Distributed Power Control for Energy Efficient Routing in Ad Hoc Networks*

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Abstract

In this paper, distributed power control is proposed as a means to improve the energy efficiency of routing algorithms in ad hoc networks. Each node in the network estimates the power necessary to reach its own neighbors, and this power estimate is used both for tuning the transmit power (thereby reducing interference and energy consumption) and as the link cost for minimum energy routing. With reference to classic routing algorithms, such as Dijkstra and Link State, as well as more recently proposed ad hoc routing schemes, such as AODV, we demonstrate by extensive simulations that in many cases of interest our scheme provides substantial transmit energy savings while introducing limited degradation in terms of throughput and delay.

1 Introduction

In the recent literature, ad hoc networks have gained much attention, due to the convenience of building mobile wireless networks without any need for a pre-existing infrastructure. An ad hoc network is a collection of wireless mobile hosts which are able to cooperatively establish communications, using no fixed infrastructure or centralized administration. In such an environment, each host acts as a router and forwards packets to the next hop in order to reach, through multiple hops, the final destination.

Many issues need to be addressed in ad hoc networking, one of the most relevant being the packet route selection [32]. A number of algorithms which can be used to find convenient routes have been presented in the past literature, e.g., in [18] [20] [28] [29]. In proactive routing protocols [18] [28], paths towards all destinations are periodically refreshed even if not used. Normally, these protocols require nodes to broadcast information about their neighbors, and, based on this information, each node in the network computes the minimum path to every possible destination. In reactive routing protocols [20] [29] the path to reach a destination is discovered only when needed by means of a procedure called *route discovery*. With this procedure, the source finds more than one path and selects the "shortest" (usually in terms of number of hops). Note that routing algorithms need to know the network topology, so a given amount of control traffic overhead is always present and should be minimized in order to increase the useful data throughput and to decrease the packet delivery time and the energy consumption.

Most of these proposals are based on the intuitive goal of choosing the shortest paths, i.e., minimizing the number of hops. In view of another primary concern in ad hoc networks, namely energy consumption [21] [31], selecting the shortest path is not the best choice in general, since a number of short hops usually results in less energy consumption compared to fewer longer hops. A few papers have recently appeared, in which various routing strategies are compared in terms of energy consumption, i.e., based on the amount of energy which is spent in correctly delivering a packet to its final destination. A simulation study in [9] compares several routing protocols with respect to energy consumption, without proposing any improvement to those protocols to achieve better energy efficiency. Another study of the energy consumption of traditional ad hoc routing protocols has been done in [16]. In [42], two algorithms for routing in energy-constrained, ad hoc, wireless networks are presented, which work on top of existing on-demand ad hoc routing protocols. [35] and [36] propose new metrics to be minimized in finding the routing path. Those metrics are power-aware, that is their target is to maximize energy efficiency (e.g., by finding the lowest energy routing path) and/or the lifetime of the whole network (e.g., by balancing traffic). [10] proposes a new path cost for a static network which can be used with any existing algorithm. The objective is to find the link cost function which will lead to the maximization of the system lifetime. Energy efficient location based routing is studied in [44].

As an alternative (or in addition) to the minimization of the energy cost of delivering a packet, the energy status of intermediate nodes is also a concern, as it directly affects the network lifetime. Several papers have considered routing metrics which explicitly include residual node energy [2] [39] [41]. Specific battery characteristics are used to devise

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smart routing strategies in [12].

In order to achieve optimal network connectivity, very recent papers propose to use power adjustments at some or all nodes. Several definitions of optimal network connectivity can be adopted, i.e., the one that minimizes the energy used in delivering packets, or the connectivity which guarantees a non-partitioned network. [30] deals with the problem of adjusting transmit power levels to achieve a desired degree of connectivity in the network, while using the minimum transmit power. [15] proposes to use power to maintain a certain degree of connectivity in terms of number of reachable neighbors. Algorithms for the generation of energy-efficient multicast trees have been proposed in [3] [25]. Energy-efficient multicast is considered in [22] as well. Additional papers on energy-efficient routing include [4] [17] [23] [24] [33] [38] [40].

In many of these studies, new metrics directly related to the transmit power and/or to the battery status of the nodes in the path are considered, but an exact knowledge of the topology is always assumed; therefore, they do not consider the signaling overhead necessary to update the topology knowledge, which on the other hand consumes energy and increases network congestion.

The main contribution of the present paper is the proposal of a novel strategy, called Distributed Power Control (DPC), which acts in combination with the routing layer. This is realized by means of a mechanism which estimates the amount of power which is needed for reliable communications over any link. [1] This power is then used both to transmit a packet over the link, and as the link weight in a minimum-weight path search algorithm. In this way, transmit power can be tuned in order to build the desired connectivity diagram. In addition, the transmit power information is used to privilege lower energy paths when looking for a packet route. Existing routing protocols, such as proactive and reactive protocols, can be modified in order to incorporate this power control feature which tries to jointly minimize the interference in the network and the energy consumption of multihop operation.

In order to assess the advantages of the proposed approach, we have performed extensive simulations under various operating conditions. We consider first the classic Dijkstra routing algorithm, in which the network topology is assumed known without overhead. While unrealistic, this case represents a performance bound and can help us understand the potential of our DPC idea. Next, we examine the Link State routing algorithm, which explicitly accounts for all the signaling overhead needed in order to gain knowledge about the network topology. We remark that this additional traffic must be considered, since it consumes energy while not being directly related to the delivery of useful traffic. Finally, as a realistic example of routing schemes specifically designed for ad hoc networks, we consider the Ad hoc On-demand Distance Vector (AODV) algorithm [29]. For all three cases, we evaluate the performance in terms of both energy efficiency (which is our main goal here) and quality of service (which should never be excessively compromised). Relevant tradeoffs and comparisons are highlighted in many different cases, including propagation effects, node mobility, protocol parameter optimizations, types of traffic and traffic intensity. Our results show that the relative gains may be significantly affected by the specific scenario considered, but they lead to the conclusion that in many cases of interest the proposed DPC scheme makes it possible to gain significantly in terms of energy efficiency while paying a small price in terms of performance degradation.

It should be remarked at this point that our approach implicitly assumes that the transmit power is the dominant source of energy consumption. Some very recent papers point out that in some practical scenarios this may not be true, and different solutions must be sought in which nodes are aggressively put to sleep, as an idle listening transceiver may consume as much as a transmitting radio [11] [34] [43]. Our results may still be applicable to environments where sleep modes are used at the MAC layer to avoid idle listening [45].

The paper is structured as follows: in Section 2 the DPC mechanism is described in detail; in Section 3 the network architecture and the simulation setup are explained; in Section 4 extensive simulation results are presented; and Section 5 concludes the paper.

2 DPC Mechanism

The proposed distributed power control strategy works at two different levels: hop-by-hop and end-to-end. In particular, it is based on the preliminary selection, hop-by-hop, of a suitable transmit power level, with the aim to reduce the energy consumption and to increase the overall network performance. Furthermore, this transmit power level is used as the link cost function in the path discovery and selection.

This method requires that each node can record in a suitable packet format field the power level, P_{TX}, used to transmit that packet. Furthermore, it requires that the radio-transceiver can estimate the received power, P_{RX} (many drivers of products based on the IEEE 802.11 standard provide this information).

