Comput Syst Sci & Eng (2018) 6: 421–428


International Journal of
Computer Systems
Science & Engineering

# Energy aware routing algorithm in manet using linear programming

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Mobile ad hoc networks (MANET) are wireless network without infrastructure and suffering from low power battery. Therefore the main objective in finding a route for traffic transfer from a given source to a given destination is to minimize the node energy consumption. This paper solves the problem of finding a route satisfying the main objective of minimum energy consumption and other QoS requirements such as minimum delay and maximum packet delivery ratio by using linear programming technique. Two cases are considered: 1. The traffic amount of a given request is transmitted into single path, and 2. The traffic amount of a request can be distributed into parallel paths. A preprocessing step is done first for network topology design. This step leads to formulate the first case as integer linear programming problem and the second case as linear programming and not mixed integer linear programming. The two obtained solutions are evaluated in terms of three criteria: energy consumption, execution time, and packet delivery ratio using an experimental study. The results show that the solution of second case is much better than the first case in terms of energy consumption and execution time. Packet delivery ratio in the second case is 100% while in the first case is only 76%.

Keywords: MANET routing algorithms, Linear programming, Integer Linear programming, Energy consumption, Traffic amount distribution

## 1. INTRODUCTION

A mobile ad hoc network (MANET) is wireless network without infrastructure and suffering from low power battery. Each device in a MANET is free to move in any direction, and will therefore change its links to other devices frequently. The nodes depend on low power battery which is a common challenge in MANETs. As soon as a node consumes its battery power, that node becomes a dead node. This node is not able to transmit or receive data. When all the network nodes have consumed their energy, then whole network becomes down.

The basic routing protocols of MANET like AODV and OLSR have the main objective to find a route that can meet the QoS requirements such as: Bandwidth, Delay, Reliability, Throughput and Packet Delivery Ratio [1, 2]. They did not consider the design of energy saving routing that can solve the previous mentioned problem of limited battery power.

In fact the required routing protocols for MANETs have to satisfy multi objectives: QoS requirements and the minimization of energy consumption. Some researches try to modify the basic routing protocols by considering the energy consumption factor [3]. Other researches consider the routing as an optimization problem with multi-objectives [4]. This paper concentrates on the optimization using linear programming technique since the previous studies suggest that linear programming can be used not only as an effective modeling tool, but also as an efficient solving method for problems of realistic size [5]. In the optimization using linear programming, the paper proposes a solution for the case of a single path data packet transfer and other solution for the case of parallel paths data packet transfer. The rest of the paper is organized as follows:

Section two gives an overview of the related work of the energy aware routing protocols categorization and discusses its shortcomings. Section three describes the system model and problem formulation, and section four explains the simulation experiment set up and shows the results of the comparative study. Then the paper is ended by conclusions in section five.

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## 2. RELATED WORK

There are different approaches to minimize the energy consumption in the routing strategy. In MANET, energy aware routing protocols can be categorized into three approaches: an enhancement of basic routing protocols; use of evolutionary algorithms, and the optimization using linear programming. The energy aware routing protocols categorization is shown on Fig. 1 and described below.

## 3. THE MODIFICATION OF THE BASIC PROTOCOLS

### 3.1 Modified AODV (Ad Hoc On-Demand Distance Vector)

In AODV basic structure, it is not possible to minimize the total energy consumption of the network. The modified AODV routing algorithm is based on the received power estimation of the intermediate nodes. Therefore only certain nodes are to be allowed to receive and process the routing request affording to the received power estimation, then the total energy consumption of the network can be minimized. This adaptation is applied on the route discovery phase of ADOV [6].

### 3.2 RMER (Reliable Minimum Energy Routing)

This energy aware routing algorithm for wireless Ad Hoc network is called Reliable Minimum Energy Routing (RMER). RMER is energy efficient routing algorithm capable of finding routes in such a way that the total energy required for transferring of packet from end to end is minimized using the Optimized Link State Routing(OLSR) basic protocol [7].

