Physical Layer-Constrained Routing in Ad-hoc Wireless Networks: A Modified AODV Protocol with Power Control

Gianluigi Ferrari[1], Simone A. Malvassori[1], Marco Bragalini[1] and Ozan K. Tonguz[2]

[1]Università di Parma
Dipartimento di Ingegneria dell'Informazione
I-43100 Parma, Italy
E-mail: gianluigi.ferrari@unipr.it
malvassori@tlc.unipr.it
URL: http://www.tlc.unipr.it/ferrari

[2]Carnegie Mellon University
Electrical and Computer Engineering Department
Pittsburgh, PA 15213-3890, USA
E-mail: tonguz@ece.cmu.edu
URL: http://www.ece.cmu.edu/∼tonguz

***Abstract*— Routing in ad hoc wireless networks is not only a problem of finding a route with shortest length, but it is also a problem of finding a stable and good quality communication route in order to avoid any unnecessary packet loss. In this paper, we propose a *modified* ad hoc on-demand distance vector (MAODV) routing protocol derived from the AODV routing protocol by considering the bit error rate (BER) at the end of a multi-hop path as the metric to be minimized for route selection. While the performance of MAODV is generally worse than that of AODV, we show that use of distributed power control (PC) dramatically improves the packet delivery ratio with MAODV routing protocol (at the cost of a delay increase), whereas has a negligible effect on the network performance guaranteed by the AODV routing protocol. Our results suggest that MAODV-PC protocol has to be preferred, in terms of packet delivery ratio, in network scenarios with *low traffic load* and *limited node mobility*.**

I. Introduction

The design issues of routing protocols in multi-hop ad hoc wireless networks include protocol capability to adapt well to a wide variety of conditions. One of the leading routing protocol for ad hoc wireless networks is the ad hoc on-demand distance vector (AODV) routing protocol [1]. Previous works have studied the performance of AODV protocol in a variety of scenarios [2]. Those works have shown that the performance tends to drop for high node speed and large number of active nodes. The AODV protocol is based on a specific path cost metric: in particular, it tends to choose the source/destination path with the minimum number of hops (shortest path routing) [3].

Cross-layer design of ad hoc wireless networks has been receiving increasing attention recently [4]. In particular, in [5]–[7] a novel communication-theoretic framework has been proposed. Part of the obtained results suggest that routing should take into account physical layer characteristics. In particular, the bit error rate (BER) at the end of a multi-hop route may, under certain conditions, represent a good indicator of the physical layer status [8].

In this paper, we investigate the performance of physical layer-constrained routing protocols derived from the AODV protocol. The performance of these routing protocols is analyzed by computer simulations based on Network Simulator 2 (NS-2) [9]. More precisely, besides AODV routing protocol, we propose a new routing protocol derived by suitably modifying the AODV protocol in order to approximately minimize the BER at the end of a multi-hop path. We define this new routing protocol as modified AODV (MAODV). While the performance guaranteed by the MAODV protocol is generally worse than that provided by using the AODV protocol, we show that use of *distributed power control* (PC) has a beneficial effect on the performance on the first routing protocol. More precisely, we show that MAODV routing protocol basically selects the multi-hop route with the shortest possible longest hop of the route. As such, this routing protocol allows to reduce the average transmit power of the nodes (since consecutive nodes are closer) and, therefore, to limit the multiple access interference. On the other hand, power control has a negligible impact on the performance of AODV routing protocol. Our results suggest that MAODV protocol with power control (MADOV-PC) is the protocol of choice, in terms of packet delivery ratio, in scenarios with (i) *low traffic load*, (ii) *limited node mobility* and (iii) *low initial node energy*. The cost to be paid for this performance improvement is the higher packet transmission delay.

II. Background

A. Ad hoc On-demand Distance Vector Routing

AODV routing protocol is an on-demand reactive routing protocol that uses routing tables with one entry per destination [1]. When a source node needs to find a route to a destination, it starts a route discovery process, based on flooding, to locate the destination node. Upon receiving a route request (RREQ) packet, intermediate nodes update their routing tables for a reverse route to the source. Similarly, the forward route to the destination is updated upon reception of a route reply (RREP) packet originated either by the destination itself or any other intermediate node that has a current route to the destination. The AODV protocol uses sequence numbers to determine the timeliness of each packet and to prevent the creation of loops. Expiry timers are used to keep the route entries updated.

