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Cross-layer Interaction in Wireless Ad Hoc Networks: A Practical Example

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Abstract This paper presents the design and the performance evaluation of a joined process between the PHY (PHYSical) layer and routing layer in a multi-hop wireless ad hoc networks. This cross-layer interaction between the PHY and routing layers allows each node in an ad hoc network to evaluate the performance of each path in its routing table in terms of Bit Error Rate (BER) and to classify each path accordingly. Routing information from poor quality links are not forwarded leading to the selection of high quality links during the routing process. An implementation of our cross-layer algorithm based on Ad-hoc On-demand Distance Vector (AODV) is presented along with simulation results showing significant improvements in terms of additional throughput and lower BER. Furthermore, inherent of our mechanism's design, the network overhead introduced by routing protocols is reduced.

1 Introduction

In Mobile Ad hoc NETWORKS (MANET), each node is involved in the process of forwarding packets and maintaining a set of valid routes. As a MANET topology is mobile and the connectivity is unpredictable, it is rather challenging to establish and maintain routing tables. Additional challenges lay in the fact that wireless communications are impacted by stochastic and time-varying phenomena such as fading or interference. Hence, alike wired networks, the behavior of ad hoc networks becomes very complex to predict and the Cross-layer interaction is a new way of managing interactions between layers introduced in previous works [1, 2]. The reader can refer to [3] for a detailed survey of cross-layer design. In wireless networks there are a large number of phenomena that have an effect on the end-to-end performance. A layered architecture like the seven layers of the OSI model has divided each networking task into the services provided by one layer. This architecture enables each layer to communicate directly only with an

adjacent layer. Alternatively cross-layer design allows direct communication between non adjacent layers. This design clearly violates the OSI model in order to enable different types of interaction between layers. This new way of managing the network stack is mainly studied in the case of wireless networks, because some effects, such as time-varying link quality or mobile architecture, lead to develop a dynamic layer model and algorithm which take into account information from several layers at the same time.

In ad hoc networks cross-layer design could help to solve the key issues like scalability, collision, noisy link, lowered throughput, reduce the waste of bandwidth due to routing overhead, save energy. But on the other hand, with cross-layer design the performance could potentially be worsted, because different layers could try to improve the same metric at the same time but in a different direction. This phenomenon could be avoided by using a central entity which pilots the information flow between layers.

In [4], the authors show that the scalability of wireless ad hoc networks is bad when only the probability of packet loss at the reception, due to noise and interferences, is taken into account. The cross-layer mechanism described in this paper takes into account this phenomenon, based on the SNIR (Signal to Noise and Interference Ratio) of each link.

To design cross-layer interactions, various approaches have been proposed in the literature. In [1], Raishingani *et al* have proposed a new layer design for wireless networks that allows the possibility to exchange information between layers through a new stack component, the Devices Management Entity (DME) which stores informations about each layer. In Kawadia *et al* [2] the authors have developed the idea that using cross-layer interactions for wireless networks could improve the performance, and have given a few examples of ad hoc networks which can

use interlayer interactions to choose the path with the best throughput with the help of link information. In [5], Klemm *et al* try to improve the performance of TCP in Ad Hoc networks by reducing the number of packet losses. To avoid errors, they measure the signal strength at the physical layer, and the MAC (Medium Access Control) layer estimates whether the failure is due to congestion or due to the neighbor moving out of range. There are two ways of reducing the number of dropped packets. First, the proactive approach: a node searches for a new route when a node detects a possible link failure to a neighbor and the second one is to increase the transmission power in case where a neighbor has just moved out of range. The simulation results show that in high mobility, the proactive approach can improve performance of a TCP session by 75% when the network is lightly loaded. In [6], Chiang describes a distributive power algorithm to improve the end-to-end performance of TCP Vegas in ad hoc networks. He uses the standard formulation of the network utility maximization and adapts it to the case when the sum of each individual source is constrained by a variable data rate on the logical link function of interferences and the power of transmission. The algorithm needs to have an inter-layer interaction between the transport and the physical layer to compute the optimal power of transmission of each frame. The author shows that the end-to-end throughput per watt of power transmitted is 82% higher with a power control and a co-design across the physical and transport layers. In [4], Mhatre *et al* determined asymptotic bounds on the capacity of a random ad hoc network, with the assumption that the mapping from SINR (Signal to Interference and Noise Ratio) to packet success probability is continuous. Hence, over each hop, for every finite SINR, there is a non-zero probability of packet loss. Consequently, it is shown that the cumulative effect of packet loss per-hop results in a per-node throughput of only $\Theta(\frac{1}{n})$ (instead of $\Theta(\frac{1}{\sqrt{n \log n}})$) as shown previously in [7] for the threshold-based link model. However, some works are interested in analysing the effect of physical phenomena on the network performance [8] [9].