### 3.3 AODVEA (Ad Hoc On-Demand Distance Vector Energy Aware)

AODVEA (AODV ENERGY AWARE) integrates local forwarding decision and routing based on max min energy algorithm to increase the lifetime of the network. The node contributes in routing only if its energy is greater than a specified threshold. The node with minimum remaining energy in the route is recognized and the route having maximum minimum remaining energy is designated [8].

### 3.4 AODVM (AODV Modified)

The difference between this AODVM scheme and the previous AODVEA scheme is that AODVM identifies an optimum route by considering the combination of the residual energy of nodes on the route and hop count of that route [8].

### 3.5 AODV-MTPR (Ad Hoc on Demand Distance Vector- Minimum Total Transmission Power Routing)

This technique suggests a routing protocol by considering two parameters: hop count as in AODV and total transmission loss as in MTPR. On the basis of these two route metrics of hop count and total transmission loss, an optimal route is selected. Simulation results show that the proposed protocol is better than other basic protocols such as MTPR and AODV [9].

### 3.6 EPAAODV (Efficient Power Aware AODV)

The proposed EPAAODV routing scheme is different from the basic AODV scheme in the way in which intermediate node manipulates an arriving route request (RREQ). An additional field of residual energy (res-energy) is added into the packet header of RREQ. When an intermediate node receives a RREQ packet, it will check the res-energy field of RREQ packet header. If the res-energy value is greater than or equals specified threshold energy, then the request is stored and considered as qualified nominee for dispatching, else the RREQ is canceled. The RREQ is then stored in the temporary memory of the intermediate node for a specified waiting time. The intermediate node will then receive other RREQs during this waiting time period. If the new request has res-energy greater than the stored one, then new one will be processed, else the stored one will be processed [10].

### 3.7 OLSR (Optimized Link State Routing) Modification

The main idea used in this scheme is the presence of multipoint relay (MPRs). MPRs represent some elected nodes which have the opportunity to forward broadcast messages during flooding process. Information about neighbors is saved from routing table made by OLSR. For each node, when the routing table is updated, the amount of neighbors is being compared with a certain threshold. If the amount of neighbors is more than this threshold then the needed transmit power is decreased to its half value [11].

## 4. THE EVOLUTIONARY ALGORITHMS:

### 4.1 ACOGA (Ant Colony Optimization and Genetic Algorithm)

The problem of finding an optimized route subject to multi constraints and multi QoS metrics is a complex problem. This problem has been proved to be NP-complete since a combination of additive, concave, and multiplicative metrics are considered. Hence, this problem can be resolved using meta-heuristic methods like genetic algorithm (GA) and ant colony optimization (ACO). The main objective of this proposed power aware ACO GA hybrid meta-heuristic approach is utilizing the benefits of both methods as a combined approach in order to reduce

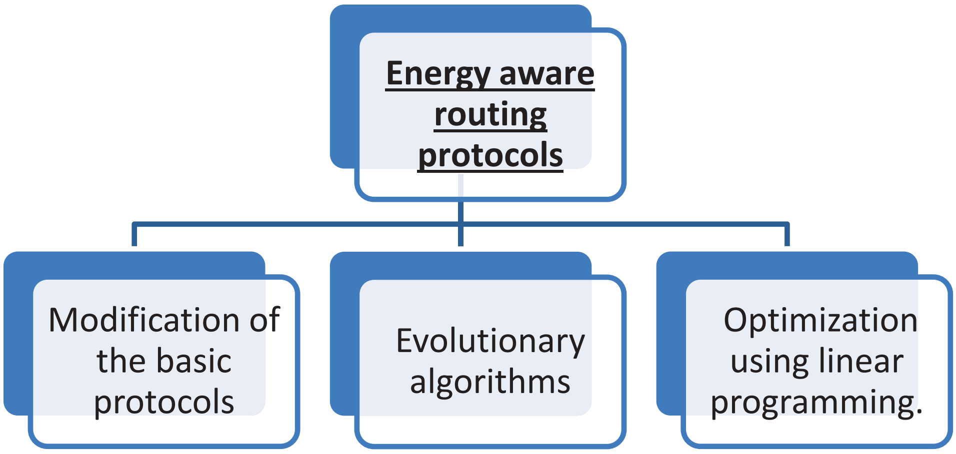


**Figure 1** Energy aware routing protocols categorization.

the routing complexities in a realistic environment. It has been shown using simulation that the proposed hybrid approach has a better performance of MANET routing and satisfying the QoS requirements in terms of constraints and metrics [12].

