ENERGY-AWARE ANT COLONY OPTIMIZATION BASED ROUTING FOR MOBILE AD HOC NETWORKS

by

Ssowjanya HariShankar

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Abstract

In mobile ad hoc networks, nodes are mobile and have limited energy resource that can quickly deplete due to the multi-hop routing activities, which may gradually lead to an unoperational network. In the past decades, the hunt for a reliable and energy-efficient MANET routing protocol has been extensively researched. In this thesis, a novel routing scheme for MANETs (so-called MAntNet) has been proposed, which is based on the AntNet approach. Precisely, the AntNet algorithm is modified in such a way that the routing decisions are facilitated based on the available nodes energy. Additionally, some energy-aware conditions are introduced in MAntNet and replicated in the conventional AODV routing protocol for MANETs. The resulting energy-aware M-AntNet (E-MAntNet) and energy-aware AODV (E-AODV) are analyzed using NS2 simulations. The results show that E-MAntNet performs significantly better than MAntNet and E-AODV both in terms of network residual energy and number of established connections in the network.

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List of Abbreviations

ABR	Associativity Based Routing
ACO	Ant Colony Optimization
AEADMRA	Ant-based Energy Aware Disjoint Multipath Routing Algorithm
AODVM	Modified Ad-hoc On demand Distance Vector
AODV	Ad-hoc On demand Distance Vector
BABR	Basic Ant Based Routing
CE	Connections Established
DN	Dead Nodes
DYMO	Dynamic MANET On-demand routing protocol
DSR	Dynamic Source Routing
DSDV	Destination Sequenced Distance Vector
E-AODV	Energy-aware Ad-hoc On demand Distance Vector
EEABR	Energy Efficient Ant Based Routing
E-MAntNet	Energy-aware Modified AntNet
IABR	Improved Ant Based Routing
LMR	Light-weight Mobile Routing
MANETs	Mobile Ad-hoc Networks
MAC	Media Access Control
MAntNet	Modified AntNet
NL	Network Lifetime (in seconds)
RE	Residual Energy (in Joules)
RERR	Route Error
RREP	Route Reply
RREQ	Route Request
WSN	Wireless Sensor Networks
ZRP	Zone Routing Protocol

Chapter 1

Introduction

1.1 Context

There has been a huge demand for investment and research in specialized computing devices over the past decades. The necessity of communication between computing devices anytime, anywhere has vastly multiplied. Wireless networks have played and continue to play a major role in turning this necessity into a possibility all over the world. These networks have evolved to be functional and mobile by means of technologies such as WiFi, HotSpot, 3G, 4G/LTE, Bluetooth, HamRadio, to name a few. Wireless ad-hoc networks are specialized in the deployment of mobile devices without any existing infrastructure, therefore, they are decentralized by nature. Devices that constitute an ad hoc network are not only wireless, but also self configuring and quick to deploy. Due to these features, ad hoc networks can be used in several applications such as disaster relief, military operations, health care monitoring, just to name a few. The demand for dynamic routing protocols that can adapt quickly to changes in the network topology and environmental interference is therefore a hot topic in todays research [1] in the area of communication networks.

Mobile ad-hoc networks (MANETs) are infrastructure-less in nature. These networks consist of mobile devices that move independently in different directions and varying speeds.

Mobile devices with energy constraints such as mobile phones, laptops and tablets can be nodes of a MANET. While moving, such a node generates the traffic for its own purpose. It can also act as a router to forward other traffic. For every packet that a node forwards or receives, it is bound to lose some amount of energy. This drains the available or residual energy of nodes; therefore at some point, some nodes may die, hence, slowly depleting the networks lifetime.

Routing consumes network's energy by depleting the residual energy of nodes participating in routing process. On the other hand, energy is a precious resource for battery-driven nodes such as MANET nodes. Hence, there is a clear demand for upgrading the conventional routing protocols for MANETs (e.g. the Ad hoc On demand Distance Vector routing (AODV) [2]) into energy-aware routing protocols or for creating new energy-efficient routing protocols for MANETs. While evading the depletion of network energy is important, it is also essential that the network remains capable of maintaining the connections among its nodes all the time. The goal of this thesis is to design some novel energy efficient routing protocols for MANETs that are also capable of maintaining the nodes connectivity almost all the time.

Energy conservation in MANETs has been intensively studied in the literature via the use of several routing techniques [3], most of which rely on controlling the transmission power of nodes, controlling the residual energy of nodes, controlling the load distribution in the network, or varying the transmission range of the nodes, to name a few. In addition, based upon the pioneered work of Di Caro et al. [4] on the concept of swarm intelligence as an approach to address the problem of routing in communication networks, several routing algorithms for MANETs (including the Ant Colony Optimization (ACO) framework [5]) have been proposed in the literature. Some of these algorithmns are energy aware [6]. Among ACO techniques is the AntNet adaptive routing algorithm for best-effort routing in IP networks [4], a distributed agent- based routing algorithm inspired by the behaviour 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 other network status as they explore the network in a non-coordinated manner, in an attempt to solve the adaptive routing problem. To the best of our knowledge, there has been very few recent proposals for energy aware routing protocols for MANETs based on the AntNet approach. This thesis proposes three energy-efficient routing protocols for MANETs, our so-called modified AntNet-based routing protocol, its improved version, and an energy-aware version of AODV (a conventional routing protocol for MANETs).

1.2 Research Problem

In communication networks, routing is in general performed to ensure that the communication between nodes happen whenever it is required. In MANETs, the nodes are mobile and multiple hops are typically used for establishing a connection, yielding the problem of energy consumption in each participating node. If ignored, routing in MANETs could cause dead nodes and gradually lead to an un-operational network. In this thesis, we address the problem of designing routing algorithms for MANETs that can solve this issue by ensuring minimal energy consumption in the network. Two of our proposed energy-efficient routing algorithms rely on the use of the AntNet heuristic, which promotes the concept of adaptive learning of the routing paths in the network. Another algorithm we propose is the energy-aware AODV, a modified version of the conventional AODV protocol.

1.3 Approach

Camilo et al. proposed an efficient energy-aware routing protocol for wireless sensor networks (WSNs) based on the ACO framework [7]. Inspired by this work, a novel routing protocol for MANETs based on the AntNet principle is proposed (so-called modified AntNet or MAntNet for short). An improved energy efficient version of the MAntNet protocol is also proposed (so-called energy-aware modified AntNet or E-MAntNet for short). Finally, AODV, the conventional routing protocol for MANETs is upgraded with the same energy-aware conditions that were introduced in the design of the E-MAntNet protocol, yielding the so-called energy-aware AODV algorithm (or E-AODV for short). These algorithms concentrate mainly on the residual energy of nodes in the network and build the routes using the most energy retaining nodes. Besides energy conservation, these algorithms are also meant to ensure a better connectivity in the network. Simulation experiments are conducted in Chapter 4 to validate the stated goals and to compare the three algorithms (namely, MAntNet, E-MAntNet, and E-AODV) in terms of some predefined performance metrics. It is found that E-MAntNet conserves more energy and has a better connectivity compared to its counterparts.

Both the MAntNet and E-MAntNet protocols follow an adaptive learning process that continuously strives to maintain connectivity and conserves energy usage in the network. The route discovery process involves control packets circulating in the network until the required connection is established, following which the data packets flow through the established connections. This route discovery process is inherited from the AntNet approach introduced in [7] in the context of WSNs.

In the natural world, ants randomly search for food source and deposit a chemical substance called pheromone to mark their trail. Other ants follow this trail and further increase the pheromone intensity (which marks the goodness of the path). This food search behavior of ants is used by ACO based algorithms in solving several computational / communication challenges. Like for other ACO-based algorithms, our approach consists of problem definition, evaluation function, local heuristic, pheromone update function, pheromone evaporation rules, and probabilistic transition rules as described in detail in Chapter 3. Ants (so-called agents) are deployed in the network in search of the destination nodes at separate times. During their search for best routes, the ants deposit pheromone on the nodes. This pheromone is a function of the nodes residual energy, which itself is involved as parameter in a probabilistic transition rule that helps in choosing the next hop of an ant. For a given ant to move from one node to the next, this transition rule is applied in its hunt to reach the destination node. Some energy-based conditions are added to this process to ensure that nodes with low energy levels are ignored during data routing, so that ants choose the nodes with higher residual energy as their next hops. Furthermore, the coordinates, speed, and direction of the nodes are completely randomized during simulations.

On the other hand, the proposed E-AODV protocol intrinsically follows the original design of the AODV protocol, with the exception that the same energy-aware conditions that have been introduced in the design of the E-MAntNet protocol prevail when establishing the routing paths in the route selection process of AODV.

1.4 Thesis Contributions

The contributions of this thesis are as follows:

- Design of an AntNet-based routing protocol for MANETs (called MAntNet).
- Design of an improved version of MAntNet (called E-MAntNet - for energy-aware MAntNet) and design of an energy-aware AODV protocol (called E-AODV).
- Comparison of the proposed routing protocols by simulations using the NS2 simulator, showing that E-MAntNet outperforms both MAntNet and E-AODV in terms of predefined performance metrics.

1.5 Thesis Outline

This thesis is organized as follows:

- **Chapter 1** introduces the subject, motivation, and contributions of our research.
- **Chapter 2** presents some background information and related works.

- **Chapter 3** describes our proposed MAntNet, E-MAntNet, and E-AODV algorithms in detail.
- **Chapter 4** describes the performance evaluation of the proposed routing algorithms.
- **Chapter 5** concludes our work and highlights some future work.

Chapter 2

Background and Related Works

2.1 Background

This section describes the concept of routing in MANETs and the importance of energy-efficient routing. Representative conventional routing protocols and ACO-based routing protocols for MANETs are also discussed.

2.1.1 The Need for Energy Efficient Routing Protocols for MANETs

This section highlights the importance of routing protocols for MANETs and how they can deplete the network lifetime. Nodes in a MANET are autonomous and mobile with varying speeds and directions. They need to be governed by a routing protocol that will help in regulating the network functions. Routing is a dynamic process that aims at providing the paths that are suitable for data transmission. These paths are optimum in terms of some criterion such as maximum bandwidth, minimum distance, shortest delay in data transmission, cost, to name a few. They should also satisfy some constraints such as limited capacity of wireless links, limited power of nodes, to name a few. In general, a routing protocol can be designed based on the information used to build routing tables. AODV's route discovery process is covered in this thesis.

Fig 2.1 is an example of MANET with 14 nodes at a given timestamp. The dotted circles around nodes 1, 2, 3 and 4 are their respective transmission ranges. The transmission range of a node is the coverage area up to which its transmitted packets can be received by other nodes located within this area. In this scenario, node 2 has four neighbors i.e four nodes within its range that it can communicate with; similarly node 3 has two neighbours and node 4 has three neighbors in their respective ranges. However, node 1 has no neighboring nodes, thus it cannot connect to any other node unless a change occurs in the network topology. In this given scenario, nodes 3 and 4 are the only ones who can communicate with each other by means of common neighbours.

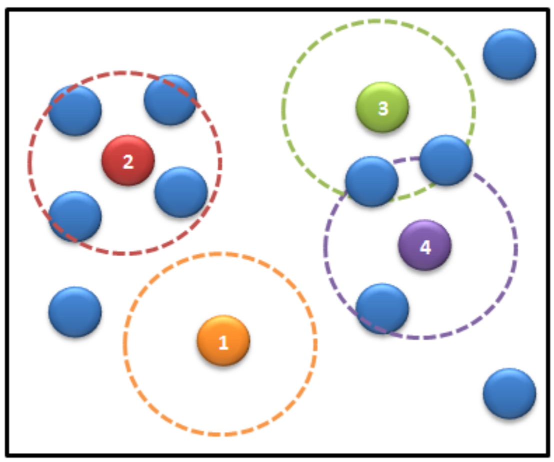

Figure 2.1: Example of MANET at a given timestamp

As the transmission range of a node increases, the number of its neighbors increases as well; this in turn increases the network activity. For every packet transmitted or received by a node, it loses some amount of its available residual energy. Each node has a limited residual energy and can be eligible to participate in the routing process, i.e. apart from sending and receiving its own desired traffic, a node can also act as a router that forwards the traffic for other nodes in the network. Hence, the available energy in the network can be consumed quickly when the transmission range is large. Thus, our objective is to propose a routing protocol that maintains a good connectivity while consuming less energy as much as possible.

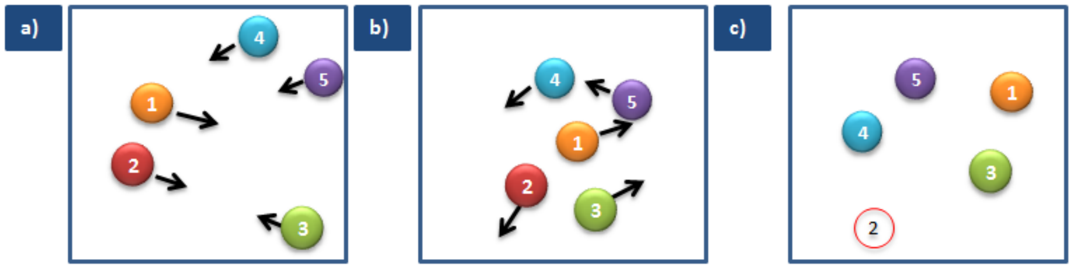

Figure 2.2: Example of MANET at 3 different timestamps

Fig 2.2 shows a sample MANET with 5 nodes at different timestamps namely a), b) and c) displaying a dynamic topology change. The dotted circle around the nodes indicate each of their transmission range. In Fig 2.2 a), five nodes are seen to travel in various directions and at the timestamp in b), the nodes have relocated and intend to travel in different directions. There is an arbitrary change in the node velocities at every timestep. In the process, different nodes come in contact with different nodes and many nodes get away from their connected neighbours. Many nodes are used for forwarding traffic for other nodes and tend to loose their available energy. In c), node 2 has lost all its energy due to routing and has become inactive or dead. At some point, all nodes tend to empty their available energy and become inactive, leading to a dead network. In this thesis, a mechanism is designed to help slowing down the energy depletion during the route discovery process.

2.1.2 Overview of Routing Protocols for MANETs

This section discusses some conventional routing protocols and ACO-based energy-efficient routing protocols for MANETs.