With the knowledge of P_{TX} and P_{RX}, the generic node is able estimate the link attenuation. In particular, when a station receives a packet from a neighbor, the channel attenuation is simply computed as the difference (in dB) of the transmitted power P_{TX} and the received power P_{RX}. For the simple case of a symmetric channel, where we neglect possible channel time fluctuations and we assume the same interference power level, the attenuation affecting the transmission of that station towards that neighbor would be the same as measured. Thus, a good choice for the transmit power $\tilde{P}_{TX}$ could be:

[1] Very similar work recently appeared in [14]. Only after submission of this manuscript did we become aware of that work, which on the other hand was published several months after the conference presentation of the present contribution [5].

$$\tilde{P}_{TX} = P_{TX} - P_{RX} + S_R + Sec_{th} \quad (1)$$

where S_R is the minimum power level required for correct packet reception and Sec_{th} (*Security Threshold*) is a power margin introduced to take into account channel and interference power level fluctuations, i.e., to make the transmission more reliable in view of the fact that the channel is not symmetric. We assume that Sec_{th} is the same for each terminal and its value should be properly set as a function of network density, terminal speed and channel conditions. Note that the $\tilde{P}_{TX}$ update can be performed also sniffing packets directed to other terminals, so that the transmit power information can be refreshed more often.

In our DPC proposal this hop-by-hop power level selection is also used to select the path guaranteeing low energy consumption. In fact, the $\tilde{P}_{TX}$ values associated to all links are considered as the cost functions used by the routing algorithms to select the packet path, thus implementing energy saving at the end-to-end level.

The proposed DPC can be applied to many routing algorithms and for each routing scheme different implementations are possible. In this paper we focus on three different routing protocols: Dijkstra (Dij) [6], Link State (LS) [37] [8] and Ad hoc On Demand Distance Vector (AODV) [27] [29].

Dij and LS are classic routing protocols, conceived for wireline networks, while AODV has been designed specifically for ad hoc networks. In order to know the network topology in every moment, these routing schemes are in general based on signaling traffic exchange between nodes. The signaling packets contain information about the neighbors of a given node and/or about the whole network topology; on the basis of this knowledge a given source can select the path to the target. Note that in order to maximize the final performance (in terms of percentage of correctly delivered packets, end-to-end delivery time, and energy efficiency) the signaling traffic is usually to be minimized.

In this paper, the LS and AODV signaling overhead has been explicitly simulated to have a realistic performance investigation. On the other hand, no signaling traffic has been considered for Dij, where the station positions are always assumed known. This provides upper bound performance which can be useful for a comparison with the LS and AODV algorithms.

The LS routing protocol falls in the class of *proactive* routing protocols, while AODV is part of the *reactive* protocol class. In *Proactive* protocols the topology update and the signaling traffic exchange is performed periodically, while in the *reactive* algorithms it is performed when strictly necessary, i.e., when a packet must be sent and no useful topology information is available. So, in general, *reactive* protocols limit the signaling traffic overhead but result in a larger latency in packet delivery.

Note that in their classic definition these algorithms try to minimize the number of hops to reach a destination. In the proposed power controlled version these schemes minimize the total energy necessary to deliver a packet (which does not necessarily result in the smallest number of hops). For example, in the classic Dij routing scheme the cost function associated to each link is always 1; in the power controlled version, the cost function of the generic link between two nodes is the power needed to transmit a packet from a node to the other, estimated as in Eq. (1). So, in the power controlled Dij version, the path is chosen by selecting the route which minimizes the sum of the powers needed on each link. The same considerations may be applied to LS and AODV.

In the DPC realization, a limited range for the transmit power has been introduced, i.e., minimum and maximum values for the transmit power, $P_{TX_{min}}$ and $P_{TX_{max}}$ (established in the start up phase) have been set. Note that in the classic version of the algorithms the transmit power is always fixed to a given value that, in our implementation, is equal to the maximum power $P_{TX_{max}}$.

In the following a general overview of classic Dij, LS and AODV are given, with a description of the changes required to implement DPC.

2.1 Dijkstra

The classic Dijkstra (Dij) algorithm [6] [37] has the aim to build a path between source (So) and final target (Ta), by minimizing the number of hops. The link between any pair of nodes a and b has unit cost, $l_{a,b} = 1$, if the involved nodes are connected, and $l_{a,b} = \infty$ otherwise.

Let D_v be the cost function relative to the link between the So-th and the v-th generic station and let $\mathcal{F}$ be the set including the nodes to be passed to reach the target Ta; the algorithm is therefore:

1) $\mathcal{F} = \{So\}$ and $D_v = l_{So,v}\ \forall v \notin \mathcal{F}$;
2) select $w \notin \mathcal{F} | \forall z \notin \mathcal{F}, w \neq z, D_w \leq D_z$;
3) if $w = Ta$ or $D_w = \infty$ then exit;
4) $\mathcal{F} = \mathcal{F} \cup \{w\}$;
5) $\forall z \notin \mathcal{F}\ D_z = \min[D_z, D_w + l_{w,z}]$;
6) go to step 2;

We assume the node locations are always known, even in a node mobility situation. Furthermore, in order to have the final paths always updated, the algorithm reported above is continuously recomputed by each node.

In the DPC implementation the algorithm is the same, but if the nodes are in visibility the cost function $l_{a,b}$ is equal to the transmit power, chosen following Eq. (1). In both classic and DPC schemes no signaling traffic is considered.

2.2 Link State

The Link State (LS) routing protocol [37] [8] is based on the exchange of suitable signaling packets, in order to discover the network topology and its changes as a consequence of the node mobility. It is an example of a *proactive* protocol and it works as follows. Each node shall:

1) Discover its one hop neighbors and the status of each discovered link (symmetric, i.e., bi-directional, or asymmetric). It accomplishes this goal by periodically sending a broadcast HELLO packet with Time to Live (TTL) equal to 1. A HELLO message contains:

- the source address
- the list of addresses of the node neighbors towards which a valid bidirectional link exists
- the list of the addresses of all nodes, i.e., the nodes which are heard by this node (i.e., from which a HELLO has been received) but whose link is not yet validated as symmetric.

Upon reception of a HELLO message, the node updates the neighbor entry corresponding to the sender node, and sets the link status to symmetric if it finds its own address in the HELLO payload.

2) Send a broadcast packet (LS_PKT) with highest TTL, containing the list of neighbors with symmetric links just discovered, and the weight of the corresponding links.

3) With the information received with the LS_PKT packet, build a network graph in which only symmetric links are present. Dij's algorithm can be used to find the minimum cost path to all possible destinations and to build the routing table.

Note that, as in the Dij scheme, we have assumed for classic LS a link cost function equal to 1 if the nodes are in visibility, and equal to ∞ otherwise. In the power controlled version of LS, the final path is selected by minimizing the sum of the transmit powers on each link, computed as in Eq. (1). Note that in both classic and DPC versions the HELLO and LS_PKT packets are sent at the maximum transmit power $P_{TX_{max}}$. The transmission rates of the HELLO and LS_PKT packets have been set according to [18].

In the DPC scheme, upon reception of a HELLO message, the generic node fixes the cost of the link to the power:

$$\overline{P}_{TX} = P_{TX_{max}} - P_{RX} + S_R + Sec_{th}$$

$\overline{P}_{TX}$ is also the transmit power used by the receiving node in a successive transmission over this link, and is inserted in the next HELLO packet as the cost function associated to that link. Furthermore, for every received data packet, the receiving node updates the cost of established links in its routing table with the same procedure used for HELLO packet but the maximum power $P_{TX_{max}}$ is replaced with the transmission power of the received packet, which may be expected to lead to a reduction of the energy spent in transmission.

2.3 AODV

AODV [27] [26] is an on-demand, *reactive*, single path, loop free, distance vector protocol. Classic AODV uses routing tables characterized by only one entry per destination, so that, with respect to the Dynamic Source Routing (DSR) [20] protocol, no multiple paths per destination are present.

