

Energy Efficient and Scalable Routing Protocol for Extreme Emergency Ad Hoc Communications^{*}

T. Arvind Ramrekha¹, Vahid Talooki², Christos Politis¹, and Jonathan Rodriguez²

¹ Wireless Multimedia & Networking (WMN) Research Group
Kingston University London, United Kingdom
{a.ramrekha, c.politis}@kingston.ac.uk

² Instituto de Telecomunicações
Aveiro, Portugal
{vahid, jonathan}@av.it.pt

Abstract. In this paper, we firstly present an energy efficient (E2) and protocol independent mechanism for Mobile Ad-hoc Networks (MANETs) routing in disaster rescue operations. In such extreme emergency scenarios, protocols need to be energy efficient and scalable. We therefore proceed to integrate the E2 mechanism with the scalable ChaMeLeon (CML) protocol and consequently term it as E2CML. We support the E2 mechanism design using an energy consumption model for MANET nodes and use a packet delivery delay model to explain the scalability and energy efficiency of CML. Through the integration process of E2-CML, we primarily aim at satisfying the requirements for emergency MANETs (eMANETs) but also intend to demonstrate that the proposed mechanism is portable across popular protocols such as Optimized Link State Routing (OLSR) and Ad hoc On-Demand Vector (AODV). Finally, the paper presents simulation results to compare the improved routing performance of E2CML against both AODV and OLSR.

Keywords: Energy efficient routing, Mobile ad-hoc network, QoS routing, MANET routing, pervasive network, Emergency services, Next generation networks, MANET delay model.

1 Introduction

Mobile Ad Hoc Networks (MANETs) consist of autonomous and collaborative communicating nodes that can transmit data directly to each other. In the realm of wireless communications where mobile lightweight devices such as PDAs are very popular, MANETs can provide an instant and purely distributed peer-to-peer wireless communication architecture. In the view of next generation networks^{*} (NGN), IP-based MANET devices can provide a lightweight and ad hoc communication solution for the rescue workers. In extreme emergencies, particular constraints apply to

^{*} This term is further defined by the International Telecommunication Union (ITU) and can be accessed on the ITU-T website at http://www.itu.int/ITU-T/studygroups/com13/ngn2004/working_definition.html

MANET devices. For instance, it is assumed that it is not possible to recharge the battery-powered devices and obstacles are prominent in the environment, restricting line-of-sight. In addition, the MANET size might be subject to regular change as more rescuers join or leave the network according to the severity of the situation. We term a MANET deployed in such a context as emergency MANET (eMANET).

In eMANET topologies, mobile nodes sending data packets are called source nodes whereas the intended recipients are termed as sink nodes. In case the source node radio coverage cannot directly reach sink nodes, intermediate MANET nodes act as mobile router to forward data packets in a multi-hop fashion towards the sink. Subsequently, unlike traditional wireless IP network routing, the MANET routing paradigm needs to cater for changes in packet delivery routes due to source, destination as well as router mobility. Hence, the provisioning of Quality of Service (QoS) guarantees for the purpose of multimedia communication becomes a formidable challenge. Furthermore, any eMANET routing protocol employed should be scalable and energy efficient.

Currently, there are three main approaches for MANET routing as defined by the Internet Engineering Task Force (IETF) and they all have two common mechanisms. The nodes use a Route Discovery Mechanism (RDM) to discover routes from source nodes to destination nodes and use a Route Maintenance Mechanism (RMM) to check whether the established routes are still valid. IETF differentiates routing approaches based on the nature of the RDM and RMM as explained next. In proactive routing approaches, RDM and RMM are used by each node periodically to store route information in a routing table. This information is refreshed regularly. Therefore, this approach is also termed as table-driven where nodes can use pre-established routes for data packet routing. Then, for the reactive routing approach, source nodes initiate the RDM 'on-demand' to establish routes whereas the RMM temporarily maintains routes. After the maintenance period, nodes need to re-initiate RDM for further data transmission. Finally, in hybrid routing approach, a mixture of RDM and RMM from both proactive and reactive approaches are integrated together.

In this paper, we consider two of the most popular routing protocols namely the Optimized Link State Routing (OLSR) [1] and Ad hoc On-demand Distance Vector protocol (AODV) [2] routing protocols. The proactive OLSR protocol requires that nodes periodically issue HELLO and Topology Control (TC) routing control packets as part of RDM and RMM. Hello packets are sent with a one hop "Time To Live" (TTL) value to discover and maintain link quality information while TC packets, containing link, neighborhood and routing information are flooded throughout the network for route establishment and maintenance purposes. Routes are then updated upon receiving periodic TC and HELLO packets. On the other hand, AODV is an "on-demand" protocol where a source node initiates route discovery when data transmission is required. The source floods the network with a Route Request (RREQ) packet in order for the sink node to receive the RREQ and to respond with a Route Reply (RREP) packet. The unicast RREP is sent towards the source by the destination and router nodes through the process of reversing the path of the RREQ by using temporarily stored route discovery information. Thus a source-destination (S-D) route is established and maintained in the routing table of each participating

nodes for a given timeout period, after which, the RDM has to be re-initiated for data transmission. However, neither OLSR nor AODV was designed to operate in a scalable and energy efficient manner as required in eMANETs.

