Energy limited Ad hoc Networks

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***Abstract*— This paper evaluates the impact on the performance of limited battery energy devices in ad hoc networks. This investigation arises because the works about ad hoc networks, present in the literature, implicitly assume nodes with an infinite energy resource. This assumption does not consider that a terminal, especially in case of mobility, power itself by means of battery, which can easily exhaust its energy. When a node switches off, as a consequence of an energy fall, its support to the ad hoc network functionalities, such as routing signaling management and packet forwarding, disappears, with a consequent impact on the global network. To have a more realistic scenario, in this paper all nodes have a limited initial battery energy, which can be exhausted during simulation. The final performance are compared to those obtained with illimited energy to underline differences.**

I. Introduction

Wireless ad hoc networks are composed by nodes having packet relaying functionalities, so that the final paths from source to destination can involve many devices and a multi-hop route is in general present. They can help communications in situations where it is difficult to install fixed network access points, such as battlefields, disaster area and so on.

Each node must have router functionality, so that, on the basis of suitable network topology and routing informations, this node can route a given packet to the right next hop until the destination node. Many routing protocols proposals for ad hoc networks [1] [2] [3] have been presented in the literature. Their main goal is to guarantee a fast network topology knowledge by minimizing the signaling traffic (necessary to learn the node positions and their variations as a consequence of channel fluctuations or mobility). The first routing protocols proposals [1] [2] [3] was the aim to guarantee connectivity by minimizing the number of hops; other successive studies have focused the attention on other problems, by trying for example to increase energy efficiency [4] or to introduce some Quality of Service features (QoS) [5]. The energy efficiency issue is present because wireless devices are in general supported by battery powers and then have a limited reservoir of energy. In the case of small mobile devices, this reservoir of energy is very likely to be small as well. So, some techniques to minimize power consumption and then to increase network lifetime should be introduced. For example, in [4] a power control mechanism, called Distributed Power Control (DPC), able to guarantee the same performance by minimizing the global network power consumption, has been presented.

A part the proposal of new schemes to minimize energy consumption, this context gives rise to an energy-limited network model, in which energy limits network functionalities and management. So, the energy limited behavior of the ad hoc network terminals is a basic issue which should be taken into account in the final performance estimation. In fact, when a node exhausts its energy, it disappear from the network scenario, by determining a lack in terms of capacity to re-route a packet and to help the topology information knowledge and update. This situation can, also, determine portion of isolated network, i.e., which can not be reached by any other node.

To take into consideration these aspects, we have performed intensive simulations by using the Simple Ad hoc siMulator (SAM) [6]. In particular, we have modified the existing OLSR [1], DSR [2] and AODV [3] protocols to compare the classic case with nodes having illimited energy, with a more realistic case of nodes with a limited initial energy level which decreases during network lifetime.

II. Energy Limited and Standard Systems

As reported in the introduction, in mobile ad-hoc networks, nodes are both routers and terminals. For lack of routing infrastructure, they have to cooperate to communicate. Cooperation at the network layer means routing, i.e., finding a path for a packet, and forwarding, i.e., relaying packets for others. This means that the mobile stations must accept to forward information for the benefit of other stations. In such as scenario some misbehaving nodes can be present [10] [11]. Misbehavior means deviation from regular routing and forwarding. It can also arises non-intentionally when a node is faulty or has exhausted its energy. Without countermeasures, the effects of misbehavior could affect final performance (such as network throughput, packet loss) and could determine problems (such as denial of service, and network portioning), depending on the proportion of misbehaving nodes.

	SIMULATION PARAMETERS
N	4,6,8,10,14,18,20,25,30,35,40,45,50
SIM_{TIME}	500 s
$X * Y$	100 m^2
TX_{rate}	2 Mbit/s
E (CONSTANT)	$4 \cdot 10^{-4}$ J
E (GAUSSIAN)	mean $4 \cdot 10^{-4}$ J, variance $1 \cdot 10^{-4}$ J mean $4 \cdot 10^{-4}$ J, variance $2 \cdot 10^{-4}$ J mean $4 \cdot 10^{-4}$ J, variance $3 \cdot 10^{-4}$ J
$SEED$	5
	POWER (dBm)
P_{TX}	-28,-27.-25,-22,-21,-19,-18,-17,-16,-15,-14
S_R	-76.0
	MOBILITY
N_{mob}	0,5,8,10,15,18,20
v_{mob}	1.38 m/s (pedestrian)
σ_{mob}	0.3
ω_{mob}	3.14
$time_{mob}$	0.3 s
	TRAFFIC
λ	10 packet/s
PKT_{size}	1024 bit
	CHANNEL
β	2.5
d_{ref}	0.2 m

TABLE I
System parameters used during simulation trials.