Even though many variations to AODV have been proposed in literature (for instance, AOMDV: On Demand Multiple Distance Vector [7]), in this paper we focus on the classic protocol by reviewing the basic features and by describing the changes needed in order to implement distributed power control.

AODV is a reactive protocol, i.e., it finds the path to a destination only when needed. The generic procedure is to flood the network in order to reach the destination; when the destination is reached, it sends back a control packet over the path from which it has received the request.

The AODV protocol is mainly based on four procedures:

- **Route Discovery**: starting phase for discovering a path;
- **Forward Path Setup**: used to inform the source and the relay nodes about a certain path;
- **Route Maintenance**: used to manage the time validity of a path and the link failures due to mobility, channel or traffic conditions;
- **Local Connectivity Management**: used to have recent information on the neighboring nodes

Every time a source needs a route to a destination, it starts a **Route Discovery** process [27] [13]. This process is based on the transmission of broadcast packets, called *Route Requests* (RREQ), each characterized by an identity number (ID), which is rebroadcast through the network until the destination is reached.

For each new RREQ received, an intermediate node creates a table entry. If the node receives the same RREQ (i.e., with the same ID) in a given interval, called BROADCAST RECORD TIME [27], it does not rebroadcast it.

The **Forward Path Setup** procedure is the following. When the destination node receives a RREQ, it replies to the source with a unicast packet, which is sent using the same path followed by the arrived RREQ. The unicast packet is called *Route Reply* (RREP). When a RREP is received, every intermediate node refreshes the route table information and forwards the RREP packet until the source is reached. The information in the table of each node is deleted if it not refreshed within a fixed time. Note that, when the destination receives multiple RREQs with the same ID and relative to the same source-destination pair (necessarily from different neighboring nodes), it does not reply to them for the BROADCAST RECORD TIME. After that, it starts again to reply to the RREQs for that node pair.

Furthermore, to limit the signaling traffic, if an intermediate node receiving a RREQ knows the route to the final destination, it directly replies to the source with a RREP. Also in this case, if this node receives other RREQs relative to that same pair of nodes, it does not send any further RREP.

The packets to be sent are stored by the source node in a buffer until the RREP is received.

The **Route Maintenance** procedure is used to manage the time validity of a path and the link failures due to mobility, channel or traffic conditions. When a target becomes unreachable, the relay node sends broadcast packets, called *Route Error* (RERR), to inform the source and the other intermediate nodes about the link failure.

Regarding the **Local Connectivity Management**, each node sends periodically a broadcast packet with TTL=1, called *HELLO* packet, to inform all neighbors that it is "alive".

Finally, to determine freshness of routing information and to prevent routing loops, a mechanism based on a *sequence number* is used. More in details, each node of the network is characterized by a number called *sequence number* which is increased every time its neighborhood topology changes.

To apply the *power control scheme* to AODV we have changed some features of the protocol. In particular, each node of the network records in its route table the total power to reach a destination and the power to reach the next hop in the path, computed as in Eq. (1). The information required to estimate the transmit power as in Eq. (1), such as the link attenuation, is collected by using the RREQ and the RREP packets that carry the knowledge of the transmit powers P_{TX} as explained in [5]. To refresh transmit power information more frequently, data packets are also used.

Even if in the classic AODV a node does not reply to multiple RREQs received within the BROADCAST RECORD TIME, in our DPC scheme it does so. This is introduced to support the power control scheme, since we need all the possible routes that a packet could use to reach the final destination, even those characterized by a large number of hops, which may correspond to lower energy consumption.

Therefore, when a node receives a RREQ already received, it only checks if the corresponding route is more energy efficient than the route in its routing table. If the route is really more efficient, the node broadcasts the RREQ or sends back a RREP (if the node is the destination or knows the route to the target).

Note that this modification increases the routing traffic. On the other hand, the changes we applied permit us to find a route with lower power consumption. So, the system is expected to introduce an energy gain if the energy saving introduced in the packet delivery is greater than the additional energy loss due to the routing signaling procedure.

3 Network Architecture and SAM Structure

To evaluate the DPC effectiveness in a realistic environment a general network architecture, integrating traffic features, terminal mobility, channel behavior, medium access scheme and routing protocols has been considered.

This architecture has been simulated, by integrating all characteristics typical of the Physical, Data Link and Network layers of the ISO/OSI model into a general Simple Ad hoc siMulator (SAM).

SAM is a discrete event simulator, composed by many modules or entities: **Traffic**, dealing with the traffic generation; **Channel**, simulating the radio propagation; **Mob**, dealing with the terminal mobility; **Radio**, simulating the hardware transceiver; **Mac** realizing the Data Link Layer; **Route**, implementing the Network layer; and **Statistics**, collecting statistics results.

The entity structures and the protocols currently available are the following:

- **Traffic**: generates the network traffic. Two different traffic types have been implemented: *asynchronous* traffic and *isochronous* traffic. The *asynchronous* traffic is realized by considering a Poisson distribution for both arrival times and service times. The *isochronous* traffic is a classic CBR traffic used to simulate multimedia streaming. The Mac module, described below, treats *asynchronous* and *isochronous* packets in a different manner: for instance, if the IEEE 802.11 DCF is used, the *isochronous* packets are sent without RTS/CTS and ACK handshake.

- **Channel**: simulates radio propagation. Path loss, shadowing and Rayleigh or Rice fading via Jakes' simulator [19] are implemented.

- **Mob**: simulates the terminal mobility. Pseudo-linear mobility is implemented: new directions and speed of terminals are recomputed at constant time intervals. The speed is chosen as a Gaussian random variable with a given mean value and the direction is computed as an uniform random variable with a mean value that is the most recent direction.

- **Radio**: realizes the transmission and the reception of packets. The packets are transmitted with a power level decided by the upper layers following the mechanism described in Section 2. Furthermore, it estimates the received power and it simulates the capture effect if present, i.e., the ability to correctly receive a packet even if collided depending on the Signal to Interference and Noise Ratio (SINR). The use of spread spectrum and channel coding can also be accounted for.

- **Mac**: simulates the channel access mechanism. An IEEE 802.11 DCF protocol [1] has been included into this module so far.

- **Route**: simulates the Network layer. It generates routing packets to discover neighbors and to compute the path to reach the destination. LS [8], Dij [37] and AODV [27] [29] have been implemented.

- **Statistics**: collects results. The performance indices we have identified are: success probability, P_{succ} (percentage of delivered packets), normalized average end-to-end packet delivery time, T_{acc} (the average time from a packet arrival until its correct delivery to the final destination divided by the average time to transmit a packet over the air interface), average energy spent per packet, E_p, (ratio between the total energy spent during simulation and the number of correctly delivered packets), throughput S (ratio between the useful time and the total time of simulation).

4 Simulation Results

In this Section some numerical results regarding the Dij, LS and AODV routing algorithms with and without DPC are shown. Note that in the classic versions the transmit power $\tilde{P}_{TX}$ is constant and equal to $P_{TX_{max}}$, while in the DPC versions it is variable in the range $[P_{TX_{min}}, P_{TX_{max}}]$, according to the attenuation and the variation rules described above.

In Dij we assume that each node always knows the network topology without signaling packet exchange (performance upper bound), and that an intermediate node, when receiving a packet to be forwarded, re-computes the path to the final target (since node mobility can change the network topology). On the other hand, in the LS and AODV simulations the signaling packet exchange is explicitly taken into consideration.

