On physical layer-oriented routing with power control in *ad hoc* wireless networks

G. Ferrari, S.A. Malvassori and O.K. Tonguz

Abstract: Routing in *ad hoc* wireless networks does not simply consist in finding a route with shortest length (as in wired networks with virtually error-free communication links), but it requires the creation of a stable and good quality communication route to avoid any unnecessary packet loss. In this paper,we discuss physical layer-oriented routing in *ad hoc* wireless networks, and we analyse the potential advantages of combining the use of power control (PC) with the chosen routing strategy. More precisely, we propose a modified *ad hoc* on-demand distance vector (MAODV) routing protocol, with and without PC, derived from the AODV-routing protocol by considering the bit error rate at the end of a multi-hop path as the metric to be minimised for route selection. In other words, we consider routing with a physical layer-oriented quality of service criterion, and we analyse the system performance in scenarios with either strong line-of-sight (LOS) or shadowed communications. Although in a scenario with strong LOS communications there are a few cases where the MAODV-PC protocol offers the best performance, in the presence of shadowed communications the proposed physical layer-oriented strategy is not attractive.

1 Introduction

An *ad hoc* wireless network is a collection of (mobile) nodes that are capable of communicating with each other without the aid of any established infrastructure or centralised administration [1, 2]. 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 protocols for *ad hoc* wireless networks is the *ad hoc* on-demand distance vector (AODV) protocol [3]. 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) [4]. Previous works have studied the performance of the AODV protocol in a variety of scenarios [5]. Those works have shown that the performance tends to degrade in an unacceptable manner for high node speed and/or large number of active nodes. Several other routing protocols for *ad hoc* wireless networks have been proposed in the literature [6–11].

Recently, a cross-layer approach for the design of *ad hoc* wireless networks has been receiving increasing attention [12]. In [13], the capacity of multi-hop wireless networks is investigated, and it has been shown that the throughput per user diminishes to zero as the number of users increases and therefore the number of hops in a communication route increase. These results have been experimentally confirmed in [14, 15]. In [16–18] a novel communication-theoretic framework has been proposed. Part of the obtained results suggests 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 [19]. The impact of the physical layer characteristics on the performance of the routing protocol in use is also analysed in [20, 21], where the authors debate on the most efficient route selection criterion, either with shortest or with longest hops. In [22], a lightweight underlay network *ad hoc* routing protocol, which builds routes with at most three hops, is presented. In [23], the authors propose a routing strategy based on the use of the expected transmission count metric, which minimises the expected total number of packet transmissions by taking into account also the physical layer characteristics of the communication links. In [24], high-throughput routing is achieved by using a physical layer-oriented metric, which assigns weights to individual links based on the expected transmission time of a packet over each link. A comparison between the empirically evaluated performance of link-quality routing metrics in static multi-hop wireless networks is presented in [25]. Finally, in [26] the authors propose a novel approach to routing, motivated by information-theoretic results on cooperative transmissions. In particular, they introduce an integrated routing and medium access control (MAC) protocol, denoted as ExOR, that increases the throughput of large unicast transfers in multi-hop wireless networks by opportunistically selecting long links, with possible low average BER, towards a batch of multiple intermediate forwarding nodes, among which the transmitted packets are distributed.

In this paper, we first propose a new routing protocol derived by suitably modifying the AODV protocol to approximately minimise the BER at the end of a multi-hop path. We define this new routing protocol as modified AODV (MAODV). The MAODV protocol can be

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interpreted as a particular instance of a routing strategy with a physical layer-oriented quality of service (QoS). Although the performance guaranteed by the MAODV protocol is generally worse than that provided by using the AODV protocol, we show that the use of distributed power control (PC) has a beneficial effect on the performance on the first routing protocol. The PC strategy is implemented by properly modifying the MAC protocol, and we refer to the obtained routing protocol as MAODV-PC. The performance of the considered routing protocols is analysed by computer simulations based on Network Simulator 2 (NS-2) [27].

The analysis in this paper is mostly conducted considering scenarios with strong line-of-sight (LOS) communications, but we also present results relative to a communication scenario with shadowing. In a scenario with strong LOS communications, our results suggest that the MAODV-PC protocol is to be chosen, in terms of packet delivery ratio, in scenarios with (i) low traffic load, (ii) limited node mobility, (iii) low initial node energy and (iv) low node spatial density. The cost to be paid for performance improvement is the higher packet transmission delay, because of a higher number of control packets, required by the MAODV-PC protocol. In a scenario with shadowing, it will be shown that the MAODV-PC protocol is not very effective, and new solutions need to be studied.

This paper is organised as follows. In Section 2, we provide the readers with background information on the AODV-routing protocol, the associated MAC protocol and the simulation model. Section 3 is dedicated to the MAODV-routing protocol. In Section 4, the considered routing protocols, that is AODV and MAODV, are compared, with and without PC, in terms of several metrics, like packet delivery ratio, average delay and normalised routing load, in a scenario with strong LOS. In Section 5, performance results relative to communication scenarios with shadowing are presented. Finally, conclusions are drawn in Section 6.

2 Background

2.1 Ad hoc on-demand distance vector routing

The AODV-routing protocol is an on-demand reactive routing protocol that uses routing tables with one entry per destination [3]. 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 route creation of the AODV protocol has been shown to lead to use unidirectional links in the wrong direction, ultimately resulting in AODV instability problems [28]. This issue goes beyond the scope of this paper, and we do not address it here explicitly. For comparison purposes, however, we assume that the MAODV protocol uses the same route selection strategy of the AODV protocol). The AODV protocol uses sequence numbers to determine the timeliness of each packet and 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 connection breaks, RERR packets are sent by the starting node of the link to a set of neighbouring 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, the AODV protocol favours the least congested route. The fact that the on-demand approach of the AODV protocol minimises routing table information potentially leads to the generation of a large number of RREQs.

The distributed coordination function (DCF) of the IEEE 802.11 standard [29] for wireless local area networks is the considered 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 neighbouring 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 [30]. Data packet transmission is followed by an acknowledgment (ACK). All packets are transmitted at maximum power. 'Broadcast' data packets and RTS control packets are sent using physical carrier sensing. An unslotted carrier sense multiple access (CSMA) technique with collision avoidance (CA) is used to transmit these packets. The node model considered in this paper has characteristics similar to those typical of the commercial radio interface in Lucent's WaveLAN [31].

2.2 Simulation model

The reference values for the major simulation parameters are presented in Table 1. In particular, the maximum transmit power is indicated, but in a network scenario with PC, the transmit power will be adjusted, as explained in more detail in the following. More generally, to study the impact of specific *ad hoc* wireless network parameters (such as, e.g. pause time, maximum node speed, node spatial density etc.), we will consider variations of these parameters around their reference values shown in Table 1, which correspond to fairly typical simulation conditions [5, 27, 32, 33].

2.2.1 Propagation model: In the remainder of this paper, we will analyse the performance in two possible propagation scenarios: with strong LOS (for most of this paper) and with shadowing (at the end of this paper).

A strong LOS communication channel can be correctly modelled as an additive white Gaussian noise (AWGN) channel. We also assume that the propagation model is characterised by a two-ray ground path loss [34]. In this case, the received power can be written as follows

$$P_r = \frac{G_t G_r h_t^2 h_r^2}{f_l} \frac{P_t}{d^4} = \frac{\alpha P_t}{d^4} \tag{1}$$

where P_t and P_r are the transmit and received powers, G_t and G_r the transmitter and receiver antenna gains, h_t and h_r the heights of transmitter and receiver antennas, f_l the system loss factor not related to propagation and d is the distance between receiver and transmitter. Note that the two-ray ground path loss model is valid for distances $d \geq d_{break}$, where $d_{break} = 4h_t h_r f_c/c$, f_c is the carrier frequency, and $c \simeq 3 \times 10^8$ m/s is the speed of light [34]. For distances shorter than d_{break}, the transmit power decays with the inverse of d^2 – this is taken into account in the NS-2 simulator. In the following, we assume $G_t = G_r = 1$ (isotropic antennas) and $f_l = 1$ (no loss not associated with propagation).

