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E-MAntNet: An ACO-Based Energy Efficient Routing Protocol for Mobile Ad Hoc Networks

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***Abstract*— In mobile ad hoc networks (MANETs), nodes are mobile and have limited energy resource that can quickly deplete due to multi-hop routing activities, which may gradually lead to an un-operational network. In the past decade, the hunt for a reliable and energy-efficient MANETs routing protocol has been extensively researched. This paper proposes a novel AntNet-based routing scheme for MANETs (so-called MAntNet), and an its enhanced energy-aware version (so-called E-MAntNet), for which the routing decisions are facilitated based on the nodes' residual energy. These protocols were evaluated through simulations using NS2, showing that E-MAntNet outperforms both MAntNet and E-AODV, in terms of network residual energy, network lifetime, number of established connections, and the number of dead nodes in the network, where E-AODV is an energy-aware version of AODV.**

Keywords —Mobile ad hoc networks (MANETs), multi-path routing, energy aware routing, Ant Colony Optimization (ACO).

I. INTRODUCTION

MANETs are specialized in the deployment of mobile devices without any existing infrastructure. Due to this feature, they are suitable for use in several applications such as disaster relief, military operations, to name a few. While moving, a node can also act as a router to forward the traffic, using multiple hops for establishing the connections among themselves. For every packet that a node forwards or receives, it is bound to lose some amount of energy. This drains the residual energy of nodes; therefore at some point, some nodes may die, hence, slowly depleting the networks lifetime. In this paper, we address the problem of designing routing algorithms for MANETs that can solve this issue by ensuring minimal energy consumption in the network.

Energy conservation in MANETs has been intensively studied in the literature using several routing techniques [1], most of which rely on controlling the transmission power of nodes, the residual energy of nodes, the load distribution in the network, or varying the transmission range of the nodes, to name a few. Among the Ant Colony Optimization (ACO) techniques that have been proposed to address the problem of adaptive routing in telecommunication networks [2] is the AntNet heuristic [3], a distributed agent-based routing algorithm inspired by the behavior of natural ants. AntNet works through indirect communication between individual nodes in the network. A group of concurrent agents update each other about the network topology, the routing information, and the network status as they explore the network in a non-coordinated manner, in an attempt to solve the adaptive routing problem. The focus on this paper is on proposing an energy-aware routing protocol for MANETs inspired from an AntNet design that was introduced in [4] in the context of wireless sensor networks.

Several energy-aware routing protocols for MANETs have been proposed in the literature, some of which were based on ACO heuristics [1, 5-10]. Mohsin et al. [1] surveyed various energy-aware routing protocols for MANETs at the network and MAC layers, and studied the performance of some of them in terms of throughput, latency, routing overhead, and delay. Similarly, Tan and Bose [5] proposed a power conservation routing protocol for MANETs based on a modifying AODV. Their scheme consists of a power-based cost function that allows the nodes to choose the best routing path during the route discovery process. Each node is assigned a power level and a corresponding cost value, calculated for each route found. To establish the connection with the destination node, the source node then chooses the route that has the minimum cost. A cost zoning concept is introduced in the route maintenance phase to adjust the cost of nodes in such a way that low power nodes are assigned very high costs and vice-versa, leading to energy-efficient routing paths. Similarly, Taneja et al. [6] proposed a power-aware scheme for MANETs also based on a modified AODV. A mechanism is introduced in the route discovery process to help achieving some energy-savings in large

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networks handling various levels of data traffic. Similar to the cost zoning concept introduced in [5], the battery decay factor of nodes is used so that any node with at least half of its initial power can be maintained in active state, thus can participate in the routing process. Jia et al. [7] also proposed an energy-aware AODV protocol for MANETs (called AODVM) based on a modified AODV. Their scheme selects the routes with minimum hop counts and maximum residual energy to transfer the data packets. A field for tracking the residual energy of the route is added to the RREQ packets so that when the destination node receives various RREQs packets, it computes a routing metric, based on which the best path are selected for routing purpose. Gupta et al. [8] introduced a comparison of three ACO-based routing protocols: Ant-AODV, Ant-DSR, and Ant-DYMO, against standard ad-hoc routing protocols such as AODV, DSR in terms of various performance metrics such as routing overhead, end-to-end delay, storage requirements, ant type, to name a few. Similarly, Radwan et al. [9] proposed AntNet-RLSR, an AntNet-based protocol in which mobile agents build the routes between the source and destination while simultaneously exploring the network activities and updating the routing information. Following the same trend, Zhengyu et al. [10] proposed the so-called AEADMRA, an Ant-based energy-aware disjoint multi-path routing protocol which is insensitive to host mobility and offers strong maintenance of routes in a MANETs. Similarly, Camilo et al. [4] proposed an energy-aware AntNet-based routing protocol for wireless sensor networks, where the concept of energy quality of paths, as well as some functions that reduce the energy expenditure and communication load, are introduced in its design, leading to an energy-efficient protocol.

