A Simple and Effective Cross Layer Networking System for Mobile Ad Hoc Networks

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Abstract — **We propose a novel cross layer design concept that could improve the network throughput significantly for mobile ad hoc networks. The channel reservation control packets employed at the MAC layer can be utilized at the physical layer in exchanging timely channel estimation information to enable an adaptive selection of a spectrally efficient transmission rate. In particular, the size of a digital constellation can be varied dynamically based on the channel condition estimated at the receiver which can be relayed to the transmitter via the control packets. In addition, this channel adaptive information gathered at the MAC layer can be communicated to the routing layer via different routing metrics for optimal route selection. We have examined the performance improvement at the network layer due to cross layer communications. For this, we present a simple cross layer design implemented with minor modifications on the IEEE 802.11 standard and the dynamic source routing (DSR) protocol. We demonstrate that the network throughput is significantly increased, as much as 50% to 100%, in low mobility scenarios simulated using *ns-2*.**

I. Introduction

An ad hoc network consists of mobile nodes which communicate with each other through multi-hop routes. To date, numerous routing protocols [10] have been proposed. Many of them well address the problem of establishing and maintaining the routes in a dynamically changing network topology. However, most routing protocols are designed with less emphasis on the issues at the lower layers. These include the variable link capacity at the physical layer and the fluctuating contention level at the MAC layer. In this paper, we attempt to bridge this gap by introducing a cross layer design concept. By exploiting the lower layer channel information, such as the variable link capacity through spectrally efficient rate adaptation and contention level estimation at the MAC layer, we will show that significant performance enhancement in both the network throughput and delay are achievable. Thus, we take an ”active” approach in designing an ad hoc networking protocol with more realistic and detailed wireless channel model. It is worthwhile to mention that in this paper we are taking a channel-adaptive approach–rather than a quality-of-service driven approach–of cross layer networking such that the channel-adaptive information is flowing from the lower layer to the higher one, with the objective of maximizing the network throughput; the resource allocation message and decisions made at the higher layer with a more global view of the network are flowing downward.

Adaptive modulation transmission techniques [3] were first proposed for cellular mobile systems as a means to increase the spectral efficiency in a point to point link. When the channel estimate is available at the transmitter, a transmission scheme can be adaptively selected in accordance with the learned channel parameters. It is shown in [3] that spectral efficiency is optimized by joint rate and power adaptation when the channel side information is used at the transmitter. Practical rate and power adaptation modulation techniques [2] have also been investigated and shown to achieve near optimal spectral efficiency.

Rate adaptation techniques has also been applied to mobile ad hoc networks. The *request to send* (RTS) packet and the *clear to send* (CTS) packet defined in the IEEE 802.11 standard could be exploited to perform channel estimation and to feed receiver's estimate of the channel back to the transmitter. In [9], a rate adaptation mechanism is introduced for frequency hopping systems. Transmission rate is adjusted based on the number of erasures and errors in the received packets. In [5], a rate adaptive MAC algorithm, similar to ours but developed independently, is proposed. Explicit channel parameter estimation is mandatory in most advanced transceiver systems for robust and spectrum efficient performance [8]. With a simple cross layer communications between the MAC and Physical layers, we could achieve a large performance improvement without incurring any significant overhead.

The following is the list of contributions in this work. First, we develop and use a more realistic, correlated shadowing channel for the simulation of ad hoc networks. In particular, the shadowing coefficient is dependent on the relative displacements of nodes, from their previous reference positions, instead of selecting a value in a purely uncorrelated fashion at each time a packet is being transmitted. It is worthy to note that without this correlation model, it would not make much sense to design a cross layer networking system being adaptive to the channel. Second, a spectrally efficient rate adaptation scheme for ad hoc networks is proposed based on the RTS/CTS access mechanism of the IEEE 802.11 standard. Third, with the choices of a few routing metrics that we propose as a means to convey the lower layer information to the routing layer, we are able to show that a very simple cross layer system being considered in this paper can indeed bring a significant performance improvement at the network level.