This paper attempts to provide an energy efficient (E2) mechanism from concepts introduced in [3] that can be integrated in most popular routing protocols such as AODV and OLSR. We integrate this mechanism into the scalable ChaMeLeon (CML) [4] protocol. The resulting Energy Efficient and scalable protocol is called E2CML. This paper is organized as follows. We first present a literature review of protocols that propose energy efficient and scalable routing solutions. Then, we briefly describe the mathematical models on which we base our protocol design and evaluation. Subsequently, the E2CML routing protocol section explains the E2 mechanism followed by its integration with CML. The paper then presents and discusses simulation results of the above models and mechanisms, in the evaluation section. The paper ends with a conclusion section containing a summary of our findings.

2 Literature Review

The provisioning of hard QoS routing guarantees in eMANETs is a Nondeterministic Polynomial time (NP)-Complete problem [5]. Instead a more realistic solution for multimedia communication in eMANETs would be to provide soft QoS routing guarantees. Hence, the eMANET routing protocols should be designed such that the protocols operate as efficiently and effectively as possible. As a result, the overall routing QoS will be improved while keeping the routing cost to a minimum. In this paper, we consider the QoS metrics end-to-end packet delivery delay as a measurement of efficiency for eMANET routing protocols whereas overall energy consumption indicate the effectiveness or cost of these protocols. In this section, we discuss popular and relevant scalable and energy efficient routing protocols for the purposes of eMANET routing.

2.1 Load-Balanced Energy Efficient Protocols

The route selection mechanisms used in current IETF routing protocols do not consider node residual energy as a criterion while making its decision. Consequently, this approach may lead to particular nodes (critical nodes) being unfairly burdened to support routing in popular paths. Such a mechanism will therefore lead to a high node failure rate due to battery exhaustion of nodes. Here, it is important to emphasize that unbalanced power consumption may not only result in earlier node failure of overloaded nodes but also can lead to network partitioning, decrease in network lifetime (especially in small networks), and a decrease in route reliability [6]. So, there is a need to both improve energy efficiency and balance battery consumption among nodes in eMANETs to reduce the number of critical nodes in the network.

There are some protocols that use different approaches to achieve energy efficiency or battery consumption balancing. One major drawback of most of these ad hoc

routing protocols is that they do not have provisions for conveying the load and/or quality of a path during the route setup. Nevertheless there are a considerable number of studies that try to improve these issues, but they usually cause some other drawbacks like requiring global topology information, increase delay or even create a blocking issue [7, 8, 9, and 10]. The blocking issue happens for example, when a source node is impeded by a timeout timer to start a data transmission before receiving all replies for a route request message. In the context of eMANETs, these energy efficient algorithms also do not contain considerations for routing protocol scalability and QoS.

There are some protocols that use different approaches to achieve energy efficiency or battery consumption balancing. However most of these protocols try to find some network layer mechanism to avoid flooding and unnecessary packet forwarding but one major drawback of most of these ad hoc routing protocols is that they do not have provisions for conveying the load and/or quality of a path during the route setup. There are a considerable number of studies that try to improve these issues, but they usually cause some other drawbacks like requiring global topology information, increase delay or even create a blocking issue [7, 8, 9, and 10]. The blocking issue happens for example, when a source node is impeded by a timeout timer to start a data transmission before receiving all replies for a route request message. Determining this time is very challengeable and finally will turn to more delay.

Besides, current ad hoc routing protocols do not have a proper mechanism to handle and save critical node failure. As aforementioned there is a high probability that some nodes turn into critical nodes due to their favorable routing location in network topology. Consequently, they consume more battery power which leads to node failure. Our protocol proposes a new mechanism to detect these nodes and decrease the load on them to save them in the network. Also most of these protocols try to find the optimized routing mechanism in terms of energy efficiency but they usually cause more delay or create additional routing load. E2CML not only tries to find the best energy balanced route but also provides energy efficiency and delay improvements on AODV and OLSR for scalable networks.

2.2 Scalable Routing Protocols

ChaMeLeon (CML) [4] is a hybrid and adaptive routing protocol that aims to improve overall QoS of the utilized routing protocol in conditions of varying network size. CML operates by adapting its routing behavior according to the network size within a pre-defined CA. It statistically establishes a network size threshold (NST) on the basis of packet delivery delay and jitter performance metrics of OLSR and AODV. For this reason, the network size is quantified by the total number of nodes in the network. It was observed that the NST corresponds to the eMANET size beyond which AODV routing outperforms OLSR. Consequently, CML routes data proactively using OLSR in a small network of size less than or equal to the NST value and uses AODV routing protocol for larger networks.

The Zone Routing Protocol (ZRP) described in [11], was one of the earliest proposed hybrid MANET routing protocols. Nodes using ZRP have to maintain a

zone radius where routes are maintained proactively. ZRP differs from CML since it uses both proactive RDM in certain zones and a reactive RDM if the destination is found outside the zone. ZRP aims only at minimizing routing overhead but do not consider the operational impact on QoS metrics. This process can be disadvantageous in large networks where periodical route discovery and maintenance messages coupled with the use of inter zone routing message result in more overhead and delay than the CML protocol for such a scenario.

