the shortest path with two 1 Mbps links, and the PARMA metric chooses the route with four 11 Mbps links. The simulation results are shown in Fig 6, 7 and 8.

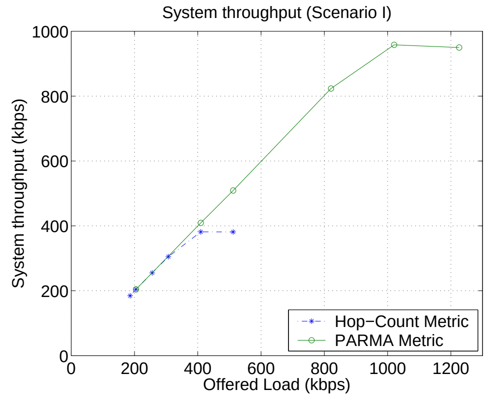

Fig. 6. Throughput v.s. Offered load

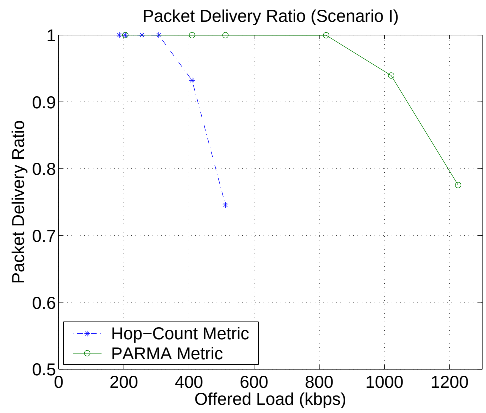

Fig. 7. Packet delievery ratio v.s. Offered load

The results show that in the simple line topology, system performance improves with the PARMA metric. In this scenario, there is a significant factor of 2.5x improvement in system throughput. Also, the packet delivery ratio and the average end-to-end delay are also improved. The end-to-end delay is reduced even when the system begins to saturate. Note that since there is only a single straight line in this scenario, the PARMA metric has the same behavior as the MTM metric.

C. Scenario II

A 6 by 7 regular grid topology is used as the second evaluation scenario. The distances between neighboring nodes in both the horizontal and the vertical directions are 350 meters. There are three possible data rates in the topology: 1, 5.5 and 11 Mbps. All nodes are stationary.

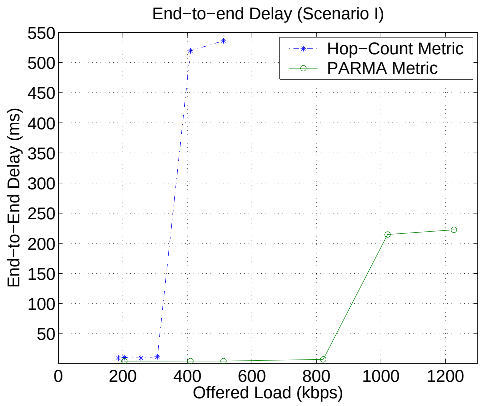

Fig. 8. End-to-end delay v.s. Offered load

There are two traffic flows in the network: flow 1 and flow 2. As shown in Fig. 9, flow 1 is from node 2 to node 3, and flow 2 is from node 30 to node 35.

We choose flow 1 to start transmitting packets earlier than flow 2. The traffic generation rate of flow 1 is fixed to be around 3 Mbps, and the traffic generation rate of flow 2 is varied as the input parameter to gradually increase the offered load to the network. As shown in Fig. 9, node 2 and node 32 are in the carrier sense range of each other, so there is interference between these two flows if flow 2 takes a route including the line from node 32 to 33. Then flow 1 and flow 2 will compete for the medium when both have started. If flow 1 is close to being saturated with a congested area around it, an ideal routing protocol will guide flow 2 to go around this congested area and achieve load balancing that prevents the whole system from becoming congested.

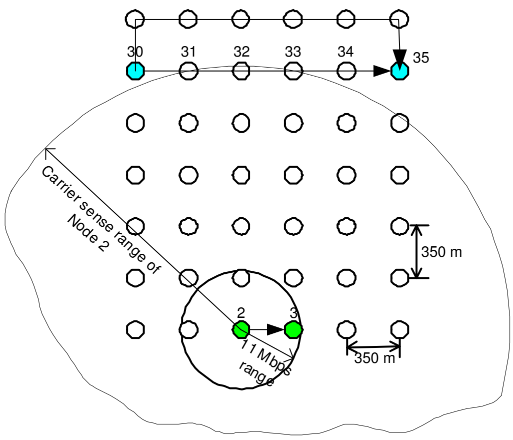

Fig. 9. Grid topology and flows

Simulations are run for three different routing metrics: the MH metric, the MTM metric, and the PARMA metric. We study how the system handles the interfered flows and avoid the congested area when using different routing metrics. Fig. 10, 11 and 12 show how the total throughput changes with time. In each run, flow 1 starts at 50 sec and flow 2 starts at 150 sec after the simulation starts. Fig. 10 and 11 implies that broken link exist due to interference which results in packet drops. Fig. 12 shows that there are metric changes when flow 2 starts transmitting packets. After some period of settling, a new route which avoids the interference from flow 1 has been used (an alternative route is shown in Fig. 9 which avoids the congestion area) and thereafter the system throughput starts to go up. Fig. 12 can also reflect the efficacy of our algorithm.