Link failures are propagated by a route error (RERR) message from a broken link to the source node of the corresponding route. When the next hop link breaks, RERR packets are sent by the starting node of the link to a set of neighboring nodes that communicate over the broken link with the destination. This recursive process erases all broken entries from the routing table at each node.

Since nodes reply to the first arriving RREQ packet, AODV protocol favors the least congested route instead of the shortest route. Note that the fact that the on-demand approach of the AODV protocol minimizes routing table information potentially leads to a large number of route requests being generated.

B. Mac Protocol - IEEE 802.11 Standard

The distributed coordination function (DCF) of IEEE 802.11 [10] for wireless local area networks (WLANs) is used as the medium access control (MAC) protocol. The IEEE 802.11 DCF uses Request-to-send (RTS) and Clear-to-send (CTS) control packets for "unicast" data transmission to a neighboring node. The RTS/CTS exchange anticipates the data packet transmission and implements a form of *virtual carrier sensing* and channel reservation to reduce the impact of the well-known *hidden terminal problem* [11]. Data packet transmission is followed by an acknowledgment (ACK). All the packets are transmitted at maximum power. "Broadcast" data packets and RTS control packets are sent using physical carrier sensing. An un-slotted CSMA technique with collision avoidance (CSMA/CA) is used to transmit these packets. The considered node model has characteristics similar to those typical of the commercial radio interface in Lucent's WaveLAN [12].

C. Simulation Model

The major simulation parameters are indicated in Table I. In particular, the *maximum* transmit power is reported, and this corresponds to the value typical of a Lucent's WaveLAN interface [12]. However, in a network scenario with power control, the transmit power will be adjusted, as explained in more detail in the following.

1) MAC Protocol: In the IEEE 802.11 standard, RREQ packets correspond to broadcast packets at the MAC level. RREP, RERR and data packets are all unicast packets with a specified neighbor as the MAC destination. Both protocols detect link failure using feedback from the MAC layer. A signal is sent to the routing layer when the MAC layer fails to deliver a unicast packet to the next hop. This is indicated, for example, by a failure to receive a CTS message after an RTS message, or by the absence of an ACK after data transmission.

2) Buffering: All considered routing protocols maintain a *send buffer* of 64 packets. Each node buffers all data packets waiting for a route, e.g., packets for which route discovery has started, but no reply has arrived yet. To prevent buffering of packets indefinitely, packets are dropped if they wait in the send buffer for more than 30 s. All packets (both data and routing) sent by the routing layer are queued at the *interface queue* until the MAC layer can transmit them. The interface queue policy is first-in first-out (FIFO), with a maximum size of 64 packets. Routing packets are given higher priority than data packets in the interface queue.

TABLE I

GENERAL PARAMETERS FOR THE NS-2 SIMULATION ENVIRONMENT OF AD HOC WIRELESS NETWORKS.

Number of nodes	50
Area [m×m]	1500×300
Source	10
MAC Protocol	802.11
Attenuation model	Two Ray Ground
Bit rate [Mb/s]	2
Carrier frequency [MHz]	914
Maximum Radio Range[m]	250
Maximum Transmit Power [W]	0.282
Initial node energy [J]	30
Send buffer [pck]	64
Interface queue [pck]	64
Source type	CBR
Packet dimension [byte]	512
Packet rate [pck/s]	4
Correct receive threshold [W]	3.652×10^{-10}
Threshold to avoid collisions [W]	1.559×10^{-11}
Collision Threshold [dB]	10
Simulation time [s]	900
Pause time [s]	900, 600, 300, 120, 60, 30, 0
Maximum speed [m/s]	20

3) Traffic and Mobility Models: Constant bit rate (CBR) traffic sources are used, and we denote by λ (dimension: [pck/s]) the constant packet generation rate. The source/destination pairs are spread randomly over the network. In the considered basic scenario the mobility is characterized by a random way-point model [2], and we first assume that each node moves to a random destination at a random speed between 0 and a maximum value $v_{\max}$, which is set, in the basic scenario, to 20 m/s. We analyze the impact of the speed by varying the maximum value. Each data point is obtained through a simulation which lasts for 900 s. Each node begins the simulation by remaining stationary for a *pause time* (dimension: [s]): a pause time of 0 s corresponds to continuous motion (according to the random way-point model), and a pause time of 900 s (the duration of the entire simulation) corresponds to no motion at all. Intermediate cases, between continuous movement or complete absence of movement, correspond to values of the pause time between 0 s and 900 s.