In the presence of shadowing, denoting by $P_r^{(0)}$ the received power (associated with a given transmit power P_t)

Table 1: Reference values for the major parameters in the used NS-2 simulation environment of *ad hoc* wireless networks

Number of nodes N	50
Area A, m $\times$m	1500 $\times$300
Node spatial density ρ_S, m^{-2}	1.1$\times$ 10^{-4}
Active source nodes N_a	10
MAC protocol	DCF(IEEE 802.11)
Attenuation model	Two-ray ground (and shadowing)
Bit rate R_b, Mb/s	2
Carrier frequency f_c, MHz	914
Maximum radio range, m	250
Maximum transmit power P_t^{max}, W	0.282
Initial node energy, J	30
Send buffer, pck	64
Interface queue, pck	64
Source type	Constant bit rate
Packet dimension L, byte	512
Packet generation rate λ, pck/s	4
Correct receive threshold, W	3.652$\times$ 10^{-10}
Threshold to avoid collisions, W	1.559$\times$ 10^{-11}
Collision Threshold, dB	10
Simulation time, s	900
Pause time, s	900, 600, 300, 120, 60, 30, 0
Maximum speed v_{max}, m/s	20

at a reference distance d_0, the received power at a generic distance d can be expressed, in logarithmic scale, as follows [34]

$$\left[\frac{P_r}{P_r^{(0)}}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \quad (2)$$

where β is the pathloss exponent ($\beta = 4$ in the considered scenario with two-ray ground pathloss model) and X_{dB} is the logarithmic version (in dB) of a random variable X which takes into account the influence of the environment on signal propagation. Extensive experimental analysis shows that X has a log-normal distribution [35], that is X_{dB} is a zero-mean Gaussian random variable (in dB).

2.2.2 MAC protocol: In the IEEE 802.11 standard, although RREQ packets are broadcast packets at the MAC level, RREP, RERR and data packets are all unicast packets with a specified neighbour as the MAC destination [29, 33]. 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 AWGN message after data transmission.

2.2.3 Buffering: In all considered routing protocols, each node buffers at most 64 data packets waiting for a route, for example packets for which route discovery has started, but no reply has arrived yet. To prevent indefinite buffering of packets, packets are dropped if they wait in the send buffer for more than 30 s. All packets (both data and routing) originated at the routing layer are queued at the interface queue until the MAC layer can transmit them. The interface queue policy per packet type is first-in first-out, and routing packets have higher priority than data packets.

2.2.4 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 reference scenario, the mobility is characterised by a random way-point model [5], 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 reference scenario, to 20 m/s. We will analyse the impact of the speed by varying its 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), whereas a pause time of 900 s (the duration of the entire simulation) corresponds to no motion at all. Intermediate cases, between continuous movement and the complete absence of movement, are associated with values of the pause time between 0 and 900 s. We point out that an interesting extension of our framework could encompass scenarios where different nodes possess different speed distributions. However, this requires further research, and an accurate characterisation of the mobility model goes beyond the scope of this paper. In particular, in [36] a generic mobility model, denoted as ‘random trip’, for random and independent node motions is proposed, together with its NS-2 implementation details. This model encompasses, as a special case, the random way-point model and solves its stationarity problems in static conditions (i.e. with pause time equal to 900 s).

2.2.5 Energy model: The energy model, as implemented in the NS-2 simulator, is a node attribute. Its initial value corresponds to the node energy level at the beginning of the simulation. It also takes into account the energy consumption associated with each packet transmission or reception act. When the node energy level goes down to zero, the node dies out, that is no more packets can be received or transmitted by the node. The initial energy of each node battery is 30 J in the reference scenario.

2.2.6 Performance metrics: The following metrics will be used to evaluate the performance of the routing protocols of interest: (i) packet delivery ratio, defined as the ratio between the number of data packets received by the destinations and those sent by active CBR sources; (ii) average end-to-end delay, defined as the delay between the time instant at which the data packet is originated at the source node and the time instant at which it reaches the destination (data packets that get lost en route are not considered, and delays because of route discovery, queuing and retransmissions are included in this delay metric); (iii) normalised routing load, defined as the number of routing packets transmitted per data packet delivered at the destination. (We point out that a data packet is generated by the source node of the route, and routing packets are generated, besides by the source, also by the intermediate (relay) and destination nodes). 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 behaviour.

Note that the used basic metrics allow to understand and characterise the network performance. Other metrics, for instance, can be derived from the considered metrics. For example, the throughput [dimension: (b/s)] can be obtained directly by multiplying the packet delivery ratio by the packet generation rate λ [dimension: (pck/s)] and the packet dimension $8 \times L$ [dimension: (b/pck))]. More specific performance metrics (such as, for example, goodput) cannot be evaluated straightforwardly, but require a proper modification of the NS-2 simulator.

3 Modified *ad hoc* on-demand distance vector routing protocol

Given a network with error-free links (e.g. a fibre 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 [20]. 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 1, the limitations imposed by the wireless channel cannot be neglected in *ad hoc* wireless networks. On the basis of a simple theoretical motivation, we then propose a new routing protocol, defined as MAODV, which corresponds to a modification of the AODV protocol with (approximate) minimisation of the BER at the final node of a route (i.e. the destination node).

At the end of each link (but the last one) of a multi-hop route, upon reception of a packet the receiving node performs detection and retransmission. Pessimistically, assume also that bit errors made in a link are not recovered in the following links. (This is valid especially at high values of the link signal-to-noise ratio (SNR), which is a necessary requirement for an *ad hoc* wireless network to correctly operate [18]. In this case, it is licit to assume that there is just one error at a time along a route). We denote as $\mathrm{BER}_{\mathrm{link}}^{(i)}$ the BER at the end of the ith link of the route, which depends on the signal-to-noise ratio (SNR) at the receiving node of the link (i.e. the link SNR) and the channel characteristics. A tight upper bound on the BER at the end of a route with n hops can therefore be written as

$$\mathrm{BER}_{\mathrm{route}} = 1 - \prod_{i=1}^{n}\left(1 - \mathrm{BER}_{\mathrm{link}}^{(i)}\right) \qquad (3)$$

To provide an acceptable BER at the end of a multi-hop route, the link BER must obviously be very low, that is $\mathrm{BER}_{\mathrm{link}}^{(i)} \ll 1$, $\forall i$. Hence, the following approximation is very accurate

$$\mathrm{BER}_{\mathrm{route}} \simeq \sum_{i=1}^{n} \mathrm{BER}_{\mathrm{link}}^{(i)} \qquad (4)$$

In general, the link BER can be written as follows (The communication-theoretic framework in [18] shows that the link BER might reach a floor in the cases where 'weak' (in terms of interference rejection) MAC protocols are used. However, in the case of CSMA/CA MAC protocol, as considered in this paper, expression (4) is valid).

$$\mathrm{BER}_{\mathrm{link}}^{(i)} = f\left(\mathrm{SNR}_{\mathrm{link}}^{(i)}\right) \qquad (5)$$

where $\mathrm{SNR}_{\mathrm{link}}^{(i)}$ is the SNR at the end of the ith link and $f(\cdot)$ is a decreasing function of its argument [35]. In particular, the link SNR can be approximately expressed as

$$\mathrm{SNR}_{\mathrm{link}}^{(i)} = c_{\mathrm{SNR}}^{(i)} P_{\mathrm{r}}^{(i)}$$

where $P_{\mathrm{r}}^{(i)}$ it the received power at the end of the i-th link and $c_{\mathrm{SNR}}^{(i)}$ is a proportionality constant which depends on thermal noise power, channel modulation/coding format, characteristics of the ith link and interference level [16, 18]. In the presence of PC, the coefficients $\{c_{\mathrm{SNR}}^{(i)}\}$ of the links along the same route might be different from each other. This suggests that an effective physical layer-routing strategy should optimise the transmit power not only on the basis of the link distance, but also on the 'status' of the link channel. This optimisation is fairly cumbersome. To grasp insights into the problem of power-controlled routing, for simplicity we assume that the coefficients $\{c_{\mathrm{SNR}}^{(i)}\}$ can be considered equal to a fixed value c_{SNR}. This assumption is reasonable in a 'steady-state' network situation, where the nodes tend to have a uniform distribution (over time) and the used power levels do not change too much from a portion of the network to another.