To the best of our knowledge, there hasn't been any proposal for energy-aware routing protocols for MANETs based on AntNet [4] in the recent past. Taking inspiration from the work in [4], this paper proposes a modified AntNet algorithm (so-called MAntNet), and its improved energy-aware version (so-called E-MAntNet). For the sake of comparison, an energy-aware modified AODV (so-called E-AODV) is also proposed.

The rest of the paper is organized as follows. In Section II, the AntNet approach is overviewed. Section III describes the MAntNet design. In Section IV, the E MAntNet and E-AODV designs are described. In Section V, the simulation results are provided, depicting the comparison of the proposed routing schemes with respect to few energy-related performance metrics. Finally, Section VI concludes the proposed work.

II. AntNet Approach

AntNet [3] is a heuristic that belongs to the family of ACO algorithms, that was designed for distributed and adaptive multi-path routing in wired best-effort IP networks. It uses the foraging behavior of ants in finding the best route from the source to the destination in the network. Each ant (so-called mobile agent) has a memory where it stores the path travelled, the number of hops, the time elapsed since its journey began at the source node, and other network information.

Typically, the forward ants are launched at regular intervals from the source to find specific destination nodes. Ants are autonomous, acting asynchronously and concurrently collecting and gathering the information about the routes and traffic patterns at each node. The ants communicate indirectly by learning from the traversed nodes and by writing to them in the form of pheromone tables about the traffic, routes, and pheromone information. For an ant to move to the next hop, a stochastic decision is made that depends on a trade-off between some parameters such as pheromone, local link status, ant memory, to name a few.

While moving, the forward ants focus on choosing the minimum delay path in their search for the destination node. On arriving at the destination node, the forward ant becomes the backward ant and move towards the source node. Based on the goodness of the path followed by the forward ant, the pheromone and routing tables of the traversed intermediate nodes are updated by the backward ant. The goodness of a path is evaluated by comparing the actual travel time against the expected travel time of the forward ant. On arriving at the source node, the backward ant is removed from the network. Following this, the data packets are transmitted along the chosen best path present in the routing tables. The pheromone tables contain the best next hops that the ants have used, and the routing tables are derived from this information. Hence, the AntNet algorithm exhibits some kind of load balancing and optimal utilization of the network resources by recommending the best-effort multi-paths for data routing purpose.

III. M-AntNet Design

The MAntNet approach relies on an adaptive learning process that continuously strives to maintain connectivity and conserves energy usage in the network. The route discovery process is inspired by the modified AntNet approach [3]. It involves control packets circulating in the network until the required connection is established, after which the data packets flow via the established connections. Like in any other ACO-based heuristic, this approach consists of problem definition, evaluation function, local heuristic, pheromone update function, pheromone evaporation rules, and probabilistic transition rules, described as follows:

Problem representation: MANET is represented as a symmetric, undirected, and weighted graph $G[N,E]$, where N is the number of nodes and E is the number of edges. Due to node mobility, the network topology is subject to dynamic change. The routing operation is based on nodes with high residual energy.

Evaluation function: This depends on the node's residual energy to calculate the most possible energy-efficient path to route the data packets.

Local heuristic: The movement of an ant from one node to its next hop depends on the residual energy of the available neighbor nodes. In MAntNet, a forward ant will prefer hopping to a node with a higher residual energy, rather than a node with a shorter path length or a node that consumes less time in data transfer. The probability $P_k(Q)$ of ant k to move to node Q (called probability transition rule) is obtained as:

$$P\kappa(Q) = \frac{[PH_Q]^{\alpha}\,[E_Q]^{\beta}}{\sum_{N\epsilon NEI}[PH_N]^{\alpha}\,[E_N]^{\beta}} \quad (1)$$

where k is the ant that checks if node Q can be its next hop, N is a node in the list NEI of neighbors of the current node, PH_Q is the pheromone value of node Q, E_Q is the energy of node Q, α and β are respectively the weights assigned to the pheromone of nodes and the energy of nodes. The pheromone value of a node is changed every time an ant uses that node as its next hop. In MAntNet, the residual energy of a node is the parameter that will help increasing or decreasing the pheromone value.

Pheromone update rule: The pheromone update value ΔPH_k that is added to PH_Q, the pheromone of node Q, when the backward ant passes node Q on its way back to the source, is given by:

$$\Delta PH_k = 1/(C - E_{avg}) \quad (2)$$

where C is the initial or maximum energy assigned to nodes, and E_{avg} is the average energy of all nodes in the network at a given timestamp.