Conventional Routing Protocols

Conventional routing protocols for MANETs can be classified into proactive, reactive and hybrid types. Proactive protocols are those in which the routes are always maintained with periodic updates to the routing tables (present in each node). These protocols generate a lot of routing overhead (excessive network traffic involved in maintaining routes). Examples of proactive protocols include the Destination Sequenced Distance Vector routing protocol (DSDV) and the Optimized Link State routing protocol (OLSR). On the other hand, reactive protocols are on-demand routing protocols that quickly adapt to topological changes. Routes are created only on demand by broadcasting the route request packets. Examples of reactive protocols are the AODV protocol, the Dynamic Source Routing (DSR), the Lightweight Mobile Routing (LMR), the Associativity based Routing protocol (ABR), to name a few. Compared to all other reactive protocols, AODV is considered to produce minimum broadcasts, giving rise to low bandwidth utilization. It is scalable to large networks and works well with high mobility networks. It can also quickly adapt to dynamic topology changes and maintain the active routes alone. Finally, hybrid routing protocols are a combination of reactive and proactive protocols; an example of such protocol is the Zone Routing Protocol (ZRP). In this thesis, an energy-aware version of the AODV protocol is proposed and evaluated.

ACO-Based Routing Protocols

In the natural world, Ants as insects exhibit collective, distributive and adaptive learning within their colonies, that are not regulated by any form of centralized control [5]. With robust self-organizing dynamics, ant colonies have inspired many in building algorithms and models for multi-agent systems in the field of robotics and telecommunications. One of the most popular works inspired by ant colonies is the Ant Colony Optimization (ACO) metaheuristic [5]. This metaheuristic is a multi agent framework which helps in solving the combinatorial problems in a nature-inspired fashion. The main components of ACO constitute a group of ant-like agents, ant memory, stochastic decision making to construct solutions, stigmergic (indirect communication among agents) learning of decision policy, pheromone updates and collective-distributive learning strategies.

ACO techniques are suitable as heuristics for designing the routing protocols for MANETs since they can be applied in the route discovery and maintenance phases of the design. Many ACO-based routing algorithms for wireless networks have been investigated in the literature [4] [5]. Few examples are the Simple ACO (SACO), the AntNet, the AntHocNet, and the Ant System algorithms.

In this thesis, our focus is on the AntNet heuristic [4], an adaptive best-effort routing protocol whose purpose is to find the shortest path to destination based on a nature-inspired meta-heuristic. Our goal in this thesis is to propose an energy-efficient version of AntNet for MANETs. More precisely, we have modified the AntNet algorithm introduced in [7] in the context of wireless sensor networks, and adapted it to work on MANETs, resulting to our so-called modified AntNet (MAntNet). An improved version of MAntNet (so-called energy-aware MAntNet or E-MAntNet) is also proposed, which considers the nodes residual energy as criterion to select the best route to carry the data packets to their destination.

2.2 Related Work

2.2.1 Energy-Aware Routing Protocols

A number of energy-aware routing protocols for MANETs have been proposed in the literature. Few of these that are more relevant to the scope of this thesis [[3], [8], [9], [10]] are described as follows.

In [3], Moshin et al. have surveyed various energy-aware routing protocols for MANETs at the network and Media Access Control (MAC) layers. Their work emphasizes the effects of high energy consumption on the network's performance in terms of throughput, latency, overheads and delay. The authors have conducted some simulations to compare the studied protocols against some energy-related performance metrics, and have showed that it is not possible to conserve energy in MANETs without having to forgot the protocol's performance in terms of other metrics. However, their work only covers the study of few energy-aware routing protocols for MANETs.

In [8], Tan et al. proposed a power conservation routing protocol for MANETs, designed by modifying the standard AODV routing protocol. A power-based cost function is defined which helps the nodes to choose the best route during the route discovery process. Each node is assigned with a power level and a corresponding cost value which is calculated for each route found. The route request (RREQ) and route reply (RREP) packets carry the power and cost of the routes covered. The source node chooses the route that has the minimum cost and then establishes the connection with the destination node. In addition to the route maintenance process, a cost zoning concept is introduced to manipulate the cost of nodes in such a way that low power nodes are assigned very high costs and vice-versa, leading to energy-efficient routes.

In [9], Taneja et al. also proposed a power-aware scheme for MANETs. Their scheme is based on AODV in the sense that it improves the AODV route discovery process, by introducing a mechanism that helps achieving the energy-optimization in large networks handling varying levels of data traffic. Similar to the cost zoning concept introduced in [8], Taneja et al. categorized the battery decay factor of nodes into three states, where a node with at least half of its initial power can remain in active state and still participate in the routing process. In this scheme, the power aware functionality is included in the RREP phase of the route discovery process. Through simulations, some improvement over AODV is obtained by generating less number of dead nodes.

In [10], Jia et al. proposed to extend the network lifetime of ad-hoc networks by introducing a modified energy-aware AODV routing protocol (called AODVM). Their algorithm 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 (precisely the ratio of the residual energy to the hop count). The route with the highest routing metric is then selected for data transfer. Through simulations, the proposed AODVM shows longer network lifetime, lesser delay and energy consumption when compared to the original AODV protocol.

2.2.2 ACO-Based Energy-Aware Routing Protocols

A number of energy-aware routing protocols for MANETs based on the ACO principle have been proposed in the literature. Few of these that are more relevant to the scope of this thesis [6], [11], [12], [13], [14], [7] are described as follows.

In [6], an interesting work by Gupta et al. have created an essential summary of a variety of ad-hoc routing protocols and their characteristics. It involves some comparison of certain state-of-the-art ACO-based ad-hoc routing protocols such as Ant-AODV [15], Ant-DSR [16], Ant-DYMO [17], to name a few, against some standard ad-hoc routing protocols such as AODV, DSDV, DSR. The types of protocols considered in this study are proactive, reactive, and hybrid. Important routing behaviors of the protocols such as routing overhead, end-to-end delay, packet delivery ratio, throughput, network lifetime, storage requirements, periodic route updates, scalability, ant type (forward or backward), to name a few, are compared. The summary of algorithm specific behaviors that are provided in [6] acts as an excellent reference that helps in finding appropriate ad-hoc protocols for varying research requirements.

In [11], Raghavendran et al. qualitatively compared some swarm-intelligence based routing protocols for MANETs. The intricate working of both the Ant swarm system and Bee swarm systems are very well narrated in their paper. On analyzing various ant and bee inspired routing protocols for MANET, Raghavendran et al. highlighted their respective advantages and disadvantages, stating that ant and bee inspired algorithms provide solutions to overcome various routing problems in computer networks, but they come with demerits such as excessive control traffic overhead and the inability to use the maximum route length.

In [12], Shirkande et al. surveyed a number of ant colony-based routing protocols for MANETs and WSNs. Their surveyed routing protocols were shown by simulations to decrease the communication overhead, adapt to network topologies, support multipath routing, while increasing the network lifetime and energy efficiency.

In [13], Radwan et al. introduced a MANET routing scheme called AntNet-RLSR, in which the AntNet protocol is adapted to support the blocking-expanding ring-search method [18], [19] and the local-retransmission based protocol [10]. In their scheme, the mobile agents build the routes between the source node and destination node while simultaneously exploring the network activities and updating the routing information. Through simulations, it was shown that their routing protocol enables optimal path routing and quick route discovery with minimal delay, routing overhead, and maximized throughput.

In [14], Zhengyu et al. proposed a multipath routing protocol called ant-based energy-aware disjoint multipath routing algorithm (AEADMRA), an extension of the location based MANET routing protocol called GRID [20], a location-aware protocol that is insensitive to host mobility and offers strong maintenance of routes in a MANET. The AEADMRA protocol improves the GRID protocol by identifying multiple energy-efficient routing paths with negligible overhead, which in turn promotes the mobility in the network.

In [7], Camilo et al proposed an energy-aware AntNet-based routing protocol for WSNs and two enhanced versions of it, namely, (1) the basic ant based routing protocol which includes some energy-related conditions (so-called BABR), (2) an improved BABR algorithm (so-called IABR) - where the improvement relies on the introduction of the notion of energy quality of paths, leading to reduced memory usage of nodes compared to the BABR scheme; and (3) another improved version of the BABR algorithm called energy-efficient ant-based routing algorithm (EEABR), where the improvement stems from the fact that some functions that reduce the energy expenditure and communication load have been introduced in the design of the BABR protocol. Through simulations, the EEABR protocol was shown to reduce the control packets overhead and to elongate the network lifetime compared to both the IABR and BABR protocols.

In this thesis, a modified version of the AntNet algorithm [4] [5] called MAntNet is proposed, based on design features inherited from the BABR algorithm [7] - but in the context of MANETs - and design features of AntNet. An improved version of MAntNet is also proposed (called E-MAntNet). Finally, an energy-aware version of the AODV protocol is proposed (called E-AODV). These three algorithms are described in-depth in Chapter 3.

Chapter 3

Methodologies

This chapter covers the main contributions of this thesis. It describes the basics of the AntNet algorithm [4], followed by the AntNet-based BABR algorithm for wireless sensor networks [7], where BABR stands for Basic Ant-Based Routing. Next, it describes our MAntNet algorithm for MANETs (inspired by the AntNet-based BABR and AntNet designs), and its improved version (E-MAntNet). Finally, the energy-aware AODV (E-AODV) protocol is described.

3.1 AntNet Algorithm

The AntNet algorithm [4] is one of the algorithms in the family of Ant Colony Optimization (ACO) algorithms, that was designed for distributed and adaptive multi-path routing purpose in wired best-effort IP networks. It uses the foraging behavior of ants in finding the best route from source to destination in the network. Each ant (also called mobile agent) in the network 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. Forward ants are launched at regular intervals from the source to find specific destination nodes. Each ant is autonomous, and acts asynchronously. It also concurrently collects and gathers the information about the routes and traffic patterns at each node. 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 (this concept of 'virtual pheromone' has been inherited from an experimental analysis of the behaviour of real ants, in the sense that when real ants move in their quest of a food place, a volatile chemical substance called pheromone is deposited on their way to the food source). For an ant to move to the next hop, a certain 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. The pheromone affects the ant's movement in the locality to reach specific destination nodes. This concept applies to the AntNet algorithm [4] [5]. In this algorithm, 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 moves 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. Here, 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, and 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-fit multi-paths for data routing purpose.

3.2 Basic Ant-Based Routing Protocol Design

The Basic Ant-Based Routing Protocol (BABR) [7] has been proposed for routing purpose in wireless sensor networks. It follows the principle of the AntNet algorithm [4] [5] and has been designed with the goal to achieve the residual energy conservation of wireless sensor nodes.

In the BABR algorithm, ants are generated at regular intervals, and the nodes visited by an ant k are stored in its memory M_k. The probability $p_k(r, s)$ based on which a forward ant k moves from node r to node s is computed based on the following equation [7]:

$$p_k(r,s) = \begin{cases} \frac{[T(r,s)]^\alpha [E(s)]^\beta}{\sum_{u \notin M_k} T(r,u)]^\alpha [E(u)]^\beta} & \text{if } s \in M_k \\ & \text{Otherwise } 0 \end{cases} \tag{3.1}$$

where T is the pheromone trail value of the path between r and s, E is the so-called visibility function, computed as $E = 1/(C - e_s)$ (where C is the node's initial energy and e_s is the residual energy of node s); and M_k is the ant's memory that contains the details on the visited node. The nodes with the higher energy levels are chosen with higher probability, thus, nodes with lower energy levels are neglected during the route discovery process. As the forward ant reaches the destination, it is converted into the backward ant. At this point, the destination node computes the pheromone update value ΔT_k that should be deposited by the backward ant on intermediate nodes on its way towards the source node:

$$\Delta T_k = \frac{1}{N - Fd_k} \tag{3.2}$$

where N is the total number of nodes in the network and Fd_k is the distance travelled by the forward ant k.

The backward ant follows the same route as the forward ant, but moves backwards from the destination node to source node, updating the pheromone on nodes that lie between them using Eq. 3.3. The routing table of nodes visited by backward ants are also updated using Eq. 3.3:

$$T_k(r,s) = (1 - \rho)T_k(r,s) + \Delta T_k \tag{3.3}$$

where ρ is the pheromone evaporation coefficient from the last time $T_k(r, s)$ was updated, and ΔT_k is obtained from Eq. 3.2. On reaching the source node, the backward ant is eliminated and the routing of the data packets begins through the best paths found. A complete description of the BABR algorithm and its experimental evaluation can be found in [7]. From a good point of observation, it is noted that if the path length Fd_k increases, the pheromone deposit ΔT_k in the path increases. One should remember that in longer paths, pheromone evaporates more frequently (as in the case of natural ant food-search behavior). Hence increase in the pheromone deposit of longer paths are made to compensate with the pheromone evaporation of the paths.

3.3 MAntNet Algorithm Design

The proposed energy-aware modified AntNet (MAntNet) is designed based on the BABR design features [7], and it also follows the AntNet principle [4], itself inherited from the ACO design principle [4] [5]. For this reason, its design must adhere to the well known generic steps for solving a problem using the ACO paradigm, which are:

- Problem representation: the problem should be represented as a graph, and the solution should be a minimum cost path.

- Evaluation function: a problem-specific function that is used to evaluate the solutions at each step of the algorithm.

- Local heuristic: information that guides the move of the ants and the search process. Here, the ants decide their transitions from one node of the graph to the other by using a predefined probabilistic transition rule that utilizes both a heuristic value and the pheromone amounts.

- Pheromone update rule: rule that determines the amount of pheromone that should be deposited on the paths by the ants.

- Pheromone evaporation rule: rule that determines the amount of pheromone that should be evaporated from each node.

For the MAntNet design, the aforementioned steps are materialized as follows:

- **Problem representation**: MANET is represented as a symmetric, undirected, and weighted graph $G[N, E]$, where N denotes the number of nodes and E denotes the number of edges. Nodes represent mobile computing devices with unique identifiers, each of which can act as a host or a router. 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 function 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. Inspired by Eq. 3.1, the probability $P_k(Q)$ of ant k to move to node Q (so-called probability transition rule) is given by:

$$P_k(Q) = \frac{[PH_Q]^{\alpha}[E_Q]^{\beta}}{\sum_{N \in NEI}[PH_N]^{\alpha}[E_N]^{\beta}} \tag{3.4}$$

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

- **Pheromone update rule**: Inspired by Eq. 3.2, 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 node, is given by:

$$\Delta PH_k = 1/(C - E_{avg}) \tag{3.5}$$

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:

$$PH_Q = PH_Q - PH_Q * \rho \tag{3.6}$$

When a backward ant passes through node Q, the pheromone it updates on the node is given by (Same as Eq. 3.3):

$$PH_Q = PH_Q(1 - \rho) + \Delta PH_k \tag{3.7}$$

where ρ is the evaporation factor, i.e. the amount of pheromone that evaporates from each node.