In this paper we focus on nodes having a non-intentional misbehaving trend, i.e., caused by a lack of energy. Thus, we consider a network with nodes having a runtime decreasing battery level, which causes a progressive death of the nodes composing the network. The aim is to evaluate the impact of such as limited energy behavior by comparing the performance with the classic case of node always switched on.

We refer in the following to the classic infinite energy implementations of the protocols as STANDARD, and to the new finite energy implementations as ENERGY LIMITED. In the STANDARD cases each nodes never exhaust its energy and then can perform all possible ad hoc operations without interruption: traffic generation and forwarding, routing protocol management (such as signaling traffic delivery and routing table creation and update).

In the ENERGY LIMITED cases we consider each node having at the start of simulation a given level of energy (i.e., not infinite energy), which is decreased at each data or signaling packet transmission. The energy spent during reception and idle states is not considered (as usual, since it gives a limited apport to the energy consumption). Thus, in the ENERGY LIMITED implementations, a given node can switch off when it has exhausted its energy.

To compare different initial energy scenarios, in the ENERGY LIMITED cases, we have considered two cases:

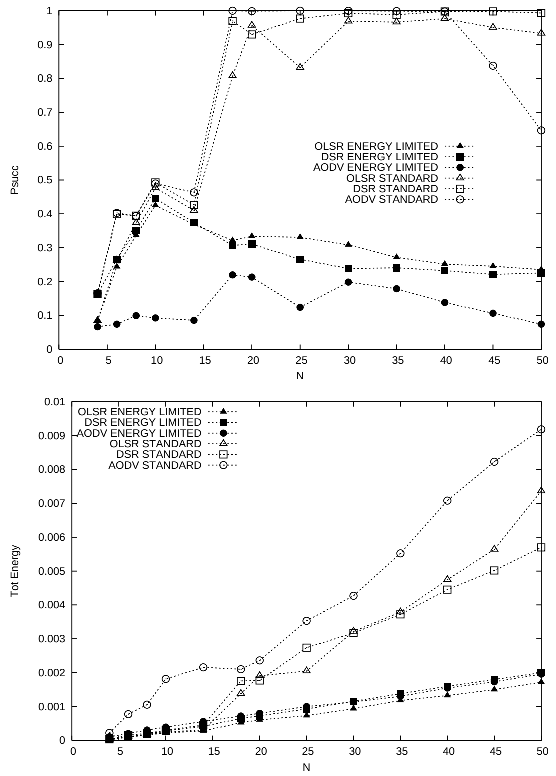

Fig. 1. P_{succ} and Total Energy as functions of N (P_{TX}=-18dBm, N_{mob}=0). ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

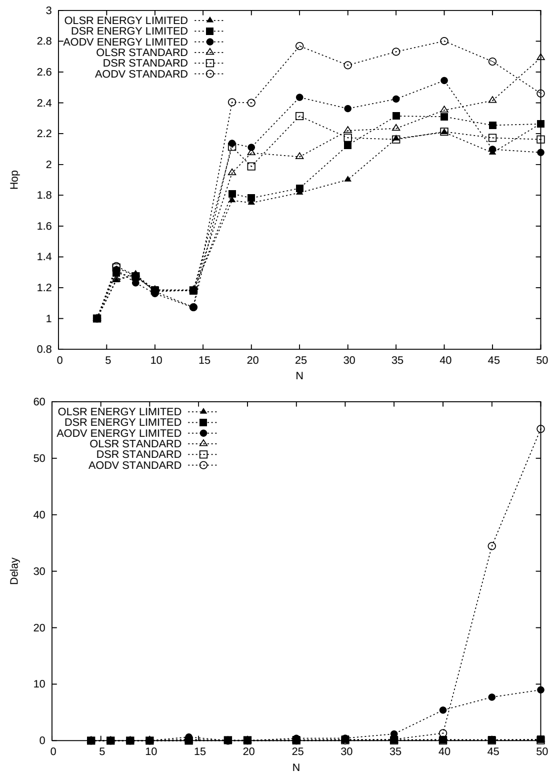

Fig. 2. Hop and Delay as functions of N (P_{TX}=-18dBm, N_{mob}=0). ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

1) a constant energy behavior, with all nodes starting the network operations with an equal fixed energy level E (CONSTANT);
2) a Gaussian energy behavior, with nodes starting the network operations with different energy levels, chosen randomly with a Gaussian distribution, characterized by a given mean and variance (GAUSSIAN).