Pheromone evaporation rule: Given that a forward ant has moved to node Q, the pheromone evaporation of that node is computed as:

$$PH_Q = PH_Q - PH_Q * \rho \quad (3)$$

where ρ is the evaporation factor, i.e. the amount of pheromone that evaporates from each node. When a backward ant passes through node Q, the pheromone it updates on the node is given by:

$$PH_Q = PH_Q * (1-\rho) + \Delta PH_k \quad (4)$$

A. Main Operations of MAntNet

The routing process in MAntNet starts when a source node initiates a transmission request for data packets. The process ends when a suitable routing path has been discovered and the data packets have been successfully transmitted over that path or when there is no possible path available from the source to destination. During the idle time, the protocol listens to all the nodes for any data transmission requests. The MAntNet mechanism works as follows:

Forward Ant activities:

1. Forward ants are generated at regular intervals from each node with a mission to reach their destinations.
2. The forward ant k chooses to move from node S to the next hop Q based on the transition probability rule $Pk(S;Q)$ defined in Eq.1. After passing each node, the forward ant updates each node's pheromone in its routing table according to Eq.3.
3. On reaching the destination, the forward ant transfers its memory information to the backward ant (this includes hop count, time elapsed, energy, pheromone on the traversed nodes, and other route information), i.e. the forward ant is converted to the backward ant.

Backward Ant activities:

4. The backward ant begins its journey from the destination, and works towards the source, travelling on the path stored in its memory.
5. The destination node calculates the pheromone trail ΔPH_k to be deposited along the path by the ant k as per Eq. (2).
6. The backward ant k deposits the amount ΔPH_k of pheromone (from Eq.(2)) in the routing tables of the nodes it traverses along the path it takes to reach the source.
7. An intermediate node Q receiving this backward ant from node S updates its routing table using PH_Q obtained as per Eq. (4).
8. On reaching the source node, the backward ant is dropped. A connection is then established between the source and destination nodes, and the data packets are transmitted using this connection.

Most of the data/packets structures used in the MAntNet implementation are inherited from the AntNet design [3] and the modified AntNet design [4].

IV. E-MANTNET AND E-AODV DESIGNS

The necessity of energy awareness in the routing process of MANETs can be justified as illustrated by the scenario presented in Fig. 1.

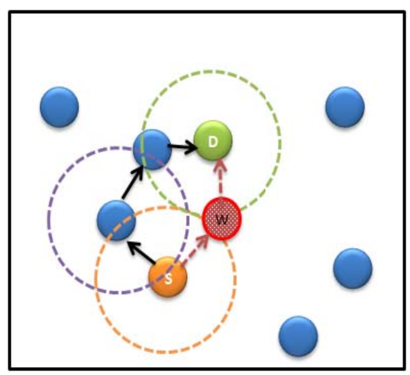

Figure 1: Applying energy-aware routing decision in MANETs

In Fig. 1, any pair of nodes can communicate with each other, even if they are outside each other's transmission range. As nodes move randomly around, any of them could be over-involved in the routing process, thereby losing a lot of energy despite the fact that none of them was neither the source nor the destination of communication. As the time progresses, the entire energy of this node might get depleted, resulting to a reduced network lifetime.

In Fig. 1, let's assume that *S* is the source node and *D* is the destination node. Then, the shortest path of communication is *S->W->D*. However, if node *W* happens to be very weak in terms of amount of residual energy, it will be fair for the routing algorithm to select a different path to node *D* so that node W saves its remaining energy for future necessity. A possible alternative path is represented by the solid arrows and the energy-draining path via node *W* is represented by dotted arrows. The problem that arises here is the: how to determine when to cut-off the path through node *W* and pick a suitable alternate path? This cut-off point must depend on the energy of node *W* relative to the total network energy. In our designs, the following condition is imposed:

*If ((node E < 0.9 * E_avg)) then ((Drop RREQ (Case of E-AODV) or Forward ANT (Case of E-MAntNet))* (5)

where *E_avg* represents the actual average energy of all nodes in the network. It should be noted that although the design of this imposed condition may help in achieving increased network energy, it is essential to verify that doing so will not drastically hamper the network connectivity, here measured in terms of the relative ease with which a desired communication between any pair of nodes can be successfully achieved. The connectivity is determined as:

Connectivity = Number of replies from destination node/ Number of requests from source node (6)

The trade-off between achieving an increased total network residual energy and ensuring a good level of network connectivity is therefore a challenge in our proposed designs.

