Energy balancing RPL-based routing for Internet of Things

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***Abstract*— RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) is a standard routing protocol for low-power low-cost and resource constrained networks. To deal with the diversity in link qualities in these networks, the Minimum Rank with Hysteresis Objective Function (MRHOF, RFC 6719) is standardized as the *de facto* Objective Function (OF) for RPL. MRHOF helps a mote to select a path to forward traffic with the minimum cost among available paths. The Expected Transmission Count (ETX) defined in RFC 6551 is the most widely used MRHOF routing metric. ETX helps to achieve good Packet Delivery Ratio (PDR) and low latency since motes choose to relay their information along the path with the least number of retransmissions. However, since ETX does not consider the energy level of the motes, it does not balance the energy consumption between motes. In this paper, we develop other routing metrics by taking into consideration the energy consumption of motes as routing metric. We develop a Radio Duty Cycle (RDC) based method to estimate mote energy consumption. We also look into diverse combinations of ETX and energy consumption as routing metrics. The proposed methods achieve better energy balance while keeping good energy efficiency and packet delivery ratios.**

***Index Terms*–RPL, Routing, WSN, IoT, Energy balance, Contiki**

I. Introduction

In most Internet of Things (IoT) based applications, which are foreseen to grow tremendously in the coming years, an essential part is data collection. This part provides information of the surrounding environment which helps to explore, understand and control the physical world. In such data collection component, hundreds to thousands of low-power embedded devices, also known as motes, are deployed in the environment and form a multi-hop network to cooperatively collect and relay information to one or several central points linked with Internet. Those devices operate over common low-power wireless technologies, e.g. Bluetooth, IEEE 802.15.4, Low Power Wi-Fi, or wireline technology, e.g. Power Line Communication (PLC). In such networks, classified as low-power and lossy networks (LLNs)[1], information relaying mechanisms are seriously constrained by the energy consumption requirement. Besides, in LLNs, the nature of fluctuating and disrupted link quality caused by problems like floor noise, impedance variation, etc. makes the challenge harder.

With the IEEE 802.15.4 standard, IETF has defined the Physical and Media Access Control layers for these wireless networks, which are so-called low-rate wireless personal area networks (LR-WPANs). Recently, the adaption layer, the IPv6 over Low power Wireless Personal Area Networks (6LoWPAN), has been released to allow the transmission of IP packets over those constrained networks which was previously considered inappropriate. It allows the usage of IP-based protocols for addressing and routing at the network layer as well as the adaptive application protocols to establish all IP connections from the embedded devices to user applications through the Internet with less effort on design of gateway translation protocols bridging different networks. The IPv6 Routing Protocol for Low-power and Lossy networks (RPL) was introduced by IETF [1] to meet all the requirements of the evolution of integrating LLNs. RPL uses the concept of directed acyclic graph (DAG) for establishing loop-free data collection trees, called Destination Oriented DAGs (DODAGs). Each tree is optimized to meet its application-specified requirements given by an objective function (OF).

To deal with the diversity in mote characteristics and link quality in LLNs, the Minimum Rank with Hysteresis Objective Function (MRHOF)[2] is standardized as the *de facto* OF for RPL. MRHOF helps a mote to select a *path/route* to the root of its tree (the data collection point or sink mote) with the minimum *path cost* among available ones. The Expected Transmission Count (ETX) is the most widely used routing metric in MRHOF [RFC 6551][3][4]. ETX tries to minimize energy consumption and keep a low latency since motes choose to relay their information through the path causing the least number of transmissions (including the retransmissions). However, the ETX-based metric does not care about the energy level (or energy already consumed) at each mote. It can induce imbalanced energy consumption when a group of motes chooses the same forwarder mote with the lower cost to relay their data and such mote would quickly deplete its own energy by relaying a lot of traffic.

In this paper, we develop a radio module operation based method for estimating a mote's energy consumption (called EE) which can be leveraged for choosing the path for relaying data to the sink mote. This method is independent of the mote type (as long as the mote does not scavenge energy) and it does not require extra messages. We use this method to propose three objective functions combining the ETX value and EE value. Our simulations show that the combination ETX and EE for calculating the path cost achieves better energy balance among motes in the network, while maintaining energy efficiency and Packet Delivery Ratio (PDR) when compared to the well-known ETX sole routing metric.

The rest of the paper is organized as follows. Section II describes background information and section III presents our proposed method. Section IV is simulation result and analysis and finally section V is the conclusion.