Finally the authors in [10] [11] propose new metrics, ETX and WCETT, based on measurements to select the path in function of criteria like the packet loss for ETX metric, and the Expected Transmission Time for WCETT metric. Authors in [12] [13] propose two MAC algorithms, the Receiver Based Auto Rate (RBAR) and the Opportunistic Auto Rate (OAR) algorithm to enhance the Auto Rate Fallback (ARF) protocol. These two mechanisms use active probe to

have feedback about the quality of the channel. In the cross-layer design introduced here, we present a modified routing AODV routing algorithm which selects only paths with a enough high SNIR level to have no loss (cf. Section §2). This mechanism has two consequences on the overall performance (cf. Section §3). First, in the case of a network with high connectivity or low connectivity, only high throughput links will be used, and packet delivery ratio will be improved. Secondly the routing overhead will be decreased by two, because only a link with high quality will carry the routing packets. Some researchers already tried or suggested to integrate a kind of SNIR based criterium in the routing algorithms (cf. [17], [16] and [18]), but no maintenance process is proposed in [17] and [18] uses a quite different approach.

The paper is organized as follows. In Section II we recall briefly the Cross-layer interaction schemes for Ad Hoc networks. In section III, We present the algorithm based on a cross-layer interaction between the physical layer and the routing layer, this cross-layer interaction uses a modified version of the AODV protocol to take into account information about the link layer, such as the average received power of a link and the BER of a link. In section IV, some numerical analysis are presented. Section V includes simulation results and a discussion. Finally sections VI and VII present our conclusion and some promising directions for future works.

2 Algorithm and Design

The designed algorithm is divided in two parts: first, the feedback process which enables the routing layer to give information about the QoS (Quality of Service) performance from the MAC/PHY layer. The second part is the process implemented in the routing layer to select the most accurate path as a function of the PHY/MAC layer information.

Let us describe now the process performed at the routing layer. We have used here an AODV based protocol which takes into account feedback information about the stability and the physical performance of each neighboring link. Depending on this information the routing protocol decides to enable packets to be routed on one link according to the performances of this link. First, the AODV protocol uses two functions to look for a path: searching for a function in the routing table and/or broadcasting a route request through the network. This algorithm acts on these two processes, first for each neighboring link added to the routing table, we join a new parameter which represents the QoS of the link (during

the hello broadcast process defined in the AODV protocol [14]). Secondly when a node receives a route Request it replies or forwards this packet only if the link of the previous hop has an acceptable QoS level or discards it as a function of the information which is stored in this routing table or the information which comes directly from the lower layer. This optimization has two effects: it reduces the routing load because each node drops routing packets which come from poor performance links and does not forward it. And secondly, only paths which have been judged acceptable will be carrying packets, because the other links which have no acceptable QoS level will not participate in the process of broadcasting the route discovery through the network.