3.3.1 MAntNet Implementation

The following specific data structures, packets structure, and parameters setting, are used for the implementation of the MAntNet algorithm based on the above MANtNet design features. Most of these are inherited from the BABR implementation [7] and AntNet implementation [4].

- **Data structures**:

- *Routing Table*: This is a standard data structure used in AntNet [4], which is maintained at each node. It also provides a relative probabilistic goodness measure to select the next hop. The pheromone values of all adjacent nodes are maintained in this table. This information can be used to decide which node can potentially become the next hop.
- *Neighbour Table*: This table is used to maintain the information about the neighbouring node identifiers and their available residual energy.
- *Unvisited Table*: This table is constructed by ants to maintain information about the unvisited node identifiers and their available residual energy.

• **Packet Structures**: There are two types: Hello packets and ANT packets.

- *Hello Packet:* This is a normal Hello packet with an additional inserted node energy field. Using this Hello packet, the available energy of the source node is broadcasted to all neighboring nodes. A Hello packet is also used to notify the other nodes about a newly added node in the network. In terms of route maintenance, subsequent data packets that traverse the paths established by the forward and backward ants help in maintaining the paths whose pheromone values keep changing. Link break is identified by a node (and cascaded to all other nodes) if its next hop is unreachable. In this case, the information of the unreachable node (i.e. node id, pheromone value) is removed from the routing table of the node that attempted the connection, meaning that the said link is deactivated, forcing the ants to select an alternative link among available ones.
- *ANT packet*: There are two types of ANT packets: ForwardANT and BackwardANT. The forward ant (or ForwardANT) is used to discover the path from the source node to the destination node whereas the backward ant (or BackwardANT) travels from the destination node to the source node, and it confirms the chosen path. These packets contain: *Source id* - representing the node that originates

the ant packet; *Ant-path* - representing the previous nodes visited by the ant; *Average path energy* - representing the average energy of the paths traversed so far by the ant; *Pheromone* - representing the amount of pheromone to be dropped at intermediate nodes by the backward ant; *ToSinkNode* - a boolean variable that identifies the type of ant (backward or forward ant); and *Destination id* - representing the destination id of the node that the ant has to reach.

- **MAntNet Parameter Settings**:
  - *Ants generation*: This is done periodically, every 10 seconds.
  - *Information carried by the ants (memory)*: they are: (i) the time elapsed between the launch of the ant and the arrival of the ant at the next chosen node; (ii) the energy available at the nodes traversed by each ant; and (iii) the number of hops travelled by each ant.
  - *Pheromone*: This is initialized to 100 on every node.
  - *Selection of the next hop*: In the probabilistic transition rule given in Eq 3.4, the coefficient α is set to 0.05 and β is set to 3.5. These values are set with the goal that they can help controlling the relative importance of the pheromone and available residual energy of nodes.
  - *Pheromone deposit*: According to Eq. 3.5 and Eq. 3.7, the pheromone deposited by ant k (denoted as ΔPH_k) is computed based on the available energy on nodes that form the path. This value is added to the already available pheromone at each node along the path.
  - *Initial energy of all nodes*: This is set to 100 Joules.
  - *Pheromone evaporation*: In Eq. 3.7, ρ, the amount of pheromone that evaporates from each node is set to 0.2.

3.3.2 Main Operations of MAntNet

The routing process in MAntNet starts when transmission request of data packets is initiated by a source node. 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 working of our proposed MAntNet mechanism is as follows:

- ***Forward Ant Activities:***
  - Forward ants are generated at regular intervals from each node with a mission to reach their destination.
  - According to Eq 3.1, the forward ant k chooses to move from node S to the next hop Q based on the ACO meta-heuristic rule $P_k(S,Q)$ defined in Eq 3.4. After passing each node, the forward ant updates each node's pheromone in its routing table according to Eq 3.6.
  - On reaching the destination, the forward ant transfers its memory information to the backward ant (which includes hop count, time elapsed, energy, pheromone on the traversed nodes, and other route information). In other words, the forward ant is converted to the backward ant.
- ***Backward Ant Activities:***
  - The backward ant begins its journey from the destination node, and works towards the source node, travelling in the path stored in its memory.
  - The destination node calculates the pheromone trail ΔPH_k to be deposited along the path by this ant k as per Eq. 3.5.
  - According to Eq. 3.2 and Eq. 3.3, the backward ant k deposits the amount ΔPH_k of pheromone in the routing tables of the nodes along the path it takes to reach

the source node following Eq. 3.5 and Eq. 3.7.

– An intermediate node Q receiving this backward ant from node S updates its routing table using PH_Q as per Eq. 3.7.

– 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.

These activities are illustrated in the MAntNet flowchart depicted in Fig. 3.1.

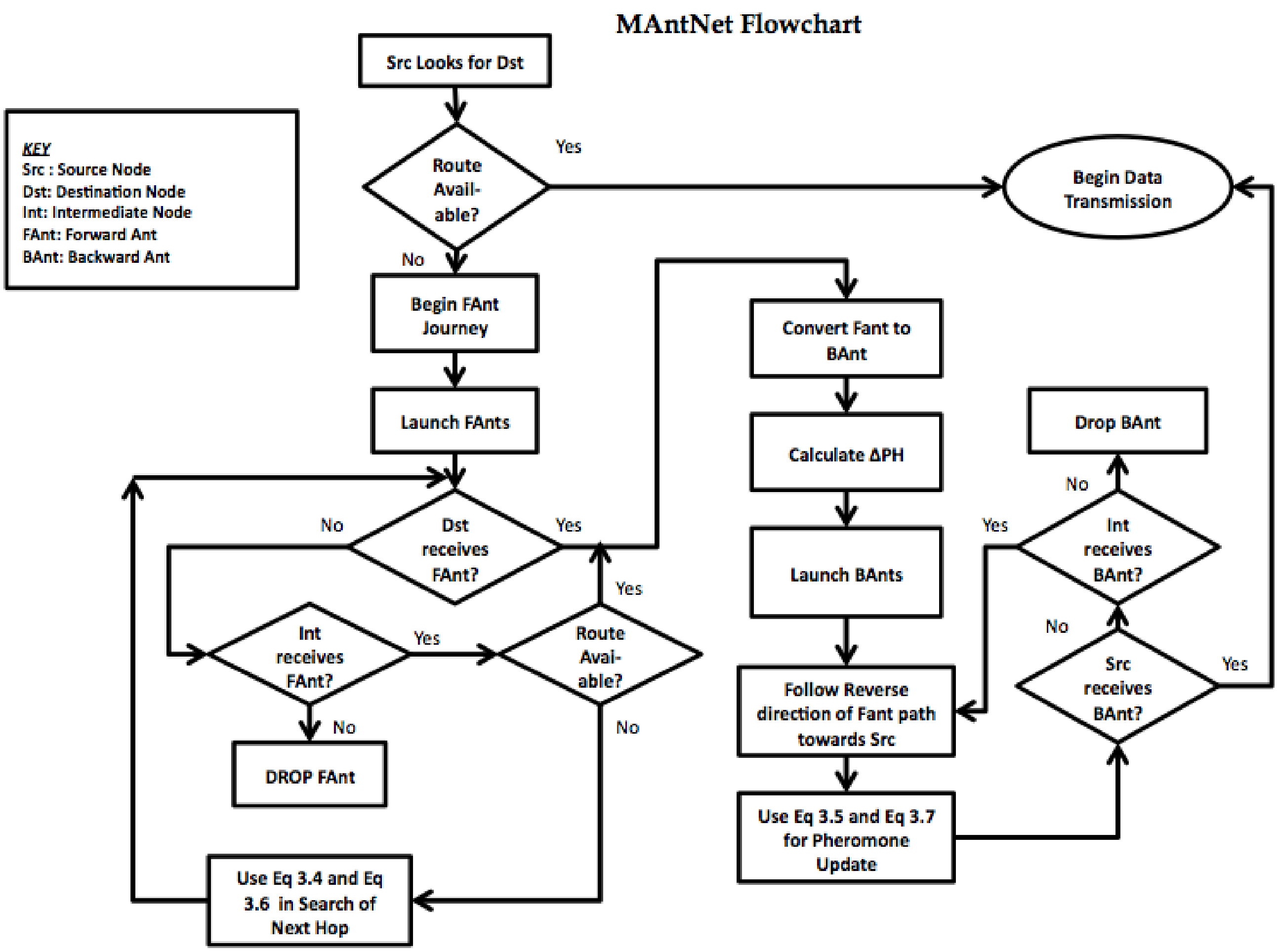

Figure 3.1: The MAntNet flowchart.

The pseudo-code of the MAntNet algorithm is as follows.

/* Modified ANTNET (MAntNet) Pseudocode*/

```
S_end := simulation_end_time;          Ant_ttl := ant_time_to_live;
t := current_time; ANT.V : list of visited nodes ; k: node ;  k.energy: Current available energy of node k;
k.pheromone: current pheromone of node k ; AVG_ENERGY : Average energy of all nodes ;
NODE_INITIAL_POWER:=100;NODE_TX:=1.0;NODE_RX=2.0;pher_α:=1.5;energy_β:=1.5; INITIAL_PHEROMONE:=100;
Δt:=time_interval_between_ants_generation; PHEROMONE_EVAPORATION := 0.2;
T_k := Node_k_routing table;
while (t < S_end )
in_parallel                    /* perform concurrent activity on each node */
if (t mod Δt = 0)
LaunchForwardAnt(destination_node, source_node);
end if
if(RecvPacketType=ANT)
antlifetime := 0;
for (i<-ANT.V ; antlifetime < Ant_ttl ; ++i)  /* updates all sub-paths */
if (antlifetime<= Ant_ttl)
if (ANT.toS inkNode= true)
activate_forward_ant(Source_node,destination_node)
else  activate_backward_ant(destination_node,source_node)
end if
end for
end if
end in_parallel
end while
Procedure activate_forward_ant[source_node, destination_node])
/* Forward_Ant Activities*/
k := source_node;  n : eligible next hop ;    fw_hops := 0;  ANT.V[fw_hops] := k;
ANT.T'[fw_hops] := 0;
While (k ≠ destination_node)
t_arrival := get_current_time();
/*Probabilistic Transition Rule in Eq 3.4}       cross_the_link(k, n);
n := select_next_hop(ANT.V, destination node, k.pheromone, k.energy, α, β);
Elapse_time :=  get_current_time() − t_arrival;  k := n;
if (k ∈ANTS.V )            /* /* If ant is in a loop, remove it */
hops_cycle := get_cycle_length(k, V );
fw_hops := fw_hops − hops_cycle;
else
fw_hops := fw_hops + 1;   /* Local Update - ANT Memory */
ANT.V [fw_hops] := k;
ANT.T'[fw_hops] := elapse_time;
ANT.power[fw_hops] := node[i].power;
ANT.pkt_src := k; ANT.toSinkNode := true;
end if
end while
/*perform Pheromone Update calculation */
ANT.pheromone: Calculate_pheromone_deposit(n.pheromone, PHEROMONE_EVAPORATION)  /*Refer Eq 3.6 */
LaunchBackwardAnt (destination_node, source_node, ANT.pheromone, ANT.toSinkNode=false,  ANT.T'[0] := 0);
end Procedure
Procedure activate_backward_ant(destination_node, source_node)
/* Backward_Ant_Activity */
k := destination node; n: next hop towards the source (n ϵ bw_hops);
bw_hops := fw_hops (backward hops are same as forward hops in reverse direction);
while (k ≠ source node)
bw_hops := bw_hops − 1;
n := V[bw_hops];
cross_the_link(k, n);
k := n;
Calculate pheromone_deposit, ΔPH: (NODE_INITIAL_ENERGY, AVG_ENERGY) as in Eq 3.5}
UpdateGlobalPheromone: (n.pheromone, ΔPH, PHEROMONE_EVAPORATION) as in Eq 3.7}
end while
Die();
end Procedure
```

3.4 E-MAntNet Algorithm Design

The energy-aware MAntNet (E-MAntNet) algorithm is an improved version of the MAntNet protocol, where novel energy-related conditions have been introduced based on some features of the route discovery process of the AntNet heuristic design [4]. In general, the necessity of energy awareness in the routing process of MANETs can be justified as illustrated by the scenario presented in Fig. 3.2.

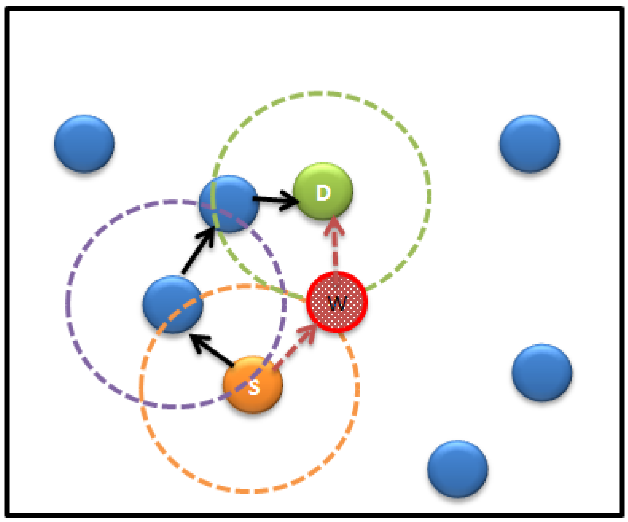

Figure 3.2: Applying Energy-aware routing decisions in MANET

In Fig. 3.2, any pair of nodes can communicate with each other, even if they are outside each otherś transmission range. This is achieved by passing the information through intermediate nodes as shown in Fig. 2.1 of Chapter 2. As the nodes move around randomly, any of these nodes could be over-involved in the routing process, thereby could loose a lot of energy despite the fact that it 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. This problem can be addressed by modifying the protocols in such a way that it becomes energy aware. Indeed, in Fig. 3.2, 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.