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II. BACKGROUND

The design of RPL is based on three main concepts defined clearly in RFC 6550 [1]: *DODAG, Trickle* and *Objective Function* (OF). This section focuses on the Objective Function which is considered the brain of the routing protocol. We first describe the concept of MRHOF which is standardized as the *de facto* OF and introduce its well-known routing metric ETX. Afterwards, a general model of power consumption in a RDC-based operation of a wireless sensor mote is discussed.

A. Objective Function in the RPL Standard

A DODAG is organized as a hierarchical tree in which a mote selects its parent along the path to a single root (the sink) via a ranking system. Since there can be several paths from a mote to the sink, the mote maintains its set of parents, but has to select one preferred parent. To avoid loops, the *Rank* of a child mote must be higher than that of its parents.

An OF clearly defines how a mote selects its parents, and selects the preferred parent from the parent set. The *de facto* OF in RPL, MRHOF, contains a set of application specific optimization rules and a set of metrics and/or constraints used by the rules. For example, if MRHOF uses delay as its metric, a mote will select the preferred path with the lowest delay value. In other words, MRHOF will find the path which has the lowest cost from the specific mote to the sink. The path cost in MRHOF is an accumulative value. It sums up all the link costs along the path, and, therefore only works for additive metrics.

With MRHOF, when the path cost of a mote is calculated by a function of selected routing metric, the *Rank* of the mote is derived directly from the cost. RFC 6719[2] suggests how to convert a cost to the *Rank* as shown in table I.

TABLE I. COST TO RANK CONVERSION

Mote/link Metric	Rank
Hop-Count	Cost
Latency	Cost/65536
ETX	Cost

In a RPL-based network, the root broadcasts a DAG Information Object (DIO) message containing information about the proposed DODAG characteristics, the Objective Function (OF) and rank. The advertised rank indicates the mote position in the DODAG hierarchy, and also represents routing metrics such as link ETX, hop count, latency and so on. Other motes also broadcast DIO packets to propagate their ranks in order to construct and maintain the DAG.

B. Expected Transmission Count (ETX)

ETX is a recommended metric for multi-hop ad-hoc wireless networks. It measures the expected total number of packet transmissions (including retransmissions) necessary to successfully deliver a packet to its final destination by per-link measurements of packet loss ratios in both directions of each wireless link. The ETX of a link is computed using the forward and reverse delivery ratios of that link:

$$ETX = \frac{1}{d_f \times d_r} \quad \text{(Eq. 1)}$$

In equation 1, d_f is the probability that a data packet successfully arrives at the recipient, d_r is the probability that the ACK is successfully received at the sender.

The forward and reverse delivery ratios are based on link-layer probes. Each mote broadcasts short messages containing its address, at a given frequency $\frac{1}{\Delta t}$ and, at the same time, counts the number of such messages received from each neighbor, in the period Δt. Doing so, a mote can compute the ratio of received messages over the expected number of messages, which translates into d_f and d_r.

Management and control of network performance parameters such as network latency or energy consumption play an important role in the deployment of sensor networks, especially for large networks. ETX improves significantly the performance parameters such as PDR and delay when compared to Hop Count. However, it does not take into account the balance of energy consumption between motes which seriously affects the lifetime of the network, since motes in a LLN often operate on batteries.

If ETX is used, the energy of the motes that have good path cost is consumed quickly, which may lead to mote energy exhaustion. It is desirable to avoid stressing some of the motes with high traffic in order to avoid battery depletion.

Research has been carried out to evaluate the performance of RPL with only ETX as link metric for MRHOF [5]-[8]. Other researchers used only the mote's residual energy as the routing metric [9]-[11]. Some researchers have worked on the combination of link quality and energy consumption as RPL metric objects [12]. However, they assume that the motes' residual energy level is obtained in the simulation [12] or they calculate the energy metric by measuring on-line real time battery level with voltages and currents, which depend on the type of mote [9]-[11]. The method presented in [12] involves extra control messages to exchange mote status information and a method for link quality measurement different from ETX.

C. Mote Energy Consumption

The consumed energy of each mote is estimated based on the energy consumed in each of the four possible states: CPU (CPU actives when processing information), LPM (Low-Power Mode, CPU idles when asleep), LISTEN (when awake and checking for incoming data), and TRANSMIT (when sending data). The energy consumed on the first two states is called TIME energy while the energy consumed on the two later states is called RADIO energy. Among these energies, RADIO energy constitutes a large proportion of energy consumption and also presents large disparities between mote energies. In contrast, TIME energy constitutes a small proportion of the total energy consumption and the TIME energy is almost the same for all the motes. As shown in Figure 1 illustrating a column graph of average power consumption of 24 motes, LISTEN and TRANSMIT energy (RADIO energy) is a representative quantity for spent energy for any mote. As an example of energy spending of motes, a Tmote Sky board, equipped with the CC2420 radio transceiver draws approximately 60 milli-watt of power when it is listening for radio traffic. Its power consumption when transmitting radio data is slightly higher. With a power draw of 60 milli-watt, a sensor mote depletes its batteries in a matter of days.