Information which is used at the network layer comes from the PHY/MAC layer. This cross-layer interaction or joint process between the PHY/MAC and the network layer is done through a new design of layers. First of all, this metric exchange between layers to define the QoS of each link, is the BER_l (bit error rate) and the FER_l (frame error rate) of each packet through one particular link l . The BER_l and the FER_l are calculated as a function of the SIR_l (signal to interference ratio) measured by the physical layer on link $l \in L(s)$ as follows:

$$SIR_l(P) = \frac{P_l G_{ll}}{N_l + \sum_{k \neq l}^N P_l G_{lk}} \quad (1)$$

$$BER_l = \alpha_M Q \left(\sqrt{\hat{\beta}_M SIR_l(P)} \right) \quad (2)$$

$$FER_l = 1 - (1 - BER_l)^n \quad (3)$$

where :

- n : number of bits in a packet
- G_{lk} : Path losses from the transmitter on the logical link l to the receiver on the logical link k
- P_l : Transmission Power from the transmitter on the logical link l
- N_l : Background noise on the logical link l
- FER_l : Frame error rate on the logical link l
- BER_l : Bits error rate on the logical link l
- $Q()$: Q function, $Q(z)$, is defined as the probability that a Gaussian random variable x with mean 0 and variance 1 is bigger than z [15]
- α_M : in $\hat{\alpha}_M = \alpha_M / (\log_2 M)$ where α_M is the number of nearest neighbours to the constellation at the minimum distance [15]
- β_M : in $\hat{\beta}_M = (\log_2 M) / \beta_M$ is a constant that relates minimum distance to average symbol energy, α_M

and β_M are constants depending on the modulation and the required bit error rate is given by BER [15].

This metric (the BER_l) comes from the PHY/MAC layer to network layer and we stored the $FER_l \in [0, 1]$ in the routing table during the moving average calculation process, which smooths the noise variation of the FER_l (γ is the smoothing factor) and enables us to calculate and average FER_l .

$$\overline{FER_l} = \gamma FER_l + (1 - \gamma) FER_l(t - 1) \quad (4)$$

The network layer has the opportunity to distinguish which link is acceptable or not as a function of the FER and a determined threshold for each link to all its neighbors. The FER is used as a metric to determine if we could forward or reply to routing solicitation, but it doesn't change the normal routing process that selects the link which leads to lowering the number of hops.

With this cross-layer mechanism a node will forward or process an RREQ packet only if the $\overline{FER_l} < \zeta$ or $FER_l < \zeta$ and ζ is a predefined threshold and the $\overline{FER_l}$ is the average Frame Error rate for one link stores in the routing table and the FER_l is the instantaneous Frame Error Rate measured by the PHY layer. This proposal is to avoid routes that have poor capacity [16] in terms of the number of errors at the physical layer and throughput.

3 Analysis

With CSMA/CA, the impact of the interference is rather low. Instead, the transmission errors are mainly due to path losses and fading. That is why we are more interested in observing the effect of the algorithm as a function of the connectivity, that is as a function of the transmission range or, which is the same, the transmission power.

Let us assume that there is no fading to simplify the analysis, but that the only transmission errors are due to path loss. Between two hosts, because of the three hand-shakes, a data packet is received in one hop after an RTS/CTS exchange at MAC level between the intermediary source and the destination, plus the sending of the data packet and its acknowledgment. In this case, the probability that a data packet sent by a node x_k to a node x_{k+1} separated by a distance d is never received, is (no packets, either RTS, CTS, data or acknowledgment is retransmitted

after three times):

$$\begin{aligned}
p_\varepsilon(d) = & 1 - [(1 - p_{RTS/CTS}(d)) \\
& (1 - p_{er}(d)) (1 - p_{ack}(d)) \\
& (1 - p_{RTS/CTS}(d))^2 \\
& [p_{er}(d) + (1 - p_{er}(d)) p_{ack}(d)] \\
& + (1 - p_{RTS/CTS}(d))^2 \\
& [p_{er}(d) + (1 - p_{er}(d)) p_{ack}(d)] \\
& (1 - p_{er}(d)) (1 - p_{ack}(d)) \\
& + (1 - p_{RTS/CTS}(d))^3 \\
& [p_{er}(d) + (1 - p_{er}(d)) p_{ack}(d)]^2 \\
& (1 - p_{er}(d)) (1 - p_{ack}(d))] \quad (5)
\end{aligned}$$