Then, some routing protocols propose clustering as a way to improve scalability of protocols. LANMAR protocol [12] operates by logically grouping nodes into logical subnets. A landmark node is elected in each subnet to segment the domain for proactive message dissemination and reduces routing overhead especially in larger networks. However, in dynamic eMANETs, groups of nodes expect to merge and partition regularly as part of rescue operations. This results in regular subnet landmark elections and routing table recalculations. Therefore, LANMAR operation will add more overhead as compared to CML. SHARP is a popular hybrid routing protocol consisting of AODV and OLSR routing mechanisms. In [13], the authors describe different modes of routing defined in the protocol that are designed for specific network constraints and traffic requirements. One such routing mode addresses the scalability issue in MANETs. Although SHARP guarantees improvement in delay jitter performance when compared to AODV, it does not discuss about improvements in packet delivery delay. Also, it does not compare its QoS performance against OLSR. Finally, the Cluster Based Routing Protocol (CBRP) requires that nodes elect cluster heads to route messages in the network. In large networks, the simultaneous operation of both reactive and proactive routing creates substantial routing overhead and the process of electing cluster heads might not be appropriate in eMANETs because member nodes and neighbors might change frequently.

Additionally, none of the above mentioned protocols presents a combined energy efficient mechanism for improving network lifetime and decreasing node failures.

3 Model

We define our model using three main definitions below for energy, delay and routing overhead models that form the basis for our protocol design. Briefly, we consider that the 802.11 MAC is used in each node so that the coverage distance of users is assumed to be restricted to 250 m. It is important to note that we do not consider propagation models in our investigations as we only observe residual energy levels in each node. Consequently, this implicitly includes considerations of energy spent due to signal propagation and any extra routing overhead due to node mobility.

Definition 3.1 (Energy model). In an eMANET network, each node can operate in a role-dependent (source, destination or router) state that changes temporally. These states include one of the following:

1. Send packet: node sends data and control packets.
2. Receive packet: node receives data, control and any overheard packets.

3. Forward packets: node receives and sends a particular packet.
4. Idle state: node does not receive or send any packets. This is a rare state in eMANETs where routing packets are regularly flooded and overheard by most of the nodes in the network. However, if some nodes spend energy in the idle state, this will be implicitly considered while observing the residual energy of nodes at different times.

Therefore, to achieve a more energy efficient mechanism via a balanced usage of residual nodal battery power, we should focus on analyzing the energy required for states 1-4.

This assumption is further supported by [14] from which we also derive our energy model. Hence, an eMANET node mainly utilizes energy for receiving and sending packet from its wireless network interface. It is also assumed that the node does not spend significant energy while in idle state and does not switch to sleep mode. We assume that the link capacity of all links in the network is equal to C . Therefore the same time T is necessary to send a packet from node u to node v in the network. Let E_{init} be the initial battery level in each node and E_{total} be the total energy of total number of nodes N in the network where energy input from external sources is not possible,

$$E_{total} = \sum_{j=1}^N E_{init,j} \tag{1}$$

Also, each transmitted packet requires energy E_t while a received packet obliges a node to consume energy E_r . If E_{fw} represents the energy required by a node to forward a packet, it can be deduced that energy required to forward a packet is given by,

$$E_{fw} = E_r + E_t \tag{2}$$

In our paper, we consider the case where multiple paths exist from source node S to destination node D . Then, the set R_{SD} of M possible routes from source node S to destination node D is given by $R_{SD} = \{R_i : 0 \leq i \leq M-1\}$ where R_i is the i th route from connecting node S to node D . Given that route $R_i = \{S, \dots, D\}$ is a set of nodes found along route i , the length of a route is defined as $|R_i|$

$$|R_i| = (N - 1) = H \tag{3}$$

where N is the number of nodes in R_i and H represents the number of hops along that route. The energy required to send a packet along route R_i can be expressed as

$$E_{Ri} = (H * E_{fw}) \tag{4}$$

Definition 3.2 (Analytical Routing Overhead model). In our routing model, we assume that the total number of participating nodes, N , are equally distributed in the emergency site. It can be then shown that total number of routing packets required

during the routing protocol depends on the value N , the average number of 1-hop neighbors N_{1H} and the average number of hops in the network Hop_{av} for a given communication time T in the network.

For OLSR, algorithm specific parameters that affect the number of routing packets are the Hello interval T_{hello} and TC interval T_{tc} . Also, we assume that the MPR set of each node consists of half of its one-hop neighbors. Then, maximum number of routing packets, R_Pkt_{OLSR} can be approximated as:

$$\begin{aligned} R_Pkt_{OLSR} &\approx (N \times (N_{1H} \times (T \div T_{hello})) + ((N_{1H} + (N_{1H} / 2)^{2*Hop_{av}}) \times N) \\ &\quad \times (T \div T_{tc})) \\ &\approx N \times ((N_{1H} \times (T \div T_{hello})) + ((N_{1H} + (N_{1H} / 2)^{2*Hop_{av}}) \\ &\quad \times (T \div T_{tc}))) \end{aligned} \quad (5)$$