Here, the possible alternate path is denoted by the solid arrows and the energy-draining path through node W is denoted by the dotted arrows. The problem now is to determine when to cut-off the path through node W and pick a suitable alternate path. The cut-off point cannot be determined naively when the energy of node W falls below a certain fixed threshold value. This is justified by the fact that the energy of each node keeps decreasing with time. Thus, the cut-off point should depend on the energy of node W relative to the total network energy. With this requirement in mind, and taking advantage of some features of the route discovery process of the AntNet heuristic design [4], we have identified various energy-aware conditions that can enable one to pick up the cut-off point when designing our proposed energy-aware algorithms. These conditions are summarized in Table 3.1, where E_{max}, E_{min} and E_{avg} denote the maximum, minimum, and average energy of all nodes, respectively. It is worth mentioning that the constant terms that appear in the conditional statements shown in Table 3.1 have been determined through simulation trials.

It should be stressed that the MAntNet algorithm is inherently energy-aware because it considers the nodes energy while determining the probability (using (Eq 3.4) to send an ant to a node. There is never a complete, constant cut-off as proposed by the conditions mentioned in Table 3.1, as the energy in the network decreases with time. So, these conditions should be considered as additional energy-aware conditions imposed to the MAntNeT design. Although the design of any of these conditions may help achieving an increased network lifetime, it is also essential to verify that doing so does 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. It is clear that if the connectivity of the network is very low, then the throughput of the network will also be low. In this case, the energy-aware condition may have saved the network's energy, but at the cost of breaking the network connections, which is undesirable. In this thesis, the connectivity is quantitatively

LABEL	ENERGY BASED DROP CONDITIONS
Plain	No DROP conditions. Represents MAntNet or AODV
C1	If ((node_E $< E_{avg}$)) then ((Drop the RREQ or Forward ANT)
C2	If ((node_E $< 0.9 * E_{avg}$)) then ((Drop RREQ or Forward ANT)
C3	If (($node\_E < 0.8 * E_{avg}$)) then ((Drop RREQ or Forward ANT)
C4	If (($node\_E < 0.7 * E_{avg}$)) then ((Drop RREQ or Forward ANT)
C5	If (($node\_E < 1.2 * E_{min}$)) then ((Drop RREQ or Forward ANT)
C6	If (($node\_E < (sqrt(E_{min} * E_{max}$))) then ((Drop RREQ or Forward ANT)
C7	If (($node\_E < 0.7 * E_{max}$)) then ((Drop RREQ or Forward ANT)
C8	If (($node\_E < 0.8 * E_{max}$)) then ((Drop RREQ or Forward ANT)

Table 3.1: Energy-efficient Conditions for E-MAntNet and E-AODV

defined as the ratio of the number of replies sent from the destination node to the number of requests sent from the source node, i.e.

$$\text{Connectivity} = \frac{\text{Number of replies from destination node}}{\text{Number of requests from source node}} \tag{3.8}$$

The trade-off between achieving a better network lifetime and ensuring a good level of network connectivity is therefore a challenge in our proposed designs. In this regards, the simulation results discussed in Chapter 4 illustrate our findings.

The E-MAntNEt algorithm follows the same steps that are presented in the pseudo-code of the MAntNet algorithm with an additional requirement imposed in the forward ant activities portion of that pseudo-code. The requirement is defined as follows: if the selection of the next hop (node) that will receive the forward ant (according to the probability transition rule in Eq. 3.4) results to an intermediate node whose residual energy matches any of the energy conditions presented in Table 3.1, 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.

The E-MAntNet flowchart is depicted in Fig. 3.3

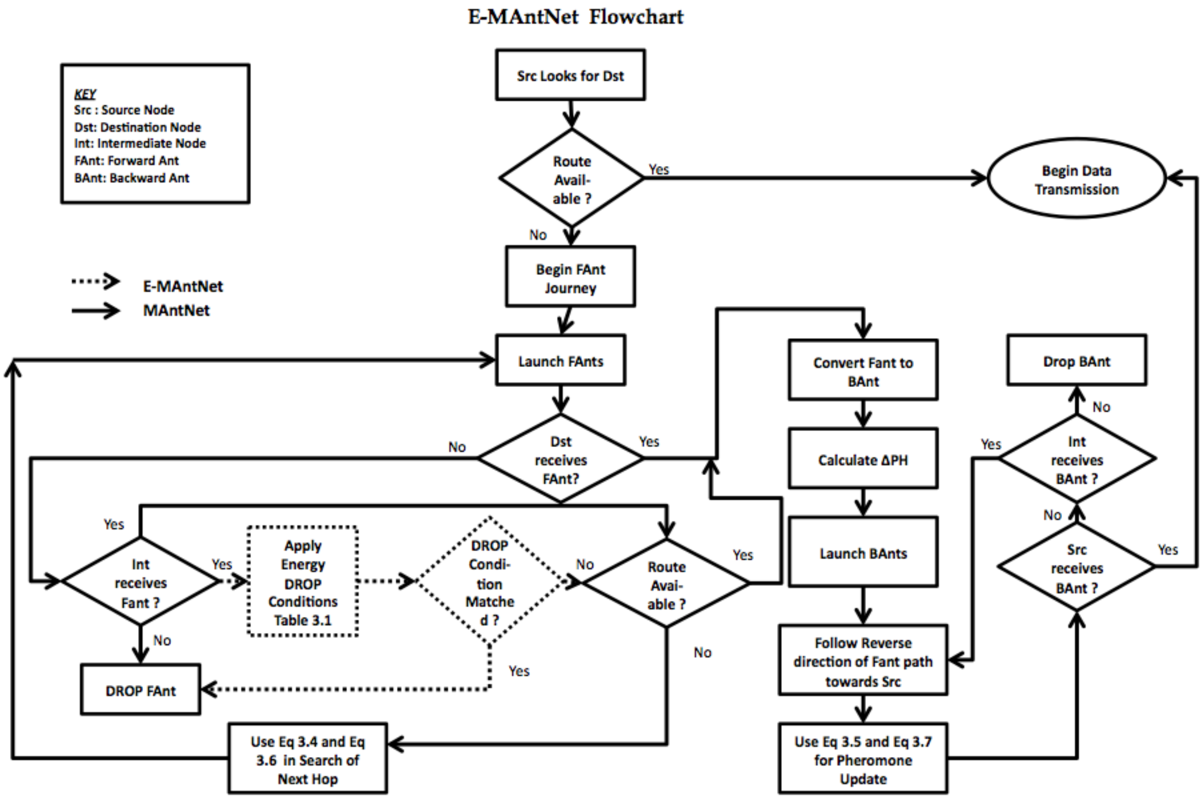

Figure 3.3: The E-MAntNet flowchart

3.5 E-AODV Algorithm Design

The AODV protocol [2] for MANETs is a reactive routing scheme in the sense that the route between the source and destination nodes is constructed as per the requirement of the source node and then maintained as long as the routes are needed. This task is accomplished using four types of messages that ensure the route-discovery and route maintenance (also called link-failure notification) phases, namely, a) Hello packets which 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 are as follows:

1. When a node (called source) tries to communicate with another node (called destination) to which it has no route, it broadcasts the RREQs to its neighbours. These RREQs are then forwarded to neighbours of neighbours, 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 destinations and next hops) in their routing tables. They record the reverse path to the source, which is used in the RREP process.

3. The 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 will then store this path between the source and destination in their respective routing tables.

4. On receiving the RREP, the source node 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, to name a few) and discards the RREP. If multiple RREPs are received by the source, the route with the shortest hop count will be selected. Now, the connection between the source and destination nodes is said to be established, and the source begins transmitting the data packets to the destination using that discovered route.

In the above route discovery phase, the route maintenance phase is invoked whenever a link failure occurs. In that case, a RERR message is generated, informing the other nodes, including the source node, about this situation. The source node then disables the route involving the broken link as soon as it receives the RERR, then reinitiates the route discovery process if necessary.

The E-AODV algorithm design follows the above-mentioned steps of the AODV algorithm, but with the additional requirement that the same energy-aware conditions introduced in the E-MAntNet algorithm design (captured in Table 3.1) are applied during step 3 of the route discovery process of AODV. More precisely, in that step, if a node that accepts to receive a RREQ packet has a residual energy that matches any of the energy conditions presented in Table 3.1, this node will drop the RREQ packet and will be prevented from participating in the routing operation, until its available energy is good enough at a later timestamp. Otherwise, E-AODV and AODV will behave similarly. It should be emphasized that the AODV protocol is not energy-aware, therefore, if the conditions in Table 3.1 were applied within its route discovery phase, it is expected that this would naturally lead to a better network lifetime for E-AODV compared to AODV. Simulation results confirming this claim are provided in Chapter 4.

The E-AODV flowchart is depicted in Fig. 3.4.

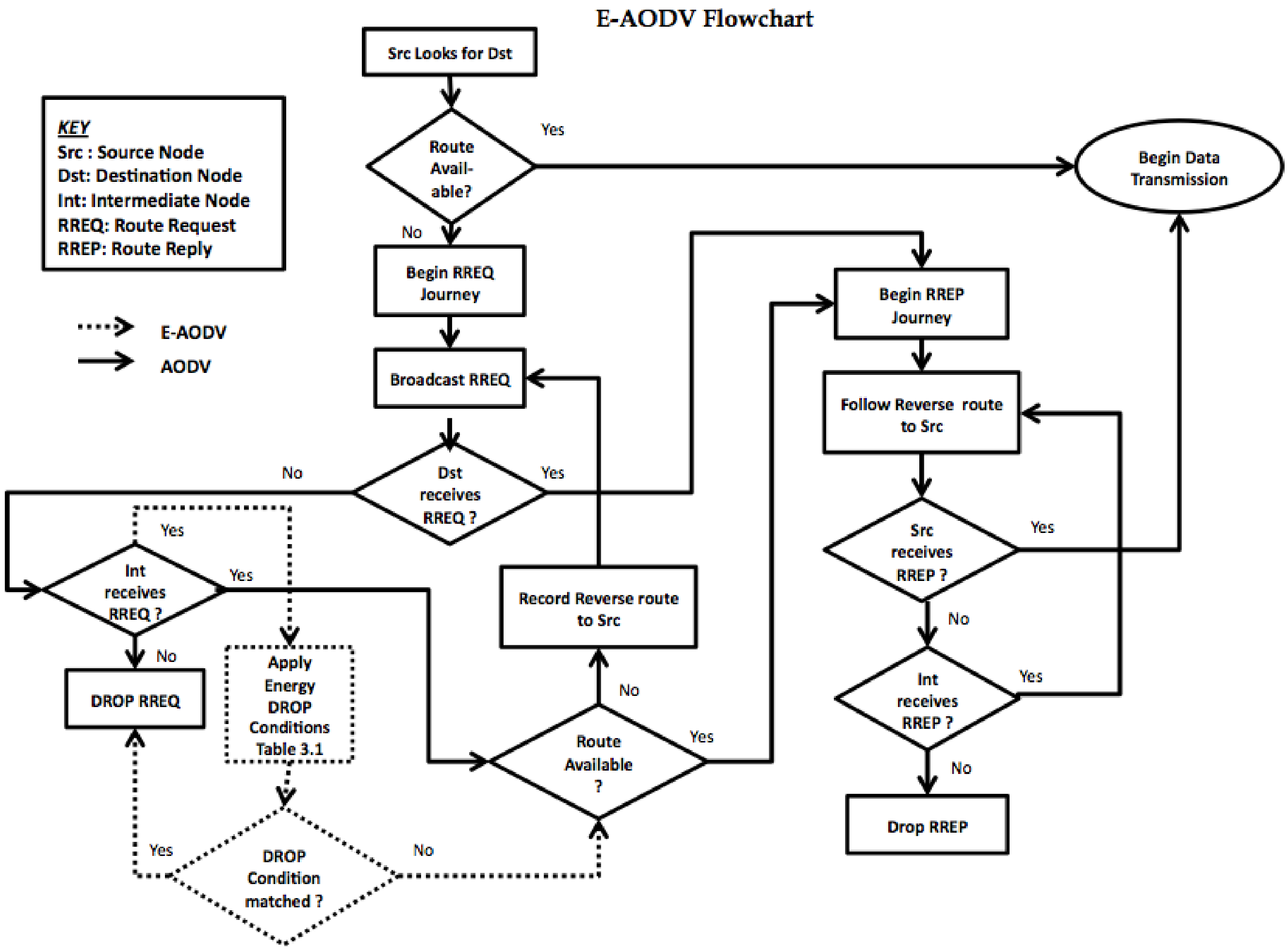

Figure 3.4: The E-AODV flowchart

Chapter 4

Performance Evaluation

This Chapter discusses the performance and analysis of the three algorithms proposed in this thesis. Different performance metrics are used to evaluate and compare the performance of these algorithms: E-MAntNet vs. MAntNet, EAODV vs. AODV, and E-MAntNet vs. E-AODV. Our goal is to prove that the proposed E-MAntNet routing protocol shows a better connectivity and energy-efficiency in the network when compared to the remaining protocols.

4.1 Simulation Settings

For implementation, we have used the network simulator NS2 version 2.34, [21]. To simulate the AODV routing in MANET, the standard AODV module available in the NS2 library, coded in C++, is used. To implement and simulate our proposed MAntNet and E-MAntNet algorithms, the ANTNET package [5] is used. This package has been integrated into NS2 by modifying the NS2 library files to incorporate the energy-aware ANTNET routing protocol [7]. AODV, E-AODV, MAntNet and E-MAntNet share the same simulation environment. A sample MANET simulation in NS2 with 100 nodes and their energy levels at a given timestamp is shown in Fig 4.1. During the start of simulation, all nodes have the same amount of energy (initialized to 100 Joules), which is indicated by green highlights in the figure. As time passes, some active nodes tend to become yellow in color due to routing activities. When a node becomes red in color, it indicates that its energy level has reached zero, and hence it becomes in-operable. An example of such node is node W in Fig. 3.2 of Chapter 3. Table 4.1 outlines the simulation settings used.

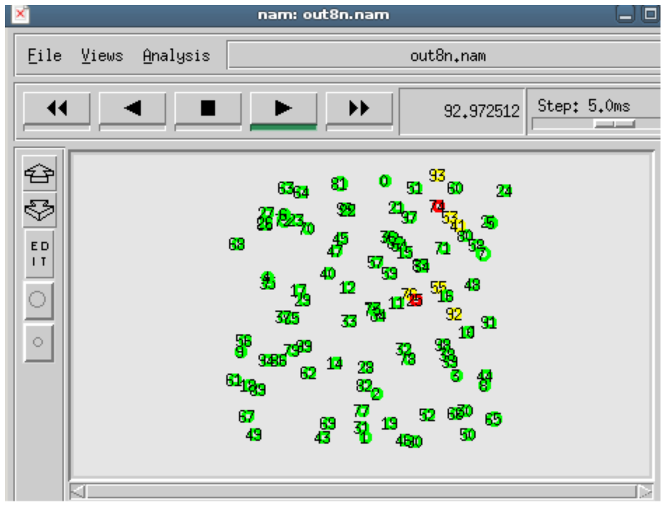

Figure 4.1: NS2 Simulation of 100 nodes in MANET.