These two different initial energy level distributions will be directly compared. The main investigated parameters are:

- **Success probability** P_{succ}: ratio between the number of correctly delivered packets and the total number of packets sent;
- **Delay**: end-to-end packet delivery time (from source to target), expressed in seconds (s);
- **Hop**: number of hops needed to reach a given destination;
- **Tot Energy**: total energy spent during simulation, expressed in Joule (J);
- **Residual energy**: residual battery energy level at the end of the simulation, expressed in Joule (J);
- **Percentage of died hosts**: percentage of hosts having exhausted energy during simulation and then switched off;
- **Signaling Overhead**: ratio between the number of routing signaling bits generated/relayed and the total number of correctly delivered data bits;

These performance indexes have been averaged during simulation and on the network, i.e, they represent average global values. At the MAC layer we use the IEEE 802.11b protocol [7], at the Network layer we consider OLSR [1], DSR [2] and AODV [3], at the Transport layer we refer to UDP [8]. In table I we report the main system parameters used during the simulation tests. In particular, we consider: a square room with size $X * Y$; N nodes; initial positions of the nodes uniformly distributed in the space, generated with initial seed, $SEED$; initial energy at each node, E (which can be selected following the CONSTANT or GAUSSIAN distributions as explained before); transmission rate, TX_{rate}; simulation time, SIM_{TIME}; transmission power, P_{TX}; minimum received power to have a correct packet reception, S_R; a Poisson traffic with average packet arrival rate λ and average packet size PKT_{size} ; propagation channel characterized by path loss [9] with power decaying, β, and reference distance, d_{ref}; fixed and mobile scenarios. In case of mobility we assume: a pseudo-linear movement, with number of mobile nodes N_{mob}; average speed, v_{mob}; speed standard deviation, σ_{mob}; maximum range of the new angle defining the new direction, ω_{mob}; time interval between two speed and direction changes $time_{mob}$. The results reported in the following are performed by varying these system parameters: N, P_{TX}, N_{mob} and E, with variation ranges reported in Table I.

III. Numerical Results

In Figs. from 1 to 6 we show the comparison between the STANDARD and ENERGY LIMITED implementations of OLSR, DSR and AODV. In Figs. 7 and 8, we report only the ENERGY LIMITED cases with a CONSTANT initial energy distribution. Finally, in Figs. 9 and 10, we show a comparison between CONSTANT and GAUSSIAN initial energy distributions, by focusing only on the OLSR routing protocol.

A. STANDARD vs ENERGY LIMITED

Fig. 1 reports success probability and total energy spent during simulation, by varying the number of nodes, N, present in the network, having considered a fixed scenario ($N_{mob} = 0$), $P_{TX} = -18$dBm and with a CONSTANT initial energy level $E = 4 \cdot 10^{-4}$ J in the ENERGY LIMITED case. If we focus the attention on P_{succ}, we can note that the STANDARD and ENERGY LIMITED versions have quite the same performance for low or medium values of N ($N <= 15$), except ENERGY LIMITED AODV which shows a very high fall in the performance for every value of N. On the other hand, the STANDARD and ENERGY LIMITED trends differ considerably for a network quite dense (with very higher P_{succ} values in the STANDARD case). This is because (as reported later) in the ENERGY LIMITED version, by increasing N, increases the percentage of dying nodes during network lifetime (the higher

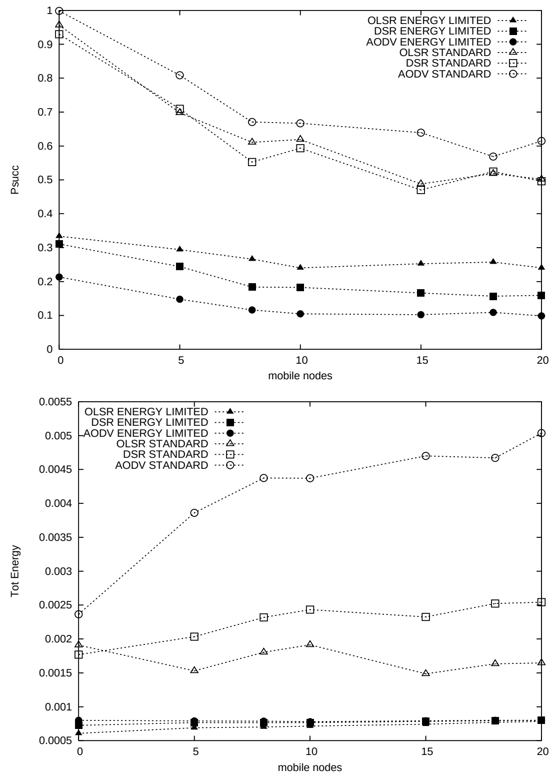

Fig. 3. P_{succ} and Total Energy as functions of N_{mob} (N=20, P_{TX}=-18dBm). ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