where

- $p_{ack}(d)$ is the probability that an acknowledgment is lost;
- $p_{er}(d)$ is the probability that a data packet is lost;
- $p_{RTS/CTS}(d)$ is obtained by

$$\begin{aligned}
p_{RTS/CTS}(d) = & 1 - [(1 - p_{RTS}(d)) (1 - p_{CTS}(d)) \\
& + (p_{RTS}(d) + p_{CTS}(d)) (1 - p_{RTS}(d)) (1 - p_{CTS}(d)) \\
& + (p_{RTS}(d) + p_{CTS}(d))^2 (1 - p_{RTS}(d)) (1 - p_{CTS}(d))]
\end{aligned}$$

where $p_{RTS}(d)$ and $p_{CTS}(d)$ are the probabilities that an RTS and an CTS are lost respectively. $p_{RTS}(d)$, $p_{CTS}(d)$, $p_{ack}(d)$ and $p_{er}(d)$ can be computed with the formula:

$$p_X(d) = [1 - BER_X(SINR(d))]^{\nu_X} \quad (6)$$

where,

- ν_X is the number of bits per packets of type X (RTS, CTS, ACK or data);
- $BER_X(y)$ is the bit error rate function giving the probability that a bit is received with an error for an SNR equal to y, for the packet of type X.

and

$$SNR(d) = P_0 \left(\frac{\lambda}{4\pi d} \right)^2 \times \frac{Rxthres}{No} \quad (7)$$

where:

- P_0 is the transmission power;
- λ is the wave length;
- $Rxthres$ is the reception threshold;
- No is the ambient noise.

The loss rate on the path between A and B is then:

$$\begin{aligned}
\tau_{AB} = & 1 - \sum_k [P(k) \times \\
& \int_{d_{Ax_1}} \int_{d_{x_1x_2}} \dots \int_{d_{x_{k-1}x_k}} \int_{d_{x_kB}} \\
& p_\varepsilon(d_{Ax_1}) \prod_{i=1}^k p_\varepsilon(d_{x_i x_{i+1}}) p_\varepsilon(d_{x_k B}) \\
& f(d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_k B}) \\
& \times dd_{Ax_1} dd_{x_1x_2} dd_{x_1x_2} \dots dd_{x_k B}] \quad (8)
\end{aligned}$$

where:

- $P(k)$ is the probability to have k nodes on the path;
- $d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_k B}$ are the distances between nodes A and x_1 , nodes x_1 and x_2, \dots , nodes x_k and B;
- $f(d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_k B})$ is the probability function of these distances;

Discarding bad routes in terms of bit error rates produces a lower loss rate and result in suppressing from the integral above, all the infinitesimal elements corresponding to a big $BER(d)$, and so all the infinitesimal elements with a high distance. It leads to have shorter distances between nodes.

On the other hand, to allow only a shorter distance between nodes leads some routes to be broken. This appears in equation (8) through a decreasing of the $P(k)$ terms for small k , thus weighting the paths for which the loss rates are lower.

So, adding the cross-layer threshold leads to modifying the path, the number of hops and the distances in between, that is exactly $P(k)$ and $f(d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_k B})$. Indexing respectively by XL and NXL the quantities corresponding to respectively the cross-layer and

non cross-layer cases, the gain is then:

$$\begin{aligned}
 G = & \sum_k [P_{XL}(k) \times \\
 & \int_{d_{Ax_1}} \int_{d_{x_1x_2}} \cdots \int_{d_{x_{k_{XL}-1}x_{k_{XL}}}} \int_{d_{x_{k_{XL}}B}} \\
 & p_\varepsilon(d_{Ax_1}) \prod_{i=1}^{k_{XL}} p_\varepsilon(d_{x_i x_{i+1}}) p_\varepsilon(d_{x_{k_{XL}}B}) \\
 & f_{XL}(d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_{k_{XL}}B}) \\
 & \times dd_{Ax_1} dd_{x_1x_2} dd_{x_1x_2} \cdots dd_{x_{k_{XL}}B}] \\
 - & \sum_k [P_{NXL}(k) \times \\
 & \int_{d_{Ax_1}} \int_{d_{x_1x_2}} \cdots \int_{d_{x_{k_{NXL}-1}x_{k_{NXL}}}} \int_{d_{x_{k_{NXL}}B}} \\
 & p_\varepsilon(d_{Ax_1}) \prod_{i=1}^{k_{NXL}} p_\varepsilon(d_{x_i x_{i+1}}) p_\varepsilon(d_{x_{k_{NXL}}B}) \\
 & f_{NXL}(d_{Ax_1}, d_{x_1x_2}, \dots, d_{x_{k_{NXL}}B}) \\
 & \times dd_{Ax_1} dd_{x_1x_2} dd_{x_1x_2} \cdots dd_{x_{k_{NXL}}B}] \quad (9)
 \end{aligned}$$

Unfortunately, it is not possible to compute analytically this gain, since it involves connectivity measures which are not known at the moment. This problem is closely related to the percolation theory, and to predicting the probability of having a path between two nodes.

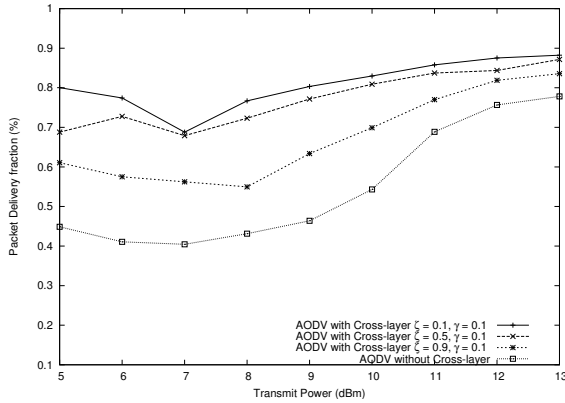


Fig. 1 Packet delivery fraction as a function of the transmission power

4 Performance analysis

4.1 Simulations parameters

We have used the event-based simulator Qualnet [19] with a simulated area of 1500×1000 m with 50

nodes. For the MAC layer we have picked the unmodified IEEE 802.11b model and a modified AODV [14] protocol which uses cross-layer interaction. The traffic sources are CBR, and the source destination pairs are spread randomly over the network. In the case of mobility the mobility model is *The Random Trip Mobility Model* [20], which generalizes random waypoints and random walks to realistic scenarios. We have selected *The Random Trip Mobility Model* because this implementation performs perfect initialization, i.e. the mobility model has no transient phase. In our simulation, a packet is considered receivable if its reception power to take into account the noise and interference is above a certain threshold. After that we calculate the packet SIR and pick a random number to simulate the error probability that normally occurs during transmission.

4.2 Performance Results

The performance evaluation in the case where all nodes move according to the *The Random Trip Mobility Model* mobility model defined by [20] with an average speed of 5m/s and a pause time of 100s. All simulations were made for the transmission power range of 5 dBm to 13dBm (cf. Table 1). This lets us show an evaluation of the performance as a function of the network connectivity, because the transmission range varies according to the transmission power. Figure 1 shows that in the cross-layer case the packet delivery fraction increases by a magnitude of 80% or 75% more in the best case according the threshold ζ which is the minimal FER (Frame Error Rate) authorized for a link. On the other hand, Figure 2 shows the ratio of RREQ not carried by the network in cross-layer case for different values of ζ versus the non cross-layer case. The result is that the cross-layer