3.1 Scenarios with strong LOS communications

Assuming two-ray ground path loss, from (1) the received power at the end of the ith link can be expressed as $P_{\mathrm{r}}^{(i)} = (\alpha P_{\mathrm{t}}/d_i^4)$, where d_i is the length of the ith link. One therefore can express (4) as follows

$$\mathrm{BER}_{\mathrm{route}} \simeq \sum_{i=1}^{n} f\left(\frac{c_{\mathrm{SNR}}\,\alpha P_{\mathrm{t}}}{d_i^4}\right) \qquad (6)$$

Under the assumption of communications with strong LOS, that is with AWGN communication links, the BER is approximately an exponentially decreasing function of the link SNR [35]. Therefore, if one link had a length sufficiently longer than those of the other links (We point out that it might happen that a few links have almost equal length, longer than those of the remaining links. In this case, the approximation in (7) is not accurate. However, in scenarios with mobile nodes (and also in scenarios with static nodes distributed uniformly over the network surface), the probability that more links have the same longest length is very small.), the corresponding link BER would be the highest possible, and one could conclude that

$$\mathrm{BER}_{\mathrm{route}} \simeq f\left(\frac{c_{\mathrm{SNR}}\,\alpha P_{\mathrm{t}}}{d_{i_{\max}}^4}\right) \qquad (7)$$

where $i_{\max} \triangleq \operatorname{argmax}_i\{d_i\}$, that is the $i_{\max}$-th link is the one with longest length. In this case, a routing strategy minimising the route BER can be equivalently reinterpreted as a strategy which leads to the selection of the route with the shortest possible longest hop. This is the route selection strategy embedded (through NS-2) in the proposed MAODV-routing protocol. We point out, however, that the NS-2 simulation scenario will take into account the realistic interference among the nodes, which does not directly appear in c_{SNR}. In this sense, the simple theoretical analysis presented in this section could be refined, for example, modelling c_{SNR} as a random variable. It remains to be investigated what is a realistic statistical distribution for c_{SNR}.

3.2 Scenarios with shadowed communications

In a scenario with shadowing, taking into account (2) the approximate expression (4) for the route BER can be rewritten as

$$\mathrm{BER}_{\mathrm{route}} \simeq \sum_{i=1}^{n} f\left(\frac{c_{\mathrm{SNR}}\alpha P_{\mathrm{t}} X^{(i)}}{d_i^4}\right)$$

where $X^{(i)}$ is the lognormal attenuation over the ith link ($X^{(i)} = 10^{X_{\mathrm{dB}}^{(i)}/10}$). In this case, it is intuitive that the link with longest length does not necessarily correspond to the link with highest BER, that is lowest SNR at the ending node of the link. Therefore the route selection strategy implemented with the NS-2 simulator (i.e. selection of the route with the shortest possible longest hop) is expected to lead to a performance degradation, with respect to a scenario with strong LOS communications, in a scenario with shadowing.

3.3 Route creation phase

Fig. 1 shows a pictorial example of the different route choices determined by the MAODV (BER-based) and AODV protocols to connect, through multiple hops, node S to node D. Although the AODV protocol leads to the selection of the route between source and destination with the minimum number of hops (i.e. route S→1→D) the MAODV protocol leads to the selection of the route with the shortest possible longest hop length (i.e. route S→2→3→4→5→6→D). Another difference between the MAODV and AODV routing protocols consists of the way in which a multi-hop route is built. Although route building with the AODV protocol is completely local, in the case with the MAODV protocol we consider 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 following a received signal strength indication (RSSI)-based approach. Consider 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. We point out that estimation of the hop

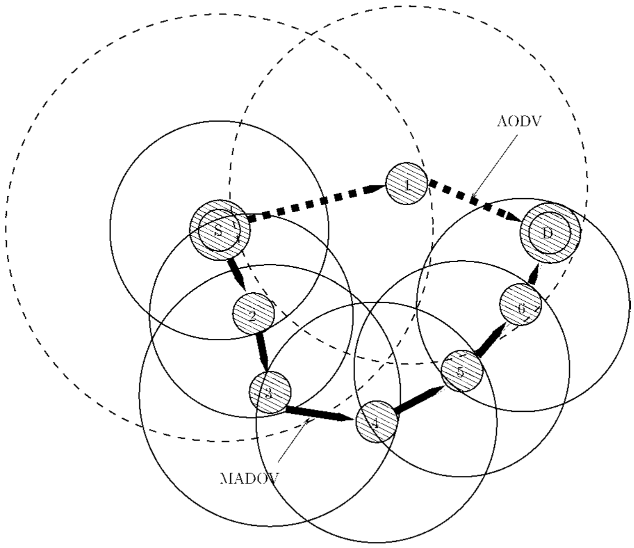

Fig. 1 *Routing strategies: MAODV (solid circles, centred at nodes, with radiuses equal to the corresponding nodes' transmission ranges) against AODV (dashed circles, centred at nodes, with radiuses equal to the corresponding nodes' transmission ranges)*

length from the received signal might be a good strategy in a scenario with strong LOS, whereas it cannot be a good strategy in a scenario with shadowing. The obtained simulation-based performance results will confirm this observation.

Accurate evaluation of the hop length is a significant problem in a decentralised wireless network, and we are currently investigating it. For example, in a scenario where nodes are equipped with positioning systems, their distances could be evaluated by the use of triangulation methods. In the simulations, we will assume 'ideal' knowledge of the hop length and the routing metric will be the maximum of the hop lengths of the links in a multi-hop path. On the other hand, direct estimation of the link BER could be considered. For example, provided that the quality of the link channel is sufficiently stable, one could predict the BER by proper evaluation of the previous packet losses in the same link.

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

Preliminary simulation results have clearly shown that the predominant cost to establish and maintain a communication route between two nodes is because of the route discovery phase, since the broadcast packets used for route discovery flood the network, creating significant interference. This critical situation is exacerbated in the case with mobile nodes. To avoid collisions when forwarding a broadcast discovery packet, the AODV protocol is such that an intermediate node selects a random delay to forward a received broadcast packet. To favour the creation of multi-hop routes with many short hops, the node broadcast timing of the MAODV protocol has been modified as follows. The delay chosen at an intermediate node is proportional to the link metric (i.e. the hop length) associated with the path terminating on the node. Note that prior work on the selection of the delay on the basis of a proper link metric exists. For example, in [37] the authors propose an energy-efficient-routing strategy such that the delay with which a node forwards a RREQ message is inversely proportional to its residual energy.

A simple example of a typical intermediate forwarding scenario during the route discovery phase is shown in Fig. 2. In this figure, node I is an intermediate relay node, which forwards an RREQ packet with the indicated transmission range. The nodes which are within its transmission range are nodes N_1, N_2 and N_3. Denoting by τ_i the retransmission delay at the ith receiving node, $i = 1, 2, 3$, the proposed MAODV protocol is such that $\tau_3 < \tau_1 < \tau_2$. This choice of retransmission delay tends to favour node N_3, since it will be the first to forward the received broadcast packet. As soon as nodes N_1 and N_2 receive the newly broadcast packet from N_3, they discard the previous packet from node I, since the packet sent by node N_3 is associated with a better metric. Moreover, this procedure

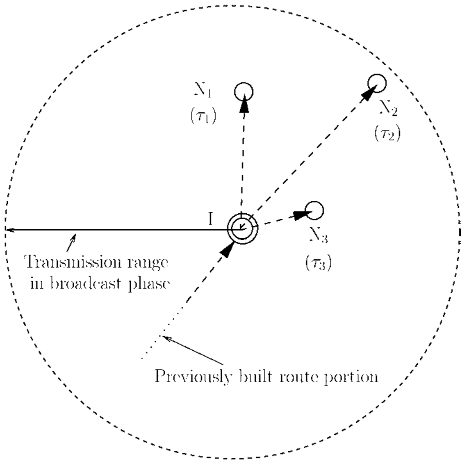

Fig. 2 *Intermediate forwarding during the broadcast phase: the RREQ packet sent from node I is received by nodes N_1, N_2 and N_3, which wait τ_1, τ_2 and τ_3 to retransmit. If the MAODV protocol is used, it holds that $\tau_3 < \tau_1 < \tau_2$*

has the positive side-effect of reducing useless broadcast transmissions. Note, however, that node N_1 (or N_2) might turn out being the only node that actually leads to the destination. In other words, the route selection strategy of the MAODV protocol seems to explore less possible routes with respect to the AODV protocol. On the other hand, assuming that the network is completely connected, the route selection strategy may lead to a selection of a longer route. Finally, we remark that some of the transmissions could still be stopped because of the hidden terminal problem. For example, a reduced transmit power over a single (short) link might silence a smaller number of nodes around the receiving node of this link. Therefore there might be a larger number of hidden terminals around this receiver. For instance, some of these hidden terminals might be the transmitters in longer links belonging to other active routes and therefore they may use a higher transmit power, thus interfering with the on-going transmission over the link of interest.

3.4 IEEE 802.11 MAC protocol with power control

Although in Fig. 1 an illustrative example of routing with PC is shown, we now give a more detailed description of the PC strategy. The PC 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: routing, data and MAC, respectively.

Routing control packets (such as, e.g. RREQ, RREP, RERR) are transmitted at maximum power, to give routing traffic the highest possible priority level. Routing control packets are typically short: the battery consumption is therefore limited.