4) Energy model: The Energy Model, as implemented in NS-2, is a *node attribute*. The energy model in a node has an initial value corresponding to the node energy level at the beginning of the simulation. It also takes into account an energy consumption associated to each packet transmission and reception. When the node energy level goes down to zero, the node dies out, i.e., no more packets can be received or transmitted by the node. The initial energy of each node battery is 30 J in the basic scenario. We also analyze in detail the impact of battery energy on the network performance in a scenario with static nodes, by varying the energy between 5 J to 60 J.

5) Performance Metrics: The following metrics will be used in the scenarios considered in this paper to evaluate different routing protocols.

- **Packet delivery ratio** - It is defined as the ratio between the number of data packets received by the destinations and those sent by active CBR sources.

- **Average end-to-end delay** - It is defined as the delay between the time instant at which the data packet is originated at the source node and the time instant it reaches the destination. Data packets that get lost *en route* are not considered. Delays due to route discovery, queuing, and retransmissions are included in this delay metric.
- **Normalized routing load** - It is defined as the number of routing packets transmitted per data packet delivered at the destination.

Note that the first two metrics are the most important metrics for best-effort traffic. The third metric, on the other hand, provides significant insights into the network behavior.

III. Problem Statement

Given a network with error-free links (e.g., a fiber optic network), routing the information via the shortest-path route is quite reasonable. In error-prone wireless links, however, shortest path routing may not be useful if the selected route leads to many bit errors. This is because any lost or corrupted packet can trigger a retransmission mechanism (in the case of an unreliable data transfer) which consequently results in an increase in terms of both delay and overhead in the network.

As mentioned in Section I, the limitations imposed by the wireless channel can not be neglected in ad hoc wireless networks. We then propose a new routing protocol, defined as MAODV, which corresponds to a modification of the AODV routing protocol with minimization of the route BER.

The key question that we try to answer is the following: is it possible, by using this physical layer-oriented routing protocol, to improve the network performance offered by the AODV routing protocol? We will show that in some conditions (low traffic load and low mobility) use of *distributed power control* makes MAODV protocol preferable, in terms of throughput, with respect to AODV protocol. This performance improvement, however, comes at the expense of higher packet transmission delay.

IV. Modified Ad hoc On-demand Distance Vector Routing Protocol

The MAODV routing protocol leads to the selection of the route which minimizes the end-to-end BER. We now analyze this strategy, in order to understand in more detail its characteristics and what it really means. In particular, we will relate this strategy to the selection of the path, among the possible ones, such that the longest link is the shortest possible.

Suppose that at the receiving node of each hop of the route there is regeneration and forwarding. Pessimistically, assume also that errors made in a link are not recovered in the following links.[1] We denote as $\mathrm{BER}_{\mathrm{link}}^{(i)}$ the BER at the i-th link of the route, which depends on the link signal-to-noise ratio (SNR) and channel characteristics. The BER at the end of a route with n hops can therefore be written as

$$\begin{aligned}\mathrm{BER}_{\mathrm{route}} &= 1-\prod_{i=1}^{n-1}\left(1-\mathrm{BER}_{\mathrm{link}}^{(i)}\right)\\ &= \sum_{i=1}^{n}\mathrm{BER}_{\mathrm{link}}^{(i)}-\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n}\mathrm{BER}_{\mathrm{link}}^{(i)}\mathrm{BER}_{\mathrm{link}}^{(j)}\\ &+\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n}\sum_{z=1,z\neq i,z\neq j}^{n}\mathrm{BER}_{\mathrm{link}}^{(i)}\mathrm{BER}_{\mathrm{link}}^{(j)}\mathrm{BER}_{\mathrm{link}}^{(z)}\\ &-\ldots\end{aligned} \tag{1}$$

In order to provide an acceptable BER at the end of a multi-hop route, it is obvious that the link BER must be very low, i.e., $\mathrm{BER}_{\mathrm{link}}^{(i)} \ll 1$, $\forall i$. Hence, the first sum at the right-hand side of (1) is the largest term contributing to the final BER. In other words, the following approximation is very accurate:

$$\mathrm{BER}_{\mathrm{route}} \simeq \sum_{i=1}^{n}\mathrm{BER}_{\mathrm{link}}^{(i)}. \tag{2}$$