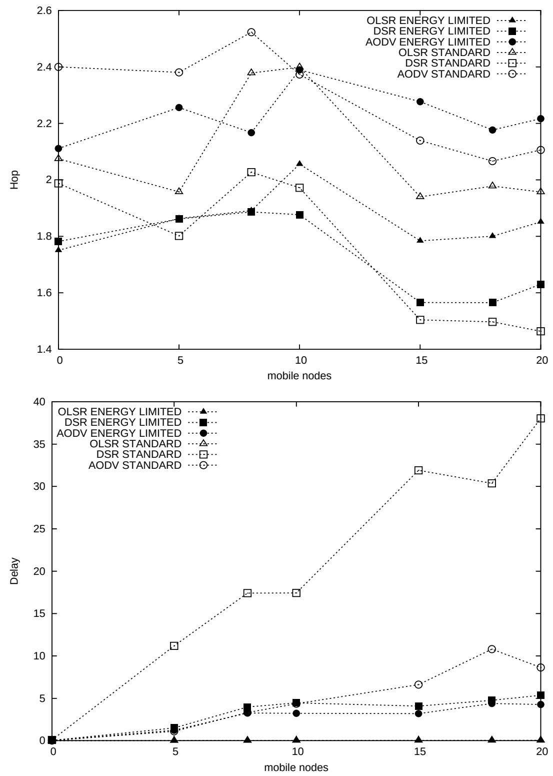

Fig. 4. Hop and Delay as functions of N_{mob} (N=20, P_{TX}=-18dBm). ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

traffic present, with high forwarding load, exhausts faster the battery energy), with a consequent fall in the packet delivery success since a lower number of relay nodes is present. On the other hand, in the STANDARD version each node has an unlimited energy and so can always forward incoming packets. This behavior confirms the high impact on the performance of nodes not participating to the network management (including packet forwarding), in this case deriving by a node energy lack, but which can derive also by misbehaving nodes. Furthermore, while in the STANDARD versions the routing protocols have quite the same P_{succ} (reaching 1 for $N > 15$), in the ENERGY LIMITED case, for $N > 15$, the routing protocols show very poor performance ($P_{succ} < 0.4$) and different behaviors. In particular, AODV seems to adapt itself worst to the lack of energy with respect to the other routing protocols.

Referring to the second graph of Fig. 1, which reports the total energy spent during simulation, in the same system conditions described above, we can see the evident difference in the STANDARD and ENERGY LIMITED performance, especially when N growths. In fact, increasing N, the energy spent increases, as expected, but with a relevant escalation in the STANDARD cases, that having illimited resources, can spend higher energy. Furthermore, in the STANDARD versions different routing protocols show different energy consumption behaviors (with a very high consumption of AODV), while in the ENERGY LIMITED implementations no particular differences can be pointed out.

In Fig. 2 the number of hops to reach the final destination and the end-to-end delay are reported as functions of N, in the same system parameter conditions of Fig. 1. Referring to the first graph, we can note that for high N values, STANDARD protocols show higher Hop with respect to the ENERGY LIMITED versions. This is because in the STANDARD case no one node is switching off during simulation, while in the ENERGY LIMITED case by increasing N some nodes are dying and then a lower availability of nodes relaying packets is present, with a consequent presence of shorter paths (i.e., the presence of faulty nodes reduce the possibility to reach farer nodes through intermediate nodes). The last graph of Fig. 2 reports the end-to-end $Delay$. We can note the poor AODV performance, especially in the STANDARD case.

To evaluate the impact of mobility in the STANDARD and ENERGY LIMITED comparison, Fig. 3 reports success probability and total energy spent during simulation, by varying the number of mobile nodes, N_{mob}, present in the network, having considered $N = 20$, $P_{TX} = -18$dBm and a CONSTANT initial energy level $E = 4 \cdot 10^{-4}$ J in the ENERGY LIMITED case.

As expected, P_{succ} decreases for all implementations by increasing N_{mob}, even if this trend is more evident in the STANDARD cases. Also in this scenario the STANDARD implementations show higher performance with respect to the ENERGY LIMITED ones (having illimited energy resources). Furthermore, while AODV seems to have the better P_{succ} in its STANDARD version (with respect to OLSR and DSR), this trend is opposite in the ENERGY LIMITED situation (since, probably this protocol has a lower capacity to react to the nodes exhausting energy, as already observed before).

Second graph of Fig. 3 shows the energy consumption in the same mobile scenario. As already observed for a fixed scenario (Fig. 1), STANDARD systems show very higher energy consumption, as a consequence of the illimited energy level at each node, which is increasing as N_{mob} increases. Furthermore, in the STANDARD situation we can appreciate relevant differences between protocols (AODV shows also in this case a very high consumption, while OLSR is the more energy efficient scheme). On the other hand, when nodes can exhaust their energy, no relevant differences between systems in their reciprocal trends are present.