In the case of AODV, values for number of traffic connections, Num_Con , the timeout of routes, $T_{timeout}$ and duration of each connection, T_{con} dictate the maximum number of routing packets used, R_Pkt_{AODV} :

$$R_Pkt_{AODV} \approx ((N_{1H} + (N_{1H})^{2*Hop_{av}}) \times (T \div T_{timeout}) \times Num_Con) \quad (6)$$

Definition 3.3 (Data packet delivery delay model). Our model assumes the use of CSMA/CA link access protocol and that queuing, D_{queue} and route computation delays, D_{proc} , are negligible. Thus, considering that the collision avoidance mechanism in CSMA requires that only one node can transmit at a time, the average delay, D_{access} , imposed on packet transmission across a given link, is directly proportional to the number of routing packets exchanged as supported in [15]. The cumulative sum of such link delays result in an overall increase in end-to-end data packet delivery delay, D_{total} . Therefore, in such a model, using less routing packets will improve QoS of the protocol while also reducing routing cost. We consider a packet transmission over a route R_i connected by links L_i where $i \in \{1, \dots, H\}$. H is the number of hops along the route and is bounded by the maximum number of hops achievable in a given operation area when transmission radius of each node is equal to R . We denote end-to-end packet delay due to packet transmissions across each link as, D_{trans} .

In the case of OLSR, where the routes are pre-established, the total data end-to-end delay, $OLSR_D_{total}$, is the sum of cumulative link layer transmission delays and backoff delays, $D_{backoff}$ due to a busy link:

$$OLSR_D_{total} = \sum_{j=1}^H (D_{trans_j} + D_{backoff_j}) \quad (7)$$

Then, in the worst case, AODV requires establishing a route before transmitting. This includes flooding the network followed by 2 unicast transmissions. Therefore total end-to-end delay in data packet delivery, $AODV_D_{total}$, is given by

$$\text{AODV_D}_{\text{total}} = \sum_{j=1}^H (3 * D_{\text{trans } j} + D_{\text{backoff } j}) \quad (8)$$

4 E2CML Routing Protocol

4.1 Protocol Overview

It can be deduced from Definition 3.1 that nodal energy consumption is a result of packet transmission, processing and idle operation costs as shown in Fig. 1. Since energy consumed for idle operation and algorithmic processing are considered negligible as compared to packet transmission and packet processing energy consumption [14], our protocol design focuses on reducing the latter two factors.

Firstly, the E2 mechanism described in section 4.2 below, aims at reducing energy consumption due to data packet transmission and processing at critical nodes that are frequently solicited for data forwarding. This is achieved by modifying the route selection process so that a more balanced route utilization mechanism based on the sum of residual nodal energy along delivery paths, is used whenever possible. The number of data packets sent from the source cannot be reduced at the network layer and the routes available are constrained by the physical proximity of nodes. Thus, the E2 mechanism only focuses on “fairly” distributing the forwarding load of data packets whenever possible.

Then, the number of control packets used by the routing protocol for conducting eMANET routing has to be minimized in order to reduce battery usage. From equations 5 and 6, it can be deduced that OLSR uses more routing packets than AODV. However, the delay model defined in equations 7 and 8 implies that there is a delay tradeoff i.e. the D_{trans} delay factor of the model might be high enough for AODV compared to OLSR so that for a given range of network size $\text{OLSR_D}_{\text{total}} \leq \text{AODV_D}_{\text{total}}$ and $\text{R_Pkt}_{\text{OLSR}} \leq \text{R_Pkt}_{\text{AODV}}$. This network size threshold, NS_T , has been first proposed solely using simulation results in [4]. In section 5 of this paper, we will attempt to establish a more mathematically driven deduction of NS_T . Following the analysis beforehand, the use of CML is justifiable as it would provide a scalable routing solution by providing improved delay performance at reduced cost over both AODV and OLSR for varying size networks operating within a pre-defined disaster area termed as Critical Area (CA). Hence, the integration of E2 mechanism to the CML protocol results in E2CML that is described in more details in later subsections. Briefly, E2CML consists of the integration of the E2 mechanism to the RDM and RMM of AODV and OLSR whereby, the routing packets are used to collect and disseminate residual energy information of nodes along routing paths. The source node then uses this information to compute the actual route for data delivery.

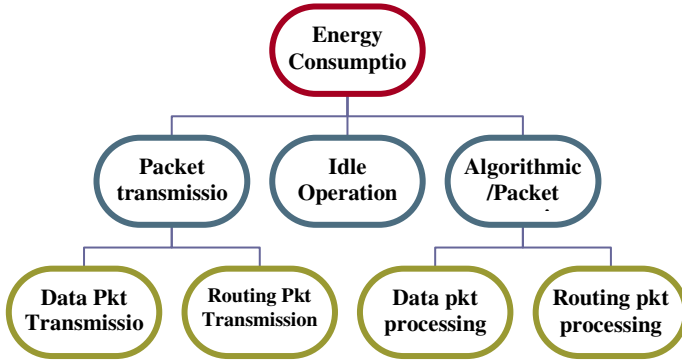


Fig. 1. The various sources of energy consumption in an eMANET node as deduced from the energy model described in Definition 3.1

4.2 Energy Efficient (E2) Mechanism

In this subsection, we use notations and equations from Definition 3.1 to design the E2 mechanism.