Data packets, which are longer, are transmitted at variable power P_t, depending on the distance between transmitting and receiving nodes. As in [38], in our simulation we adopt ten possible transmit power levels: 1, 2, 3.45, 4.8, 7.25, 10.6, 15, 36.6, 75.8 and 281 mW, which roughly correspond (according to the considered two-ray ground propagation model) to transmission ranges equal to 40, 60, 80, 90, 100, 110, 120, 150, 180 and 250 m, respectively. This choice of transmit levels is such that the corresponding transmit ranges are spread around the average internode distance $1/\sqrt{\rho_S} \simeq 100$ m, where $\rho_S \triangleq N/A$ is the node spatial density.

MAC control packets (such as, e.g. RTS, CTS and ACK) are transmitted at the same power of the corresponding packet received from the routing layer. Like routing control packets, MAC packets are short.

Although the proposed PC strategy is effective in a scenario with strong LOS communications, the impact of shadowing will be deleterious on its performance. To understand this impact, in Fig. 3 it is shown (from left to right) how the shape of the surface covered by a transmitting node changes when the transmit power (hence, the transmission range) reduces. As one can observe from Fig. 3, assuming that a transmission power reduction does not affect the statistics of the log-normal random variable X (in particular, its variance remains constant), the impact of shadowing is proportionally much stronger when the transmit power is reduced. Therefore reducing the transmit power according to the link length without taking into account the presence of shadowing might increase the negative impact of shadowing. We point out, however, that in reality the variance of the log-normal random variable should decrease for decreasing distances [34]. Therefore the negative impact of shadowing in the presence of a transmit power reduction should be more limited.

4 AODV-and MAODV routing protocols: performance comparison in scenarios with strong LOS

In this section, the AODV-and MAODV-routing protocols are compared by using NS-2, both in the absence and the presence of PC. In all scenarios considered in this section, we assume the presence of strong LOS communications. Each result is obtained by averaging over a number of simulations, with corresponding spatially uniform starting node topologies, between 5 and 10 (the highest possible value allowed by our computational resources). The same simulator set-up will be considered also in Section 5.

4.1 Performance with variable pause time

To quantify the interference level, we define more accurately the traffic load. According to the CBR source assumption, a node generates constantly λ pck/s and the duration of a packet can be written as $T_{pck} = \frac{L}{R_b}$ [dimension: (s)], where R_b is the bit-rate [dimension: (b/s)] and L is the packet length [dimension: (b/pck)]. We denote (Provided that λ is sufficiently small, one can observe that the per-node traffic load measured in Erlang, given by $G_{Node-Erlang} \triangleq T_{pck}/1/\lambda = \lambda L/R_b$, can be equivalently re-interpreted as the channel utilisation ratio, that is it quantifies the

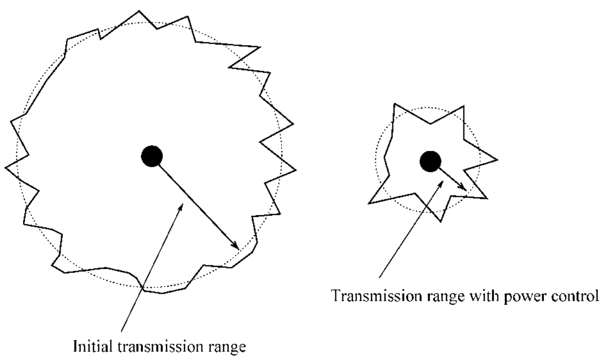

Fig. 3 *Impact of shadowing on the transmission area of a node: before power control (left) and after transmit power reduction (right)*

percentage of time during which a node is transmitting [39]. In correspondence to the reference values for the major network parameters in Table 1, it follows that $G^{\text{ref}}_{\text{Node-Erlang}} \simeq 0,012$ Erlang). as total offered load [dimension: (b/s)] the following quantity

$$G \triangleq N_a \lambda L \tag{8}$$

where N_a is the number of active source nodes.

The performance of the routing protocols under consideration are shown, as a function of the pause time, in Fig. 4. The network parameters are set as in Table 1: in particular, there are $N = 50$ nodes and the corresponding node spatial density is $\rho_S^{\text{ref}} \simeq 1.1 \times 10^{-4}\,\text{m}^{-2}$. Fig. 4*a* shows the delivery ratio performance. It can be observed that the use of PC has a beneficial influence for the MAODV protocol. In fact, for a sufficiently high pause time (from 200 to 900 s), that is in a scenario with slowly moving nodes, the MAODV-PC protocol offers higher delivery ratio than the AODV protocol. On the other hand, for high node mobility (i.e. for a pause time

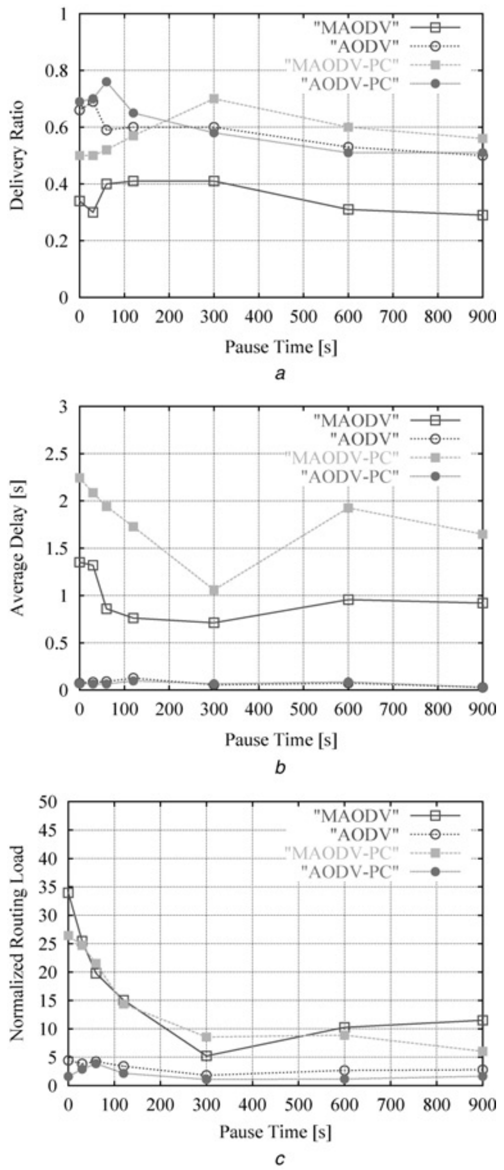

Fig. 4 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 10$ active source nodes. In all cases, strong LOS communications are considered*

a Delivery ratio
b Average delay
c Normalized routing load

lower than 200 s) the AODV-PC protocol is the best routing protocol. One can also observe that use of PC has a minor impact on the performance of the AODV protocol, noticeable only at low values of the pause time. The poor performance of the MAODV protocol in scenarios with high node mobility is because of a higher link failure probability, which leads to increased broadcast with respect to the AODV protocol. This explanation is motivated by the results shown in Fig. 4*c*, where the routing load is reported. As one can see, in a scenario with high node mobility, the normalised routing load with the MAODV protocol is significantly higher than that with the AODV protocol. This is because of the fact that the larger number of hops in a path leads to a larger number of transmissions and contentions. Therefore the interference level in the network increases as well, and the transmit power reduction is not sufficient to counteract this interference increase. The average delay is shown in Fig. 4*b*, which highlights that the AODV protocol offers better performance than the MAODV protocol. In fact, in a scenario with the MAODV protocol a route is formed, on average, by more nodes than in a scenario with the AODV protocol: therefore, owing to the characteristics of the IEEE 802.11 MAC protocol, it takes longer for a packet to reach its destination.

As one can see from the results in Fig. 4*c*, the normalised routing load characterising the MAODV and MADOV-PC protocols is very high.

To investigate the impact of the number of nodes, Fig. 5 shows the network performance, as a function of the pause time, in a scenario with $N = 100$ nodes and $N_a = 10$ active sources. The area of the network surface is $2200 \times 600\,\text{m}^2 = 1.32\,\text{km}^2$ and therefore, the node spatial density is $\rho_S \simeq 7.6 \times 10^{-5}\,\text{m}^{-2}$ – note that there is a slight reduction of the node spatial density with respect to that in the scenario in Fig. 4. Comparing the results in Fig. 5*a* with those in Fig. 4*a*, although the delivery ratio with the AODV and AODV-PC protocols remains basically constant for values of the pause time lower than 600 s, the delivery ratio with the MAODV and MAODV-PC routing protocols significantly degrades, increasing the number of nodes from 50 to 100, at low values of the pause time, that is in the high mobility region. This is because of the fact that in the presence of a larger number of nodes N, the average number of hops in a multi-hop route increases, and this phenomenon is more pronounced in a scenario with the MAODV and MAODV-PC protocols. (In a scenario with BER-based routing, it is possible to show that the number of hops is of the order of $\sqrt{N}$ [16, 18].) Therefore with the latter protocols there is a higher probability that at least a link of a multi-hop route will break down, as confirmed by a significant increase of the normalised routing load shown in Fig. 5*c*. Comparing Fig. 5*b* with Fig. 4*b*, one can conclude that, delaywise, the performance does not change appreciably if the number of nodes increases. This suggests that the number of active nodes influences significantly the average delay.