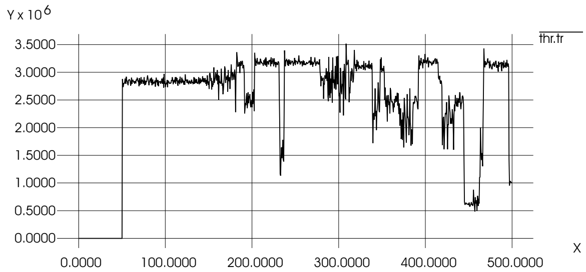

Fig. 10. Total system throughput v.s. Time (MH)

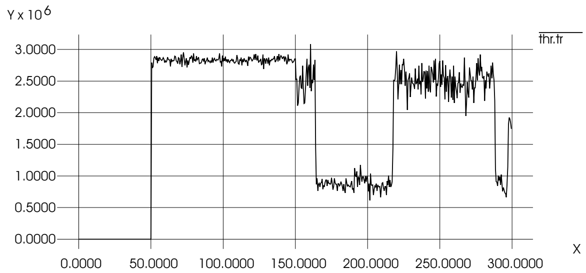

Fig. 11. Total system throughput v.s. Time (MTM)

Fig. 13 gives the throughput achieved using different routing metrics. The x-axis indicates the offered load of flow 2. The offered load of flow 1 keeps constant of about 3 Mbps, and the reason for this value is to keep the medium around flow 1 busy enough such that the congestion can occur when flow 2 is added.

We can observe that using the MTM metric, system throughput drops when the offered load is increased to 550 kbps. The system throughput also drops for the MH metric. However, the throughput curve of the PARMA metric keeps increasing slowly, and is expected

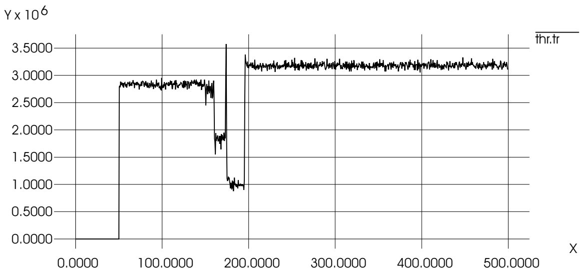

Fig. 12. Total system throughput v.s. Time (PARMA)

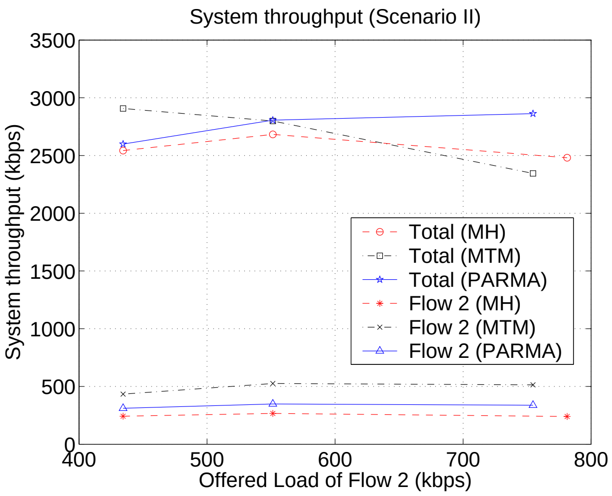

Fig. 13. System throughput v.s. Offered load

to increase until the system becomes excessively congested. The MH and MTM metrics will always choose horizontal paths from node 30 to 35 for flow 2. If there is no interference, the PARMA metric will also choose horizontal paths for flow 2. But since there is interference between flow 2, if it takes these horizontal paths, and flow 1, the PARMA metric will guide flow 2 to avoid the congested area, using the routes with more hops or low rate links. The curves also show that the throughput of flow 2 using the PARMA metric is lower than using the MTM metric, since low data links are used in the PARMA metric.

V. Conclusions and Future Work

We have studied a specific PHY/MAC aware routing metric working with distance vector routing protocols taking DSDV as an example. In order to make DSDV work well with the PHY/MAC aware routing metric, we propose an enhancement to the routing protocol. In addition, a smoothing technique is introduced for the link portion of the proposed metric in order to help routes converge. Our simulation results show that routing metrics which only consider the number of hops can not achieve high throughput in multi-rate networks. Using a metric based on the medium transmission time as proposed recently [4] as the routing metric would have the effect of guiding traffic to high speed links but this could cause MAC layer congestion in some area. With both the data rate and the MAC occupancy level being taken into account in the routing metric, packets can choose the high rate links and also avoid congested areas in the network.

We have observed that with the distance-vector routing protocol, there is fluctuation in routing information since the routing metric we are using is not discrete like the hop-count. Therefore, smoothing is required in order to adjust the different change variations between the MAC layer and the network layer. This paper presents preliminary results on PHY/MAC aware routing as part of a cross-layer design for ad-hoc networks. Further work is planned on investigating trade-offs between settling time, routing overhead and network performance over the range of possible methods and parameters. We believe that our results show promising improvements with cross-layer routing metrics (such as PARMA proposed here) but that careful design is needed to avoid unintended effects.

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