4.2 Performance Metrics

The performance metrics used to evaluate our proposed algorithms are: residual energy (denoted RE), connections established (denoted CE), dead nodes (denoted DN), and network lifetime (denoted NL).

- Residual energy (RE): This represents the available energy in the network at the end of the simulation, i.e the average of all the node's residual energy at the end of every simulation forms this metric.

- Connections established (CE): This is a metric that helps to measure the ability of a routing protocol to maintain the connections in the network. In case of the MAntNet and E-MAntNet algorithms, CE is the ratio of the number of backward ants sent from Destination towards the source to the number of forward ants sent towards destination,

Simulation Parameters	Value
NS2 Version	2.34
Mobility Model	Random Way Point
Radio Propagation Model	Two-ray ground reflection model
MAC Protocol	IEEE 802.11
Node Interface	Wireless
Traffic	Constant Bit Rate (CBR)
Network Layer Protocols	AODV and AntNet
Terrain Dimension	1000 x 1000 sq. Metres
Number of Nodes	100 (or variable)
Simulation Time	100 seconds
Initial Node Energy	100 Joules
Transmission Power	3 Watts (34.77 dBm)
Receiving Power	1.5 Watts (31.76 dBm)
Default Transmission Range	100 meters (default), 25m-200m(Variable)
Antenna	1.5Hz
Pause time	1 second
Node Speed	Default: 1 m/s Variable: 1 - 10m/s
Packet Size	Variable (in Bytes) Control packet: 30-44 Bytes, Data packet: 1000-1020 Bytes

Table 4.1: Simulation parameters.

which is given by Eq. 4.1. In case of AODV, CE is the ratio of the number of RREP packets sent from Destination towards the source to the number of RREQ packets from source towards the destination, given by Eq. 4.2, i.e.

$$\text{Connectivity\_MAntNet} = \frac{\text{Number of Backward Ants from Destination}}{\text{Number of Forward Ants from Source}} \tag{4.1}$$

$$\text{Connectivity\_AODV} = \frac{\text{Number of RREPs from Destination}}{\text{Number of RREQs from Source}} \tag{4.2}$$

- Number of dead nodes (DN): This refers to the total number of inactive nodes in the network. In our simulation settings, we have assumed that a node whose energy level is less than 70 Joules is considered as inactive or dead.

- Network lifetime (NL): This represents the time at which the first node in the network becomes inactive or dead i.e. its energy level drops below the threshold of 70 Joules. In other words, NL is the time period for which all the nodes in the network are alive (have an energy level of at least 70 Joules).

We also randomized certain network properties when running the simulations. These include: the node's initial coordinates and its random walk (which includes a change in direction and speed at every timestamp).

4.3 Simulation Results

This section studies the performance of the proposed routing protocols using the above-mentioned performance metrics and the energy drop conditions given in Table 3.1.

4.3.1 Preliminaries

Before proceeding, it is necessary to decide on the values of the ACO-based coefficients used in the MAntNet algorithm (henceforth the E-MAntNet algorithm). The performance of MAntNet in terms of the above mentioned performance metrics, for a variety of α, β combinations is shown in Fig. 4.2. In Fig. 4.2a, it is observed that the residual energy in the network is maintained steadily, meaning that MAntNet is quite stable in conserving the energy for these α, β settings. In Fig. 4.2c, it is observed that MAntNet establishes a good number of connections (0.65 to 0.85), meaning that more than half of the forward ants sent during the route discovery have successfully discovered the routes and established the connections. This also means that MAntNet can maintain its connections while conserving the network's residual energy for the selected α, β settings. On the other hand, there is no significant change in the number of dead nodes (between 7 and 9). In Fig. 4.2d, it is observed that for the same α, β combinations, longer network lifetime is achieved when $\beta = 3.5$. In fact, for $\alpha = 0.05$ and $\beta = 3.5$, MAntNet yields the best results in terms of all studied

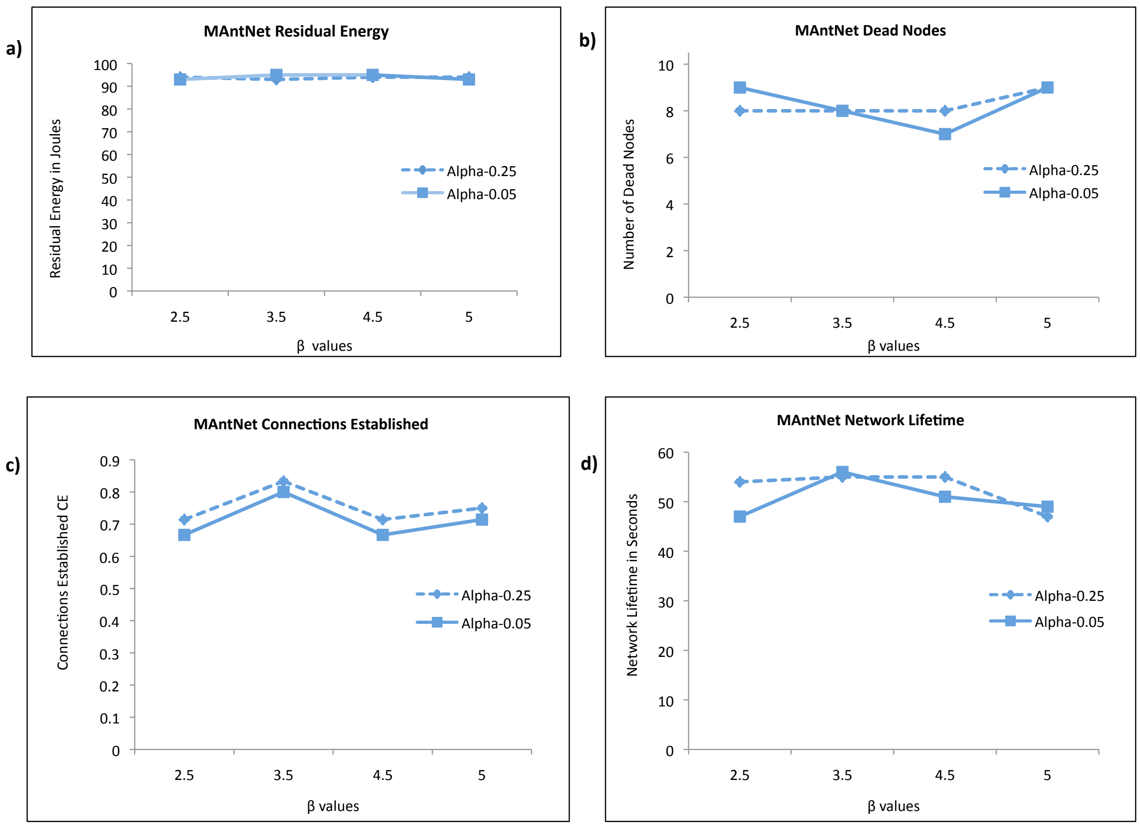

Figure 4.2: Performance of MAntNet for varying values of α and β.

performance metrics. Thus, $(\alpha, \beta) = (0.05, 3.5)$ is the most desirable setting, and we will use it in all subsequent studied simulation scenarios for MAntNet and E-MAntNet.

Fundamentally, the contribution of this thesis is the proposal of an efficient routing protocol for MANETs (so-called MAntNet) and its improved energy-aware version (E-MAntNet). To assess by simulations the effectiveness of these protocols, it is imperative to compare them against at least one state-of-the-art routing protocol for MANETs. This justifies our choice of AODV as benchmark. Accordingly, the comparison of MAntNet and AODV is justified. In the case of E-MAntNet, its design relies on the AntNet principle and is achieved by incorporating the energy-aware conditions shown in Table 3.1 in the route selection process of MAntNet. For this reason, it will be fair to compare E-MAntNet against E-AODV, and AODV against E-AODV, where E-AODV is an updated version of AODV with the same aforementioned energy conditions applied to its route discovery process. Before doing so, the question is whether all the energy-aware conditions in Table 3.1 should be tested or not.

To address this question, we have tested the performance of (1) E-MAntNet against E-AODV, and (2) E-AODV against AODV; both for all the energy-aware conditions, under the above-mentioned performance metrics. The results for E-MAntNet vs. E-AODV are captured in Fig. 4.3. In Fig. 4.3, it is observed that when conditions C2 and C8 are applied,

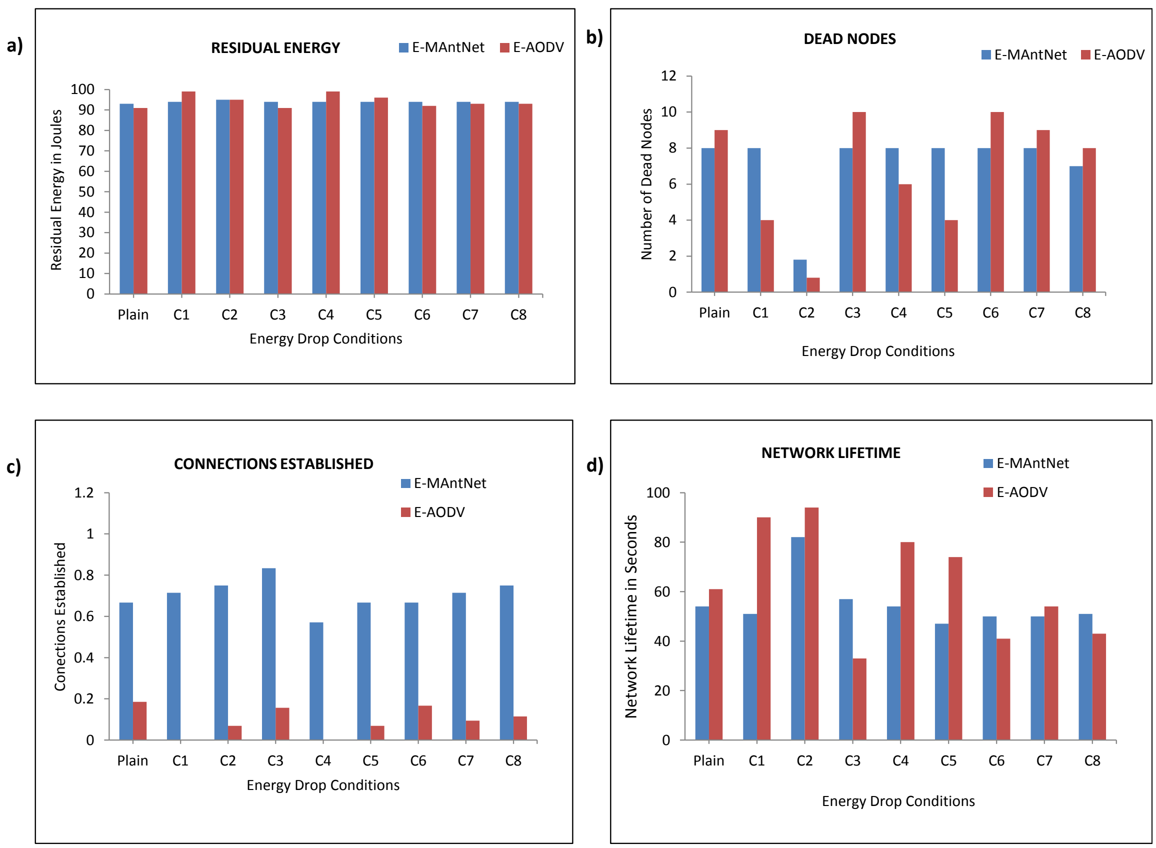

Figure 4.3: Comparison of E-MAntNet and E-AODV under all energy-aware conditions.

E-MAntNet and E-AODV generate almost the same number of dead nodes and residual energy. In Fig. 4.3a, when any of the conditions C1, C4, C5 is applied, E-AODV conserves more energy than E-MAntNet. In Fig. 4.3c, it is observed that the number of connections established by E-MAntNet is much higher for most of the energy conditions when compared to E-AODV. C2 yields the least number of dead nodes for both E-MAntNet and E-AODV. The dead nodes, network lifetime and residual energy yielded under condition C8 are similar in both E-MAntNet and E-AODV. When all other conditions are applied, no conclusive statement can be made. In terms of connection established, no conclusive remark can be stated since this metric is computed in two different ways, i.e. by using Eq. 4.1 (case of E-MAntNet) and Eq. 4.2 (case of E-AODV). The results obtained for E-AODV under C1 condition from Fig 4.3 shows best performance in terms of residual energy and network lifetime when compared to all other conditions in E-AODV. For the above reasons, we will use *Plain, C1, C2 and C8* conditions in our subsequent simulations.

4.3.2 Comparison of MAntNet and E-MAntNet

The E-MAntNet algorithm is compared against the MAntNet algorithm under the conditions C1, C2, and C8 from Table 3.1 using the aforementioned performance metrics. The results are shown in Fig. 4.4. In Fig. 4.4a, it is observed that independently of the energy condition used, the network's residual energy obtained with E-MAntNet is higher than that obtained with MAntNet. In comparison with MAntNet, when condition C2 is applied, it is observed that the lowest number of dead nodes is achieved by E-MAntNet (see Fig. 4.4b) as well as the longest network lifetime (see Fig. 4.4d) and the highest number of connections established (see Fig. 4.4c). This means that under condition C2, E-MAntNet performs significantly better than MAntNet and the remaining energy conditions in terms of the four studied performance metrics.