A. E-MAntNet Design

The E-MAntNEt algorithm design follows the same steps as in case of the MAntNet protocol, with the following additional requirement imposed to the forward ant activities portion: if the selection of the next hop (i.e. node) that will receive the forward ant (according to the probability transition rule in Eq.(1)) results to an intermediate node whose residual energy matches the condition stated in Eq.(5), this intermediate node will drop the forward ant without further processing so as to retain its available energy level; otherwise, E-MAntNet and MAntNet will behave similarly.

B. E-AODV Design

The AODV protocol [2] for MANETs is accomplished using four types of messages that ensure the route-discovery and route maintenance phases, namely, a) Hello packets - these are used by nodes to learn about their neighbours, b) Route Request (RREQ) message, c) Route Reply (RREP) message, and Route Error (RERR) message. The key steps involved in the route discovery process can be described as follows:

1. When a source node (or source) wishes to communicate with a destination node (or destination) to which it has no route, it broadcasts the RREQs to its neighbors. These RREQs are then forwarded to neighbors of neighbors, and so on, until one of the receiving node has an active route to the destination in its routing table.
2. Nodes learn about the local topology during the process described in Step 1, by updating their routing information (in terms of destination and next hops) in their routing tables. They also record the reverse path to the source, which is used in the RREP process.
3. An intermediate node (that has an active route to destination) or the destination node itself, on receiving the RREQ packet, responds to this by unicasting a RREP message along the reverse route to the source. The validity of this route is confirmed after a comparison between the sequence number of the intermediate nodes and the destination sequence number of the RREQ packet is found to match. All the intermediate nodes then store this path between the source and destination in their respective routing tables.
4. On receiving the RREP, the source stores the information on this discovered route (such as elapsed time it has taken to discover the route since the source emitted a RREQ, hop count, etc) and discards the RREP. If multiple RREPs are received by the source, the route with the shortest hop count is selected. The connection between the source and destination is said to be established, and the source begins transmitting the data packets to the destination using that discovered path.

In the above route discovery phase (Step 3), the route maintenance phase is invoked whenever a link failure occurs. In such case, a RERR message is generated, informing the other nodes, including the source, about this fact. The source then disables the route involving the broken link upon receiving the RERR, and reinitiates the route discovery process if necessary.

The E-AODV algorithm design follows the same steps as that of AODV described above, but with the additional requirement that the same energy-aware condition in Eq.(5) is also imposed during the route discovery phase of AODV (Step 3). More precisely, at the above Step 3, if a node that accepts to receive a RREQ packet has a residual energy that satisfies the energy condition in Eq.(5), this node will drop the RREQ packet and will be prevented from participating to the routing operation until its available energy is good enough at a later timestamp. Otherwise, E-AODV and AODV will behave similarly.

The E-MAntNet flowchart (including that of MAntNet) is shown in Fig. 2, and the E-AODV flowchart (including that of AODV) is depicted in Fig. 3, where the dotted lines illustrated the portion implementing the energy constraint given in Eq.(5).

I. Performance Evaluation

We used the NS2 ver. 2.34 as simulation tool [11] to compare the performance of the proposed protocols, on the basis of the following performance metrics: (1) *Residual energy (RE)*: The average of all the node's residual energy at the end of every simulation form this metric; (2) *Connections established (CE)*: This metric helps to measure the ability of a routing protocol to maintain the network connectivity.

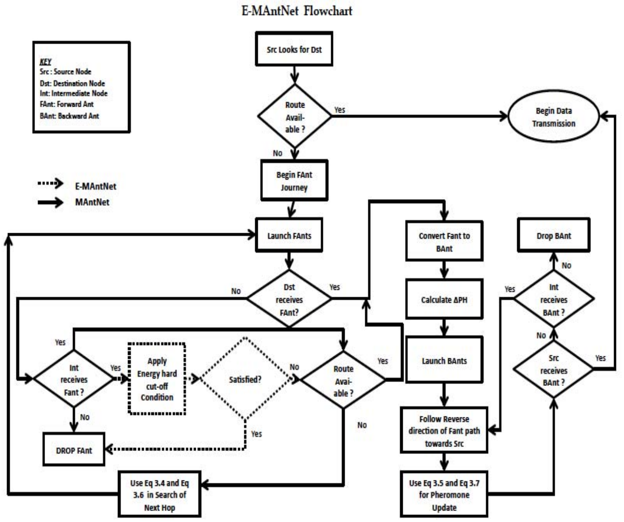

Fig. 2: E-MAntNet flowchart.