4.2 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. We first consider a scenario with pause time equal to 300 s, which corresponds to a medium mobility level, and then analyse a scenario with continuously moving nodes, that is pause time equal to 0 s. The other parameters are set as in Table 1.

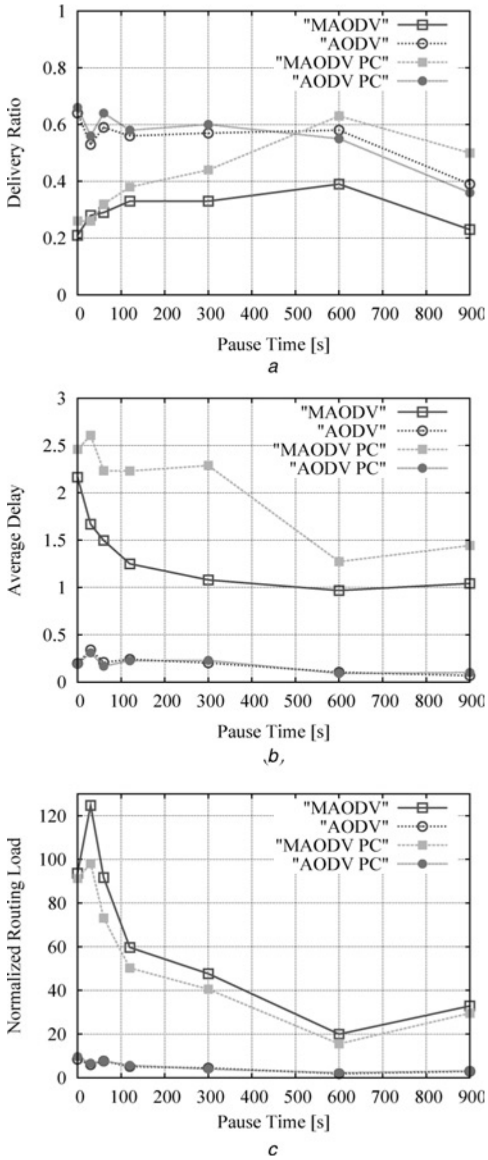

Fig. 5 *Scenario with N = 100 nodes, radio range equal to 250 m, packet generation rate λ = 4 pck/s and N_a = 10 active source nodes. In all cases, strong LOS communications are considered*

a Delivery ratio
b Average delay
c Normalized routing load

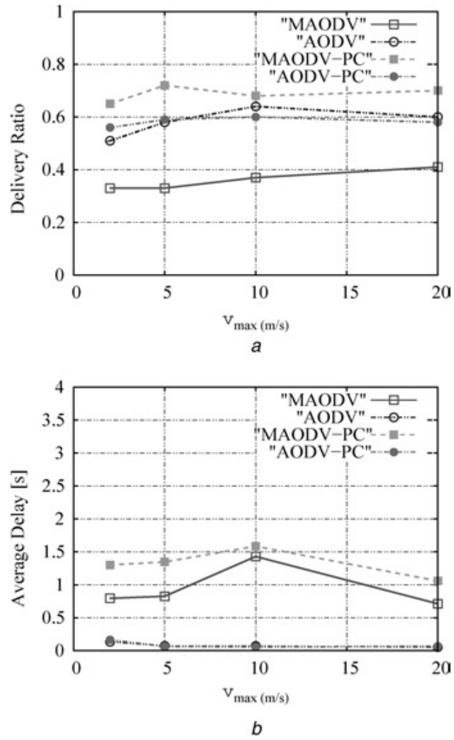

Fig. 6 *Scenario with N = 50 nodes, radio range equal to 250 m, packet generation rate λ = 4 pck/s, N_a = 10 active source nodes and pause time set to 300 s. In all cases, strong LOS communications are considered*

a Delivery ratio as a functions of the maximum node speed
b Average delay as a functions of the maximum node speed

In Fig. 6, the performance, in terms of delivery ratio (Fig. 6*a*) and average delay (Fig. 6*b*), is shown in a scenario with pause time equal to 300 s. According to the results in Fig. 6*a*, the best performance, in terms of delivery ratio, is obtained with the MAODV-PC protocol, regardless of the maximum node speed. Although the improvement brought by the use of PC with the AODV protocol is negligible, the delivery ratio with the MAODV-PC protocol is basically twice that obtained with the MAODV protocol without PC, with highest possible value around 70%. In other words, the results in Fig. 6*a* show that, even in a scenario with relatively high node mobility (the pause time is 300 s), the advantages introduced by the MAODV-PC protocol, 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}. As shown in Fig. 6*b*, the price to be paid for the higher delivery ratio guaranteed by the MAODV-PC protocol, with respect to the AODV (or AODV-PC) protocol, is a significantly higher (in relative terms) delay. As a partial justification for the negative delay performance of the MAODV-PC protocol, one can observe that this can be ascribed to the fact that the average number of hops required by the MAODV-PC protocol is higher than that with the AODV-PC protocol. Consequently, intermediate (relay) nodes have to process a higher number of transmitted packets and this increases the overall delay for packet delivery at the destination.

In Fig. 6, we do not show (for conciseness) the normalised routing load. Our results, however, show that the normalised routing load is approximately constant, with respect to the maximum speed, for each routing protocol. More precisely, the normalised routing load is approximately equal to the value shown in Fig. 4*c* in correspondence with the value of the pause time considered in Fig. 6, that is 300 s. The same behaviour of the normalised routing load has been observed (besides in the scenario considered in Fig. 7 with pause time equal to 0 s), also in the scenarios considered in Section 4.3, 4.4 and 4.5. In other words, our results suggest that the pause time, that is the mobility behaviour (rather than the mobility level, that is the maximum speed v_{max}), has the strongest impact on the normalised routing load. This observation will be confirmed also in the scenarios with shadowing analysed in Section 5.

We now consider the impact of the maximum node speed in a scenario with pause time equal to 0 s, that is with continuously moving nodes. The corresponding results (the counterpart of those in Fig. 6) are shown in Fig. 7, in terms of delivery ratio (Fig. 7*a*) and average delay (Fig. 7*b*). Observing the results in Fig. 7*a*, the

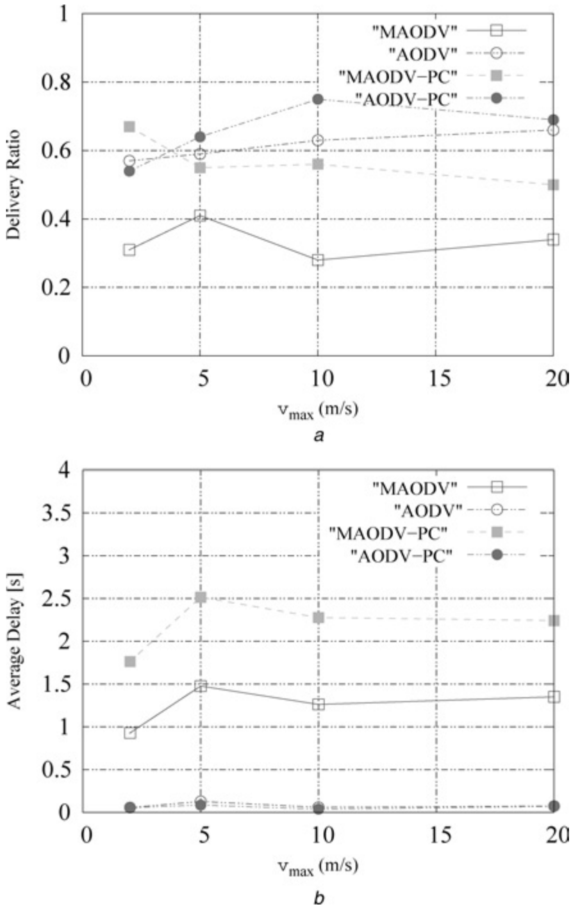

Fig. 7 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s, $N_a = 10$ active source nodes and pause time set to 0 s. In all cases, strong LOS communications are considered*

a Delivery ratio as a functions of the maximum node speed
b Average delay as a functions of the maximum node speed

MAODV-PC protocol guarantees a delivery ratio higher than that of the AODV protocol only for low values of the maximum speed (lower than 5 m/s). This performance degradation, with respect to the results in Fig. 6*a* (where the pause time is 300 s), is because of the fact that in a scenario where nodes move continuously, link failures are more frequent. This phenomenon is more pronounced for the MAODV (or the MAODV-PC) protocol, since links are (relatively) shorter that in the case with the AODV (or AODV-PC) protocol. Therefore for the same maximum speed, in a scenario with the MAODV protocol nodes are likely to move farther apart (relatively) than in a scenario where the AODV protocol is used (and links have a longer average length). The fact that links fail more often, for values of the maximum speed higher than 5 m/s, with the MAODV-PC protocol rather than with the AODV-PC protocol, is confirmed by the delay performance in Fig. 7*b*. In fact, comparing the delay behaviour of the MAODV-PC protocol in Fig. 7*b* with that in Fig. 6*b*, one can observe a drastic delay increase, in the former case, around 5 m/s.