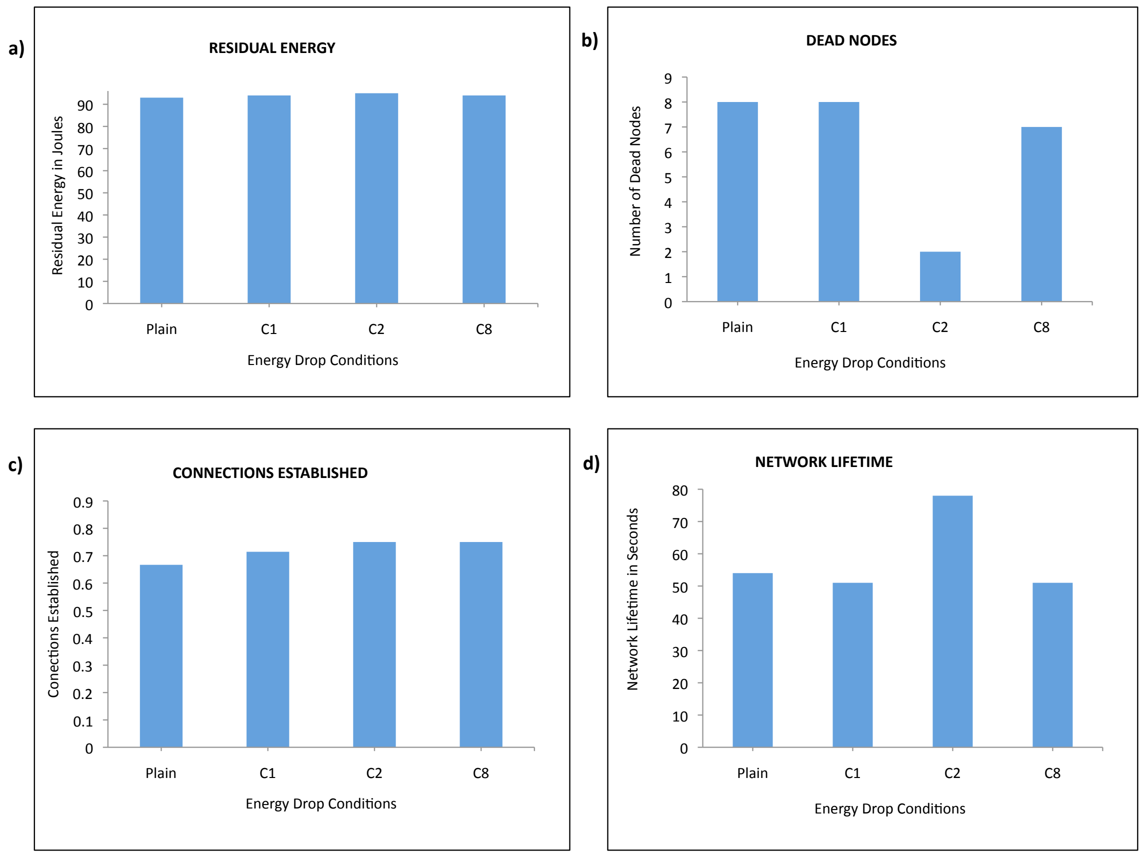

Figure 4.4: Comparison of MAntNet and E-MAntNet.

4.3.3 Comparison of AODV and E-AODV

The E-AODV algorithm is compared against the AODV algorithm under the conditions C1, C2, and C8 from Table 3.1 using the aforementioned performance metrics. The results are captured in Fig. 4.5. It can be observed that compared to AODV, E-AODV yields a better energy conservation behaviour (see Fig. 4.5a), and less number of dead nodes (see Fig. 4.5b) but is worse in terms of number of connections established (see Fig. 4.5c). Also, the highest network lifetimes are achieved when conditions C1 and C2 are applied (see Fig. 4.5d).

The conditions C1 particularly shows highest residual energy and less number of dead nodes, which are very desirable. But consequently, the number of connections established

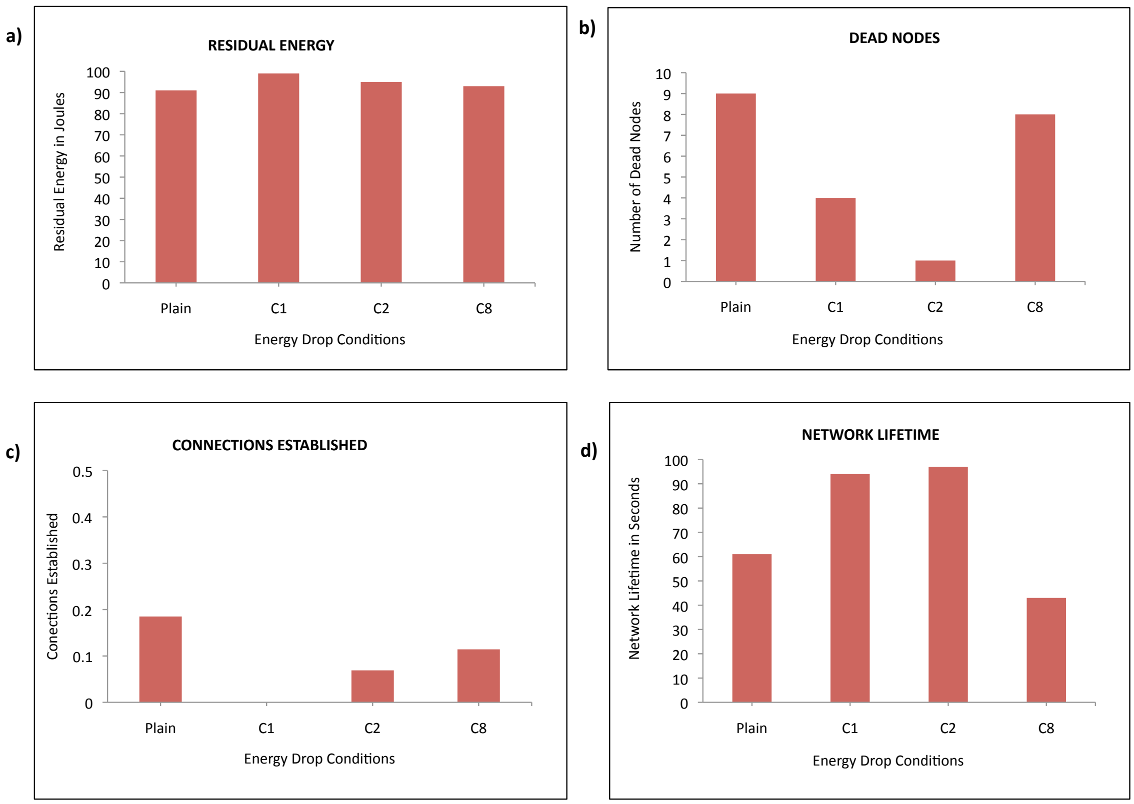

Figure 4.5: Comparison of E-AODV and AODV.

falls to zero. C2 on the other hand performs better than C1 by yielding longer network lifetime, more connections and less dead nodes. C8 and C2 perform better than C1 in terms of connectivity (Fig 4.5c), and perform better than AODV in terms of conserving energy (Fig 4.5a). So, we cannot conclude on a single energy-aware condition for E-AODV that performs better than AODV in all aspects. Overall, E-AODV appears to conserve the network energy by dropping most of the RREQ packets, with the undesirable side effect that it generates less connectivity than AODV does.

4.3.4 Performance of the Proposed Protocols Under Varying Transmission Power and Reception Power

In this section, the performance of the proposed protocols is studied when varying the (Tx,Rx) values, where Tx is the transmission power and Rx is the receiving power, using any of the energy conditions *C2, C8*, and *Plain*. It can be recalled that Tx is the energy lost by a node while transmitting a packet whereas Rx is the energy lost by a node in receiving a packet. For these simulations, the node speed is set to 1 m/s, the transmission range is set to 100 meters and all other simulation parameters are already given in Table 4.1.

1. ***Comparison of MAntNet and AODV for Varying Tx,Rx***

   Increase in Tx,Rx values signifies that the network utilizes larger amounts residual energy from the nodes for each communication. In Fig. 4.6, it is observed that as the transmission or reception power increases, it is natural to see that the residual energy in the network decreases (in Fig 4.6a) in both MAntNet and AODV, due to increased utilization of power resource for each communication in the network. For lower Tx,Rx powers, AODV yields better residual energy, less dead nodes and longer network lifetime when compared to higher values. From Fig 4.6 it is clearly seen that MAntNet performs better than AODV by steadily conserving more energy with less number of dead nodes while maintaining number of connections established, even at challenging times when large amounts of energy is consumed in the normal routing process.

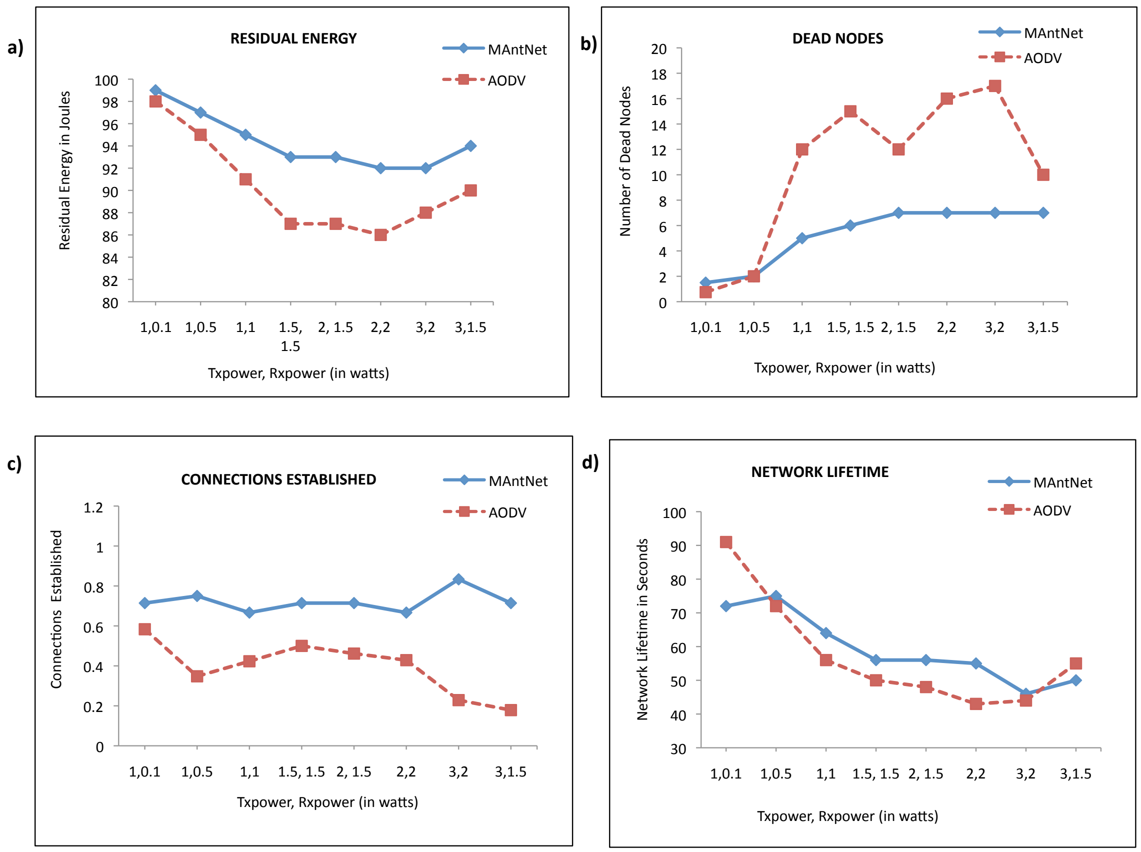

Figure 4.6: Comparison of MAntNet and AODV for varying Tx,Rx.

2. ***Comparison of E-MAntNet and E-AODV for Varying Tx,Rx Under Energy-Aware Condition C2***

As in Fig 4.6, we expect that when the power increases, the residual energy should decrease, which is the general trend that we observe in Fig 4.7. When more energy is being drained from the network, more nodes tends to meet the C2 energy condition(see Table 3.1). Hence beyond a particular value of TX,RX, more number of packets are being dropped by the condition, leading to a decrease in number of dead nodes which thus extends network lifetime in case of both E-MAntNet and E-AODV. In C2 condition, this appears to happen beyond Tx,Rx values of 2,2. In Fig 4.6c, E-AODV

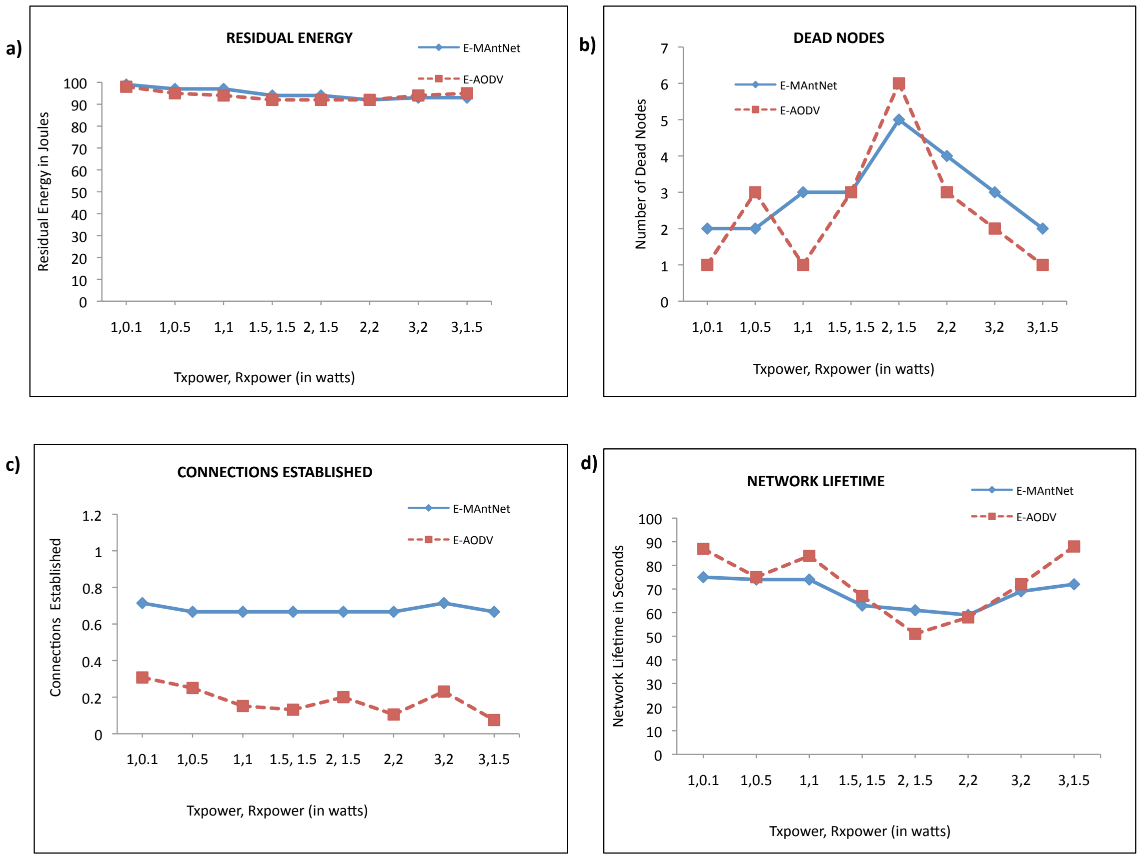

Figure 4.7: Comparison of E-MAntNet and E-AODV for varying Tx,Rx under energy-aware condition C2.

under C2 condition yields higher number of connections, better residual energy, less dead nodes and much longer network lifetime for lower Tx,Rx powers. However, E-MAntNet performs marginally better than E-AODV in terms of residual energy and connectivity.