Route Selection Process. We assume that for the (source, destination) pair S-D nodes in the network, the routing table of node S has a set of routes $R_{SD} = \{R_i : 0 \leq i \leq M-1\}$. E2 defines a two phase checking process to choose the best route R_i such that the variance between average residual energy of nodes in RSD and actual residual energy of nodes along route R_i is minimum. Importantly, routes that contain nodes having critical battery levels are avoided if possible. Therefore, route selection process consists of two phases as described below.

First Phase check: Critical Nodes. Despite the fact that the summation of remaining energy for nodes in a route may be high, the route may still consist of nodes with very low energy levels (termed as critical nodes). There is a high probability of route breakage due to the presence of critical nodes. Hence, these routes should be avoided. For the purpose of E2 mechanism, we represent the energy values of nodes in a 4 bit string so that we quantify 16 (=2⁴) different energy levels where each level shows nearly 6% of battery charge. The Min Level implies that the node is off (MinL=0) and Max Level shows a fully charged battery (MaxL=15) with energy E_{init} . Also we use the notation of $E_{min}(R_i)$ to designate the minimum residual energy level of a node from all nodes along route R_i . Furthermore, a critical node n is defined as a node with energy E_n such that $E_n \leq 2$. As a first step, all M routes will be checked so that routes R_i with condition $E_{min}(R_i) \leq 2$ are not considered for routing as long as other “non-critical” routes exist. We suppose that from an initial set of M candidate routes, N routes pass the first phase check.

Second Phase check: Route Priority: Then, we define a Route Priority Factor (RPF) that determines the priority of each route. For a given S-D pair, the number of candidate routes for the second phase is N . The route R_i that has the maximum RPF

among all N candidate routes will be selected for transmission. The RPF for each route is calculated using two parameters: (i) length and (ii) sum of energy level of each node. Length and energy level parameters are normalized in range [0...1] to make them comparable. These input parameters are defined next:

- Length of route R_i – from Definition 3.3, we deduce that longer routes produces more delay and additionally may lead to a higher probability of route breakage. Here, $L(R_i)$, indicates the route length factor that defines the priority of route R_i :

$$L(i) = \frac{|R_i|}{Max_Length} = \frac{H}{Max_Length} \tag{9}$$

where $|R_i|$ is the actual length of route R_i (i.e number of hops, H, along R_i) and Max_Length is the maximum length that a route can i.e NS-1 where NS is the network size. From equation 9, it can be deduced that $0 < L(R_i) \leq 1$ for $i \in \{1, \dots, N\}$. As formerly discussed, small length routes are preferable so RPF is inversely proportional to $L(R_i)$.

- Residual Energy Level of Route - the remaining energy level of nodes in route R_i is of central importance to the E2 mechanism. Thus routes with higher summation value of nodal residual energy levels are favored. The energy factor, $E(R_i)$, indicating the preferred routes due to favorable energy levels, is defined below:

$$E(R_i) = \frac{\sum_{j=1}^{j=n_i} E_{ji}}{n_i * E_{init}} = \frac{E_{sum}(R_i)}{n_i * E_{init}} \tag{10}$$

where n_i is the number of nodes along route R_i , E_{ji} denotes the remaining energy level of the j th node along the route, $E_{sum}(R_i)$ is the summation of battery levels of all nodes in route R_i , and E_{init} is the nodes battery level at the beginning of simulation. Since we require routes with high residual energy levels, the Route Priority Factor (RPF) of route R_i is defined to be proportional to $E(R_i)$. It can be inferred from equation 10 that $0 < E(R_i) < 1$ for any $i \in \{1, \dots, n_i\}$.

- RPF - the RPF will be computed for all N routes to destination D and the route with maximum RPF will be selected. RPF is given by:

$$RPF(R_i) = K_E \times E(R_i) + K_L \times \frac{1}{L(R_i)} \tag{11}$$

where K_E and K_L are coefficients for factors of energy level and route length respectively. The desired coefficient values obtained through simulation are set to 2 and 1 respectively thus giving a higher priority to balanced energy consumption across routes over route length. The processes involved in the E2 route selection mechanism is shown below.

The code shows the two phase route selection process algorithm for E2 mechanism.

E2 algorithm (index of R_i)

```

{
  For(i=1 to M)//M = number of routes for S-D
  {
    //First Phase Check
    N=0; //N = routes passing first phase check
     $E_{sum}(R_i)=0$ ;
    For (j=1 to  $n_i$ )
    {
       $E_{sum}(R_i) = E_{sum}(R_i) + E_{ji}$ ;
      If ( $E_{ji} < E_{min}(R_i)$  )
         $E_{min}(R_i) = E_{ji}$ ;
    }
    //Second Phase Check
    If ( $E_{min}(R_i) > 2$  )
    {
      N++;
       $L(R_i) = |R_i| / Max\_Length$ ;
       $E(R_i) = E_{sum}(R_i) / (n \times E_{init})$ ; //n is the number of
nodes of  $R_i$ th route
       $RPF(R_i) = KE \times E(R_i) + KL \times 1/L(R_i)$ ;
      If (  $MaxRPF < RPF(R_i)$  )
      {
         $MaxRPF = RPF(R_i)$ ;
         $BestRouteIndex=i$ ;
      }
    }
  }
  Return(i) as the index of best route;
}

```

4.3 Integrating E2 with CML (E2CML)

The E2 mechanism is designed so that it can be integrated with any route selection mechanism that can collect information of node residual energy levels. In this subsection we describe two such instances where this mechanism is integrated with AODV and OLSR as part of the CML protocol. It consists of gathering node energy level information and transferring this to the source node.