In the case of Binary Phase Shift Keying (BPSK) over an additive white Gaussian Noise (AWGN) channel, the link BER can be written as [5]

$$\mathrm{BER}_{\mathrm{link}}^{(i)} = Q\left(\sqrt{2\,\mathrm{SNR}_{\mathrm{link}}^{(i)}}\right) \tag{3}$$

where $\mathrm{SNR}_{\mathrm{link}}^{(i)}$ is the SNR at the end of the i-th link and $Q(x) \triangleq \frac{1}{\sqrt{2\pi}}\int_x^{+\infty} e^{-\frac{t^2}{2}}\,\mathrm{d}t$. In particular, the link SNR at the end of the i-th hop can be expressed, in the considered case with BPSK, as follows [5]:

$$\mathrm{SNR}_{\mathrm{link}}^{(i)} = \frac{P_{\mathrm{r}}^{(i)}}{P_{\mathrm{thermal}}+P_{\mathrm{int}}^{(i)}} \tag{4}$$

where $P_{\mathrm{r}}^{(i)}$, P_{thermal} and $P_{\mathrm{int}}^{(i)}$ are the received, thermal and interference powers at the end of the i-th link, respectively—note that the thermal noise is the same for all nodes, depending on the receiver front-end. Assuming two-ray ground path loss, one can write [13]:

$$P_{\mathrm{r}}^{(i)} = \frac{\alpha P_{\mathrm{t}}}{d_i^4} \tag{5}$$

where P_{t} is the transmit power, α is a propagation constant (which depends on the receiver/transmitter antennas gains, antennas heights and carrier frequency) and d_i the length of the i-th link. One therefore obtains:

$$\mathrm{BER}_{\mathrm{route}} \simeq \sum_{i=1}^{n} Q\left(\frac{1}{d_i^2}\sqrt{2\frac{\alpha P_{\mathrm{t}}}{P_{\mathrm{thermal}}+P_{\mathrm{int}}^{(i)}}}\right). \tag{6}$$

The interference power $P_{\mathrm{int}}^{(i)}$ depends on the node topology and MAC protocol. Assuming that the topology is not too irregular, one can assume that $P_{\mathrm{int}}^{(i)}$ is similar for all links of a route. Therefore, since $Q(x)$ is a rapidly decreasing function of x, if one hop had a length sufficiently larger than the others the

[1] This is valid especially at large values of the link signal-to-noise ratio, which is a necessary requirement for an ad hoc wireless network to correctly operate.

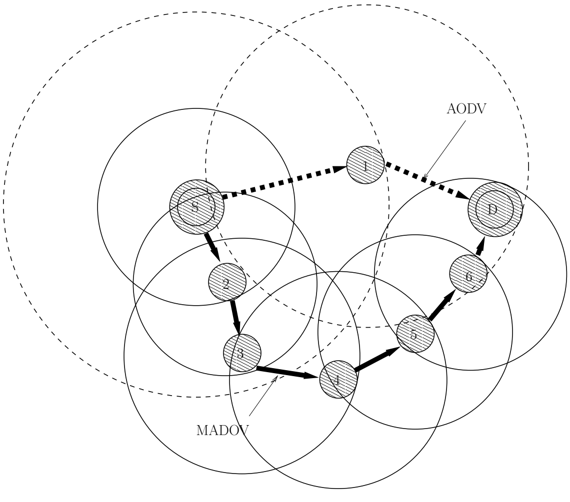

Fig. 1. Routing strategies: MAODV vs AODV.

corresponding BER term would be the highest possible, and one could conclude that

$$\mathrm{BER}_{\mathrm{route}} \simeq Q\left(\frac{1}{d_{i_{\max}}^2}\sqrt{2\frac{\alpha P_{\mathrm{t}}}{P_{\mathrm{thermal}}+P_{\mathrm{int}}^{(i_{\max})}}}\right) \tag{7}$$

where $i_{\max} \triangleq \mathrm{argmax}_i\{d_i\}$, i.e., the $i_{\max}$-th link is the one with largest length. In this case, a routing strategy minimizing the route BER can be equivalently reinterpreted as a strategy which leads to the selection of the route with the lowest possible maximum hop length. This is the route selection strategy implemented (through NS-2) in the proposed MAODV routing protocol. Obviously, this is an approximate interpretation, since in reality the interference power is likely to be different from link to link in the same route and the hop lengths in the same route might be very different.