At the MAC level, the IEEE 802.11 DCF protocol has been considered. In the DPC scheme, the MAC signaling packets, such as RTS, CTS and ACK, are sent with the same power as the data packets. On the other hand, at the network layer, the signaling packets, if present, are sent at the maximum power, $P_{TX_{max}}$, so as to increase the number of neighbors able to hear these packets, thereby decreasing the traffic overhead needed to build the whole network topology.

Regarding the physical layer, a channel behavior with path loss and log-normal shadowing has been taken into account. The impact on the system performance of more complex channel models, such as Rayleigh or Rice fading is currently under investigation.

The cases with and without mobility, i.e., with nodes in pseudo-linear movement and in fixed positions, are discussed, by varying some system parameters.

Simulation results for both Poisson and CBR traffic are shown, with an arrival rate of λ packets/s per node. λ is relative to the data traffic only, i.e., it does not include the signaling traffic generated at the Network layer.

The system parameters used in the simulations are the following: number of nodes, $N = 30$, located in a square room of size 10x10m; power decay law with the distance, $\beta = 2.5$; log-normal shadowing deviation $\sigma = 6$ dB; minimum power necessary to correctly receive a packet before de-spreading, $S_R = -76$ dBm; capture threshold active, simulation time, 500s; coding gain 2 dB (used only for the routing packets); spread spectrum gain, 10.41 dB; minimum transmit power, $P_{TX_{min}} = -44$ dBm; mobility refresh time, $t_{mob} = 0.3$ s; average speed of the generic node, $v_{mob} = 0.75$ m/s; speed deviation, $\sigma_{mob} = 0.3$ m/s; maximum mobility angle, $\theta = 180$ degrees.

Furthermore, we have considered two different values for the maximum transmit power, $P_{TX_{max}} = -22$ dBm and -12 dBm, to simulate two multihop behaviors: the first with higher number of hops in the generic path, the second with lower number of hops in the generic path. All simulations have been performed with the security threshold Sec_{th} spanning the range from 0 to 15 dB and from 0 to 10 dB in the $P_{TX_{max}} = -12$ dBm and $P_{TX_{max}} = -22 dBm$ cases, respectively.

The node locations are chosen randomly in the selected area, with uniform distribution. In particular, with fixed terminals, we have focused the attention on connected topologies. This choice is because the system performance is evaluated by averaging over all nodes in the network, so that isolated nodes would negatively bias the performance results.

As performance metrics we have considered: average success probability, P_{succ}, average delivery time, T_{acc}, energy spent per packet, E_p, and throughput S. Finally, in many cases a comparison between DPC and classic schemes will be performed by reporting the performance gaps. These gaps are computed, for E_p and P_{succ}, as the percentages: $\mathcal{E} = (E_p^C - E_p^{DPC})/E_p^C \cdot 100, \mathcal{P} = (P_{succ}^{DPC} - P_{succ}^C)/P_{succ}^C \cdot 100$, where the superscripts C and DPC refer to classic and DPC schemes, respectively. For the delivery time we consider: $\mathcal{T} = T_{acc}^{DPC}/T_{acc}^C$. For the first two parameters, positive values denote a performance improvement obtained with DPC. For the third parameter, the improvement is shown whenever $\mathcal{T} < 1$.

4.1 Poisson Traffic

In this Section some results are presented in order to test the effectiveness of DPC, for the case of Poisson traffic. The SAM Poisson traffic implementation is based on service and inter-packet times having exponential distribution and the generic source-destination pair is independently chosen at random, with uniform distribution on all stations.

Due to the specific type of traffic considered here and to the reactive nature of AODV, a route discovery would need to be performed for every packet. This of course would produce too much signaling traffic, which results in extremely poor performance. For this reason, in this section on Poisson traffic, no results will be presented for AODV.

For these simulations we have considered Dij and LS, by setting: channel data rate, 1 Mbit/s; average arrival rate, $\lambda = 1$ packet/s, average service rate, $\mu = 128$ packets/s, corresponding to a packet size of 1024 bytes; channel behavior with path loss only.

4.1.1 Poisson Traffic and Dij

In Figure 1, a performance comparison between the classic and DPC version of Dij algorithm is shown, for $P_{TX_{max}} = -12$ dBm, by considering two cases: (i) fixed nodes and (ii) all nodes moving at pedestrian speed (MOB). In particular, T_{acc} and P_{succ} are reported as a function of E_p in order to highlight the relevant tradeoffs between quality of service and energy efficiency. The classic versions are represented by two points, while the DPC versions by curves obtained varying Sec_{th} in the range from 0 to 15 dB. Note that when $Sec_{th} = 15$ dB, the DPC scheme achieves roughly the same P_{succ} and the same average delivery time, with slightly lower energy consumption (a gap $\mathcal{E} = 5.5\%$ can be seen). The curves with and without mobility are basically the same,

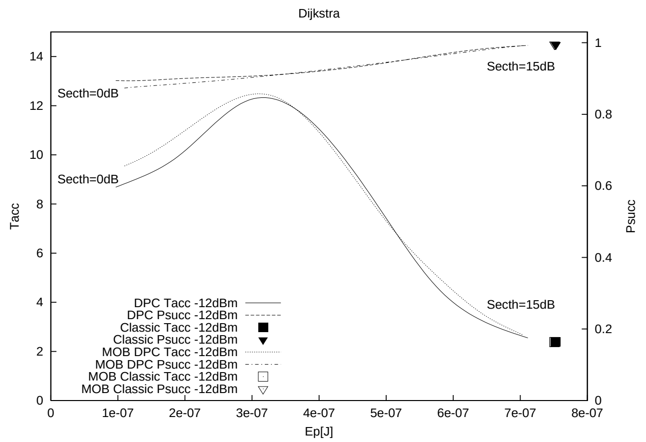

Figure 1: P_{succ} and T_{acc} vs. E_p for Dij, with fixed and mobile nodes. Path loss only, Poisson traffic and $P_{TX_{max}} = -12$ dBm.

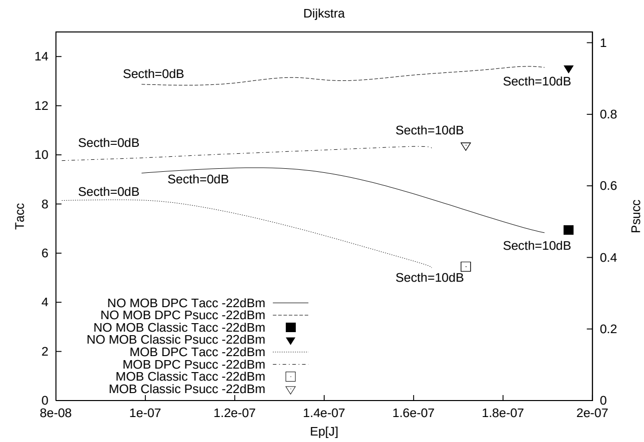

Figure 2: P_{succ} and T_{acc} vs. E_p for Dij, with fixed and mobile nodes. Path loss only, Poisson traffic and $P_{TX_{max}} = -22$ dBm.