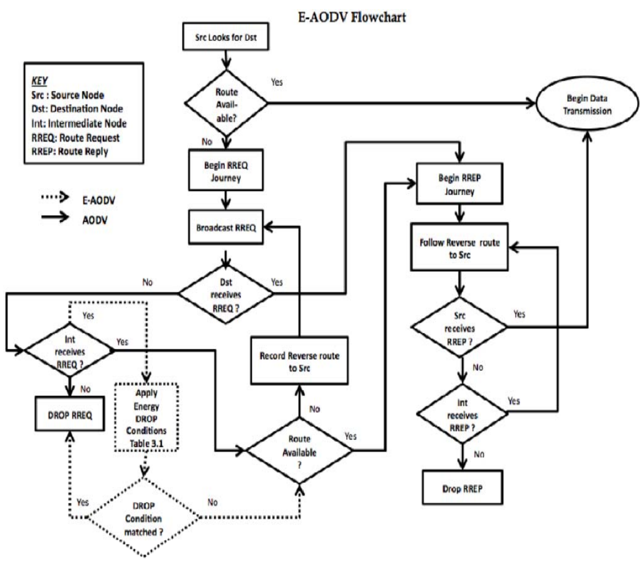

Fig. 3: E-AODV flowchart.

It is quantified as: *Number of Backward Ants from Destination/ Number of Forward Ants from Source* (Case of MAntNet) and *Number of RREPs from Destination/ Number of RREQs from Source* (Case of AODV); (3) *Dead node (DN):* This refers to the total number of inactive nodes in the network. A node whose energy level is below 70 Joules is assumed to be inactive. The simulation parameters are captured in Table I. The considered simulation scenarios are: (1) Varying the (T_x,R_x) values, (2) Varying the transmission range; and (3) Varying the node speed.

TABLE 1: SIMULATION PARAMETERS

Mobility model	Random Way Point
Terrain dimension	1000 m x 1000 m
Radio propagation model	Two-ray ground reflection model
MAC protocol	IEEE 802.11
Node interface	Wireless
Traffic	CBR
Network layer protocol	AODV, AntNet
Number of nodes	100 (or variable)
Simulation time	100 seconds
Initial node energy	100 Joules
Transmission power (T_x)	3 Watts (34.77 dbm)
Receiving power (R_x)	1.5 Watts
Transmission range	100 m (default), 25-200m (variable)
Antenna	1.5 Hz
Pause time	1 second
Node speed	1-10 m/s
Packet size	Control packet: 30-44 bytes; Data packet: 1000-1020 bytes

A. E-MAntNet vs. MAntNet (resp. E-AODV vs. AODV) Under Varying (T_x,R_x)

In this scenario, the (T_x,R_x) values are varied and the impact of this variation on the residual energy (RE), number of connection established (CE) and dead nodes (DN), for E-MAntNet vs. MAntNet, are studied. The results are captured in Fig.4, Fig.5, and Fig.6. The impact of the above variation on the network lifetime for E-AODV vs. AODV is also examined. The results are captured in Fig. 7.

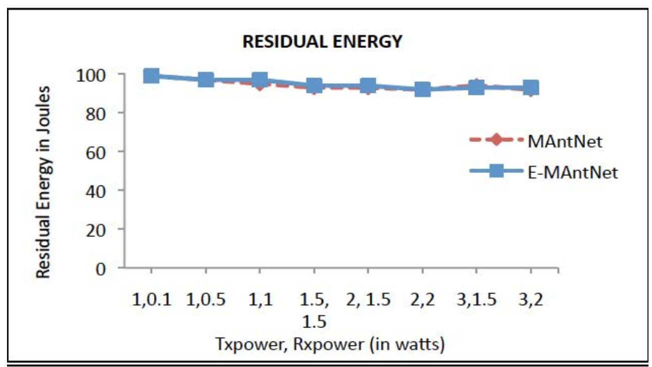

Fig. 4: E-MAntNet vs. MAntNet in terms of RE, under varying (T_x, R_x)

In Fig. 4, it is observed that the residual energy generated by E-MAntNet is slightly better than that obtained using MAntNet. In Fig. 5, E-MAntNet and MAntNet show almost similar performance in terms of network connectivity. In Fig. 6, it is observed that the number of dead nodes generated by E-MAntNet is much lesser than that generated by MAntNet.

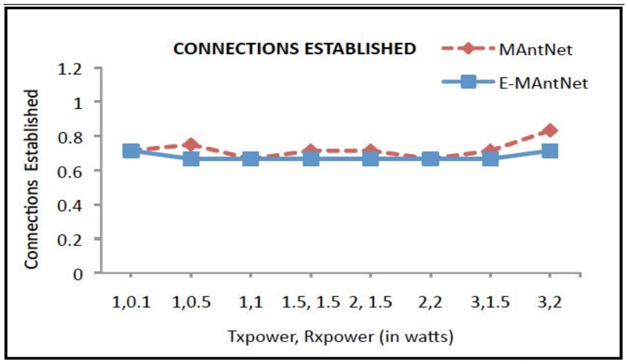

Fig. 5: E-MAntNet vs. MAntNet in terms of number of CE, under varying (T_x, R_x).