4.3 Impact of initial node energy

In this subsection, we evaluate the impact of the initial node battery energy. The chosen energy values are 5, 10, 20, 30 and 60 J, respectively. The pause time is fixed to 600 s (low mobility level) and the other parameters are set as in Table 1. In particular, there are $N = 50$ nodes and $N_a = 10$ active source nodes. The performance, in terms of delivery ratio and average delay, is shown Fig. 8. As one can observe from Fig. 8*a*, the delivery ratio is an increasing function of the initial node energy level, regardless of the used routing protocol. As in the scenarios previously considered, in this case as well use of PC leads to a dramatic performance improvement only with the MAODV protocol. However, at low initial node energy, the MAODV-PC protocol offers a higher delivery ratio than the AODV protocol, since its efficient node energy consumption allows the nodes to increase their lifetimes. At high initial energy level, the AODV protocol is to be preferred because the energy consumption constraint is less stringent. Comparing the delivery ratio results in Fig. 8*a* with the average delay results in Fig. 8*b*, one can observe that the delay performance of the AODV (or AODV-PC) protocol is basically insensitive to the initial node energy. However, the average delay with the MAODV-PC (or MAODV) protocol is almost a linearly increasing function of the initial node energy. This is because of the fact that for increasing initial node energy, most of the nodes do not die in a short time. Therefore they are used to create routes with a larger number of short hops, and this, in turn, increases the average delay.

In a scenario with $N_a = 40$ active source nodes, our results (not shown here for conciseness) show that the MAODV-PC protocol still guarantees the best delivery ratio for low initial energy density. However, the delivery ratio becomes lower than that of the AODV protocol for an initial energy level approximately equal to 35 J (rather than 45 J as in Fig. 8*a*).

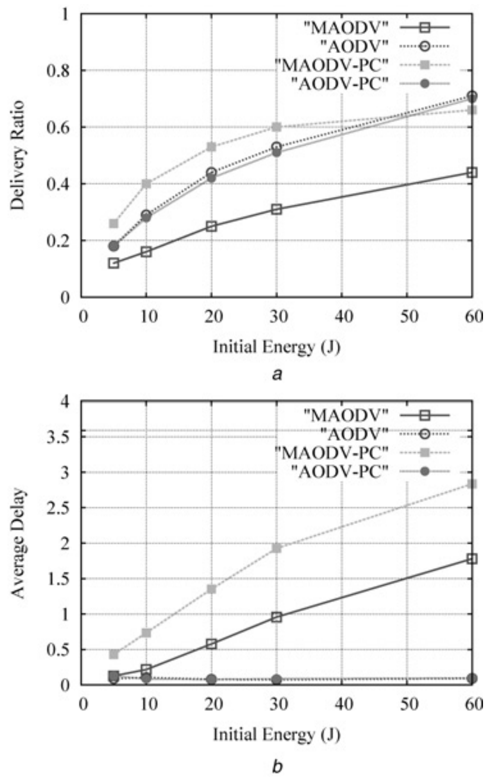

Fig. 8 *Scenario with N=50 nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s, $N_a = 10$ active source nodes and pause time set to 600 s. In all cases, strong LOS communications are considered*

a Delivery ratio as a functions of the initial node energy
b Average delay as a functions of the initial node energy

4.4 Impact of node spatial density

The impact of the node spatial density on a network performance is analysed in a scenario with static nodes, that is with pause time equal to 900 s. The number of nodes is kept equal to $N = 50$, so that a variation of the node spatial density corresponds to a variation of the network area.

In Fig. 9, the impact of the node spatial density on the performance with the four routing protocols considered in this paper is analyzed in a scenario with $N_a = 10$ active source nodes. From the delivery ratio results shown in Fig. 9*a*, it is immediate to recognise that all routing protocols have approximately the same performance for very low node spatial densities (for instance, lower than $5 \times 10^{-5}\,\mathrm{m}^{-2}$). In correspondence with the reference node spatial density ($\rho_S^{\mathrm{ref}} \simeq 1.1 \times 10^{-4}\,\mathrm{m}^{-2}$), the MAODV-PC protocol offers the best performance. For node spatial densities higher than $2 \times 10^{-4}\,\mathrm{m}^{-2}$, the behaviour of the considered routing protocol can be characterised as follows: the AODV protocol guarantees a 100% delivery ratio, whereas the MAODV-PC protocol reaches the maximum delivery ratio only at a node spatial density equal to $10^{-3}\,\mathrm{m}^{-2}$; the MAODV protocol guarantees a delivery ratio higher than that of the MAODV-PC protocol, but this ratio saturates around 80% for increasing node spatial density. In all cases (with both the AODV and MAODV protocols), the use of PC degrades the performance for increasing values of the node spatial density. This is because of the fact that reducing the transmit power jointly with the CSMA/CA MAC protocol increases the vulnerability from the remaining (dense) transmitting nodes. Therefore the use of PC in scenarios with high node spatial density might become effective only if the MAC protocol is properly modified. A modification of the MAC protocol in this direction is beyond the scope of our paper, but it represents an important research direction.

In Fig. 10, the impact of the node spatial density on the network performance is analysed by increasing the number of active node N_a from 10 (as considered in Fig. 9) to 40. As one can see from Fig. 10*a*, although the delivery ratio with the AODV protocol does not change appreciably, for high node spatial densities the performance of the MAODV protocol significantly degrades, and the impact of PC is much more detrimental than in the scenario with ten active sources (considered in Fig. 9). This is because of the fact that increasing the number of active source nodes leads to a heavy interference increase.

4.5 Impact of offered load

Finally, we analyse the network performance as a function of the total offered load G defined in (8). In Fig. 11, numerical results relative to a scenario with static nodes (i.e. pause time equal to 900 s) and $N_a = 10$ active source nodes are shown. Considering the delivery ratio, the results in Fig. 11*a* show a common decreasing trend, for increasing values of the total offered load, regardless of the specific protocol. More precisely, for each value of the total offered load, the AODV, AODV-PC and MAODV-PC protocols have approximately the same delivery ratio, which approximately reduces to half in a scenario with the MAODV protocol (without PC). As usual, the use of the

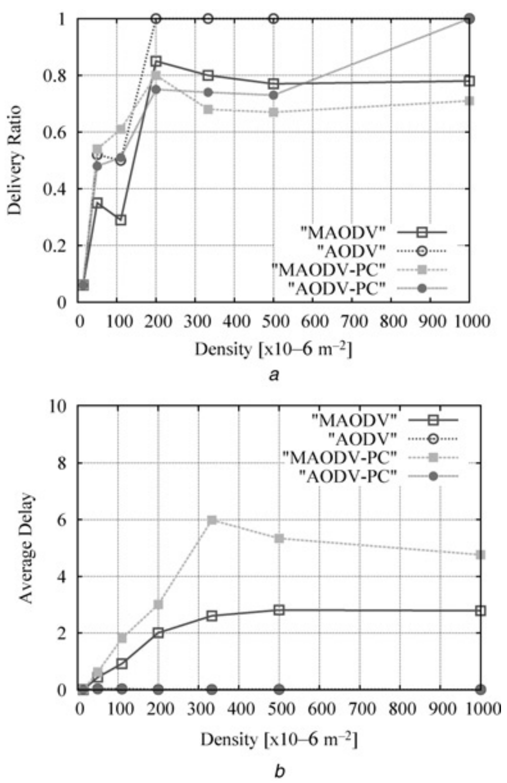

Fig. 9 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 10$ active source nodes. The pause time is set to 900 s. In all cases, strong LOS communications are considered*