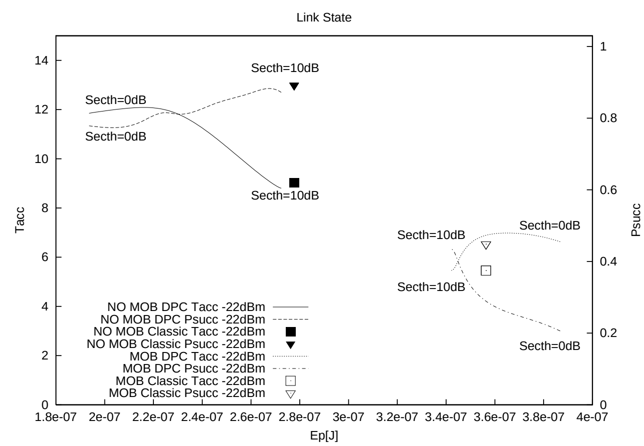

Figure 3: P_{succ} and T_{acc} vs. E_p for LS, with fixed and mobile nodes. Path loss only, Poisson traffic and $P_{TX_{max}} = -22$ dBm.

since the Dij algorithm recomputes the path at each intermediate node (to counteract possible network topology changes) and the transmit power is sufficiently high to avoid link failure as a consequence of mobility.

If we consider $Sec_{th} = 0$ dB, the system performance decreases, since no power margin is used, but very large energy gains can be achieved. In fact, P_{succ} decreases ($\mathcal{P} = -10\%$) and T_{acc} increases ($\mathcal{T} = 4$), with an energy gain of $\mathcal{E} = 87\%$ (i.e., energy consumption is reduced by a factor of 8!). By considering intermediate values of Sec_{th}, we can trade-off performance degradation for energy savings.

In the classic case the average number of hops in the path is 1.3, while in the DPC case, it spans from 4.4 to 1.3 for Sec_{th} from 0 dB to 15 dB. So, the effect of power control is to increase the number of hops, especially with low Sec_{th}, with consequent degradation of the final delivery time.

Regarding the curve trends, P_{succ} slightly increases with Sec_{th} because of the increase of the transmit power, which results in a smaller number of packet relays (i.e., of hops) and then limits the collision probability. Note also that for the selected system parameters P_{succ} is spanning quite high values, close to 1. T_{acc} has a trend with a maximum: the initial power increase is not sufficient to decrease the number of hops, and results in higher interference, more packet collisions and more packet retransmissions, all of which negatively impact on the delivery time. When the power is sufficient to decrease the number of hops, the delivery time decreases.

The trends of P_{succ} and T_{acc} as a function of E_p for Dij, for $P_{TX_{max}} = -22$ dBm, by considering both fixed nodes and all nodes in movement, are reported in Figure 2, where Sec_{th} is varied in the range from 0 to 10 dB. In both cases of mobility and no mobility, in the same performance conditions the DPC scheme achieves a $\mathcal{E} = 3.0\%$ energy gain with respect to the classic scheme. If $Sec_{th} = 0$ dB a P_{succ} reduction ($\mathcal{P} = -5.0\%$) and a T_{acc} increment ($\mathcal{T} = 1.4$) are seen, with an energy gain of $\mathcal{E} = 50\%$. So, when $P_{TX_{max}} = -22$ dBm, we can achieve at $Sec_{th} = 0$ dB a lower performance degradation, but also a lower energy gain with respect to the case with $P_{TX_{max}} = -12$ dBm.

This lower energy gain is probably due to a lower gap between the transmit power used in the DPC case and that used in the classic scheme, with respect to the case with $P_{TX_{max}} = -12$ dBm. This behavior is present both with fixed nodes and with mobile nodes. On the other hand, the case with mobile nodes shows lower P_{succ} (-22%) and lower T_{acc} (-21%) with respect to the case of fixed nodes in both the classic and DPC schemes. This is a consequence of the limited transmit power that is not sufficient to counteract the link failure due to the node mobility even if the path is updated node-by-node. This phenomenon determines a decrease of the packet delivery probability and reduces the delivery time since shorter paths are more reliable. Another possible interpretation is related to the occurrence, when nodes are moving, of poorly connected network conditions, i.e., with isolated nodes or subnetworks, which degrade the success probability.

In the system situations of Figure 2, the classic case is characterized by an average number of hops in the network equal to 3.2 for fixed nodes and 2.9 for mobile nodes, i.e., higher than in the $P_{TX_{max}} = -12$ dBm case, as expected, while in the DPC case it is spanning from 4.6 to 3.0 when Sec_{th} ranges from 0 dB to 10 dB. Note also that the maximum P_{succ} is not close to 1, as in Figure 1, as a consequence of a higher average number of hops and then of a higher packet collision probability.

So, in the Dij case the DPC effectiveness, in terms of energy savings, is present both with and without terminal mobility and is quite relevant if some limited performance degradation can be tolerated.

4.1.2 Poisson Traffic and LS

The same performance indices of Figure 1, with $P_{TX_{max}} = -22$ dBm, are shown in Figure 3 for the LS protocol, where both fixed and mobile nodes are considered. With respect to the Dij algorithm (Figure 2) the energy spent per packet, E_p, is higher, since LS implies considerable signaling traffic, which is absent in Dij. The presence of this signaling traffic also justifies a lower P_{succ} (especially with terminal mobility) and a higher T_{acc} with respect to the Dij case, due to higher network load.

The average number of hops with fixed nodes is the same as for the Dij scheme. Furthermore, with fixed nodes, when $Sec_{th} = 0$ dB, i.e., no transmit power margin, the P_{succ} gap with respect to the classic case is about $\mathcal{P} = -13\%$, the T_{acc} ratio is about $\mathcal{T} = 1.3$ and the energy gain is about $\mathcal{E} = 30\%$. So, with respect to Dij a lower energy gain is achieved with higher performance decrease in terms of success probability, due to the signaling traffic overhead. In the case of mobile nodes the maximum energy gain ($\mathcal{E} = 4\%$) of the DPC scheme is present when $Sec_{th} = 10$ dB which is the margin value guaranteeing also the same P_{succ} and T_{acc} of the classic algorithm. In fact, by decreasing Sec_{th} the system performance decreases not only in terms of success probability and of access time but also in terms of energy gain. This behavior could be related to a low margin to counteract mobility, which determines a poor performance behavior and a higher energy consumption since more retransmissions and signaling traffic are present. Furthermore, P_{succ} is very low (ranging from 0.2 to 0.4), as a consequence of the lateness in the topology update with respect to the terminal mobility. Note that on average the packets experience a low T_{acc} with respect to the case without mobility, probably because only packets sent over paths characterized by a small number of hops are correctly delivered, which results in an optimistically biased delay average. In fact the average number of hops is ranging from 2.4 to 2.8, while in the case of fixed nodes it was ranging from 3.3 to 4.5. Finally, E_p is higher in the case with mobility, due to the higher number of retransmissions, consequence of a generally higher link failure probability.

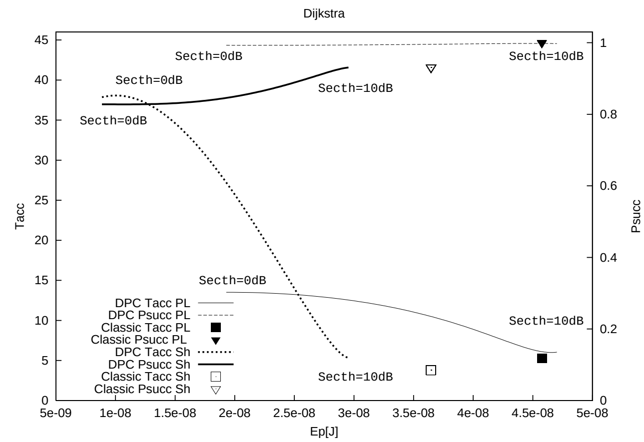

Figure 4: P_{succ} and T_{acc} vs. E_p for Dij, with fixed nodes. Path loss and shadowing, CBR traffic and $P_{TX_{max}} = -22$ dBm.