3. ***Comparison of E-MAntNet and E-AODV for Varying Tx,Rx Under Energy-Aware Condition C8***

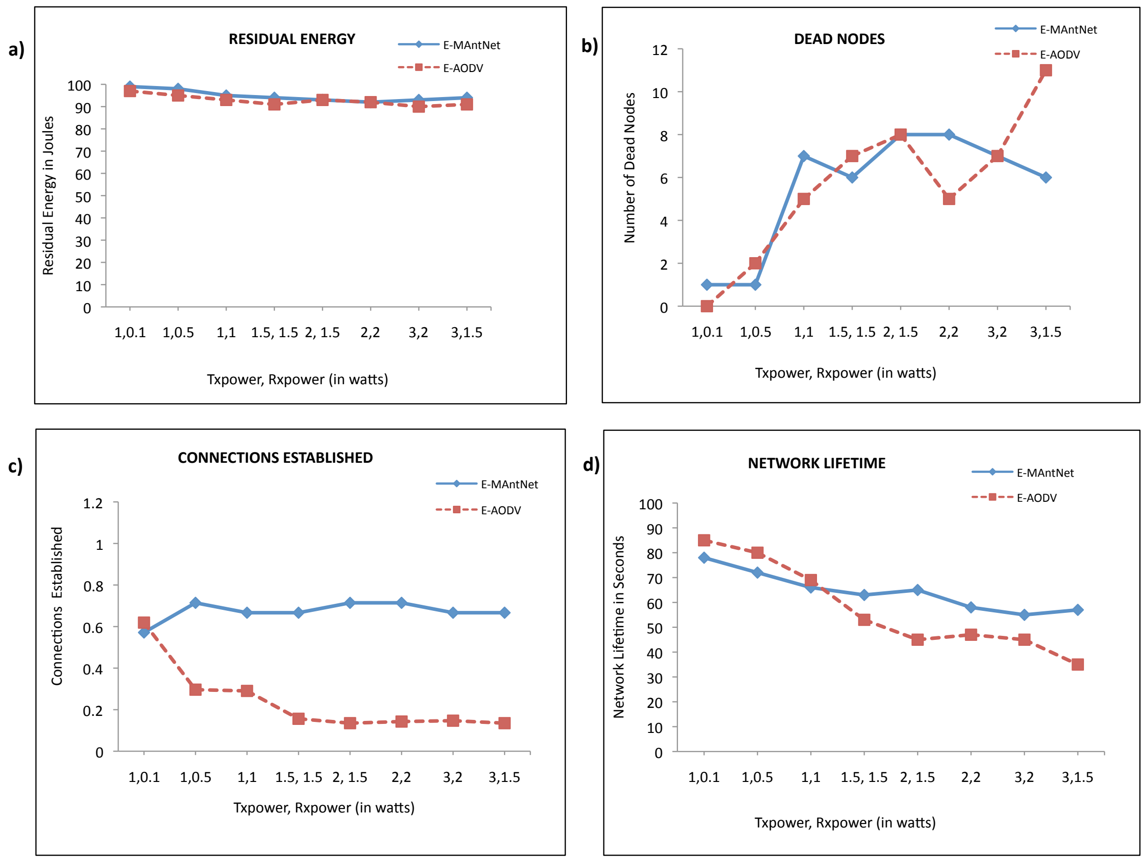

Figure 4.8: Comparison of E-MAntNet and E-AODV for varying Tx,Rx under energy-aware condition C8.

In Fig. 4.8, though it can be observed that with an increase in Tx,Rx values, both protocols show a gradual decrease in residual energy(Fig. 4.8a) and network lifetime (Fig. 4.8d), E-MAntNet manages to conserve more energy compared to E-AODV. There is no significant change in terms of number of dead nodes (Fig. 4.8b) yielded by both protocols. Again similar to Figures 4.7 and 4.6, it is interesting to observe that for lower Tx,Rx values, E-AODV with C8 condition performs really well in terms of all the performance metrics.Finally, for higher Tx,Rx values, the tendency is that

E-MAntNet generates a longer lifetime compared to E-AODV (Fig 4.8d).

4.3.5 Performance of the Proposed Protocols Under Varying RMS Speeds

In this section, the performance of the proposed protocols is studied when varying the root mean square speed (RMS) (as shown in Table 4.3.5), using any of the energy conditions *C2, C8*, *Plain*. For higher values of 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. The following parameters setting are also considered: Tx=3 watts, Rx=1.5 watts, and the transmission range is set to 100 meters. All other parameters setting remains as stated in Table 4.1.

RMS Speed	Node movement (in m/s)
1	-1 to +1
5	-5 to +5
10	-10 to +10
15	-15 to +15
20	-20 to +20
25	-25 to +25
30	-30 to +30

Table 4.2: RMS speed variations used in this scenario.

1. ***Comparison of MAntNet and AODV for varying RMS speeds.***

   As the RMS speed of the nodes increase, the near neighbours frequently move in and out of transmission ranges of each other, requiring a frequent update of the routing table. In Fig 4.9, we observe that AODV behaves similar to E-MAntNet and shows no significant performance variations for increase in RMS speed, though E-MAntNet performs marginally better than AODV in all aspects. So, we do not expect a significant variation in the residual energy and connections established for larger speeds.

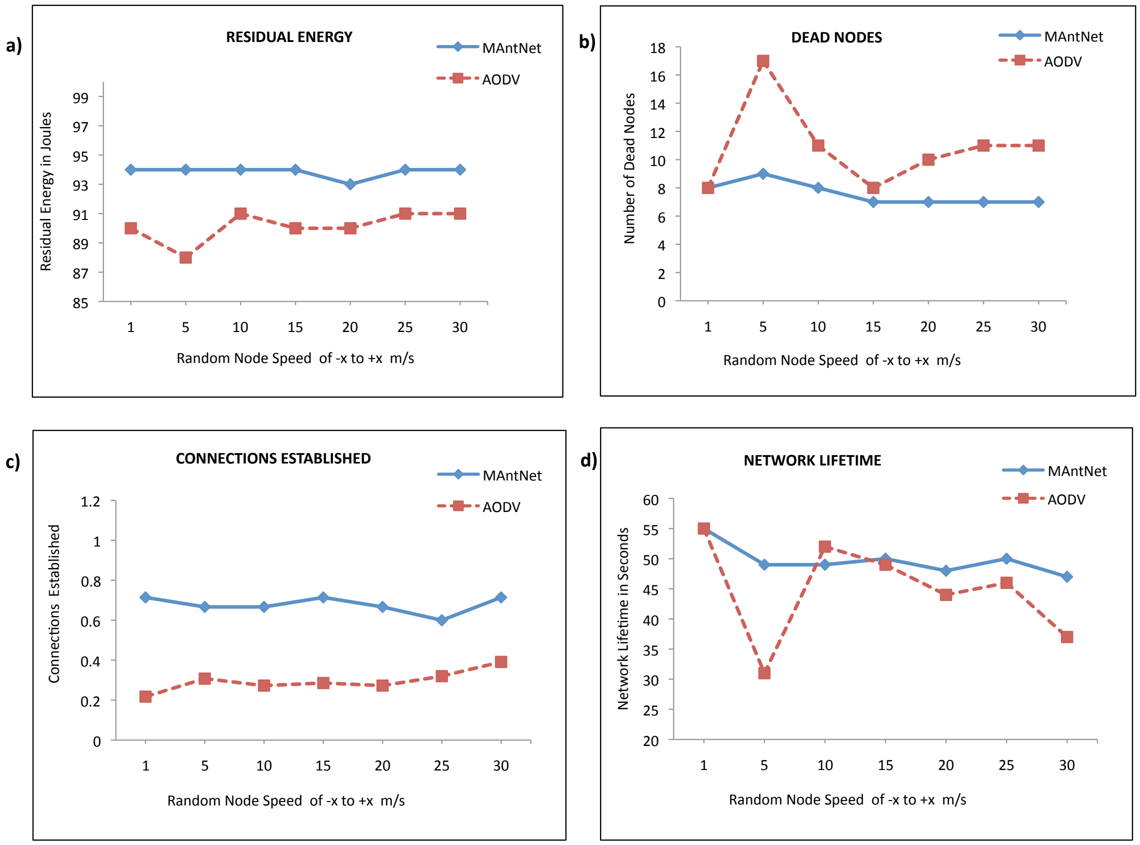

Figure 4.9: Comparison of MAntNet and AODV for varying RMS speeds

This is consistent with the Fig 4.9. Both, in high or low speed conditions, MAntNet marginally performs better than AODV in terms of all performance metrics.

2. ***Comparison of E-MAntNet and E-AODV for Varying RMS Speeds Under Energy-Aware Condition C2***

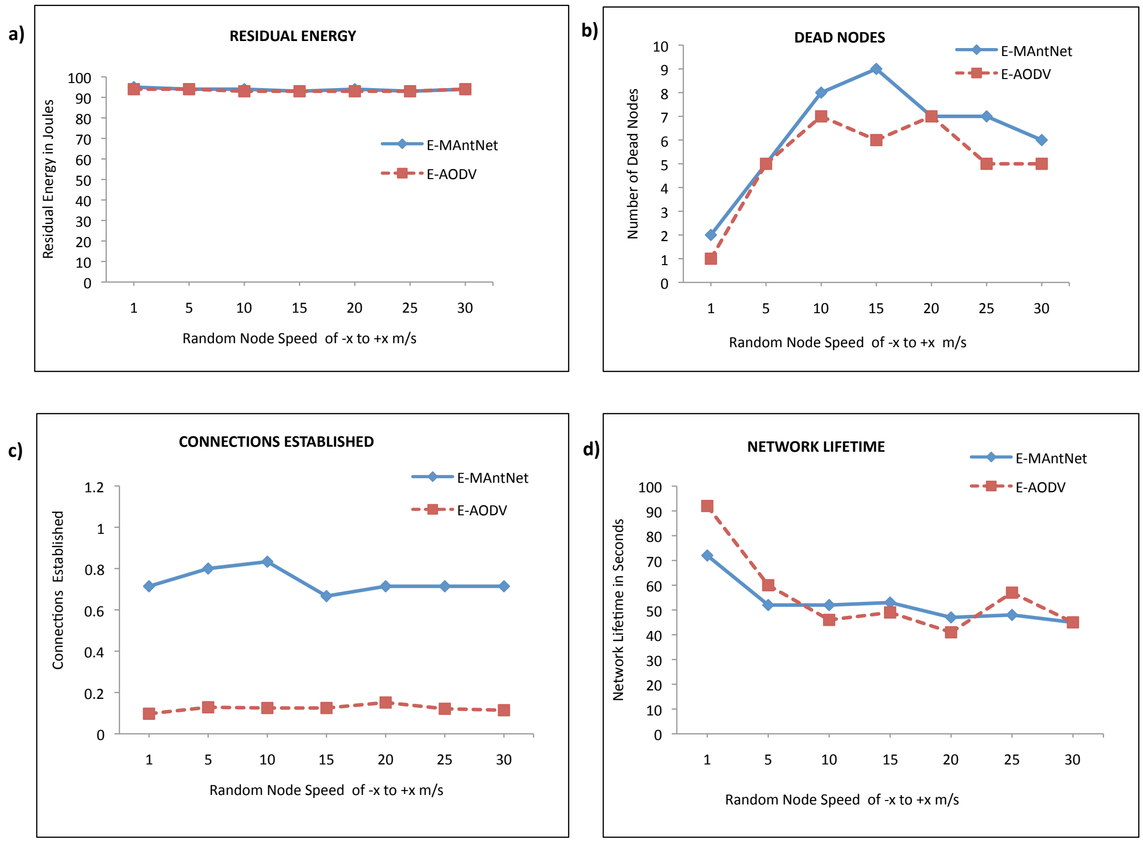

Figure 4.10: Comparison of E-MAntNet and E-AODV for varying RMS speeds Under energy-aware condition C2

In Fig 4.9, since the node movements are random, we do not expect the residual energy and connections established to vary a lot when the node speeds are increased, which is consistent in case of both E-MAntNet and E-AODV under C2 condition as in Fig 4.10. E-MAntNet and E-AODV yield almost similar amount of residual energy (Fig. 4.10a). It is observed that the connections established by E-AODV under condition C2 (Fig 4.10c) is very low when compared to that of AODV (Fig 4.9c) and E-MAntNet (Fig 4.10c), which is why E-AODV produces less dead nodes than E-MAntNet (Fig 4.10b).

Overall, E-MAntNet and E-AODV tend to maintain their levels of residual energy and connectivity for increasing RMS speeds under condition C2. Interestingly, when the node velocities are high, the low energy nodes are sufficiently well spread out in the terrain, and the re-routing process introduced by the C2-condition is not effective in maintaining low number of dead nodes. Consequently, for larger node velocities the number of dead nodes increases and the network lifetime decreases, as seen in the figure 4.10.

3. ***Comparison of E-MAntNet and E-AODV for Varying RMS Speeds Under Energy-Aware Condition C8***

   In Fig 4.11, it can be observed that when the RMS speed increases, E-MAntNet yields more residual energy (Fig. 4.11a), a higher number of connections established (Fig. 4.11b), longer network lifetime (Fig. 4.11d) but generates more dead nodes (Fig. 4.11b) compared to E-AODV.

   E-AODV under C8 condition (Fig. 4.11a) conserves less energy when compared to E-AODV with C2 condition (Fig 4.10a) and E-MAntNet with C8 condition (Fig. 4.11a), which shows that C2 condition for E-AODV conserves more energy than C8. E-AODV generates slightly lesser number of dead nodes than E-MAntNet in Fig. 4.11b. The connections established in C8 E-AODV is slightly lesser than that in AODV (Fig 4.9), while connections in E-MAntNet under C8 condition is similar to that of MAntNet in Fig 4.9.