a Delivery ratio
b Average delay

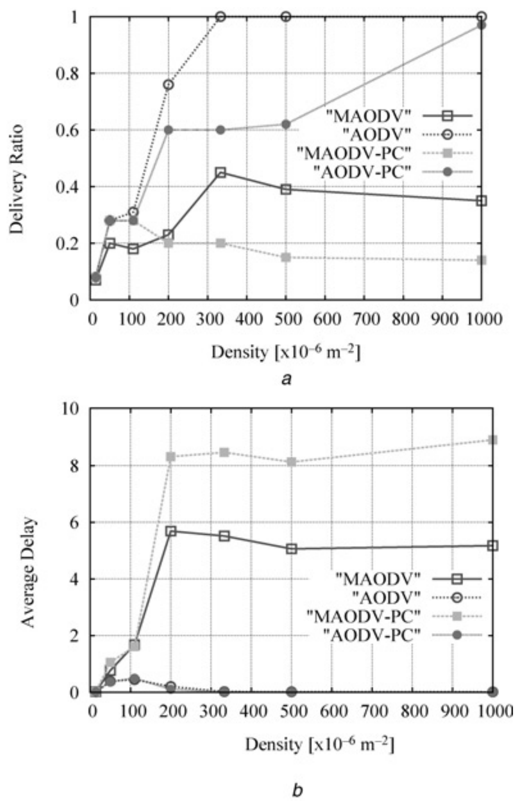

Fig. 10 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 40$ active source nodes. The pause time is set to 900 s. In all cases, strong LOS communications are considered*

a Delivery ratio
b Average delay

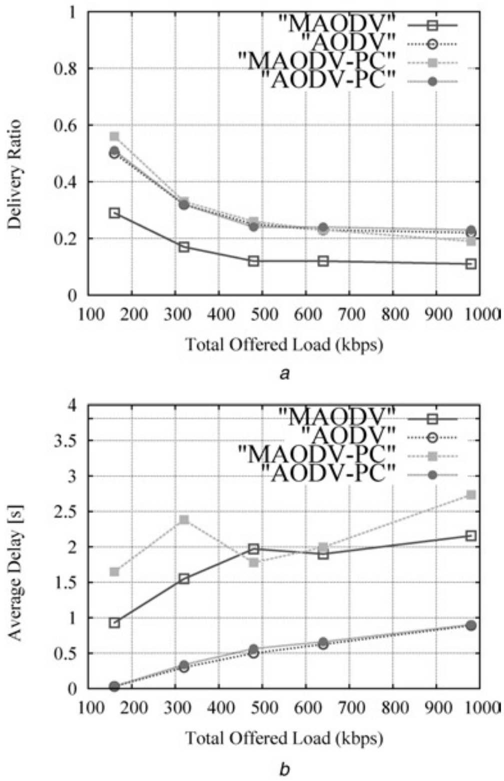

Fig. 11 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 10$ active source nodes. The pause time is set to 900 s. In all cases, strong LOS communications are considered*

a Delivery ratio
b Average delay

MAODV/MAODV-PC protocols leads to a higher average delay, which is shown in Fig. 11*b*.

Considering a scenario with $N_a = 40$ active source nodes, the obtained performance curves (not shown here for conciseness) are basically identical to those shown in Fig. 11. In other words, for a given value of the total offered load, if the number N_a of active source nodes increases, then the average packet generation rate λ at each node reduces proportionally, and the two effects compensate, leaving the performance (either in terms of delivery ratio, delay, or normalised routing load) basically unchanged. This suggests that the total offered load is a concise and meaningful parameter for *ad hoc* wireless networks performance evaluation.

4.6 Discussion

The results presented in this section suggest that in scenarios with strong LOS communications there exist situations where the use of routing strategies with a physical layer-constrained QoS, implemented through the proposed MAODV routing protocol, is attractive to maximise the delivery ratio. However, to exploit the benefits of a BER-based routing strategy, PC (implemented through adaptive minimisation of the transmit power) has to be used. In fact, if PC is not used, the 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.

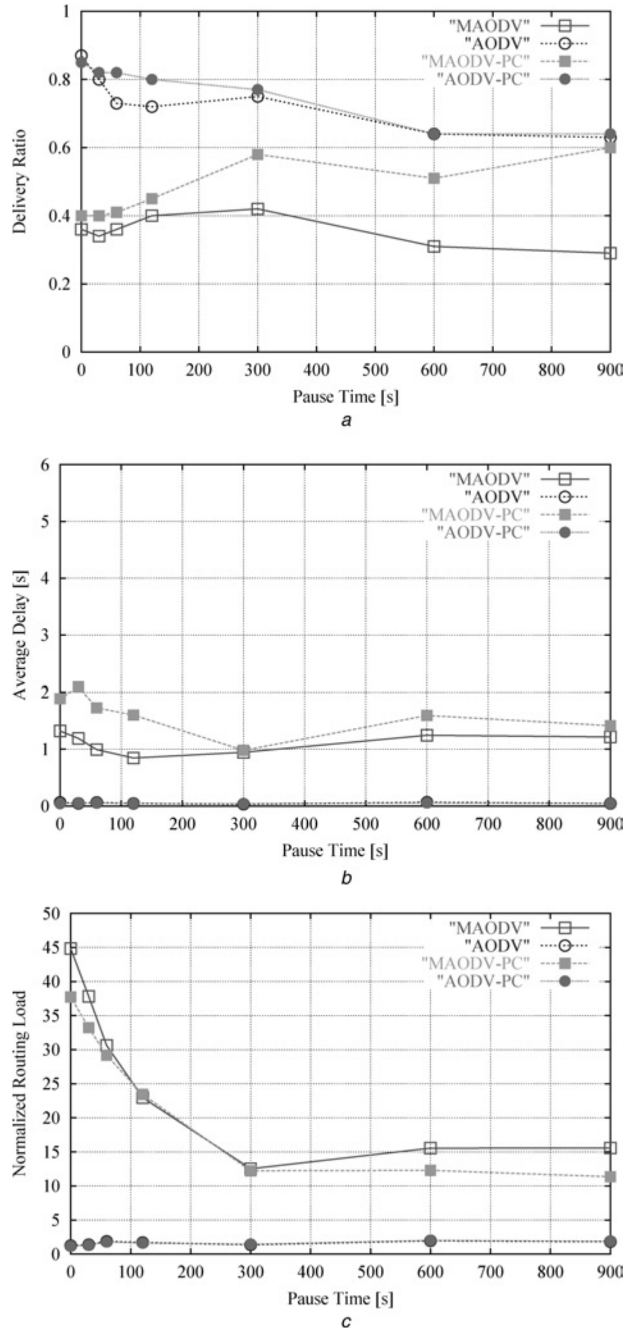

Fig. 12 *Scenario with shadowing, $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 10$ active source nodes. In all cases, communications are affected by shadowing*

a Delivery ratio
b Average delay
c Normalized routing load

Another observation concerns the route creation (broadcast) phase. In fact, throughout this paper, we have assumed that the transmission range during this phase is constantly equal to 250 m ($P_t \simeq 281$ mW). However, this is particularly detrimental if the MAODV-PC protocol is used, since the multi-hop routes are formed by (relatively) many hops. Therefore use of a large transmission range in the broadcast phase would damage a higher number of active link communications than in a scenario where the AODV (or AODV-PC) protocol is used. Note that this performance degradation is more severe in a scenario with a high node mobility level (i.e. small pause time), since in

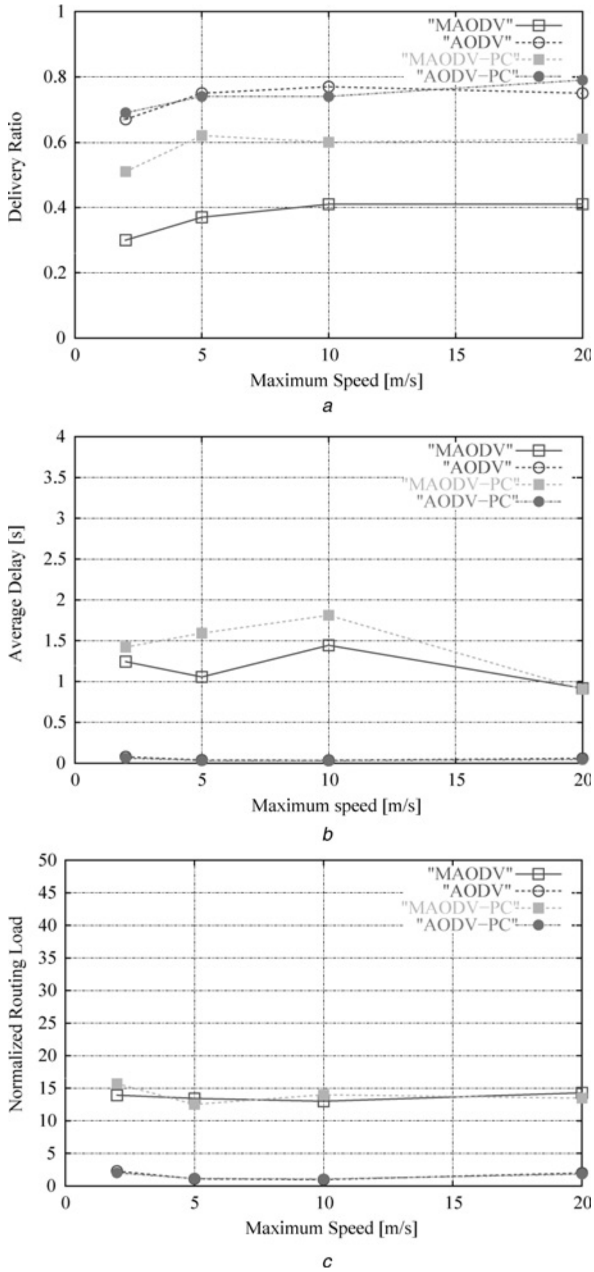

Fig. 13 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s and $N_a = 10$ active source nodes and pause time set to 300 s. In all cases, communications are affected by shadowing*

a Delivery ratio function of the maximum node speed
b Average delay function of the maximum node speed
c Normalized routing load function of the maximum node speed