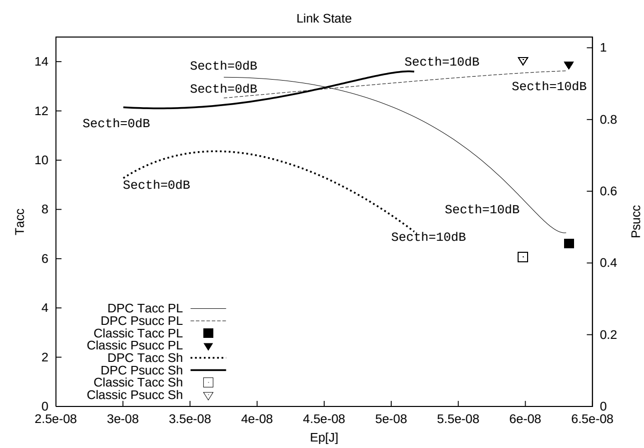

Figure 5: P_{succ} and T_{acc} vs. E_p for LS, with fixed nodes. Path loss and shadowing, CBR traffic and $P_{TX_{max}} = -22$ dBm.

So, in the LS case the DPC effectiveness, in terms of energy savings, is present especially without terminal mobility (in this case if some limited performance degradation can be tolerated, the energy gain is considerable). However, with respect to Dij, the energy gain is lower and the performance degradation is higher, as expected, as a consequence of the signaling traffic. On the other hand, by considering all nodes mobile with pedestrian speed, the DPC LS gives only limited energy gains, as a consequence of the lateness in the topology update and of the presence of signaling traffic.

4.2 CBR traffic

In this Section we investigate the case of CBR traffic, which is the traffic considered in almost all papers on ad hoc routing, by comparing Dij, LS and AODV both in classic and DPC cases. CBR traffic is characterized by constant service and inter-packet times. Furthermore, the source-destination

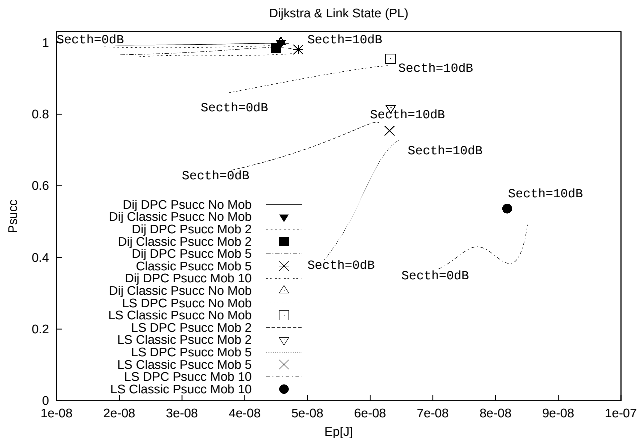

Figure 6: P_{succ} vs. E_p for Dij and LS, with fixed nodes and increasing number of mobile nodes (2 through 10). Path loss only, CBR traffic and $P_{TX_{max}} = -22$ dBm.

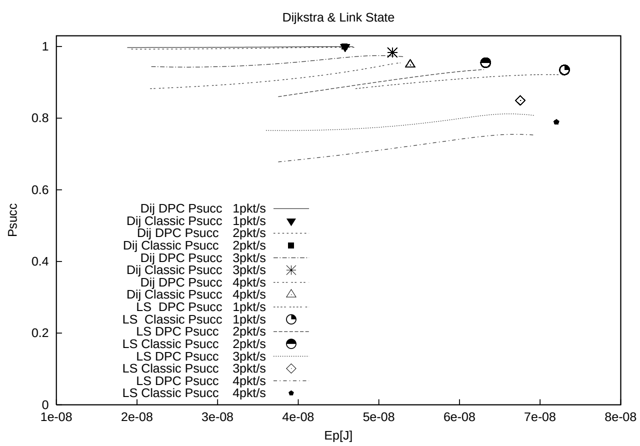

Figure 7: P_{succ} vs. E_p for Dij and LS, with fixed nodes and increasing packet rate (1 through 4 packet/s). Path loss only, CBR traffic and $P_{TX_{max}} = -22$ dBm.

pairs are chosen randomly (with uniform distribution over all nodes) in the start-up phase and they remain the same for all packets of each connection. For these simulations we have considered Dij, LS and AODV, by setting: channel data rate, 2Mbit/s; average service rate, $\mu = 256$ packets/s, corresponding to a packet size of 512 bytes, channel behavior with path loss and shadowing.

In Figures 4 and 5 the same performance indices of Figures 1, 2, 3 are reported for Dij and LS, respectively, by comparing the cases with path loss only (PL) and with path loss and shadowing (Sh). We have set $\lambda = 2$ packet/s per user and $P_{TX_{max}} = -22$ dBm.

4.2.1 CBR with Dij and Fixed nodes

Figure 4, relative to Dij, shows that shadowing determines a P_{succ} decrease with respect to the case of path loss only, both in classic and DPC schemes. In the PL case, P_{succ} is

	#	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{E}$	Sec_{th}
Dij	0	-0.7	2.5	58	0
Dij	2	0.25	2.2	61	0
Dij	5	-1.5	2	58	0
Dij	10	-0.65	2	52	0
Dij	20	-0.25	2	52	0
Dij	30	0.6	1.9	54	0
LS	0	-10	2	41	0
LS	2	-21	2.4	40	0
LS	5	-48	1.7	16	0
LS	10	-60	1	-1	0
LS	20	-72	1.2	-36	0
LS	30	-84	0.8	-129	0
LS	0	-2	1	0.3	10
LS	2	-3.9	1	4	10
LS	5	-3.3	1.2	2.5	10
LS	10	3.6	1	5.2	10
LS	20	6	0.8	5.7	10
LS	30	-7	0.9	3.5	10

Table 1: Performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$, for Dij and LS. Path loss only, $\lambda = 2$ packet/s per user, for an increasing number, $\#$, of mobile nodes.

always close to 1; in the Sh case, P_{succ} is 0.92 for classic and DPC with $Sec_{th} = 10$ dB, and it decreases by decreasing the Sec_{th} margin. Regarding T_{acc}, it is about the same for PL and Sh in the classic version.

Note that for a given topology which in the PL scenario corresponds to a connected network, there is no guarantee that the network will also be connected in the presence of shadowing. If a node is unreachable from the others, Dijkstra simply drops the packet at its source, since it cannot find a path towards the destination. The result is a lower energy consumed to deliver a packet because many packets are not transmitted at all and they are not lost for collisions. Moreover, the time required to deliver a packet is also smaller than in the Path Loss scenario due to the fact that longer routes are more likely to be partitioned. The main conclusion is that there is a considerable energy saving also when DPC is used in shadowing environments, at the price of somewhat higher packet loss rate.

Regarding the energy efficiency of DPC, in the PL situation it can achieve high gains ($\mathcal{E} = 58\%$) with the same P_{succ} and $\mathcal{T} = 2.5$, at $Sec_{th} = 0$ dB. In the Sh case, the maximum energy gain ($\mathcal{E} = 76\%$) is achieved for $Sec_{th} = 0$ dB, but some performance degradation ($\mathcal{P} = -11\%$ and $\mathcal{T} = 10$) must be tolerated in this case. It is sufficient to increase Sec_{th} to 8 dB to have no P_{succ} degradation and $\mathcal{T} = 1.5$, while still maintaining a sizable energy gain of $\mathcal{E} = 25\%$.

So, with CBR traffic, fixed nodes and path loss DPC Dij shows very good performance and high energy saving. In the presence of shadowing an interesting trade-off between performance degradation and energy gain can be achieved, by suitably setting the value of Sec_{th}.