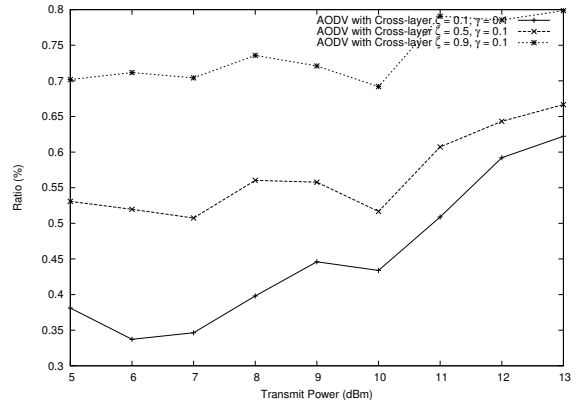


Fig. 2 Ratio of RREQ packets not carried by the network in the cross-layer case for different values of ζ versus non cross-layer case

Table 1 Summary of Simulation Parameters

Parameter	Value
Simulation Time	2000s
Number of Nodes	100
Pathloss Model	Two Ray Ground
Physical Model	802.11b
Mac layer Data Rate	11 Mbps
Transmission Power	5 to 13 dBm
Receiver Sensibility at 11Mbps	-83 Dbm
Typical Transmission Range at 11Mbps	271.979m
<i>Traffic</i>	
Number of Traffic Sources	50
Packet Size	1460 bytes
Average Flow duration	200s
Number of Flow	500
<i>Movement</i>	
Mobility Model	Random Trip Mobility Model
Speed	5 m/s
Pause time	100s

case carries around 54% less RREQ packets in the case of poor connectivity and 66% in the case of a fully connected network for $\zeta = 0.1$.

The performance shows that the cross-layer mechanism reduces the routing load by carrying fewer RREQ packets, because with the cross-layer mechanism we carry only packets from links with a Frame Error Rate under the threshold ζ . This is more obvious in the case of a fully connected networks (when transmission power equals 13 dBm). On the other hand the packet delivery fraction is greatly improved when the network coverage is low (when the transmission power is equal to 5dBm), because in this case the path through the network is close to the optimal, in terms of the number of hops and distance. It also appears from the simulations that a large proportion of the links is of very poor quality (cf. Fig. 1 for $\zeta = 0.9$). Over these links with a measured $FER > 0.9$ transmission will be very poor, and these links are the main source of damage to the end-to-end performance. For all communication over the wireless link, this kind of link must be avoided.

5 Conclusion

We presented a cross-layer framework based on an AODV protocol. It consists of allowing the routing algorithm to only select routes with sufficiently high quality according to information which comes from the Physical layer. The quality of the links is periodically measured by exchanges of HELLO messages between nodes. It leads to suppressing poor quality routes, and also to reducing the data load which would be transmitted in poor conditions. When the connectivity is sufficient, this mechanism allows routes to be found with more hops but with a lower loss rate. Simulations show some significant improvement in terms of packet delivery fraction which improve by 10% to 80% depending on the transmission power and also in terms of routing load which is reduced by half.

This framework could be used for a large set of other protocols and mechanisms which need a QoS information. It would be of great benefit to a lot of systems: those using TCP, where transmission errors, being interpreted as congestion, lead to a degradation of the performance, and also, sensor networks, for which errors are a source of energy consumption since they generate many retransmissions.

6 Future Work

This mechanism could be implemented in other ad hoc routing protocols, like OLSR [21] because lots of functionalities used here, like monitoring the link quality (FER) of each HELLO packets, could be implemented in OLSR during the exchange process of routing table between nodes. This work also raises a wide range of topics in adaptive mechanism based on this mechanism, like Adapting the Frame error Rate (ζ) threshold as a function of the available connectivity in the networks, or adapting the smoothing factor (γ) as a function of the speed of the node. This framework could even be used to study the goodput improvement for TCP connexion in ad hoc networks, because the loss rate of a wireless link has a great impact on the TCP goodput. This mechanism could be used for a large set of networks. By reducing transmission errors, our mechanism would alleviate the impact of transmission errors in wireless networks. It would be of great benefit to a lot of systems: those using TCP (Transmission Control Protocol), where transmission errors, being interpreted as congestion, lead to a degradation of the performance, and also sensor networks, for which errors are a source of energy consumption since they generate many retransmissions.

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