Fig. 1 shows a pictorial example of the different route choices determined by MAODV (BER-based) routing protocol and AODV routing protocol. While AODV protocol leads to the selection of the route between source and destination with the minimum number of hops (i.e., S-1-D), MAODV routing protocol leads to the selection of the route with the lowest possible maximum hop length (i.e., S-2-3-4-5-6-D). Another difference between MAODV and AODV routing protocols consists of the way in which a multi-hop route is built. While route building with the AODV protocol is completely local, in the case of MAODV protocol we considered the insertion of a specific tag, in the headers of both RREQ and RREP packets, with the recursively updated information (i.e., the maximum hop length in the corresponding route) for the choice of the best path. Observe that estimation of the hop length is essential in order for the MAODV protocol to be implemented. This could be done, for example, by considering transmission of a particular impulse with known power: assuming that the propagation model is accurate, the receiver could recover the hop length from the received power. In a scenario where nodes are equipped with positioning systems, their distances could be evaluated by the use of triangulation methods. Accurate evaluation of the hop length is a significant problem in a decentralized wireless network, and is currently under investigation.

In Fig. 1, each node is the center of a circle with radius corresponding to the transmission range used after the multi-hop route has been created. The transmission range with AODV protocol is significantly larger than the transmit power with MAODV protocol. The pictorial description in Fig. 1 can be interpreted as follows. We preliminary assume that in the route discovery phase all nodes use the same (maximum) transmit power.

- In a scenario with AODV routing protocol, each node selects the farthest possible node within the initial transmission range. Therefore, after a multi-hop route has been selected, the transmit power is likely to remain the same: otherwise, links would likely break.
- In a scenario with MAODV routing protocol, since each node selects, on average, the nearest possible node for the next hop, it follows that the transmit power used after route activation can be reduced.

V. IEEE 802.11 MAC Protocol with Power Control

The power control mechanism implemented in the *modified* IEEE 802.11 MAC protocol tries to reach a compromise between energy saving and channel collisions, by selecting the transmit power according to the packet type: control, routing and data, respectively. The MAC control packets (such as, for example, RTS, CTS and ACK) are transmitted at maximum power, as in the standard IEEE 802.11 MAC protocol. This packets are shorter than data packets: the time needed to transmit them is low, so that the battery consumption is limited. Routing control packets (such as, for example, RREQ, RREP, RERR) are transmitted at maximum power, to give routing traffic the highest possible priority level. Like MAC control packets, routing control packets are short: the battery consumption is, therefore, limited. Data packets, which are longer, are transmitted at variable power, depending on the distance between transmitting node and receiving node. As in [14], in our simulation we adopt ten possible transmit power (i.e., P_{t}) levels: 1 mW, 2 mW, 3.45 mW, 4.8 mW, 7.25 mW, 10.6 mW, 15 mW, 36.6 mW, 75.8 mW and 281 mW, which roughly correspond (according to the considered two-way ground propagation model) to transmission ranges equal to 40 m, 60 m, 80 m, 90 m, 100 m, 110 m, 120 m, 150 m, 180 m and 250 m, respectively.

VI. Performance Comparison

In this section, AODV and MAODV routing protocols are compared by using NS-2, both in the absence and presence of power control.

A. Performance with Variable Pause Time

In order to quantify the interference reduction, we define more precisely the traffic load. According to the CBR source assumption, a node generates *constantly* λ pck/s. Since the duration of a packet is

$$T_{\mathrm{pck}} = \frac{L}{R_b} \tag{8}$$

where R_b is the bit-rate and L is the packet length, the *traffic load per node*[2], in Erlang, can be written as:

$$G_{\rm Node} \triangleq T_{\rm pck}\lambda = \frac{\lambda L}{R_b}. \tag{9}$$

For the values in Table I, it follows that $G_{\rm Node} \simeq 0,012$ Erlang.