### 4.2 MOQEER (Multi Objective QoS aware Energy Efficient Routing)

The problem of discovery an energy efficient route for MANET as a multi objective QoS optimization problem is the main objective for the MOQEER protocol. The proposed routing protocol is evaluating the optimal route using Genetic Algorithm, which is an evolutionary computational approach. This model purposes to find an energy efficient route with the rise of quality under other QoS metrics [13].

## 5. THE OPTIMIZATION USING LINEAR PROGRAMMING

### 5.1 Integer Programming Formulations for Maximum Lifetime

The main objective of this work is to prove that the technique of integer linear programming can be used to solve the complex problem of MANET topology and cope with the latest technology and research in different communication models and different energy consumption models. The author of this work [5] showed that the technique of integer linear programming is not over-theoretical and realistic, and can be considered as a suitable framework to include different models to maximize network life time. Three models of increasing realism have been formulated.

The shortcoming of this work is that it considered only the topology design of wireless sensor network; it means the selection and placement of the nodes and their transmission power. It did not consider the issue of MANT routing at all.

### 5.2 Online Power-Aware Routing

Based on the linear programming technique, the author of this work [14] proposed an algorithm, to combine the gains of choosing the route with the lowest power consumption and the route that maximizes the minimum remaining power in the nodes of the network. This algorithm is termed the max-min algorithm. The algorithm has to route messages along the route with the maximum minimum portion of remaining power. But the max-min route is going through the nodes with high remaining power may be costly as compared to the route with the minimal power consumption. The proposed algorithm makes a balance between minimizing the total power consumption and maximizing the minimal remaining power of the network. Therefore the author introduces an update to the original algorithm that represents an improvement to the max-min route by limiting its total power consumption [14].

The shortcoming of the proposed algorithm is that it requires information about the power level of each node in the network. To know this information accurately is difficult to obtain and maintain particularly for large network. It means that the proposed algorithm is not scalable.

### 5.3 Evaluating Wireless Reactive Routing

The authors introduce linear programming models to evaluate and improve MANET reactive routing protocols. They practically studied the constraints of respective linear programming models over reactive protocols [15]. The new contribution of this work is the establishment of a mathematical framework to examine reactive routing protocols for MANETs. For this purpose, it is developed a three linear programming models that list all possible constraints for different network parameters and varying network traffic demands. In this mathematical framework each model has a different objective function. Throughput, energy cost and delay are considered as three different objective functions. Using this framework a performance evaluation of standard protocols such as DSR and AODV is carried out.

The shortcoming of this work is that it concentrates mainly on the evaluation of the standard protocols and it does not introduce a routing model.

# 6. SYSTEM MODEL AND PROBLEM FORMULATION

## 6.1 Energy Model

In this paper the proposed system models are using an energy consumption model as described in the following equations [16].

The total consumed energy **E** by a given node can be computed as follows:

$$\mathbf{E} = E_a + E_t + E_r + E_c \tag{1}$$

Where:
$E_a$, is the energy spent by a node to survive
$E_t$, is the energy spent by a node to transmit a packet
$E_r$, is the energy spent by a node to receive a packet
$E_c$, is the energy spent by a node in the computation process
$E_t$, is calculated by equation (2)

$$E_t = K \cdot d^{\alpha} \cdot b \tag{2}$$

Where:
$E_t$, is the energy spent by a node to transfer a packet of series of bits.
$K$, is a constant $= 100 \times 10^{-}$ j/bit$^{\propto}$.
$d$, is the distance for packet transmission in meters
$\alpha$, is packet loss constant (2 for the routes with no interference and 4 for the routes with interference)
$b$, is the packet size in bits
$E_r$ is computed by equation (3)