AODV Integration. The integration with AODV consists of extending the route discovery mechanism so that multiple RREQ packets are processed at the destination, resulting in multiple RREP packets being sent back to the source. The RREP is extended to include a minimum energy field and a cumulative energy field where

information for the minimum nodal residual energy recorded along the route and the sum of energy levels at each node along the path are stored respectively. The source then uses the information gathered through the RREPs to generate an RPF value for each route so that the appropriate route can be selected.

OLSR Integration. The E2 mechanism can be merged with the OLSR protocol by firstly extending the Hello and TC packets so that they can send the required energy information of each node to the source. These energy values are then use to compute the minimum as well as the sum of energy levels of the routes. The RPF of each route is then calculated and stored in the node repositories so that the node can use the pre-established route information to send data in an energy efficient manner.

5 Protocol Evaluation

5.1 Evaluation Metrics

Energy Consumption Balance (ECB). We define the balanced energy consumption metric to determine the effectiveness of the energy balancing algorithm used by E2 mechanism. If the ECB for each node n is E_n , the relationship between the ECB of node n and the total consumed energy in all the network's nodes is

$$E_n(ECB) = \frac{E_{n_consumed}}{E_{total_consumed}} \quad (12)$$

The obtained value will be the metric for balanced energy consumption of the protocol. A smaller deviation value implies better energy balance in the network.

Node Failure Degree (NFD). The node failure degree is, for a time window T , the percentage of nodes in the topology that have failed because of low battery power. This value can be computed by using the following formula:

$$NodesFailureDegree(NFD) = \frac{Num_Nodes_{failed}}{Num_Nodes_{total}} \quad (13)$$

Furthermore, we also consider the end-to-end packet delivery delay metric as an indication of the effectiveness of the routing protocol and the routing overhead load as the corresponding routing cost.

5.2 Simulation Setup

We setup the simulation environment according to the model defined in Definition 3.1. The energy required for packet transmission, et and for packet reception, er , within the simulator were set at 0.28J. The initial energy in each node was set at 40000J so that the node battery could last for the simulation period which was set at 2000seconds. The traffic was generated using 5 UDP based CBR connections set at 64kbps. The simulation area was set to 1000m*1000m with nodes moving at 0.5m/s on a random waypoint model with a pause time of 10seconds.

Further simulation setup was twofold. Firstly, we aimed at proving that the assumptions made for models defined in Definition 3.2 and Definition 3.3 were valid. Therefore, we setup a simulation environment for different size networks starting at 6 nodes and increasing by 2 nodes in each scenario up to a maximum network size of 20 nodes. AODV and OLSR were then utilized separately to investigate the actual traffic generated as compared to a theoretical plot of Definition 3.2. The packet delivery delay was also calculated to illustrate the assumptions made in Definition 3.3. Then, we then implemented and simulated the E2CML protocol to investigate its ECB and NFD as compared to the performance of both AODV and OLSR. The simulation was run for a fixed network of size 20 nodes with the same configurations as above.

5.3 Simulation Results and Discussion

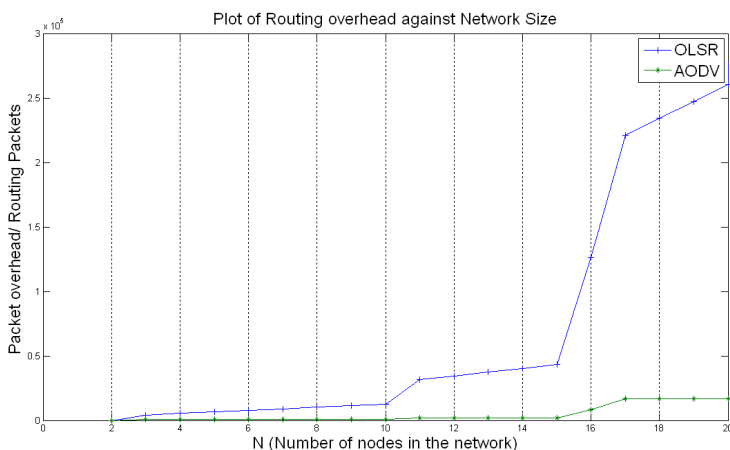


Fig. 2. Illustration of theoretical packet overhead from the mathematical model for AODV v/s OLSR routing