The performance of the routing protocols under consideration is shown in Fig. 2 as a function of the pause time. In Fig. 2 (a), the delivery ratio is shown. It can be observed that the use of power control has a beneficial impact for MAODV protocol. In fact, for sufficiently high pause time (from 300 s to 900 s), i.e., in a scenario with slowly moving nodes, MAODV-PC protocol offers higher delivery ratio than AODV protocol. On the other hand, for high node mobility (i.e., for pause time lower than 100 s) AODV protocol is the best routing protocol. One can also observe that use of power control has a minor impact on the performance of AODV protocol. These results depend on the different metrics used by the considered protocols: AODV protocol sets up multi-hop paths with highest possible transmit power and, as such, leads to higher battery depletion at the node; MAODV protocol, instead, sets up paths with short radio range (i.e., low transmit power) and, therefore, the energy consumption at each node is reduced. The poor MAODV protocol performance in scenarios with high node mobility is due to a higher link failure probability, which leads to increased broadcast with respect to AODV protocol. This explanation is motivated by the results shown in Fig 2 (c), where the routing load is reported, as one can see, in a scenario with high node mobility, the normalized routing load with MAODV protocol is significantly higher than with AODV. The average packet transmission delay is shown in Fig. 2 (b), which highlights that AODV protocol offers better performance than MAODV protocol. In fact, a route in a scenario with MAODV protocol is formed by more nodes than in a scenario with AODV protocol: therfore, owing to the characteristics of the IEEE 802.11 MAC protocol, it takes more time for a packet to reach its destination.

B. Impact of Maximum Node Speed

We now present the results obtained by varying the maximum node speed $v_{\max}$ among the following values: (i) 2 m/s, (ii) 5 m/s, (iii) 10 m/s, and (iv) 20 m/s. The pause time is fixed to 300 s and the other parameters are set as in Subsection VI-A. According to the obtained results, shown in Fig. 3, the best performance is obtained with MAODV protocol, regardless of the maximum node speed. While the improvement brought by the use of power control with AODV protocol is negligible, the delivery ratio with MAODV-PC protocol is basically twice that obtained with MADOV protocol without power control, with highest possible value around 70%. In other words, the results in Fig. 3 show that, even in a scenario with relatively

[2]Provided that λ is sufficiently small, one can observe that the per-node traffic load $G_{\rm Node}$ can be equivalently re-interpreted as a channel utilization ratio, i.e., it quantifies the percentage of time during which a node is transmitting.

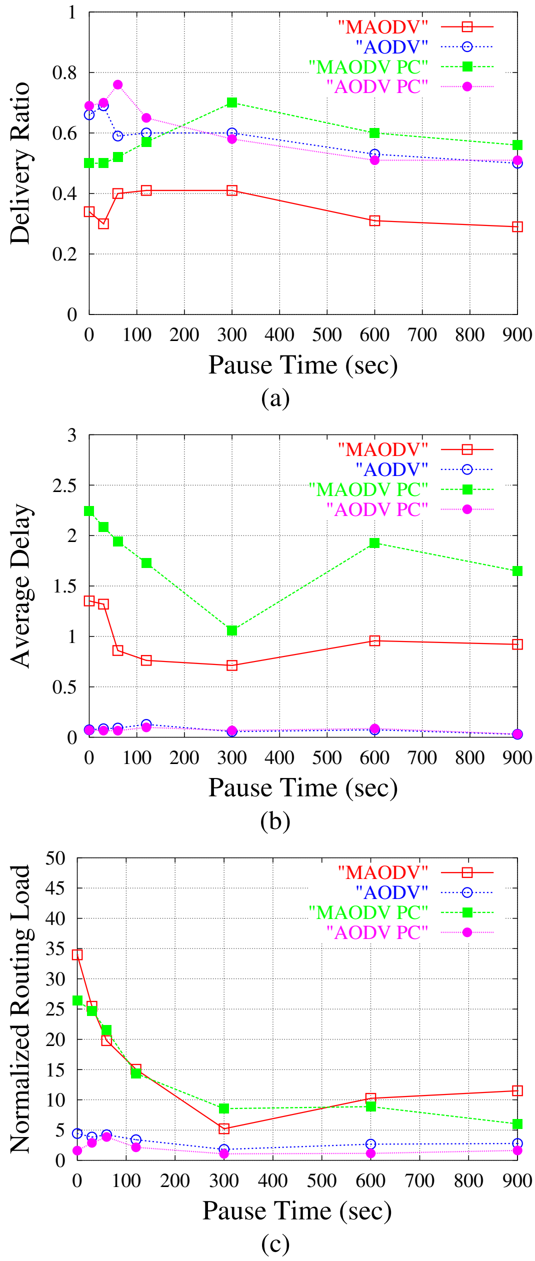

Fig. 2. (a) Delivery ratio, (b) average delay and (c) normalized routing load in a scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and 10 active source nodes.

high node mobility (the pause time is 300 s), the advantages introduced by MAODV-PC, like higher energy saving and higher channel spatial reuse, are more than the disadvantages, like link failures, for every value of the maximum speed $v_{\max}$. Other results (not reported here for lack of space) confirm that the same considerations hold for lower node mobility levels, i.e., higher values of the pause time.