Fig. 4 shows the number of hops to reach the final destination and the end-to-end delay as functions of N_{mob}, in the same system parameter conditions of Fig. 3. Regarding the hop number, as still underlined for a fixed scenario (see Fig. 2) STANDARD protocols show higher Hop with respect to the ENERGY LIMITED versions (consequence of a lower availability of nodes performing relaying actions in this last case); so this trend is maintained also in case of node mobility. Furthermore, all protocols are characterized by shorter

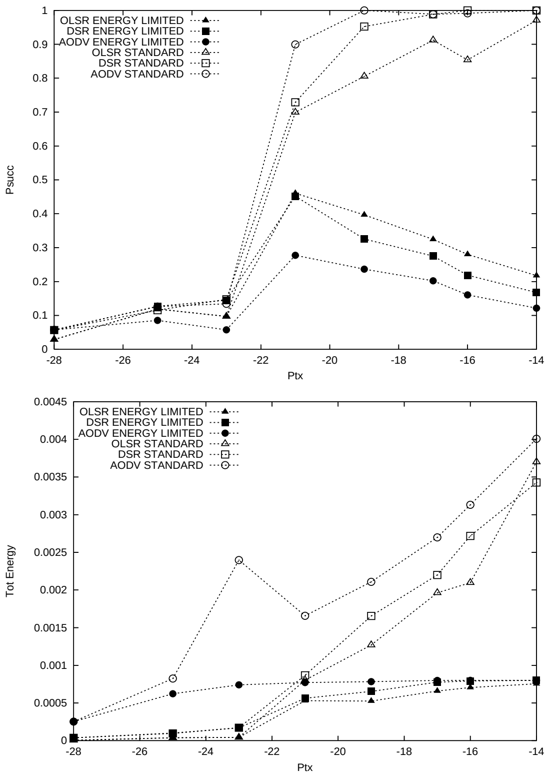

Fig. 5. P_{succ} and Total Energy as functions of P_{TX} (N=20, N_{mob}=0). ENERGY LIMITED ($E = 4{\cdot}10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

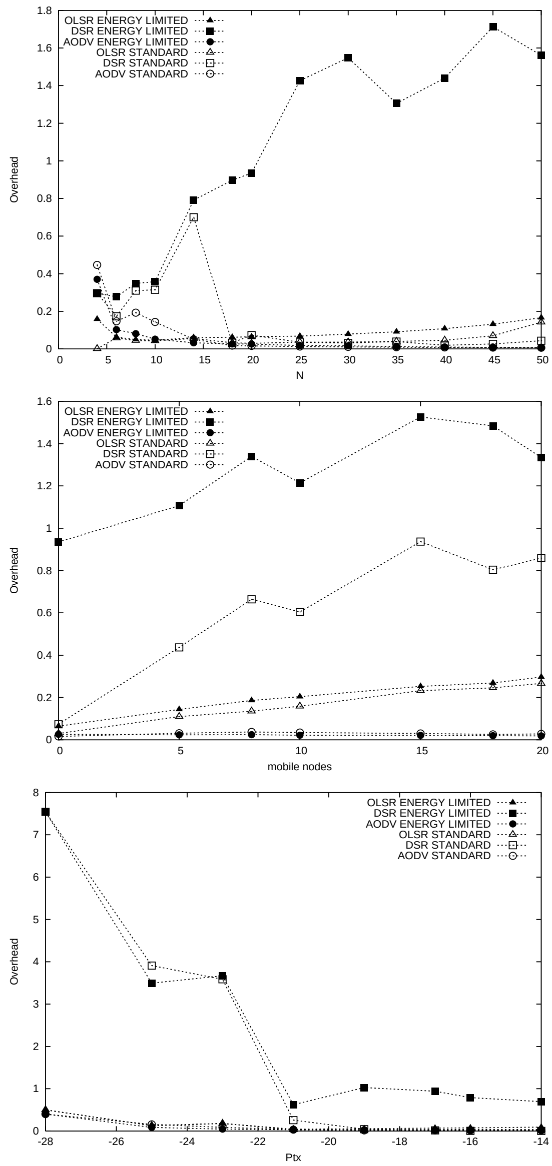

Fig. 6. Signaling Overhead as a function of N, N_{mob} and P_{TX}. ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) and STANDARD OLSR, DSR, AODV.

paths by increasing the mobile numbers. This can be explained as follows: in case of a relevant number of mobile nodes, it is more probable to fail in the delivery of packets characterized by a high number of hops, since when a packet is reaching the farer nodes these in general have changed their locations. So, packets are sent with higher success on shorter paths.

In the last graph of Fig. 4 the packet delivery time in a mobile scenario is reported. $Delay$ increases with N_{mob}, probably as a consequence of higher packet processing time when mobility increases (as observed by the packet queuing times reported in the statistics obtained with SAM and not reported by graphs for brevity). STANDARD implementations show higher $Delay$ with respect to ENERGY LIMITED: AODV in particular shows very high end-to-end delivery times, followed by DSR and then by OLSR.