$$E_r = L \cdot b \tag{3}$$

Where:
$E_r$, is the energy spent by a node to receive a packet
$L$, is a constant $= 50 \times 10^{-9}$ j/bit
$b$, is the packet size in bits
Since $E_c$ and $E_a$ given in Equation (1) are used as constant values in other algorithms too, they can be neglected for comparison purposes. The energy spent by a node to transmit and receive a packet of size b and for a distance $d$, is then approximately given by equation (4).

$$\mathbf{E} = K \cdot d^{\alpha} \cdot b + L \cdot b \tag{4}$$

## 6.2 Network Model

The network is modeled by a graph $G = (V, A)$, where $V$ is the set of n nodes and $A$ is the set of undirected curves. Each node has a bandwidth capacity $B$, and a maximum level of transferring power $P_{\max}$. The bandwidth of a node is mutual for both transmitting and receiving signals. That is, the total bandwidth for transmitting signals plus the total bandwidth for receiving signals at each node cannot exceed $B$. The total expended power of a node cannot exceed $P_{\max}$.

Two cases are measured: 1) end-to-end traffic amounts are transmitted into a single path (not split-table),

2) end-to-end traffic amounts are distributed into parallel paths (split-table).

## 6.3 Preprocessing

This preprocessing step is done before the considered two cases of not split-table traffic amounts and the split table traffic amounts. It includes the network topology design as follows:

- Select the number of nodes ($n$) and the terrain area.
- Generate randomly the locations (co-ordinates) of the $n$ nodes using the uniform distribution.
- Find the distance matrix between each node pairs.
- Assume the transmission range of each node (usually all the nodes have the same range).
- Find the neighbors according to the distance between nodes and the transmission range.
- Determine the connectivity matrix $X_{i,j}$, where each matrix element $x_{i,j}$ is a Boolean variable, such that $x_{i,j} = 1$ if there is a link from node $i$ to node $j$; otherwise, $x_{i,j}, = 0$.

## 6.4 Problem Formulation for the Case of not Split-table Traffic Amount

This case of not split-table traffic amount requires that whole traffic amount of a given request has to be transmitted into one single path.

Input variables:

- $V$ set of $n$ nodes and their locations.
- $B$ the bandwidth of each node.
- $T_{s,d}$, traffic amount for each request from a source node s to a destination node $d$.
- $H_{s,d}$, maximally allowed hop-count for any node pair ($s$, $d$).
- $X_{i,j}$, is a Boolean variable, such that $x_{i,j} = 1$ if there is a link from node $i$ to node $j$, otherwise, $x_{i,j} = 0$.
- $P_{\max}$, maximally allowed transmitting power of nodes.

Output variables:
$y_{i,j}^{s,d}$, Boolean variables, $y_{i,j}^{s,d} = 1$ if the route from $s$ to $d$ goes through the link $(i, j)$; otherwise $y_{i,j}^{s,d} = 0$.

Objective function:

- Minimize the total power consumption of nodes.

$$\text{Min} \sum_{(i,j)} \times y_{i,j}^{s,d}$$

Constraints:

- Delay constraint:

$$\sum_{(i,j)} y_{i,j}^{s,d} \leq H_{s,d} \quad \forall (s, d) \tag{5}$$

This constraint ensures that the delay given by the hop-count for each node-pair $(s, d)$ does not exceed the pre-specified maximum allowed hop-count $H_{s,d}$.

- Bandwidth constraint:

$$\sum_{(s,d)} \sum_{j} y_{i,j}^{s,d} T_{s,d} + \sum_{(s,d)} \sum_{j} y_{j,i}^{s,d} T_{s,d} \le B \quad \forall i \in V \qquad (6)$$

The availability of bandwidth along the route is ensured by this constraint.