We now illustrate the cross layer concept in the flow diagram depicted in Figure 1. At the physical layer, channel estimation is performed to obtain the instantaneous SNR_i of a link. A transmitter then chooses a transmission rate R_i based on the estimated SNR_i. This in turn affects the packet delay D_i of the link. At the network layer, routing decisions are made based on the packet delay associated with each link. The routing decisions in turn affect the offered load distribution in the network and impact the parameters D_i, R_i and SNR_i on individual links. Thus the communication of various layers are inter-related.

The rest of the paper is organized as follows. In section II, we give the system model. We describe the joint rate and routing algorithm section III. The simulation setup is given at section IV, and extensive simulation results are presented in section V. Finally, we give our concluding remarks in section VI.

II. System Model

We consider an ad hoc network with n nodes uniformly distributed in an area. Nodes move according to the random waypoint model. Each node begins the simulation by remaining stationary for a fixed duration of *pause_time*. It then selects a random destination at a random speed distributed uniformly between 0 and *max_speed*. Upon reaching the destination, the node

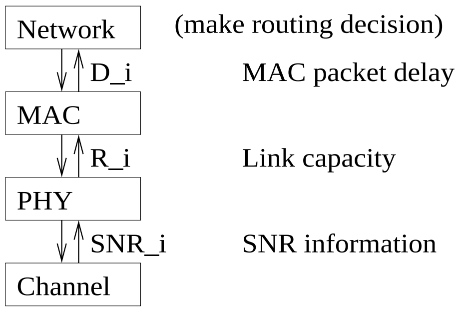

Fig. 1. Illustration of cross layer communications in the network stack. Physical layer parameters affect the parameters in the MAC and the network layer. The decisions made at the network layer in turn impacts the parameters in the underlying layers.

repeats the cycle by pausing for *pause_time*, selects another destination and moves with the same random speed.

In our channel model, we consider three signal strength attenuation factors, namely, path loss, shadowing and multipath fading. The modeling of the random process representing the signal attenuation, is critical in this research since the performance of a rate adaptive scheme is sensitive to the delay incurring in the feedback of the channel estimates.

Multipath fading process could be readily simulated using the Jakes model [6]. In particular, the technique is based on the summation of a finite number of sinusoids which produce the bandlimited Rayleigh fading process. The maximum Doppler shift frequency f_{dm} of this process is determined by,

$$f_{dm} = f_c v / c, \tag{1}$$

where f_c is the carrier frequency, v is the relative speed between the transmitter and the receiver, and c is the speed of light. This model captures the time correlation structure of multipath fading process and is being widely used.

On the other hand, the shadowing attenuation process which typically exhibits strong spatial correlation is generally not well represented in the literature of ad hoc networking; thus we propose the following approach.

In [4], Gudmundson proposes an exponential spatial correlation model to represent the attenuation factor A (in dB) due to shadowing. For two points separated by a distance d, the correlation between the shadowing factors A_1 and A_2 is represented by

$$E[A_1 A_2] = \sigma^2 \exp(-d/D_0), \tag{2}$$

where D_0 is the correlation distance, and σ is the standard deviation of the process. Gudmundson's model assumes that two nodes are connected to the same point, say a base station, and thus it is proposed for the cellular networks. In ad hoc networks, both the transmitting and receiving nodes could be in motion. Thus, we extend the exponential correlation model in the following way.

Figure 2 illustrates how we generate new shadowing value in determining the SNR of a link between any two nodes. When a node i receives a packet from a node j, the current positions of both nodes are compared with their respective reference positions. We assume the shadowing attenuation of a link is constant unless one of the nodes moves out of a disc of radius δ drawn from their respective reference positions. With reference to Figure 2, the nodes in black denote the reference positions of node i and j respectively. When node i moves out of the disc, the new attenuation is computed by modelling the correlation as a Gauss-Markov process,

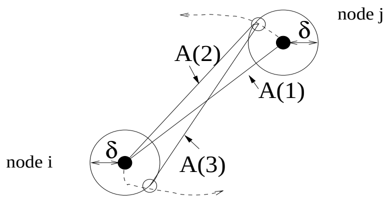

Fig. 2. Illustration of the correlated shadowing model for mobile ad hoc networks.

$$A(n+1) = \rho_i A(n) + \sqrt{1-\rho_i^2} W, \tag{3}$$

where W is a zero mean Gaussian random variable with variance σ^2, the correlation coefficient $\rho_i = \exp(-\delta/D_0)$ and δ is the reference range. The new position is then taken as the reference position for node i.