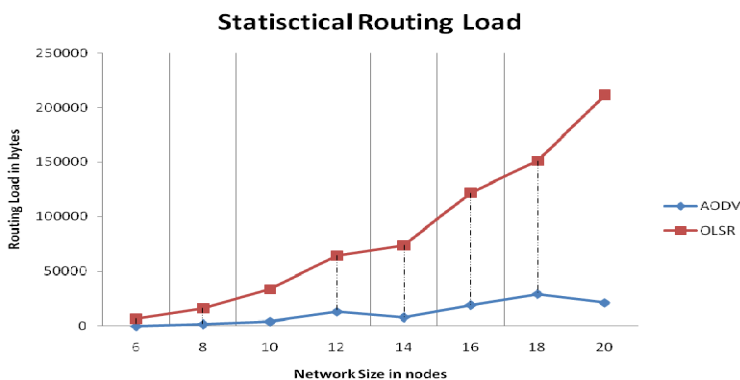


Fig. 3. Routing overhead of AODV and OLSR routing protocols as obtained through simulations

From equations (3) and (4), it can be deduced that for each data connection in the network, given that T_{timeout} , T_{hello} and T_{tc} have comparable magnitudes (as proposed in [1] and [2]), the routing packet overhead required by OLSR is more significant than that of AODV routing as the network size NS increases. More particularly, there is a sudden increase in overhead packet when NS = 10 nodes as shown in Fig. 2. As shown in Fig. 3, the actual simulated results (in an event based packet simulator for MANETs) support the theoretical claims made in Definition 3.2 that the routing overhead $R_{\text{Pkt}}_{\text{OLSR}} \approx R_{\text{Pkt}}_{\text{AODV}}$ for smaller networks but $R_{\text{Pkt}}_{\text{OLSR}} \gg R_{\text{Pkt}}_{\text{AODV}}$ for larger networks larger than NS_T value. In addition, from the delay models defined in Definition 3.3, a higher number of overhead packets will increase the total packet delivery delay D_{total} due to higher values of D_{backoff} [15].

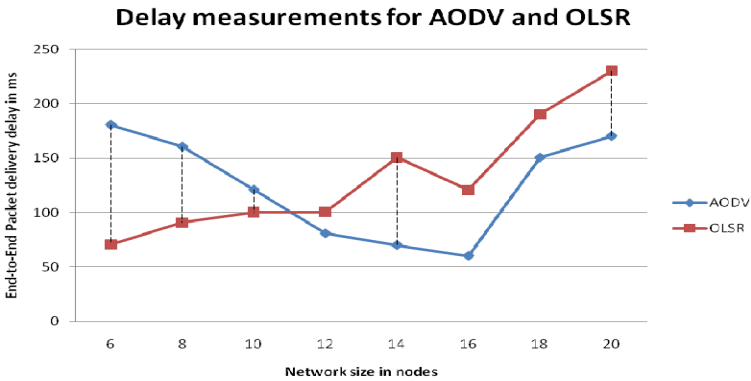


Fig. 4. End-to-end data packet delay measurements using AODV and OLSR

Thus, the total delay value OLSR_ D_{total} surpasses delay for AODV, $AODV_{D_{\text{total}}}$, for network sizes of more than 10 nodes in uniformly distributed MANETs as shown in Fig. 4. This justifies the utilization of CML for eMANET scenarios presented in this paper where scalability of the routing protocol in terms of data delivery delay is important for multimedia communication. Consequently, for our scenario, the appropriate values for NS_T can be considered as 10 nodes.

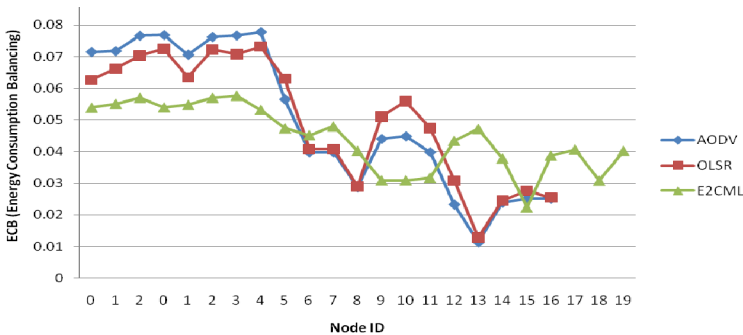


Fig. 5. The average value for energy consumption balancing metric for each node in the network.

The Fig. 5 above shows the average value for the ECB of each node over the duration of the simulation. The ECB indicates the variation in Energy consumption of nodes as a fraction of total energy consumed in the network. Therefore, the fraction denotes the energy consumption load per node as compared to total energy load. It can be seen from this figure that in the case of E2CML, the energy consumption is spread more evenly across the nodes of the network as compared to both AODV and OLSR. The latter protocols select nodes based on the best hop-count path and therefore have a tendency to use the same “best nodes” whenever possible.

Finally, Fig. 6 uses the NFD to show the merits of the E2 mechanism when applied to AODV and OLSR operating within the CML protocol. The value of NFD indicates the number of nodes that have failed as a proportion of the total number of nodes. As mentioned before, high number of node failures can lead to partitioning of the network and reducing the overall lifetime of the network. In the figure above, it can be observed that the NFD of the E2CML protocol is less than both AODV and OLSR over the period of simulation. This is because E2CML balances energy consumption load more evenly as shown in Fig. 5. In addition, the OLSR protocol has a higher NFD than AODV because as discussed above, the OLSR protocol utilizes more routing packets than AODV for evenly distributed networks of 20 nodes given that the same amount of traffic is circulating in the network.