- Transmitting power constraint:

$$d_{i,j}^{\propto} \le P_{\max} \quad \forall i < j \text{ and } i, j \in V \qquad (7)$$

$d_{i,j}$, is the distance between nodes $i$ and $j$, and is a parameter typically taking a value between 2 and 4.

- Route constraints:

$$\sum_{j} y_{i,j}^{s,d} - \sum_{j} y_{j,i}^{s,d} = \begin{cases} 1 & \text{if } s = i \\ -1 & \text{if } d = i \quad \forall i \in V \\ 0 & \text{otherwise} \end{cases} \qquad (8)$$

Route constraints ensure the validity of the route for each node-pair

Solution:

This optimization problem is solved using an integer linear programming approach since all the output variables are Boolean. The preprocessing step here decreases the number of the output variables which can shorten the solution time.

### 6.5 Problem Formulation for the Case of Split-table Traffic Amount

This case of split-table traffic amount means that the traffic amount of a given request can be distributed into parallel paths. This ensures better load balancing, more reliability and high packet delivery ratio.

Input variables:

- $V$ set of $n$ nodes and their locations.
- $B$ the bandwidth of each node.
- $T_{s,d}$, traffic amounts for each node pair $(s, d)$.
- $X_{i,j}$, is a Boolean variable, such that $x_{i,j} = 1$ if there is a link from node $i$ to node $j$; otherwise, $x_{i,j} = 0$.
- $P_{\max}$, maximally allowed transmitting power of nodes.

Output variables:

$f_{i,j}^{s,d}$, real variables representing the amount of traffics of node pair $(s, d)$ that go through link $(i, j)$.

Objective function:

- Minimize the total power consumption of nodes

$$\text{Min} \sum_{(i,j)} E_{ij} \times f_{i,j}^{s,d}$$

Constraints:

- Bandwidth constraint:

$$\sum_{(s,d)} \sum_{j} f_{i,j}^{s,d} T_{s,d} + \sum_{(s,d)} \sum_{j} f_{j,i}^{s,d} T_{s,d} \le B \quad \forall i \in V \qquad (9)$$

The availability of bandwidth along the route is ensured by this constraint.

- Transmitting power constraint:

$$d_{i,j}^{\propto} x_{i,j} \le P_{\max} \quad \forall i < j, i, j \in V \qquad (10)$$

$d_{i,j}$, is the distance between nodes $i$ and $j$, and $\propto$ is a parameter typically taking a value between 2 and 4.

- Route constraints:

$$\sum_{j} f_{i,j}^{s,d} - \sum_{j} f_{j,i}^{s,d} = \begin{cases} T_{s,d} & \text{if } s = i \\ -T_{s,d} & \text{if } d = i \quad \forall i \in V \\ 0 & \text{otherwise} \end{cases} \qquad (11)$$

This constraint is for flow conservation along all the routes for node pair $(s, d)$.

Solution:

This optimization problem is solved using a linear programming approach instead of mixed integer linear programming due to the preprocessing step explained above which leads to the fact that all the output variables are real. The mixed integer linear programming normally is more complex than linear programming and takes a longer time to find a feasible solution.

## 7. EXPERIMENTS

### 7.1 Simulation Setup

The simulations are conducted in a 180×180 meters two dimensional free-space region. The co-ordinates of the nodes are randomly and uniformly distributed inside the region. All nodes have the same bandwidth capacity $B = 300$. The maximum allowable hop-count $H_{s,d} = 5$. The set of requests $R = \{(s, d, T_{s,d})\}$ are generated by using the Poisson distribution function (i.e., the number of requests originating from a node follow the Poisson distribution).For each node, we use the random Poisson function with the mean value = 1 to generate a number $k$, which is the number of requests originating from this node. The destinations of the $k$ requests are randomly picked from the other nodes. The traffic amount $T_{s,d}$ for a pair of nodes $(s, d)$ is assigned by a random function of a normal distribution with variance equal to half of the mean value. In this study 15 nodes and 60 requests are considered.