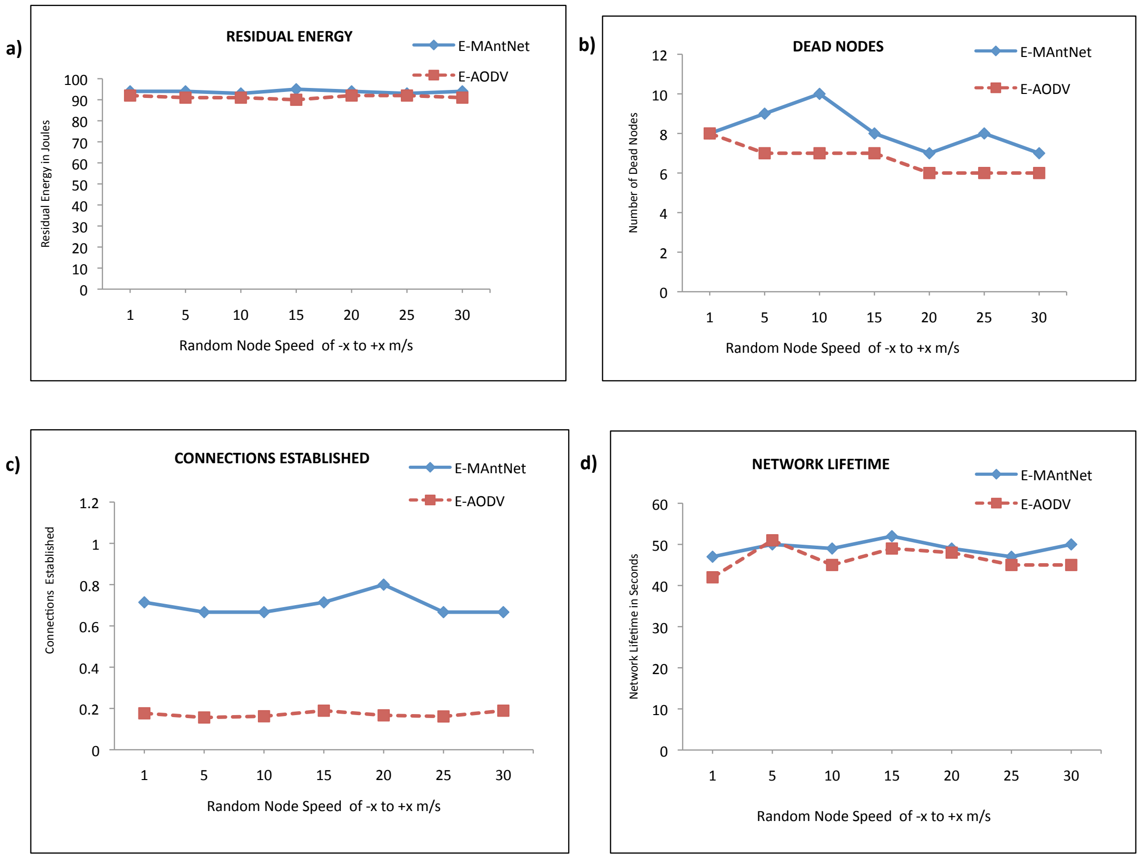

Figure 4.11: Comparison of E-MAntNet and E-AODV for varying RMS speeds under energy-aware condition C8

4.3.6 Performance of E-MAntNet and E-AODV for Varying Transmission Range

Transmission (or communication) range of a wireless network marks the area around a node, within which its transmitted packets can be received by other nodes [21]. nodes located within the transmission range of a sending node are the ones assigned with a copy of the packet being sent. For lower values of the transmission range, the neighbour circle shrinks, thereby the number of directly connected neighbours of each node in the network is reduced, decreasing the possibility of control packets reaching the endpoints on time, hence reducing the number of connections established.

In this section, the performance of E-MAntNet and E-AODV is studied when varying the transmission range, under the settings given in Table 4.1, and using the energy conditions *C2, C8*.

1. ***Comparison of E-MAntNet and E-AODV for varying transmission range under energy-aware condition C2***

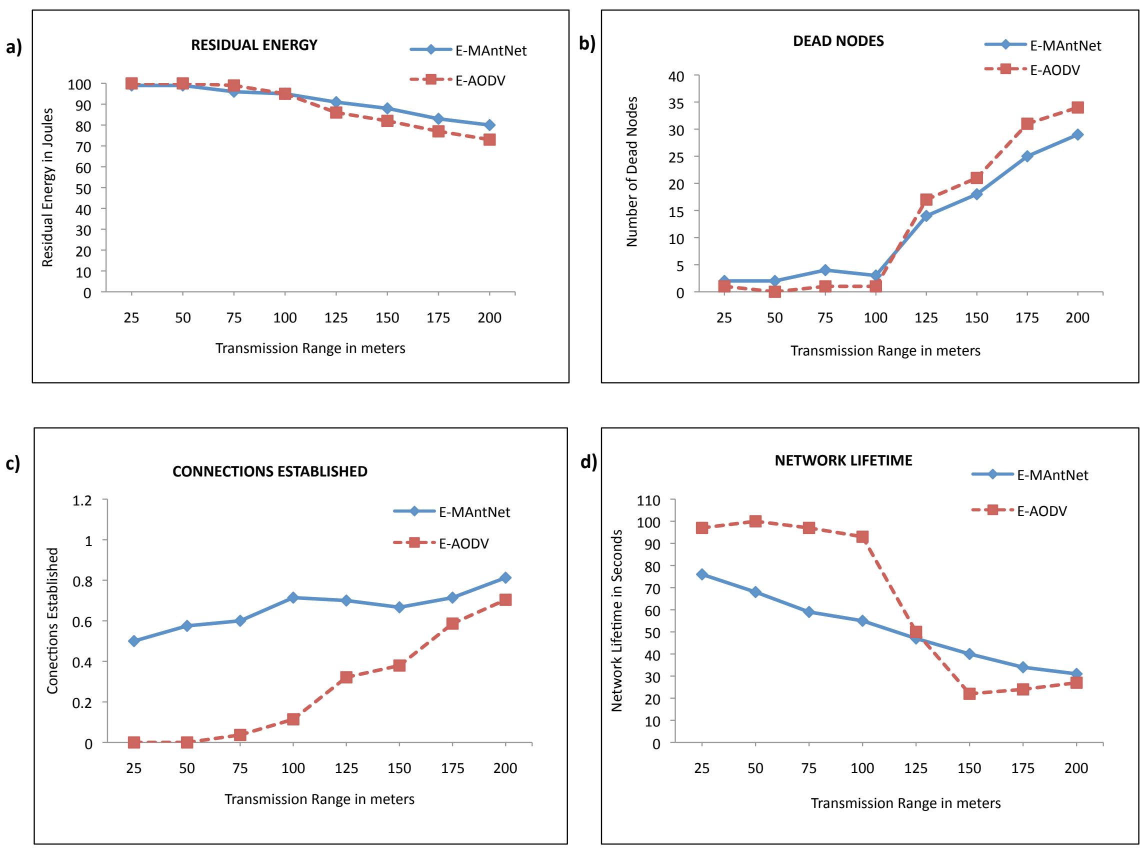

Figure 4.12: Comparison of E-MAntNet and E-AODV for varying transmission range under energy-aware condition C2

In Fig. 4.12, it can be observed that when the transmission range increases, the number of connections established in E-MAntNet is higher (Fig. 4.12c) compared to that in E-AODV. For smaller transmission range (below 100 meters), E-AODV establishes minimal connections, thereby maintains a higher residual energy and generates no dead nodes compared to E-MAntNet. It also shows a better network lifetime than E-MAntNet. On the other hand, for larger transmission range (more than 100 meters), E-MAntNet conserves more energy (Fig. 4.12a), generates less number of dead nodes (Fig. 4.12b), and yields a longer network lifetime (Fig. 4.12d), meaning that E-MAntNet would perform better in densely populated MANETs.

2. ***Comparison of E-MAntNet and E-AODV for varying transmission range under energy-aware condition C8***

   In Fig. 4.13, it can be observed that when the transmission range increases, the number of connections established in E-MAntNet is higher compared to that generated in E-AODV (Fig. 4.13c). In most cases, E-MAntNet also generates marginally less number of dead nodes (Fig. 4.12b) and maintains a slightly higher residual energy compared to E-AODV (Fig. 4.12a).

   Both the protocols are observed to show decreasing tendency in terms of residual energy and network lifetime for an increase in transmission range. This is simply because there are many more near neighbors within the transmission range that promotes activity level in the network, thereby consumes energy in routing activity. The behavior observed in C8 condition Fig 4.13 in case of both protocols for smaller transmission range values appears to be better than that observed in case C2 condition in Fig 4.12. Particularly in case of E-AODV for smaller transmission range values (below 75 meters) better number of connections established, much higher network lifetime are observed. In case of both protocols, it appears that not so many nodes meet the C8 condition or drops as many packets as in case of C2 condition seen in Fig 4.12

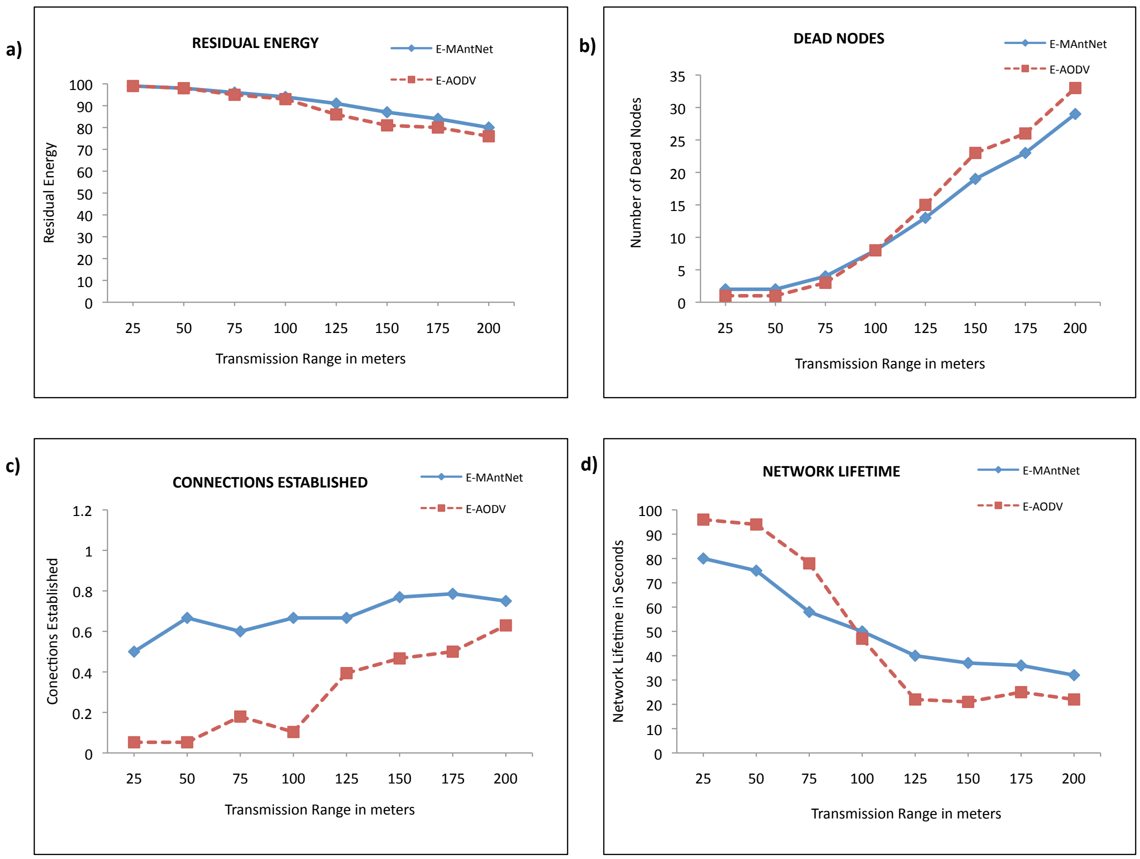

Figure 4.13: Comparison of E-MAntNet and E-AODV for varying transmission range under energy-aware condition C8.

Chapter 5

Conclusion

In this thesis, an energy-efficient Ant-based routing protocol for MANETs (so-called M-AntNet) is proposed, along with an improved version (so-called E-MAntNet), which is based on the introduction of some additional energy-aware conditions. For the sake of comparison, the same conditions have been introduced in the route discovery process of the well known conventional AODV routing protocol, yielding the proposed E-AODV protocol. Simulation results have been conducted to study the performance of the proposed routing protocols. The findings are:

1. The residual energy generated by the energy aware protocols (E-MAntNet and E-AODV) are higher than those generated by their plain versions (MAntNet and AODV). Our simulations show that not all the studied energy-aware conditions consistently perform better than the plain case. Hence the optimal choice of energy conditions would critically depend on the protocol. Although the residual energy in the network can be increased by appropriately choosing the energy-aware condition that would help in dropping the control packets, the drawback is that an unwise choice of such condition may lead to a worse network connectivity.

2. The energy-aware condition C2 performs significantly better than other conditions, primarily because this choice generates a higher residual energy and a lesser number

of dead nodes for both E-MAntNet and E-AODV. However, the total connections established when using E-AODV falls off significantly when compared to AODV. On the other hand, it is found that the number of connections established when using E-MAntNet is comparable to that obtained when using MAntNet, its plain version. Hence, it is reasonable to conclude that the energy-aware condition C2 significantly enhances the performance of AODV in terms of energy efficiency, but minimizes the connectivity in the network.

3. Irrespective of the imposed energy-aware conditions, it is found that the connections established using E-MAntNet is stable for a wide range of transmission ranges. For transmission ranges less than 100 meters, the connections established is extremely low in case of E-AODV while stable in E-MAntNet (around 0.8). For small transmission ranges, AODV establishes no connections at all while preserving the residual energy. This means that the imposed energy-aware conditions do not improve the performance of AODV with respect to the connectivity objective, naturally decreasing the expenditure of energy.

As future work, we intend to strengthen our proposed MAntNet algorithm by making it a secured routing protocol. This can be achieved by incorporating some cryptographic schemes into its route discovery phase in order to protect the data packets when transmitted and to check the authentication of the data packets sender.

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