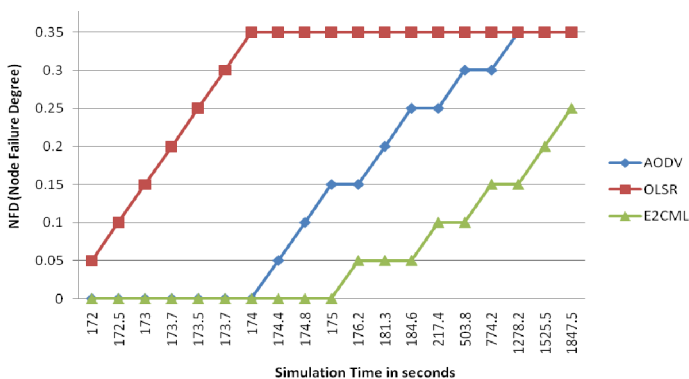


Fig. 6. Graph of node failure degree as taken over the simulation time period in seconds

6 Conclusion

In this paper we introduce an energy, delay and packet utilization model for the MANET routing protocols OLSR and AODV. We then present an energy balancing mechanism, E2, that is protocol independent and that could be utilized to increase network lifetime and decrease node failure degree. Furthermore, using the defined models, we demonstrate that a hybrid approach such as that employed by CML will decrease overall delay and improve energy efficiency in the case of scalable MANETs. We support the latter using simulation results. We finally implement an integrated version of E2- CML to demonstrate the energy balancing and node failure reduction characteristics by using simulation based statistical results. Hence, the use

of the E2CML is justifiable for extreme emergency ad-hoc rescuer communications (eMANETs) where scalability, network lifetime and network segmentation are critical factors for reliable multimedia communication.

Acknowledgement. The authors wish to acknowledge the support of the ICT European Research Programme and all the partners in PEACE (FP7 STREP with Contract number: 225654): PDM&FC, Instituto de Telecomunicaes, FhG Fokus, University of Patras, Thales, Telefónica I+D, CeBit.

References

1. Clausen, T., Jacquet, P.: RFC3626: Optimized Link State Routing Protocol (OLSR). RFC Editor United States (2003)
2. Perkins, C., Belding-Royer, E., Das, S., et al.: RFC3561: Ad hoc on-demand distance vector (AODV) routing. RFC Editor United States (2003)
3. Talooki, V., Rodriguez, J.: A Load Balanced Aware Routing protocol for Wireless Ad hoc networks. In: Proceedings of IEEE International Conference on Telecommunications 2009 (IEEE ICT 2009), pp. 25–30 (2009)
4. Ramrekha, T.A., Politis, C.: A Hybrid Adaptive Routing protocol for Extreme Emergency Ad Hoc Communication. In: ICCCN 2010 IEEE Workshop on Convergence of Heterogeneous Wireless Systems (ICCCN 2010 CON-WIRE Workshop), August, 2-5 (2010) (to appear)
5. Chen, L., Heinzelman, W.: Qos-aware routing based on bandwidth estimation for mobile ad hoc networks. *IEEE Journal on Selected Areas in Communications* 23(3), 561–572 (2005)
6. Woo, K., Lee, B.: Non blocking localized routing algorithm for balanced energy consumption in mobile ad hoc networks. In: Proc. IEEE MASCOTS 2001, pp. 15–18 (2001)
7. Singh, S., Woo, M., Raghavendra, C.S.: Power-Aware Routing in Mobile AD Hoc Networks. In: International Conference on Mobile Computing and Networking (MobiCom 1998), pp. 181–190 (1998)
8. Chang, J.-H., Tassiulas, L.: Energy Conserving Routing in Wireless Ad Hoc Networks. In: Proceedings of Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (IEEE Infocom), pp. 22–31 (2000)
9. Zhou, A., Hassanein, H.: Load-Balanced Wireless Ad Hoc Routing. In: Proceedings of Canadian Conference on Electrical and Computer Engineering, pp. 1157–1161
10. Chakrabarti, G., Kulkarni, S.: Load Balancing and resource reservation in mobile ad hoc networks. *Ad Hoc Networks* 4(2) (March 1, 2006)
11. Haas, Z., Pearlman, M., Samar, P.: The zone routing protocol (ZRP) for ad hoc networks. draft-ietf-manet-zone-zrp-02.txt (work in progress) (1999)
12. Pei, G., Gerla, M., Hong, X.: LANMAR: landmark routing for large scale wireless ad hoc networks with group mobility. In: Proceedings of the 1st ACM International Symposium on Mobile Ad Hoc Networking & Computing, p. 18. IEEE Press (2000)
13. Ramasubramanian, V., Haas, Z., Sireer, E.: SHARP: A hybrid adaptive routing protocol for mobile ad hoc networks. In: Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing, pp. 303–314. ACM, New York (2003)
14. Rango, F., Cano, J., Fotino, M., Calafate, C., Manzoni, P., Marano, S.: Olsr vs dsr: A comparative analysis of proactive and reactive mechanisms from an energetic point of view in wireless ad hoc networks. *Computer Communications* 31(16), 3843–3854 (2008)
15. Ziouva, E.: CSMA/CA performance under high traffic conditions: throughput and delay analysis. *Computer Communications* 25(3), 313–321 (2002)