Similarly, when node j moves out of the disc, the new shadowing attenuation is computed as

$$A(n+1) = \rho_j A(n) + \sqrt{1-\rho_j^2} W. \tag{4}$$

In the case when both i and j move out of their respective discs, we assume

$$A(n+1) = \rho_{ij} A(n) + \sqrt{1-\rho_{ij}^2} W \tag{5}$$

where the correlation coefficient is $\rho_{ij} = \exp(-2\delta/D_0)$. Thus, in our simulation the attenuation value of a link due to shadowing generally will not change in a packet-by-packet manner.

The fast fading process–Rayleigh fading, on the other hand, changes in a packet-by-packet manner. The degree of time-correlation of the fast fading process is determined by the maximum Doppler rate f_{dm} which is proportional to the relative speed v of the transmitting and receiving nodes. Thus, the maximum fading rate is one of the most critical factors which will greatly impact the performance of our design. After all, when the relative speed exceeds a certain threshold, it would be better off not to adapt to the fast fading channel, but to stay with a nominal rate. For this, we examine a few relative speed values, i.e., $v = 1.0$, 5.0, and 10.0 [m/s]. At these speeds, the maximum Doppler rates f_{dm} are given by Eq. (1) as 3.33, 16.7, and 33.3 [Hz] respectively, assuming $f_c = 1$ GHz. In addition, with the use of 500-byte packets, the duration of a packet transmission time–denoted as T_p–is 4.0 msec on a 1.0 Mbps link. A normalized maximum Doppler rate, $f_{dm}T_p$, will give us an idea how the two Rayleigh fading attenuations separated by a packet transmission time T_p are correlated from one another. For the example given above, we have $f_{dm}T_p$ = 0.013, 0.067, and 0.133 respectively. The correlation values at the three fading rates can be obtained from the autocorrelation function of the Rayleigh fading process[1], and they are 0.998, 0.957, and 0.832 respectively. From this example, it should be noted that the rate-adaptive system on the Rayleigh fading process up to a pedestrian speed is very reasonable.

[1] The correlation value can be obtained by substituting the normalized fading rate $f_{dm}T_p$ into the argument of the autocorrelation function of the Rayleigh fading process, which is given by $J(2\pi f_{dm} \triangle t)$, the zeroth order Bessel function of the first kind. [6]

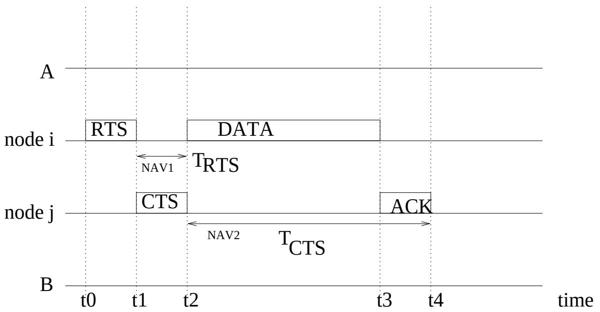

Fig. 3. Illustration of the 802.11 RTS/CTS access mechanism. The network allocation vector (NAV) should be modified when the transmission rate of data packets varies.

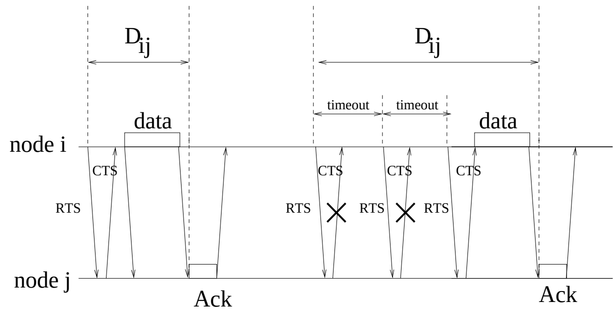

Fig. 4. Illustration of the MAC delay. It is a measure of the contention experienced by a node.