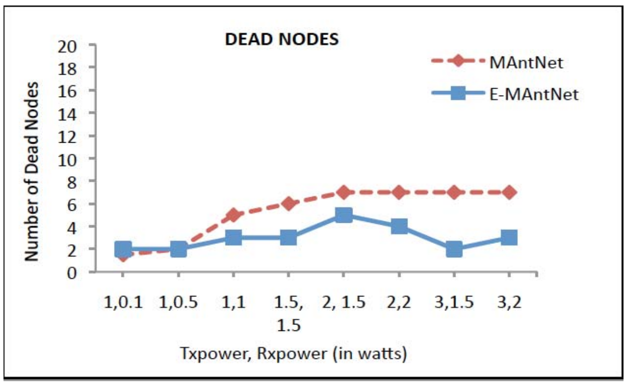

Fig. 6: E-MAntNet vs. MAntNet in terms of number of DN, under varying *(T_x, R_x)*

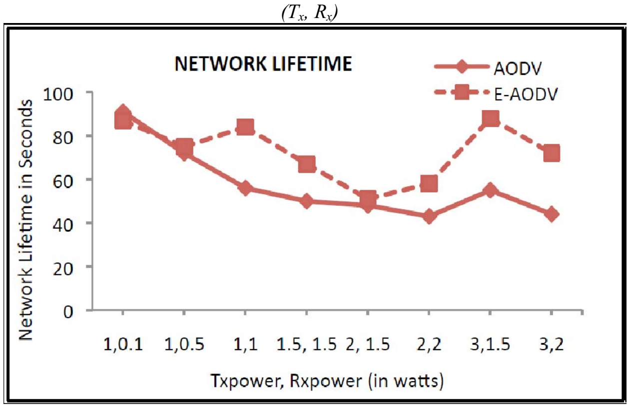

Fig. 7: E-AODV vs. AODV in terms of network lifetime, under varying (T_x, R_x)

In Fig. 6, it is observed that the number of dead nodes generated by E-MAntNet is much lesser than that generated by MAntNet. We also found that the network lifetime is much higher in the case of E-MAntNet when compared to MAntNet. Thus, on the whole, E-MAntNet shows a better performance than MAntNet in terms of residual energy, dead nodes and network lifetime. It is also observed that when the transmission power increases, E-AODV tend to generate a longer network lifetime compared to AODV (Fig. 7). These results may be attributed to the cut off energy constraint that has been imposed in the route discovery process of E-MAntNet (resp. E-AODV), preventing low energy nodes from taking part in this process.

B. E-MAntNet vs. E-AODV Under Varying Transmission Range

In this scenario, the transmission range is varied and the effect of this variation on the residual energy (RE), number of connections established (CE) and dead nodes (DN), for E-MAntNet vs. E-AODV, are studied. The results are captured in Fig.8, Fig.9, and Fig.10.

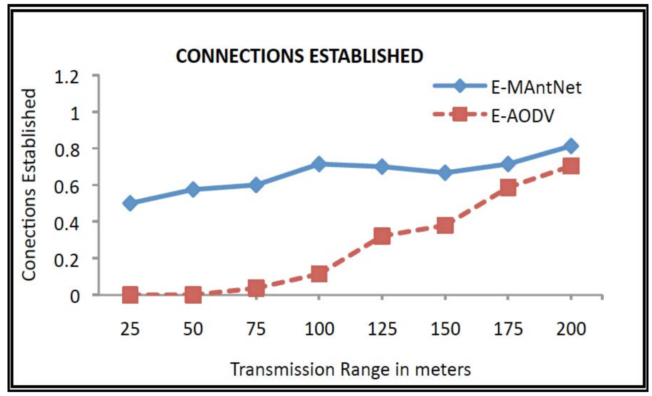

Fig. 8: E-MAntNet vs. E-AODV in terms of number of CE, under varying transmission range