C. Impact of Initial Node Energy

In this subsection, we evaluate the impact of the initial node battery energy. The chosen values are 5 J, 10 J, 20 J, 30 J and 60 J, respectively. The pause time is fixed to 600 s and

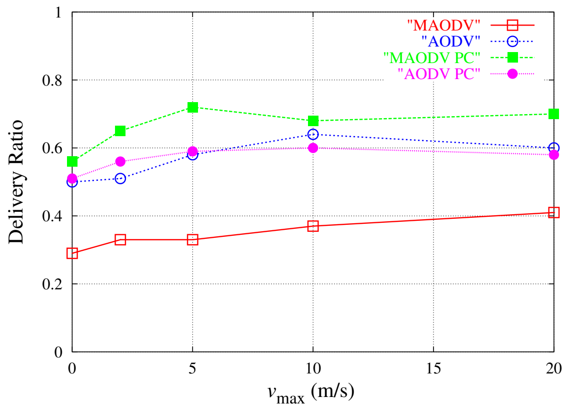

Fig. 3. Delivery ratio versus maximum node speed.

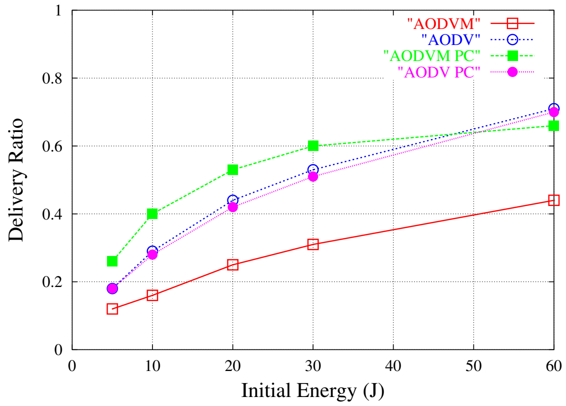

Fig. 4. Delivery ratio versus initial node energy.

the other parameters are the same as in Tab. I. The obtained results, shown Fig. 4, indicate that the delivery ratio is an increasing function of the initial node energy level, regardless of the used routing protocol. As before, in this case as well use of power control leads to a dramatic performance improvement only with MAODV protocol. However, at low initial node energy, MAODV-PC protocol offers a higher delivery ratio, with respect to AODV protocol, since its efficient node energy consumption allows the nodes to increase their lifetime. At high initial energy level, AODV protocol is to be preferred because the energy consumption constraint is less stringent.

VII. Discussion

The results presented in this paper suggest that there exist situations where the use of physical layer-constrained routing, implemented through the proposed MAODV routing protocol, is the best choice to maximize the delivery ratio. However, in order to exploit the benefits of a BER-based routing strategy, *power control* (implemented through adaptive minimization of the transmit power) has to be used. In fact, if power control is not considered, MAODV routing protocol does not allow to take advantage of the lower energy consumption and higher spatial reuse which can be guaranteed by a minimum BER routing criterion. On the other hand, especially in high mobility scenarios, a variable transmit power leads to a higher number of link failures.

VIII. Conclusions

In this paper, we have investigated the design of physical layer-constrained routing protocols. This approach is crucial in ad hoc *wireless* networks, where the channel influences significantly inter-node communications. In order to take into account the impact of the physical layer on the network performance, we have considered, as a meaningful criterion for routing, the minimization of the BER at the end of the route with a power control MAC. In particular, MAODV routing protocol has been proposed as a possible modification of the AODV routing protocol by replacing the shortest path routing criterion with the minimum BER routing criterion. Minimization of the route BER has been implemented as minimization of the maximum hop distance in a multi-hop route. We have shown that *power control* is essential for MAODV protocol, whereas it has a negligible impact for AODV routing protocol. Our results show that in some situations, characterized by *low node mobility* and *low traffic load*, MAODV-PC can offer a better performance, in terms of packet delivery ratio, than AODV protocol. The price to be paid is increased delay in packet transmission.

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