4.2.2 CBR with LS and Fixed nodes

Figure 5, relative to LS, shows a lower sensitivity of this protocol to shadowing with respect to Dij. In fact, the P_{succ} trend is quite the same in PL and Sh, in both the DPC and

	#	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{E}$	Sec_{th}
Dij	0	-11	10	76	0
Dij	2	-11	1.4	79	0
Dij	5	-10	2	75	0
Dij	10	-13	2.2	77	0
Dij	20	-21	3.5	79	0
Dij	30	-21	2.7	71	0
Dij	0	-0.6	1.5	25	8
Dij	2	0	1.4	0	8
Dij	5	-0.85	1.1	17	8
Dij	10	-2	1.2	31	8
Dij	20	-1.6	1.6	34	8
Dij	30	-2.7	1.3	24	8
LS	0	-13	1.5	50	0
LS	2	-38	1.4	27	0
LS	5	-45	2	7	0
LS	10	-59	1.4	-21	0
LS	20	-68	1.3	-69	0
LS	30	-88	1	-381	0
LS	0	-3.4	1.2	14	10
LS	2	-3.2	1	11	10
LS	5	-8	1.2	-0.17	10
LS	10	-11	1.2	2	10
LS	20	-7	1.2	11	10
LS	30	-26	1.2	-18	10

Table 2: Performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$, for Dij and LS. Path loss and shadowing, $\lambda = 2$ packet/s per user, for an increasing number, $\#$, of mobile nodes.

	N	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{E}$	Sec_{th}
Dij PL	1	-0.26	2.2	59	0
Dij PL	2	-0.7	2.5	58	0
Dij PL	3	-4	3.3	58	0
Dij PL	4	-7	106	60	0
Dij Sh	1	-10.68	2.6	76	0
Dij Sh	2	-11.06	10	76	0
Dij Sh	3	-14.34	587	75	0
Dij Sh	4	-8.04	3000	77	0
Dij Sh	1	-0.6	1.5	25	8
Dij Sh	2	-0.6	1.5	25	8
Dij Sh	3	-1.5	1.3	25	8
Dij Sh	4	1	1.5	25	8
LS PL	1	-5.6	1.7	35	0
LS PL	2	-10	2	41	0
LS PL	3	-9	2	47	0
LS PL	4	-14	3.6	48	0
LS Sh	1	-17	1.5	29	0
LS Sh	2	-14	1.5	50	0
LS Sh	3	-18	1.9	56	0
LS Sh	4	-11	1.3	67	0
LS Sh	1	-0.9	1.2	10	10
LS Sh	2	-3.4	1.1	14	10
LS Sh	3	-4.6	1	13	10
LS Sh	4	-3.7	1	18	10

Table 3: Performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$, for Dij and LS, for the PL and Sh cases and fixed nodes, and for increasing network load, $\mathcal{N}$ (packets/s).

the classic version. The difference in terms of T_{acc} between PL and Sh seen for DPC Dij is not observed here.

Furthermore, T_{acc} is lower with Sh. A brief data analysis can justify such a behavior: shadowing can allow some links which are not present in the case of path loss only, so, in this simulation topology, the mean number of hops to reach the destination may be lower with Sh than PL. Regarding the energy efficiency of DPC LS, in the PL situation it can achieve high energy gains ($\mathcal{E} = 41\%$) with $\mathcal{P} = -10\%$ and $\mathcal{T} = 2$, at $Sec_{th} = 0$ dB.

By increasing Sec_{th} the performance improves and the energy gain decreases. In the Sh case, the maximum energy gain ($\mathcal{E} = 50\%$) is for $Sec_{th} = 0$ dB with $\mathcal{P} = -13.5\%$ and $\mathcal{T} = 1.5$. It is sufficient to increase Sec_{th} to 10 dB to have $\mathcal{P} = -3.5\%$, $\mathcal{T} = 1$ and $\mathcal{E} = 14\%$.

So, with CBR traffic, fixed nodes, path loss and shadowing, DPC LS shows energy saving effects, even if less relevant than in the Dij case, due to the presence of signaling traffic. Both in PL and Sh cases the maximum energy gain ($\mathcal{E} = 40/50\%$) can be achieved at $Sec_{th} = 0$ dB with a performance gap $\mathcal{P} = -10/-13\%$. By increasing the security margin the performance gap reduces, by maintaining a lower, but still non-trivial, energy gain ($\mathcal{E} = 14\%$).

4.2.3 CBR with Dij and LS, Mobile nodes

To investigate the effects of node mobility, we have considered different network scenarios by increasing the number of mobile nodes in the network from 0 to 10. Figure 6 shows P_{succ} as a function of E_p for Dij and LS in the PL case, by considering a number of mobile nodes equal to 0, 2, 5 and 10. Each mobile node moves with pseudo-linear movement and average speed 0.75 m/s. Note that Dij performance is not affected by mobility, since the topology is always assumed known. On the other hand, LS suffers from node mobility, both in classic and DPC versions. P_{succ} progressively degrades by increasing the number of mobile nodes. Regarding DPC the loss of P_{succ} is more evident if no security margin is considered, as expected.

To summarize the performance behavior with mobility and path loss, in Table 1 the performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$ are reported for both Dij and LS, by considering $\lambda = 2$ packets/s per user and an increasing number, $\#$, of mobile nodes. Note that without security margin DPC Dij achieves an energy gain $\mathcal{E} > 52\%$ with quite the same P_{succ} and T_{acc} about 2 times that of the classic case. This behavior is maintained also when all 30 nodes move. Regarding LS, if no security margin is considered, we can note that the $\mathcal{P}$ negative gap increases with the increase of the number of mobile nodes and also the energy gain vanishes for $\# \geq 10$. By considering $Sec_{th} = 10$ dB, the $\mathcal{P}$ gap reduces considerably, but the energy gain is quite limited. So, the DPC applied to LS is deeply affected by node mobility, as a consequence of the joint effect of the lateness in the topology update with respect to the node speed and of the reduced radio coverage (causing a more rapid link failure with mobility with respect to the classic case, where the radio coverage is higher).

Regarding the impact of node mobility on Dij and LS in the presence of shadowing, the P_{succ} trend as a function of E_p is similar to that of Figure 6 where only path loss was considered. The only difference is relative to the Dij case where if a low Sec_{th} is considered, a P_{succ} degradation is observed (as expected since channel fluctuations are not taken into consideration in the transmit power selection). This Dij trend becomes more evident by increasing the node mobility.

To summarize the performance behavior with mobility and shadowing, in Table 2 the performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$ are reported for both Dij and LS, by considering $\lambda = 2$ packet/s per user and an increasing number, $\#$, of mobile nodes. Note that, as anticipated above, with shadowing DPC Dij needs the presence of a security margin ($Sec_{th} = 8$ dB) to maintain the same performance as in the classic scheme (in the PL case this was achieved without margin), and that this increased Sec_{th} implies a lower energy gain (ranging from 17 to 34 %, except the situation of 2 mobile nodes, probably due to a poorly connected network topology). As far as LS is concerned, the behavior is similar to that of Table 1 with path loss only.

4.2.4 CBR with Dij and LS, Network load

Other investigations have been performed to test the impact of the network load on the final performance. In a fixed node scenario, we have varied the packet rate per user, λ, from 1 to 4 packet/s. In Figure 7 P_{succ} as a function of E_p is shown for Dij and LS, by considering no mobility and path loss only. As expected, the percentage of delivered packet decreases by increasing the network load, and this trend is more evident in LS where lower P_{succ} than for Dij is achieved. The same trend is seen with shadowing, where, as in the mobility investigation case, Dij shows lower performance if no security margin is present.