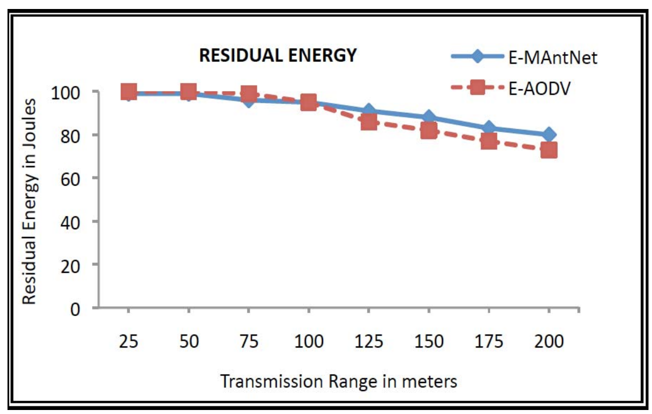

Fig. 9: E-MAntNet vs. E-AODV in terms of RE, under varying transmission range

In Fig. 8, it is observed that when the transmission range increases, the number of CE in E-MAntNet is much higher compared to that generated by E-AODV. For smaller transmission ranges (below 100 meters), E-AODV yields minimal connections because most of the control packets are dropped, and may literally lead to zero connections established, even though it yields much higher RE (Fig. 9) and minimal DN (Fig. 10) compared to E-MAntNet. This means that E-MAntNet is better than E-ODV in sparsely populated network. For larger transmission ranges (more than 100 meters), it is observed that E-MAntNet conserves more energy, generates less number of dead nodes (and yields a longer network lifetime – although not shown) compared to

E-AODV, meaning that E-MAntNet would perform better than E-AODV in dense MANETs. This may be attributed to the intrinsic energy-aware route discovery mechanism (local heuristic function) used in E-MAntNet

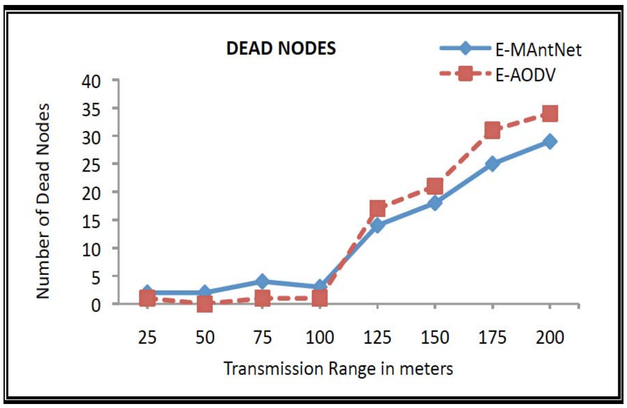

Fig. 10: E-MAntNet vs. E-AODV in terms of number of DN, under varying transmission range

C. *E-MAntNet vs. E-AODV Under Varying RMS Speed*

For higher values of the root mean square (RMS) speed, the nodes move at greater distances in a single time step. At every second (pause time), a node moves to a different position with respect to its randomly assigned RMS speed at that time, where RMS speed of Z means that the node movement (in m/s) is in the range [-Z, Z]. In this scenario, the RMS speed is varied and the impact of this variation on the residual energy (RE), number of connection established (CE) and dead nodes (DN), for E-MAntNet vs. E-AODV, are studied. The results are given in Fig.11, Fig.12, and Fig.13. The impact of the above variation on the number of dead nodes for MAntNet vs. AODV is also examined. The results are captured in Fig. 14.

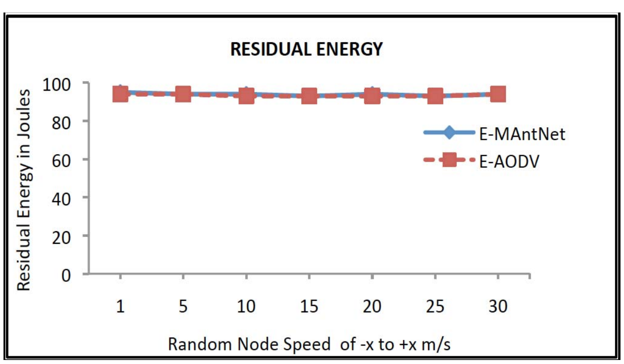

Fig. 11: E-MAntNet vs. E-AODV in terms of RE under varying RMS speed.

In Fig. 11, it is observed that E-MAntNet and E-AODV yield almost the same amount of residual energy. The number connections established by E-AODV is lesser than that established by E-MAntNet (Fig. 12). The drastic drop in connections established observed in Fig. 12 in the case of E-AODV might be attributed to the fact that the cut-off energy-aware condition imposed in the route discovery in E-AODV systematically drops the packets from lower energy nodes.