In the battery operated Wireless Sensor Network (WSN), the MAC layer enables the RDC (Radio Duty Cycle) protocol to save energy. RDC is responsible of keeping the radio in sleep mode for most of the time, usually about 90-99% of the time cycle (if the traffic allows) and only wakes up to listen and transmit data when necessary.

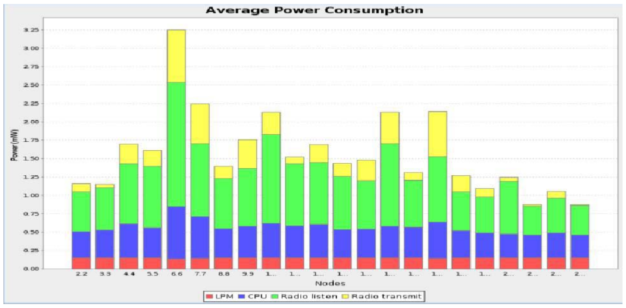

Fig. 1. An example of representation of energy consumption in each component state of WSN motes. The red portions are LPM parts and the blue portions are CPU parts which are almost the same for all motes while the green (radio LISTEN) and yellow (radio TRANSMIT) portions are varying between motes.

III. ENERGY BALANCING SCHEME FOR RPL-BASED ROUTING

To design an objective function with an energy metric, it is necessary to be able to measure the energy consumption of a mote. This measurement can be hardware-based or software-based. The hardware-based approach gives accurate measurement for the current mote energy level however, in WSNs, it also requires many resources (time, memory and energy). The software approach is constitutes an easier but less accurate method and might be different for each type of mote.

The software based on-line energy estimation mechanism uses a linear model for the sensor mote energy consumption. The energy consumption (EC) of a mote is typically defined as [9]:

$$\frac{EC}{V} = I_m t_m + I_r t_r + I_t t_t + \sum_i I_{c_i} t_{c_i} \qquad \text{(Eq. 2)}$$

Where V is the supply voltage, I_m the current draw of the microprocessor when running, t_m the time in which the microprocessor has been running, I_l and t_l the current draw and the time of the microprocessor in low power mode (when sleeping), I_t and t_t the current draw and the time of the communication device in transmit mode, I_r and t_r the current draw and time of the communication device in receive mode, and I_{ci} and t_{ci} the current draw and time of other components such as sensors and LEDs. The idle current draw of the board is included in the low power mode draw of the microprocessor.

To use mote energy as an OF metric, one way is to use mote energy consumption or to use mote residual energy (by taking the subtraction between mote initial energy and mote energy consumption) at a time using the formula (Eq. 2). This formula obviously depends on the mote type. In our assumption, initially each mote is fully charged with a maximum level of battery power to maintain stable operation. Therefore we use the denominator quantity for the energy consumption formula to track the *difference* of energy consumption between motes.

A. Proposed energy estimation formula

As can be seen in Fig. 1, the amount of energy consumed in LPM are the same in all motes, therefore we focus on the period of time when a mote is woken up. This period is denoted as *CPU_time*. The part of CPU_time, in which a mote turns on its radio, is defined as *Radio_time*. An estimation of the energy consumption of a mote (EE) is defined and can be obtained at any time as follows:

$$EE = \frac{\text{Radio\_time}}{\text{CPU\_time}} * 100 = \frac{t_r + t_t}{t_m + \sum_i t_{c_i}} * 100 \qquad \text{(Eq. 3)}$$

We choose the Radio_time (radio transmit and radio listen time) over CPU_time as the estimation of energy consumption of a mote. This estimation also reflects a mote's traffic load and does not depend on mote type. Timestamp modules for the values of the radio activity periods are available in most lightweight OSs such as TinyOS or Contiki.

B. Energy balanced Objective Function

In order to maintain balanced energy consumption of motes in a LLN, it is important to design an OF taking into account the energy consumption of a mote while maintaining the travel through good quality links. We designed three OFs using EE defined in Eq. 3. While maintaining the ETX as rank for the different OFs, the mote will have three approaches to choose the preferred parent as follows:

1. OF e2eEnergy, denoted as OF1: the preferred parent is the neighbor mote that has lower path cost and lower rank. Path cost is a function of path energy metric only.