To investigate the effect of the transmit power used by each node, in Fig. 5 we show success probability and total energy spent during simulation, by varying P_{TX}, having considered a fixed scenario ($N_{mob} = 0$), $N = 20$ and with a CONSTANT initial energy level $E = 4 \cdot 10^{-4}$ J in the ENERGY LIMITED case. By increasing P_{TX} relevant differences appear between STANDARD and ENERGY LIMITED systems, both for P_{succ} and total energy spent (both higher in the STANDARD protocols). In fact, in the ENERGY LIMITED case, if we use a higher transmit power, it is more probable that a higher number of dying nodes occur, by reducing dramatically the packet delivery success. Furthermore, while in the illimited energy systems the total energy spent can growth indefinitely, in the limited energy one it saturates quite fast. Finally, note that, regarding P_{succ}, opposite reciprocal trends between protocols are present if we compare energy limited solutions with the energy illimited ones: in the first case OLSR seems the best protocol, followed by DSR and then AODV; in the second case the better protocol seems to be AODV followed by DSR and then OLSR. So, the energy lack can also change the reciprocal protocol behavior.

The general trend of Hop and $Delay$ as functions of P_{TX} are similar to those observed by varying N and N_{mob} and then are not reported in the paper for brevity.

To conclude the STANDARD vs ENERGY LIMITED comparison we depict in Fig. 6 the signaling overhead of OLSR, DSR and AODV, as a function of N, N_{mob} and P_{TX}. DSR shows in all conditions very high overhead, in many case greater than 1 (referring to a situation where the number of bits used for routing signaling purposes overcomes the useful data bits correctly sent). Furthermore, especially in case od mobility and by increasing N, the difference between STANDARD and ENERGY LIMITED DSR becomes relevant. On the other hand, the other protocols seem more stable in term of signaling overhead by passing from STANDARD to ENERGY LIMITED implementations.

The numerical results presented in this Section show that relevant differences, especially regarding packet delivery success, number of hops and total energy spent, could be present if we compare a system with nodes having illimited battery energy with a more realistic system having limited battery energy (with nodes which can die during their network activities). The difference is not only present in the comparison between energy limited and illimited version of a given protocol but can reflect also on a different reciprocal trend of many different protocols which can work in different ways in the two cases. Anyway, by considering all investigated performance indexes,

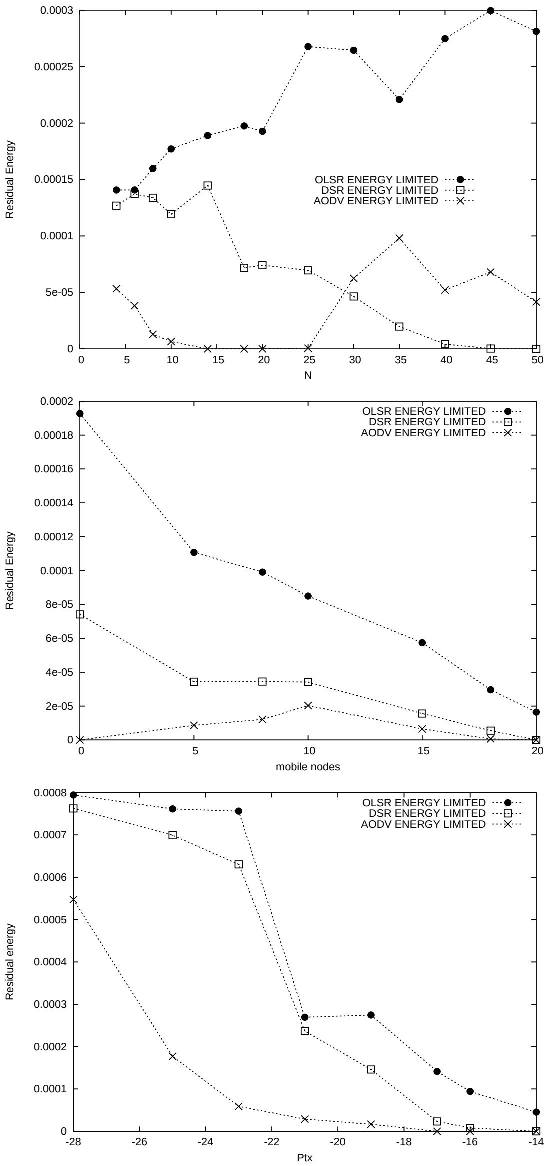

Fig. 7. Total Residual energy as a function of N, N_{mob} and P_{TX}. ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) OLSR, DSR, AODV.