### 7.2 Simulation Results and Analysis

- Network topology

Figure 2 shows the designed network topology for square terrain of 180 × 180 meters and 15 nodes whose locations are

**Table 1** The QoS requests for not split-table case.

| Request | S. | D. | Amount | Route | Consumed Energy (mj) | Execution Time (sec) | Packet Delivery | Delay |
|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 7 | 134.0073 | 5–>14–>10–>7 | 1.1413 | 2.0124 | Delivered | 3 |
| 2 | 12 | 9 | 155.8939 | 12–>9 | 0.9915 | 2.0904 | Delivered | 1 |
| 3 | 2 | 7 | 157.7645 | Lost | 0.0000 | 1.6692 | Not Delivered | None |
| 4 | 11 | 12 | 154.4390 | 11–>12 | 0.5703 | 0.3432 | Delivered | 1 |
| 5 | 15 | 12 | 151.2962 | Lost | 0.0000 | 3.2448 | Not Delivered | None |
| 6 | 15 | 7 | 142.3168 | 15–>7 | 0.3330 | 0.0624 | Delivered | 1 |
| 7 | 2 | 9 | 146.3674 | 2–>11–>6–>9 | 0.9508 | 0.1092 | Delivered | 3 |
| 8 | 14 | 13 | 167.5240 | Lost | 0.0000 | 1.6224 | Not Delivered | None |
| 9 | 13 | 14 | 145.2640 | 13–>6–>4–>14 | 1.5182 | 0.0780 | Delivered | 3 |
| 10 | 10 | 11 | 145.0172 | 10–>9–>6–>11 | 0.8067 | 0.0780 | Delivered | 3 |