To summarize the performance behavior by changing the network load, in Table 3 the performance gaps $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{E}$ are reported for both Dij and LS, in PL and Sh cases, by considering fixed nodes and an increasing network load, $\mathcal{N}$ (packet/s). In both the Dij and LS cases no relevant performance gap changes are observed by varying the network load within the specified range.

4.2.5 CBR and AODV

Regarding AODV, in Figure 8 T_{acc} and E_p are reported versus Sec_{th}, with fixed nodes, path loss only and packet rate $\lambda = 2$ packets/s. In this case P_{succ} is very close to 1 for both DPC and classic cases and constant for all values of Sec_{th}. The main result shown here is that, with stationary nodes and $Sec_{th} = 0$ dB, DPC AODV consumes about 40% less than classic AODV with the same number of successfully delivered packets and a negligible delivery time degradation. Note that in this case the access time suffers very little when Sec_{th} increases, while for LS and Dij the opposite is true, due to the large number of routing control packets that are generated to find an energy-efficient path and to keep it alive. For higher Sec_{th}, more nodes are blocked, and the delivery time is consequently degraded, even though the gap is at most about 10%. The minimum of the access time curve for $Sec_{th} = 2$ dB (and not for 0 dB) is mainly due to a negligible number of lost packets, i.e., simulation fluctuations.

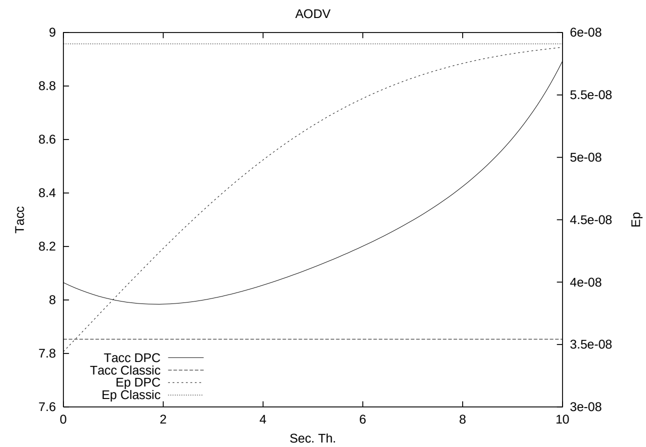

Figure 8: T_{acc} and E_p vs. Sec_{th} for AODV with fixed nodes, packet rate $\lambda = 2$ packets/s, path loss only, and $P_{TX_{max}} = -22$ dBm.

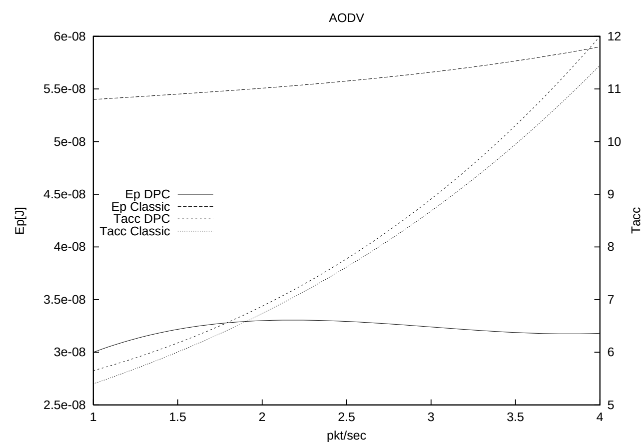

Figure 9: T_{acc} and E_p vs. the packet rate λ for AODV with fixed nodes, path loss only, $P_{TX_{max}} = -22$ dBm, and $Sec_{th} = 0$ dB for DPC.

Shadowing does not impact the performance compared to the PL environment, and the corresponding performance results are not shown here, as they are very similar to those shown in Figure 8.

In Figure 9, access time and energy per packet versus the packet arrival rate are shown for both versions of AODV (with $Sec_{th} = 0$ dB for DPC). The delay time of the DPC version is very close to the classic case even though the packet arrival rate increases, a first interesting result. Moreover, DPC AODV shows a very interesting result that proves the effectiveness of our proposal; the energy gain grows when the packet arrival rate increases. The energy reduction is very close to 50% for an arrival rate of 4 packets per second per node.

Our implementation of DPC AODV can achieve a very high energy saving. Unfortunately, the best results are obtained with very low values of Sec_{th}. When nodes are mobile, even moderate mobility may compromise the correct

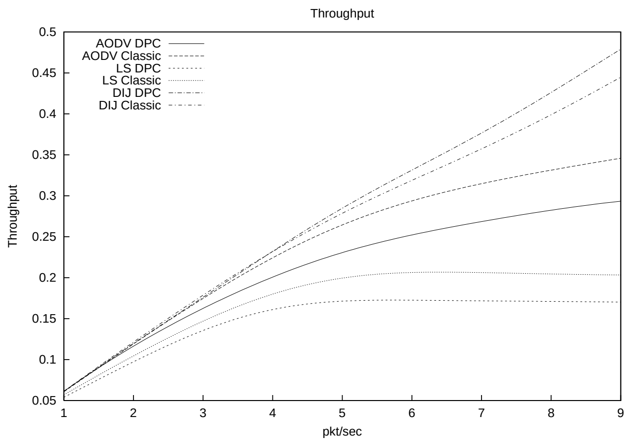

Figure 10: Throughput vs. packet rate per user, for Dij, LS and AODV, with CBR traffic, path loss only and fixed nodes.

transmission and the performance suffers. Nevertheless, we are investigating the possibility to realize a new version of DPC AODV that addresses this problem. The main goal is to realize a dynamic protocol able to be aware of mobility and to automatically set Sec_{th} in order to get the best performance in every situation.

4.2.6 CBR performance comparison with Dij, LS and AODV

In Figure 10 the throughput (ratio between the useful time and the total time of simulation) as a function of the packet rate per user, for Dij, LS and AODV, with CBR traffic, path loss and fixed nodes is reported, for $Sec_{th} = 0$ dB in the DPC schemes. As expected, the best channel utilization is relative to Dij (due to the fact that Dijkstra does not generate control packets) which shows an always increasing throughput with the offered load. The worst performance is that of LS, whose throughput is always less than 0.2. AODV shows an intermediate behavior with a curve which tends to saturate at 0.4. Furthermore, DPC performance follows the trend of the classic schemes but is characterized by lower throughput. This behavior is very clear for AODV where the routing signaling traffic of DPC is always greater than in the classic case. Similar considerations can be made when shadowing is considered.

5 Conclusion

In this paper, we have proposed a distributed power control scheme as a means to improve the energy efficiency of routing algorithms in ad hoc networks. Each node in the network estimates the power necessary to reach its own neighbors, and this power estimate is used both for tuning the transmit power (thereby reducing interference and energy consumption) and as the link cost for minimum energy routing. We have included this technique in three routing protocols, namely the classic Dijkstra and Link State, as well as AODV, specifically designed for ad hoc networks. It has been shown how some limited degradation of the quality of service (in terms of throughput and delay) can effectively be traded off for energy savings that in some cases can be very significant.

Further investigations include applying DPC to other ad hoc routing protocols such as DSR and Optimized Link State Routing (OLSR). Also, we are investigating in more detail the effect of node mobility on the performance of the various protocols. Preliminary results for AODV show that some critical situations may arise in this case, and some initial ideas on how to solve this problem by suitably defining the power control mechanism are currently being tested.

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