III. Joint Rate Adaptation and Routing Algorithm

In this section, we describe a spectrally efficient rate adaptation scheme and a few routing metrics that utilize the information from the MAC layer. These metrics are then used as edge weights in the shortest path routing algorithm. We show that the rate adaptation scheme and the routing metric could be integrated to the IEEE 802.11 MAC protocol and the *dynamic source routing* (DSR) protocol with minor modifications.

A. Rate Adaptation Scheme

Our rate adaptation scheme is implemented with a slight modification to the IEEE 802.11 protocol. In this protocol, request-to-send (RTS) and clear-to-send (CTS) packets are used before the actual data transmission begins. When a node receives a RTS packet addressed to itself, it estimates the SNR of the packet by performing channel estimation. The SNR is then mapped to a transmission rate based on a spectrally efficient rate adaptation scheme [2]. This transmission rate is appended to the CTS packet and sent back to the transmit node. Subsequently the transmit node sends the data packet at this rate.

The rate adaptation scheme is applied to each data packet; the RTS and CTS control packets are transmitted at the nominal rate. An uncoded M-QAM scheme is used in which the constellation size is dynamically changed with the SNR [2]. It is a practical scheme that is near optimal in spectral efficiency. We restrict our attention to constellation sizes of $M_0 = 0$, $M_1 = 2$ (Binary Phase Shift Keying), and $M_j = 2^{2(j-1)}, j = 2, 3, ..., N$. At each packet's transmission time, we choose a constellation size from the set $\{M_j : j = 0, 1, ..., N\}$. The choice of constellation depends on the received SNR of the packet. Choosing the M_0 constellation corresponds to no data transmission. If the M_j constellation is chosen, the corresponding M-QAM scheme is used. The transmission rate is then given by $b_j = \log_2(M_j)$. It was shown in [2] that the optimal transmission policy consists of rate assignment using a threshold rule and continuous power control that is water filling in time. When power control is not used, the rate adaptation scheme is still near optimal in spectral efficiency. We denote γ as the SNR. We define

$$M(\gamma) = \frac{\gamma}{\gamma_K^*} \tag{6}$$

where γ_K^* is a constant that is determined numerically based on the power constraints to the modulation scheme. The threshold rule is that if $M_j \leq M(\gamma) < M_{j+1}$, we assign the constellation M_j to γ.

The implementation of the rate adaption in IEEE 802.11 needs a minor modification to the protocol. The RTS and CTS packets carry information of the length of the data packet. This information is read by any listening node, which then updates its network allocation vector (NAV). The NAV contains the information on the period of time in which the channel remains busy. Thus, when a node is hidden from either the sending or the receiving node, it will defer further transmissions by detecting either the CTS or the RTS packet. With reference to Figure 3, suppose node i transmits a RTS packet at t_0. Since data packets are transmitted at different rates, the NAV's of the RTS and CTS packets must be set accordingly so that packet collisions are avoided. NAV1 is unmodified because the RTS packet is always transmitted at the nominal rate. Any neighbor node of i, say A, that overhears the RTS and the data packet transmission will remain silent in the interval $[t_1, t_3]$. At the destination node j, the NAV2 field in the CTS packet is set to $t_4 - t_2$, which is the sum of the transmission time of the data and the acknowledgment packet. Any neighbor node of j, say B, that overhears the CTS packet will refrain from transmission until the transmission of the acknowledgment packet is completed.

B. Routing Metrics

At each link, a routing metric is assigned which indicates how favorable the link is, to be used in a route. The value of the routing metric is determined from the information provided by the MAC layer. The routing algorithm then computes the shortest path in which each link is weighed by its routing metric. Depending on the information that is passed from the MAC layer, the routing algorithms could exhibit various properties, such as bandwidth aware, interference aware and congestion aware.