2. OF ETX+singleEnergy, denoted as OF2: the preferred parent is the neighbor mote that has a lower path cost and lower rank. Path cost is a function of ETX link metric and mote energy metric of choosen neighbor.

3. OF ETX+e2eEnergy, denoted as OF3: the preferred parent is the neighbor mote that has lower path cost and lower rank. Path cost is a function of ETX link metric and the path energy metric.

In this way, the network avoids quick energy depletion in some motes while ensuring good PDR.

C. Implementation of the proposed approach

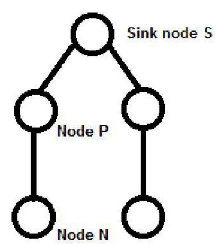

Fig. 2 A simple DODAG

Figure 2 depicts a scenario where mote S is the sink and mote P is the potential preferred parent of mote N with *lower rank* than mote N. Value cost(N_P,S) is denoted as the path cost value from mote N to mote S via hop P. Value cost(N,S) is denoted as the path cost value from mote N to the sink via mote N's current preferred parent. If cost(N_P,S)<cost(N,S), mote P becomes the preferred parent of mote N, the current cost of mote N to the sink cost(N,S)=cost(N_P,S). Specifically, the following objective functions are considered:

1. ETX link metric (OF ETX)

According to RFC6551 [4], link metric is the link quality level and link quality levels must be recorded along the path. On the path from S to N via P, the path cost for OF ETX is calculated as

$$\text{cost}(N_P,S)=\text{ETX}(N,P)+\text{ETX}(P,S) \qquad \textbf{(OF ETX)}$$

Where ETX(N,P) is the ETX value of the link between mote N and mote P; ETX(P,S) is the current ETX path value from the mote P to the sink via P's preferred parent. If the calculated $\text{cost}(N_P,S) < \text{cost}(N,S)$, the preferred parent of N is set to P and Rank(N) is set as:

$$\text{Rank}(N)=\text{Rank}(P)+\text{ETX}(N,P)$$

Note that Rank(S) = 0.

2. Mote energy metric (OF1)

Mote metrics are used to provide information on mote characteristics (RFC 6551). In our proposed approach, for OF1 we use the path energy as energy-based routing metric of mote P. We calculate the path cost as follows:

$$\text{cost}(N_P,S)=\text{cost}(P,S)+\text{EE}(P) \qquad \textbf{(OF1 - OF e2eEnergy)}$$

Where cost(P,S) is the current cost path value from mote P to the sink via P's preferred parent, EE(P) is the energy estimation value of mote P calculated using the energy estimation equation Eq. 3. If $\text{cost}(N_P,S)<\text{cost}(N,S)$, the preferred parent of N is set to P and Rank(N) is set as:

$$\text{Rank}(N)=\text{Rank}(P)+\text{ETX}(N,P)$$

It is worth to note that EE(S) is 0 as the sink S is the only powered mote, Rank(S) = 0.

3. Combination of link metric and mote metric (OF2 and OF3)

Now we combine ETX metric with energy mote metric to calculate path cost

In the second OF, we use a combination of ETX metric and a single mote energy metric for the path cost.

$$\text{cost}(N_P,S) = \text{ETX}(N,P) + \text{ETX}(P,S) + K.\text{EE}(P) \qquad \textbf{(OF2 - OF ETX+singleEnergy)}$$

In the third OF, we use a combination of ETX metric and end-to-end path energy metric for the path cost.

$$\text{cost}(N_P,S) = \text{cost}(N,P) + \text{ETX}(P,S) + K.\text{EE}(P) \qquad \textbf{(OF3 - OF ETX+e2eEnergy)}$$

K weighs the amount of energy balancing.

If $\text{cost}(N_P,S)<\text{cost}(N,S)$, preferred parent of N is set to P and Rank(N) is set as:

$$\text{Rank}(N)=\text{Rank}(P)+\text{ETX}(N,P)$$

D. Piggy-backing of the path cost in a DIO message

One of the most important options in DIO message is the DAG Metric Container (MC) because it holds the information necessary for other motes to correctly join a DAG. Option of MC with corresponding RPL instance is set up at the mote sink and advertised by means of DIO messages. The general format of the MC is shown in fig. 3.

0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7					0 1 2 3 4 5 6 7		0 1 2 3 4 5 6 7
Type = 0x02	Opt.Len = 6	MC type	Flags	P	C	O	R	A	Prec.	Obj. Len
(metric object)										

Fig. 3. DAG metric container

Inside a DAG's MC, one or more routing metrics and constraints may be filled, the order of them being set in the precedence field. The most widely used ETX link metric object is store in 2 bytes. OF ETX uses only this metric object.