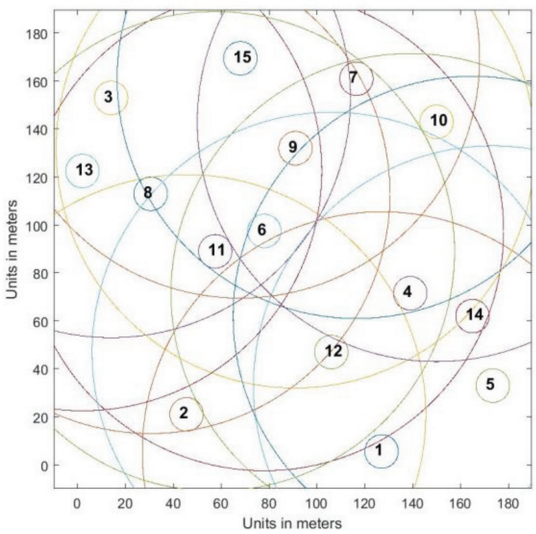


**Figure 2** Topology of 15 nodes.

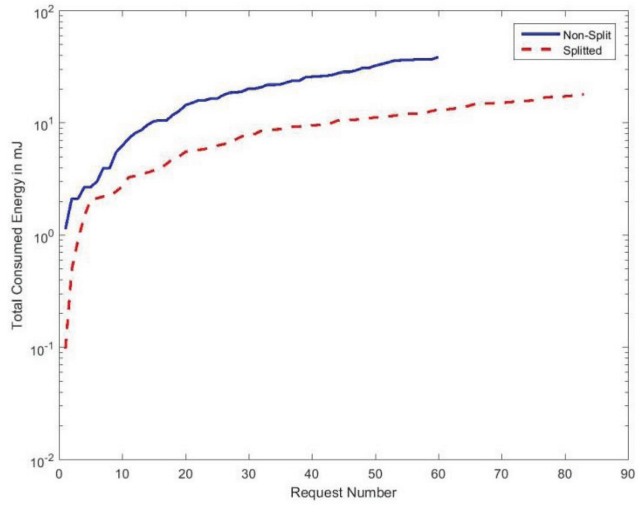


**Figure 3** The consumed energy for the two cases.

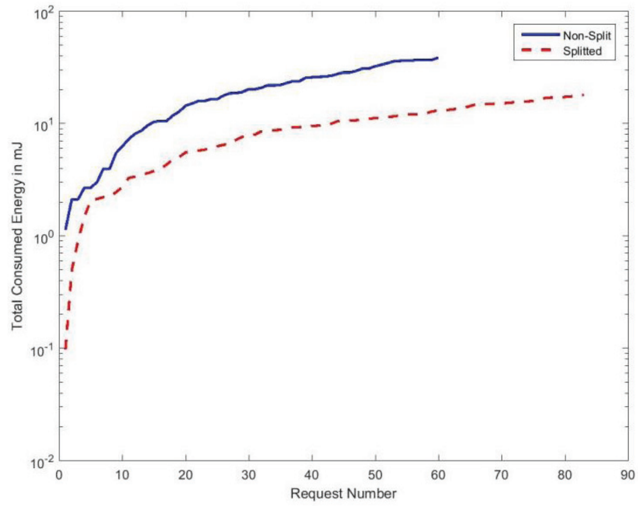


**Figure 4** The execution time for the two cases.

uniformly distributed and shown by their centers $(x, y)$. This topology is the same for the two considered cases.

- First Case: end-to-end traffic amounts are not split-table

Table 1 gives the exact values of the consumed energy and the execution time for the first 10 requests out of the executed 60 requests in our first case (traffic amounts are not split table) associated with the optimum routes obtained. The delay is given by the hop-count of the optimum route.

- Second Case: end-to-end traffic amounts are split table

Table 2 gives the exact values of the consumed energy and the execution time for the first 10 requests out of 60 executed requests in our second case (traffic amounts are split-table) associated with the optimum obtained routes.

**- Comparison between the two cases:**

When we consider the accumulated consumed energy as shown in figure 3, it is clear that the total consumed energy of the traffic amounts in not split-table case is greater than the case of the split-table amounts case.

Fig. 4 shows the relationship between accumulated consumed time route and the number of requests for both cases. From fig. 8 we conclude that the accumulated consumed time of the not split-table amounts is greater than the split amounts.

- Results analysis:

**Table 2** The QoS requests for split table case.

| Request | S. | D. | Amount | Split Amounts | Route | Consumed Energy (mj) | Execution Time (sec) | Packet Delivery | Delay |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 7 | 134.0073 | 134.0078 | 5–>14–>4–>10–>7 | 0.0979 | 2.0904 | Delivered | 4 |
| 2 | 12 | 9 | 155.8939 | 150.000 | 12–>6–>9 | 0.4001 | 0.2340 | Delivered | 3 |
| 2 | 12 | 9 | | 5.8939 | 12–>11–>9 | 0.4195 | 0.2808 | Delivered | |
| 3 | 2 | 7 | 157.7645 | 150.0000 | 2–>11–>6–>9–>7 | 0.5722 | 0.1248 | Delivered | 4 |
| 3 | 2 | 7 | | 7.7645 | 2–>12–>4–>10–>7 | 0.5991 | 0.1560 | Delivered | |
| 4 | 11 | 12 | 154.4390 | 150.0000 | 11–>6–>12 | 0.0591 | 0.1092 | Delivered | 2 |
| 4 | 11 | 12 | | 4.4390 | 11–>12 | 0.0737 | 0.1092 | Delivered | |
| 5 | 15 | 12 | 151.2962 | 1.2962 | 15–>8–>11–>12 | 0.0048 | 0.0936 | Delivered | 3 |
| 5 | 15 | 12 | | 150.0000 | 15–>9–>6–>12 | 0.2370 | 0.1092 | Delivered | |
| 6 | 15 | 7 | 142.3168 | 142.3168 | 15–>7 | 0.2760 | 0.0936 | Delivered | 1 |
| 7 | 2 | 9 | 146.3674 | 146.3674 | 2–>11–>6–>9 | 0.5583 | 0.0936 | Delivered | 3 |
| 8 | 14 | 13 | 167.5240 | 150.0000 | 14–>4–>6–>8–>13 | 0.0919 | 0.1092 | Delivered | 4 |
| 8 | 14 | 13 | | 17.5240 | 14–>12–>11–>8–>13 | 0.1439 | 0.1248 | Delivered | |
| 9 | 13 | 14 | 145.2640 | 145.2640 | 13–>8–>11–>6–>4–>14 | 0.1049 | 0.1404 | Delivered | 5 |
| 10 | 10 | 11 | 145.0172 | 145.0172 | 10–>7–>9–>6–>11 | 0.1678 | 0.0936 | Delivered | 4 |