- Bandwidth awareness: We define the routing metric of a link, i–j, to be $\frac{1}{R_{ij}}$. The sum of the routing metrics along the chosen route is proportional to the total time for a packet to traverse the route, assuming there is no queueing delay or packet retransmission. Since a link with high bandwidth has a smaller weight, more routes can be assigned to utilize the link.
- Interference awareness: As illustrated in Figure 4, the MAC delay D_{ij} is defined as the interval from when the RTS packet is sent to when the data packet is received. This delay is used as as the routing metric. In regions where there is a lot of interference from other nodes, MAC delay is high due to the contention of the channel. This discourages new routes from using the link.
- Congestion awareness: The queueing delay Q_i in the node buffer of the transmit node i is used as the routing metric. The queueing delay is a measure of congestion in a node. The routing algorithm exhibits load balancing behavior. Nodes with a large number of packets in the buffer are avoided.

C. Implementation in DSR

We implement the interference aware routing metric by slightly modifying the *dynamic source routing* (DSR) protocol

[7], [1]. Since our objective is to demonstrate the benefits of cross layer interactions in low mobility scenarios, we apply the routing metric only to route discovery. The route maintenance mechanism is not modified. To perform a route discovery, the source node broadcasts a *route request* (RREQ) packet that is flooded through the network and is answered by a *route reply* (RREP) packet from either the destination node or another node that knows a route to the destination. The original description of DSR [7] supports unidirectional routes. The 802.11 MAC protocol, however, assumes that links are bidirectional. [1] describes a modified DSR implementation such that only bidirectional routes are discovered. RREP packets are sent back using the reverse route of the RREQ packets. If the route taken by the RREQ packet contain unidirectional links, then the RREP will not reach back to the source. When the RREP packets are received at the source, the shortest path route is selected.

In section III, we have described how rate adaptation is achieved using RTS and CTS packets during data transmission. The RTS and CTS scheme, however, is not applicable to route discovery since RREQ packets are broadcast packets. Channel estimation must be accomplished by the RREQ packets. Whenever a node receives a RREQ packet, the SNR is determined and then appended to the packet. At the destination node, the received SNR along the path of all routes is known. RREP packets are then sent with the current time as the time stamp. The RREP packets propagate along the reverse paths with rate adaptation at each hop. When the source node receives all the RREP packets, the MAC delay for the reverse paths are computed by subtracting the packet time stamp from the current time. The route with the minimal MAC delay is selected.

IV. Simulation Setup

The simulations were performed using *ns-2* [11] with its wireless extensions developed by the Monarch Project [12]. We use the mobility and channel models described in section II. Since our objective is to demonstrate the effect of rate adaptation and the use of the routing metrics in Section III, we consider the stationary and the pedestrian scenarios only. For the pedestrian scenario, we assume the *max_speed* of each node is 1.0 meter/sec. In both scenarios, the *pause_time* is set to 1.0 second. For each speed we generate 10 different mobility scenarios. The application traffic pattern consists of 20 CBR sources running on UDP that start at staggered times. We use the same communication pattern in all simulations. 20 CBR source destination pairs are generated randomly. The offered load could be varied by changing the CBR packet size, the number of CBR flows or the CBR packet rate. In our simulations we fixed the packet size and the number of CBR flows. We varied the packet rate from 10 packet/s to 60 packet/s at a step of 10 packet/s. These 6 offered load regimes were combined with 20 mobility scenarios as input files to the network simulator. Altogether we performed 120 simulations.

We evaluate the routing algorithms by comparing three performance metrics, namely

- *Throughput*: the average bit rate at the destination node
- *Delay*: the average delay a packet takes to travel from the source to the destination node
- *Packet delivery ratio*: the fraction of generated packets that are received at the destination node

We do not compare the routing algorithms in *routing overhead* since all the routing schemes are running on DSR. In each scenario, the traffic of five randomly picked flows are logged for performance analysis. The same five flows are logged in each scenario. For each node mobility there are ten mobility scenarios. The performance metrics are obtained by averaging over the monitored flows in all scenarios.

The following three routing schemes are investigated in this paper.