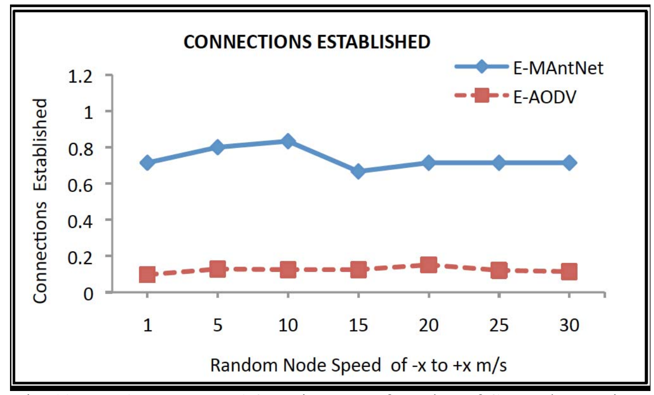

Fig. 12: E-MAntNet vs. E-AODV in terms of number of CE, under varying RMS speed.

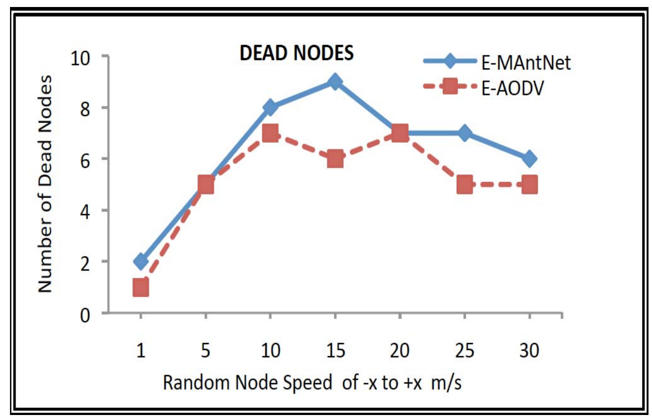

Fig. 13: E-MAntNet vs. E-AODV in terms of number of DN, under varying RMS speed

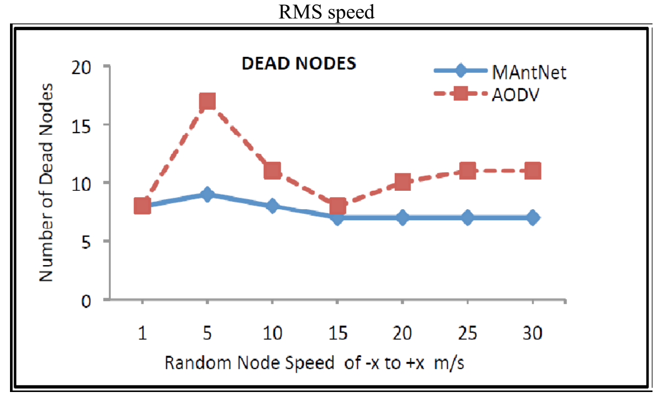

Fig. 14: MAntNet vs. AODV in terms of number of DN, under varying RMS speed

In general, E-MAntNet and E-AODV tend to maintain their levels of connectivity for increasing RMS speeds. Interestingly, when the node speeds are high, the low energy nodes are sufficiently well spread in the terrain, and the rerouting process introduced by the above cut-off energy-constraint is not effective in maintaining less dead nodes. Consequently, for larger node speeds, the number of dead nodes increases (as shown in Fig 13). As the node speed increases, the nearby neighbors of that node frequently move in and out of the transmission range of each other, requiring a frequent update of the routing tables. However, since the motion is random, for the default transmission range of 100 m, a significant variation in the residual energy and number of connections established for larger speeds is not expected (as illustrated in Fig. 11 and Fig. 12). In Fig. 14, it is observed that the number of dead nodes generated by MAntNet is less than that generated by AODV, yielding a better network lifetime for MAntNet compared to AODV.

VI. CONCLUSION

This paper proposes an AntNet-based routing scheme for MANETs (called MAntNet) and its energy-aware version (called E-MAntNet) as well as an energy-aware version of AODV (called E-AODV). It has been observed through simulations that: (1) the residual energy generated by the energy aware protocol E-MAntNet (resp. E- AODV) is comparable or higher than that generated by its plain version MAntNet (resp. AODV); (2) E-MAntNet (resp. E-AODV) generates an equivalent or lesser number of dead nodes compared to its plain version MAntNet (resp. AODV). However, the total connections established when using E-AODV falls off significantly when compared to AODV; (3) the number of connections established when using E-MAntNet (resp. E-AODV) is comparable to that obtained with MAntNet, its plain version (resp. E-AODV); and (4) when compared to E-AODV, E-MAntNet shows a better CE, an equivalent or better generated residual energy. Hence, for most of the studied performance metrics, it is reasonable to conclude that E-MAntNet outperforms MAntNet. As future work, we intend to strengthen the proposed MAntNet scheme by making it secure. This can be achieved by incorporating some cryptographic schemes during the route discovery phase.

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