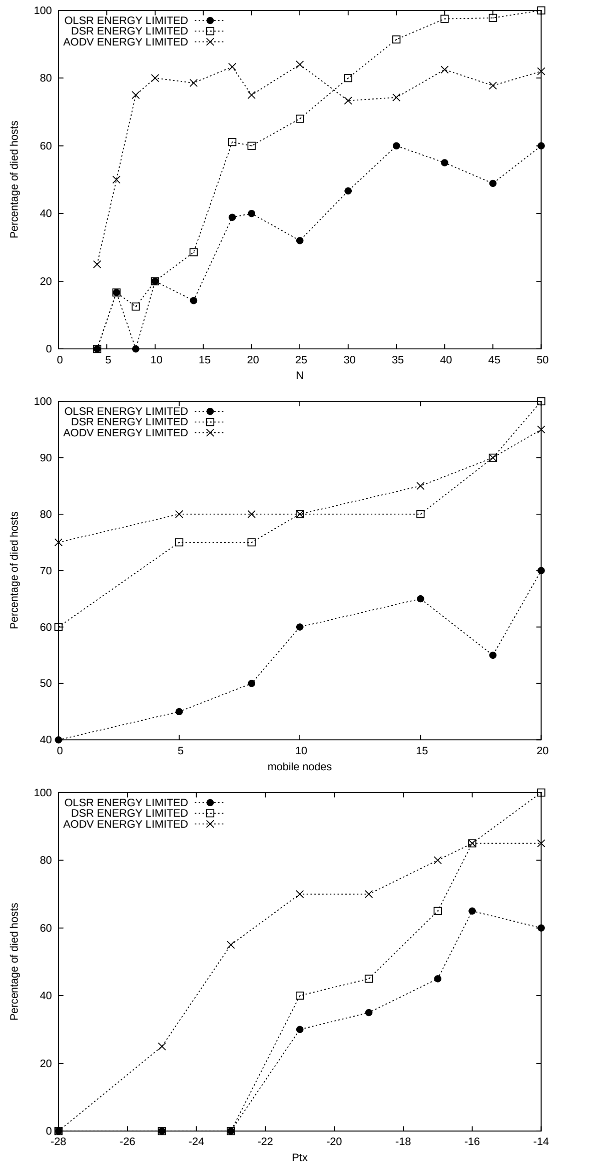

Fig. 8. Percentage of hosts "died" as a function of N, N_{mob} and P_{TX}. ENERGY LIMITED ($E = 4 \cdot 10^{-4}$ J, CONSTANT) OLSR, DSR, AODV.

the better protocol seems to be OLSR, for both implementations. In fact, with respect to DSR and AODV it shows no relevant fall in performance for all investigated situations.

These considerations are confirming some analysis performed in the literature [10] [11] with nodes not cooperating to the network management, as a consequence of selfishing or faulty behavior. So, when investigating ad hoc networks, the possibility to have switching off nodes, for example for energy considerations should be inserted.

B. ENERGY LIMITED

In this Section we consider only ENERGY LIMITED systems and reports some new performance indexes appliable only to a network with limited initial energy, such as residual energy at the end of the simulation and percentage of died hosts. Figs. 7 and 8 consider all three routing protocols (OLSR, DSR and AODV) with a CONSTANT initial energy behavior ($E = 4 \cdot 10^{-4}$ J). Figs. 9 and 10 focus only on OLSR (which is the protocol presenting the better performance) by comparing the CONSTANT and GAUSSIAN initial energy behaviors (in the GAUSSIAN case we vary the energy variance).

Fig. 7 refers to the residual energy at the end of simulation, by varying N, N_{mob} and P_{TX}, for OLSR, DSR, AODV. In all cases OLSR confirms itself as the protocol spending lower energy, followed by DSR and AODV. Furthermore, as expected, the residual energy present in the network decreases by increasing both number of mobile nodes and transmit power.

Fig. 8 reports the percentage of hosts "died" during simulations, by varying N, N_{mob} and P_{TX}, for OLSR, DSR, AODV. This parameter increases by growing N (more hosts in the network imply more traffic to be relayed and then more probability to exhaust energy), by increasing N_{mob} (the node mobility implies higher signaling traffic and then a higher probability to exhaust energy) and by growing P_{TX} (higher transmit power exhausts more rapidly battery). Also referring to this performance index, OLSR shows better performance in all situations followed by DSR and AODV.

Figs. 9 and 10, show only OLSR, by reporting residual energy and percentage of hosts "died" during simulations, respectively, by varying N, N_{mob} and P_{TX}, by considering CONSTANT and GAUSSIAN initial energy distribution. In all cases the choice of a different initial energy profile can determine evident differences in the final performance. This is noticeable in particular by varying the number of nodes composing the network and the number of mobile nodes.