1. **IARA**: rate adaptation is used at the MAC-Physical layer, and the interference aware routing metric is used in the discovery phase of DSR
2. **RA**: rate adaptation is used at the MAC-Physical layer, and the plain DSR is used
3. **DSR**: no rate adaptation is used at the MAC-Physical layer, and the plain DSR is used

By comparing the DSR and RA schemes, we could evaluate the impact of the rate adaptation. Similarly, by comparing the IARA and the RA schemes, we could evaluate the performance enhancement of the routing metric.

V. Simulation Results

We study the performance of the routing algorithms in different offered load regimes. The performance metrics for the stationary scenario and the pedestrian scenario in various offered load regimes are plotted and discussed as follows.

Consider the stationary scenario in Figure 5. As the offered load increases, the average throughput increases. For the DSR scheme, congestion begins to build up at a packet rate of 40 packets/s. The throughput falls slightly when packet rate is further increased. Since rate adaptation is used in the RA and IARA schemes, the network capacity is much higher and no congestion is observed at higher packet rates. Both the RA and the IARA schemes offer more than 40% throughput enhancement compared to the DSR scheme. The IARA scheme is marginally better than the RA scheme throughput-wise.

The packet delay of each routing algorithm increases along with the offered load. The IARA algorithm consistently outperforms the RA algorithm in the delay performance in all offered load regimes. The packet delay of the IARA is only 80% of that of the RA algorithm, and is only about 50% of the packet delay of the DSR algorithm. Although the RA and the IARA schemes have almost the same throughput performance, IARA is superior by exhibiting a smaller packet delay.

The packet delivery ratio of the routing algorithms decreases with increase in the offered load. The IARA scheme has marginally better delivery ratio than the RA scheme, which in turn has a higher packet delivery ratio compared to the DSR scheme by more than 40%. We observe that the packet delivery ratio is much less than 1 even in the low offered load regimes. For the DSR scheme, the packet delivery ratio is slightly over 0.4 at a light offered load of 10 packets/s. For the RA and the IARA schemes, the corresponding packet delivery ratio is slightly more than 0.6. In this regime, packet loss is neither due to mobility nor congestion, but is due to the wireless transmission impairments of Rayleigh fading. In slow fading environments, the deep fades span over a duration of several consecutive data packets. Thus packets generated by the source will be queued up and dropped when the node buffer is full.

Consider the pedestrian scenario in Figure 6. We observe that mobility degrades the throughput of all routing schemes by comparing with Figure 5. However, there are more disparity in the performance between the IARA , RA schemes and the DSR scheme. Both the IARA and RA scheme have larger throughput than the DSR scheme by 80% to 90%. In general, mobility introduces faster variations in link capacity. A rate adaptation scheme could better exploit the dynamics of link capacity in high mobility scenarios. We also observe that the IARA scheme consistently outperforms the RA scheme in throughput. This in-

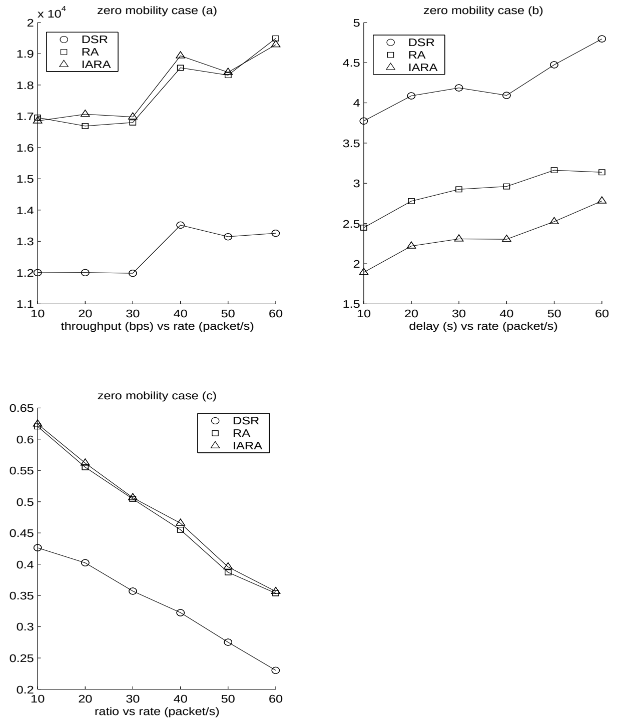

Fig. 5. Offered load simulations, stationary scenario. (a)Throughput vs. packet rate per flow, (b)Delay vs. packet rate per flow, (c)Goodput vs. packet rate per flow. IARA and RA are superior to DSR in throughput and packet delay. IARA is superior to RA in packet delay.