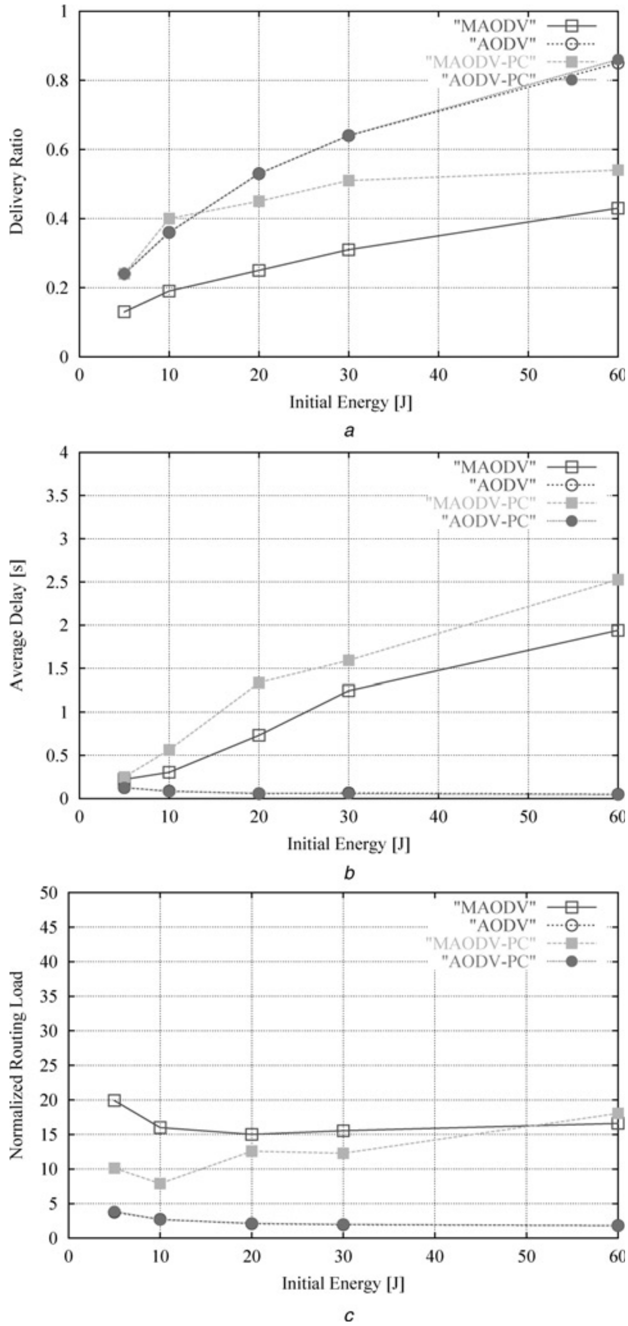

Fig. 14 *Scenario with $N = 50$ nodes, radio range equal to 250 m, packet generation rate $\lambda = 4$ pck/s, $N_a = 10$ active source nodes and pause time set to 600 s. In all cases, communications are affected by shadowing*

a Delivery ratio functions of the initial node energy
b Average delay functions of the initial node energy
c Normalized routing load functions of the initial node energy

this case links tend to fail and broadcast operations are required to discover new routes. This observation is confirmed by the results shown in Fig. 4*c*. Moreover, our analysis shows also that the AODV protocol outperforms the MAODV-PC protocol if the node spatial density increases, which further confirms these observations.

Finally, we make another observation regarding the modified broadcast timing used in the MAODV (and MAODV-PC) protocol, as described at the end of Section 3.3. This timing reduces, by itself, the overhead during route creation. However, an open problem is how to further modify it to decrease the transmission overhead in the broadcast phase and therefore improve the overall network performance.

5 AODV and MAODV routing protocols: performance comparison in scenarios with shadowing

In this section, we briefly consider the performance of the proposed routing schemes in scenarios with shadowed communications, as described in Section 2.2. In this case, we limit ourselves to analysing the impact of (i) pause time, (ii) maximum speed and (iii) initial node energy in scenarios with $N = 50$ nodes and $N_a = 10$ active sources. The goal of this section is to allow a simple, yet insightful, comparison with the performance in scenarios with strong LOS communications (analysed in Section 4).

In Fig. 12, the impact of the pause time on the performance of the considered routing protocols in the presence of shadowing is analysed. Considering Fig. 12*a*, for a pause time equal to 0 s (i.e. with continuously moving nodes) the impact of PC is negligible, and the delivery ratio with the MAODV (or MAODV-PC) protocol is basically half of that with the AODV (or AODV-PC) protocol. For increasing values of the pause time, the delivery ratio with the MAODV-PC protocol increases significantly with respect to that with the MAODV protocol, and reaches approximately that of the AODV protocol for a pause time equal to 900 s (static nodes). It is interesting to observe that for sufficiently low values of the pause time, the delivery ratio in a scenario with shadowing and $N = 50$ nodes degrades with respect to the equivalent scenario with strong LOS communications and $N = 100$ nodes (shown in Fig. 5*a*). However, the normalised routing load with the MAODV-PC protocol in Fig. 12*c* ($N = 50$ nodes and presence of shadowing) is about half of that with the MAODV-PC protocol in Fig. 5*c* ($N = 100$ nodes and strong LOS communications). This can be explained as follows. The presence of shadowing increases the probability of link breakage with respect to a scenario with strong LOS: in fact, the normalised routing load in Fig. 12*c* is higher than that in Fig. 4*c*. However, increasing the number of hops makes the impact of shadowing stronger and leads to a significant increase of the normalised routing load.

Finally, in Figs. 13 and 14, the impact of the maximum node speed and initial node energy in a scenario with shadowing is analysed, considering pause time values equal to 300 and 600 s, respectively. Comparing the results in Figs.13 and 14 with the equivalent results in the presence of strong LOS communications (Figs. 6 and 8), respectively, one can conclude that the MAODV-PC protocol never outperforms, in terms of delivery ratio, the AODV protocol. The performance, in terms of delay and normalised routing load, does not change appreciably from a scenario with strong LOS communications to a scenario with shadowing. This suggests that the effect of shadowing is highly correlated with the pause time, that is the mobility behaviour.

6 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 status of the physical layer influences significantly inter-node communications [18]. To take into account the impact of the physical layer on the network performance, we have considered, as a meaningful criterion for routing, the minimisation of the BER at the end of the route with a MAC protocol using PC mechanisms. In particular, the MAODV 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. Minimisation of the route BER has been (approximately) implemented as minimisation of the longest hop length in a multi-hop route. To exploit the potential advantages of BER-based routing, proper PC has been considered, and the corresponding routing protocol has been denoted as MAODV-PC.

The performance of the proposed physical layer-oriented routing protocols (MAODV and MAODV-PC) has been evaluated considering scenarios with either strong LOS or shadowed communications. In both scenarios, we have investigated the impact of PC. In a scenario with strong LOS communications, our results show that in some situations, characterised by low node mobility, low traffic load and low node spatial density, the MAODV-PC protocol can offer a better performance, in terms of packet delivery ratio, than the AODV protocol. The price to be paid consists of increased delay in packet delivery to the desired destination and increased routing overhead. In a scenario with shadowing, the MAODV protocol never outperforms, in terms of delivery ratio, the AODV protocol. Moreover, the proposed PC mechanism may, in some cases, degrade the system performance. This suggests that a novel joint routing/PC strategy has to be developed. In particular, given the extensive number of existing routing protocols, it would be interesting, as a first step, to investigate the applicability of a physical layer-oriented approach to other routing protocols (besides the AODV).

7 Acknowledgments

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