For the comparison of the two solutions the authors used three criteria: 1. Consumed energy, 2. Execution time, and 3. Packet delivery ratio. From the given tables and figures above it is very clear that the solution of split-table case (linear programming) is much better than that of not split-table case (integer linear programming) in terms of the three criteria. Packet delivery ratio in case of split-table amount is 100% and that of not split-table amount is 76% only for the same set of the 60 input requests and same topology. The delay given by the number of hop-count of the optimum route in both cases is not exceeding the maximum allowable hop-count.

## 8. CONCLUSIONS

This paper presents a survey in the form of taxonomy of the energy aware routing algorithms in MANET. This taxonomy is categorizing these algorithms into three types: 1. Modification of basic routing protocols, 2. Use of evolutionary algorithms, and 3.Use of linear programming. To solve the MANET routing problem, the authors have to consider the QoS multi-objectives such that minimum energy consumption, minimum execution time, high packet delivery ratio, and minimum bandwidth.

The authors decided to use linear programming for this multi-objective optimization problem but concentrating in minimum energy consumption as the main objective and modeling other QoS objectives as constraints. Both cases of not split-table traffic amounts and split-table traffic amounts are considered. The first case is formulated as an integer linear programming problem. The second case is formulated as a linear programming problem due to the preprocessing step of network topology design. Exactly the same input variables and the same topology are used for both cases. The experiment is done for 60 traffic amounts requests using Poisson distribution function. To evaluate and compare the two solutions for the obtained routes of 60 traffic amounts requests, the paper uses three criteria: total energy consumption, total execution time, and packet delivery ratio. The results show that the solution of split-table case (linear programming) is much better than that of not split-table case (integer linear programming). In dynamic environment where nodes are mobile and traffic amounts are dynamic, the proposed algorithms can be run periodically to keep the routing solution optimal in the sense that it balances the energy consumption, and at the same time meets other QoS requirements such as delay, bandwidth, and packet delivery ratio.

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## Table of symbols

| Symbol | Meaning |
|---|---|
| $E_a$ | is the energy spent by a node to survive |
| $E_t$ | is the energy spent by a node to transmit a packet |
| $E_r$ | is the energy spent by a node to receive a packet |
| $E_c$ | is the energy spent by a node in the computation process |
| $K$ | is a constant = $100 \times 10^{-12}$ j/bit. $m^{\alpha}$ |
| $d$ | is the distance for packet transmission in meters |
| $\alpha$ | is packet loss constant (2 for the routes with no interference and 4 for the routes with interference) |
| $b$ | is the packet size in bits |
| $L$ | is a constant= $50\times10^{-9}$ j/bit |
| $V$ | Is the set of $n$ nodes and their locations |
| $B$ | Is the bandwidth of each node |
| $P_{\max}$ | Maximally allowed transmitting power of nodes. |
| $T_{s,d}$ | Is the traffic amount for each node pair $(s, d)$. |
| $H_{s,d}$ | The maximally allowed hop-count for any node pair $(s, d)$. |
| $X_{i,j}$ | Is a Boolean variable, such that $x_{i,j} = 1$ if there is a link from node $i$ to node $j$, otherwise, $x_{i,j} = 0$. |
| $y_{i,j}^{s,d}$ | Boolean variables, $y_{i,j}^{s,d}$ =1 if the route from $s$ to $d$ goes through the link $(i, j)$; otherwise $y_{i,j}^{s,d}= 0$. |
| $f_{i,j}^{s,d}$ | Real variables representing the amount of traffics of node pair $(s, d)$ that go through link $(i, j)$. |