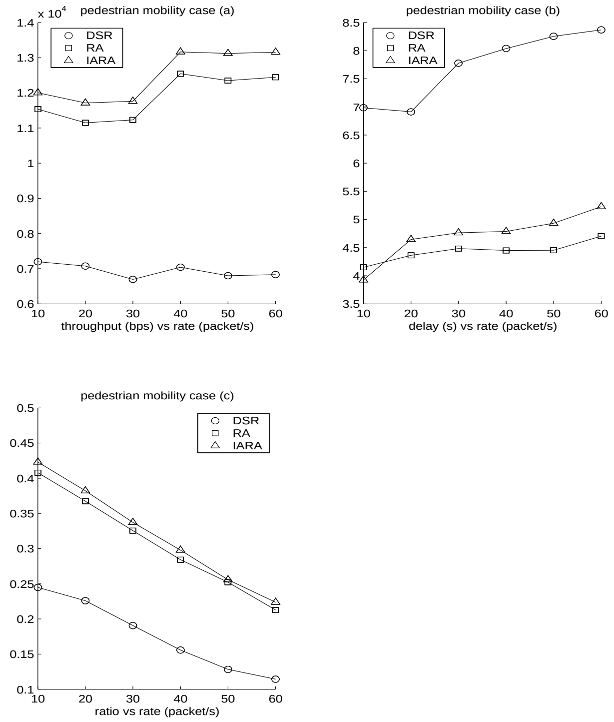

Fig. 6. Offered load simulations, pedestrian scenario. (a)Throughput vs. packet rate per flow, (b)Delay vs. packet rate per flow, (c)Goodput vs. packet rate per flow. IARA and RA are superior to DST in throughput and packet delay. IARA is superior to RA in throughput but not in packet delay.

dicates the use of routing metrics leads to routes that are more robust to mobility.

Compared with the stationary scenario the delay of all routing schemes are increased by more than 50%. This could be attributed to the occurrence of link failure due to mobility. We observe that the IARA scheme exhibits a higher delay than the RA scheme. The phenomenon that a scheme has a higher throughput and a higher packet delay could be explained as follows. Since the IARA scheme is more robust to mobility, routes with more hops are more stable in the IARA scheme and a large fraction of packets pass through these routes. The RA scheme is less robust to mobility. Most received packets of the RA scheme are routed through shorter hop routes. This explains the smaller overall delay in packet delivery. We note that the delay performance in this case is misleading. The higher delay of the IARA scheme is due to the robustness of the algorithm in mobility.

In the pedestrian scenario, the packet delivery ratio is much smaller than the stationary scenario since mobility contributes to route failures and packet loss. Nevertheless, the packet delivery ratio of the RA and the IARA schemes is 90% higher than the DSR scheme. Whereas the improvement of our schemes over the DSR scheme is about 50% in the stationary scenario. This indicates the use of rate adapation and routing metric techniques has significant impact on the performance of routing protocols in less benevolent wireless environments where there is fading and mobility.

VI. Conclusion

In this paper, we advocate a new design concept in routing protocols for mobile ad hoc networks. We argue that by exploiting information from the MAC and the physical layer, significant performance enhancement of a routing protocol could be achieved. This is demonstrated by incorporating a spectrally efficient rate adaptation scheme to IEEE 802.11 and a simple routing metric to the DSR protocol. In our simulations we show that a large performance margin is obtained with our rate adaptation scheme. The benefit of the routing metric is more modest, and moderate reduction in packet delay is obtained compared with the rate adaptation scheme. In this work, the routing metric is used only in route discovery. Thus the benefit of cross layer interactions is apparent only in low mobility scenarios. Further work involves designing a route maintenance scheme that exploits the availability of time-varying routing metric from the MAC layer.

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