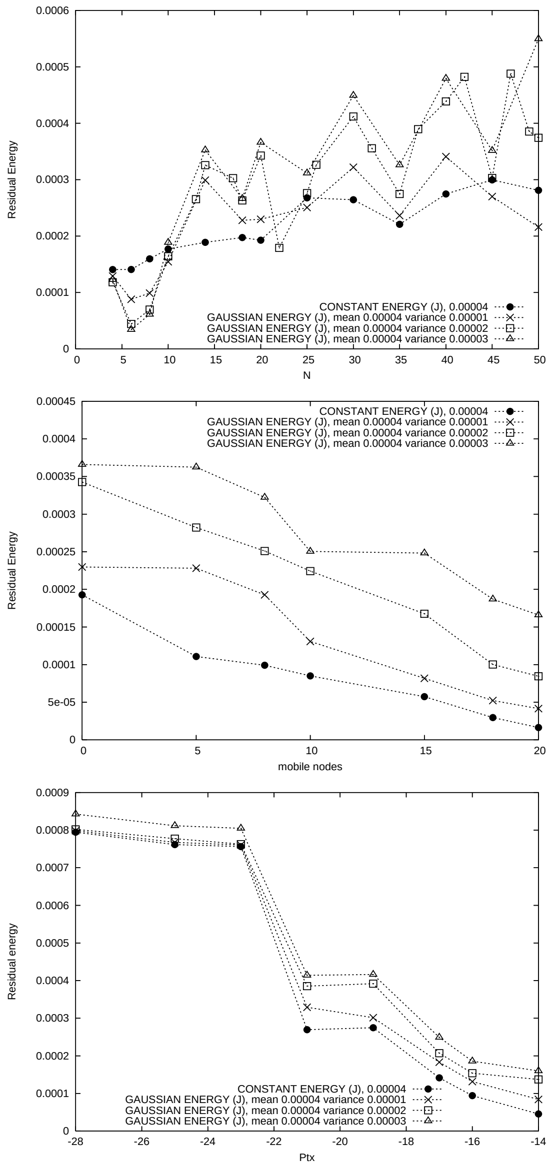

Fig. 9. Total Residual energy as a function of N, N_{mob} and P_{TX}. ENERGY LIMITED OLSR with CONSTANT and GAUSSIAN energy distributions.

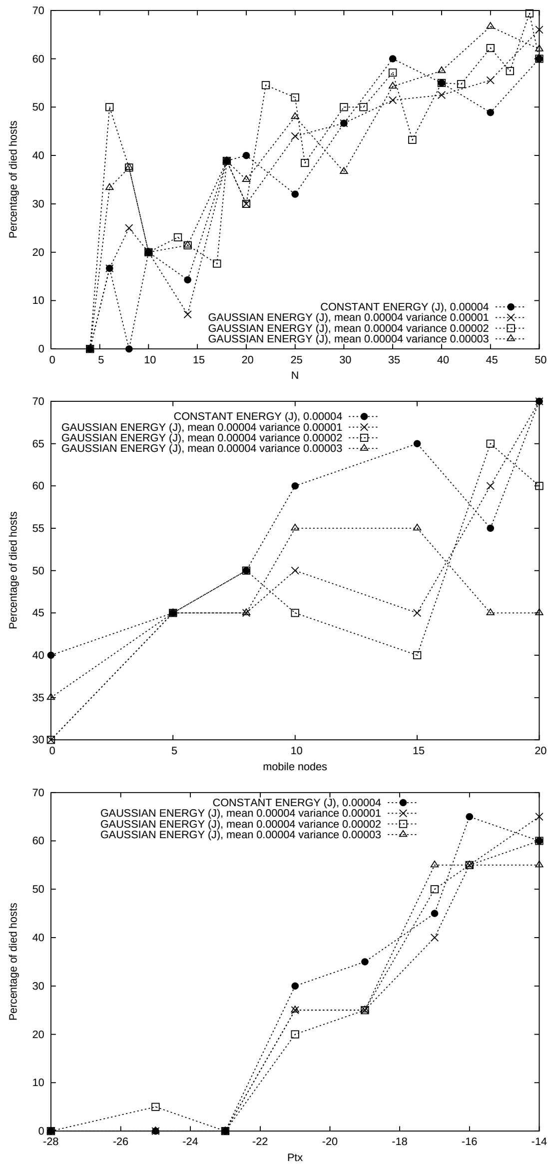

Fig. 10. Percentage of hosts "died" as a function of N, N_{mob} and P_{TX}. ENERGY LIMITED OLSR with CONSTANT and GAUSSIAN energy distributions.

IV. CONCLUSIONS

The paper presents a discussion on the usefulness to consider nodes with limited energy battery levels, as normally verified in a real network. The main routing protocols used in one ad hoc network have been investigated by means of simulations to take into account this aspect. Evident differences have been revealed by comparing systems with nodes having illimited energy and systems with limited batteries. The lack of energy can in fact determine situations with died nodes which can not continue to cooperate to the network management, with an evident fall in the main indexes parameters. Furthermore, performance seem to be conditioned by the distribution used to model the initial energy behavior in the network. So, the study, encourage the use of an energy-limited model for ad hoc networks, where the initial energy behavior should be accurately specified.

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