0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7
ETX link metric

Fig. 4. ETX link metric object

While ETX object is stored in 2 bytes, energy object is also stored in 2 bytes. The first byte of the energy object is used to represent routing constraints and the second byte is to store the energy estimation routing metric.

0 1 2 3 4 5 6 7				0 1 2 3 4 5 6 7
Flags	I	T	E	Energy estimation

Fig. 5. Energy mote metric object

The most important fields in the energy object are the Type flag (T), the Estimation flag (E) and the energy estimation (EE) fields. E flag is set when the value of EE exists. T flag represents whether motes are with *mains-powered*, *battery-operated* or *energy-scavenger*.

To implement our objective functions, the metric object is extended to store both ETX link metric and energy mote metric as shown in figure 6.

0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7			0 1 2 3 4 5 6 7
ETX link metric		I T	E	E_E

Fig. 6. ETX + Energy mote metric

Field Obj. Len for the length of metric object is increased from 2 bytes to 4 bytes.

IV. SIMULATION SETUP

The performance of the three designed objective functions is given by comparing them with ETX as OF, in terms of energy balance, total energy consumption and PDR. The simulated network consists of 25 motes dispersed over a 200x200m area as shown in figure 7. According to the path loss radio model in the Cooja simulator, the probability of successful reception of a packet at a receiver mote can be defined as RX ratio. This probability increases when the distance between this receiver mote and the transmitter mote decreases. In this experiment, parameter RX ratio is set to 100% at the distance of 0m and 0% at the distance of 70m to simulate lossy links. As shown in figure 7, the condensed green circle depicts transmission range of mote 1 which is the sink and the grey condensed circle depicts interference range. Mote 4 is nearby the border of transmission range therefore RX ratio is 7%, mote 3 which is close to mote 1 has RX ratio of 80%.

Each mote sends data to the sink every 60s. Several simulation runs are organized with different seed for the random generator. The change of the seed will influence momentary path quality and momentary packet interarrival times.

We evaluate the mote's individual energy consumption estimation, total network energy consumption estimation and average PDR of the network for each simulation run. The individual energy consumption estimation of each mote is measured after 30 minutes and the sum over all the motes is the total energy consumption. The PDR is measured using the formula:

PDR=(Total_Packets_Received)/(Total_Packets_Sent) (Eq. 4)

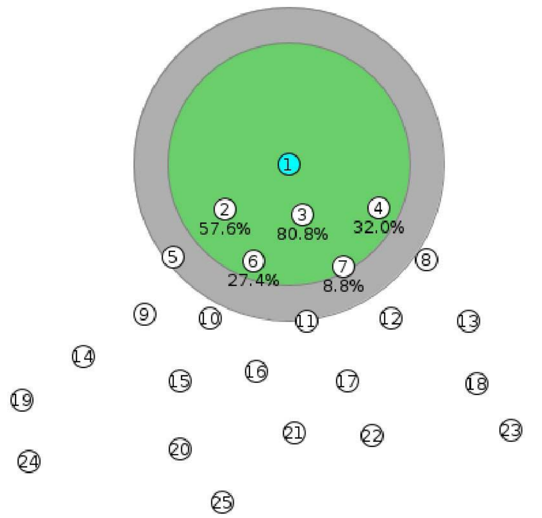

Fig. 7. Simulated network

TABLE II. SIMULATION PARAMETERS

Parameters	Values
OS	Contiki
Simulator	Cooja
Communication Protocols	IEEE 802.15.4 Channel 26, CSMA, ContikiMAC RDC, 6LoWPAN, ContikiRPL, UDP
RPL MOP	NO_DOWNWARD_ROOT
DIO Min	14
DIO Doublings	12
RDC Chanel Check Rate	8
Packet Payload	46 bytes
Client Motes	24 client motes and 1 sink mote
Simulation Times	30 minutes each
Send Interval	60s
Transmission Range	70m
Interference Range	90m

V. SIMULATION RESULT AND ANALYSIS

Individual mote energy estimation, total network energy estimation and network PDR were recorded after 30 minutes of simulation for all the considered OFs.

In order to find the best value for the K parameter for OF2 and OF3, we ran multiple simulations for different K values, in a range from 2 to 512. Per K value we ran 15 simulations with different seed. Then, we compared energy balance (mote individual EE), total energy consumption and PDR of each OF for each value of K. We found that the best value of K for the network under study is 256 since this value brings better energy balance, better energy efficiency estimation and better PDR.

Figure 8, 9, 10, 11 show the level of energy consumption estimation of each mote after 30 minutes of data collection for 4 cases of objective functions being OF(ETX), OF1, OF2 and OF3.

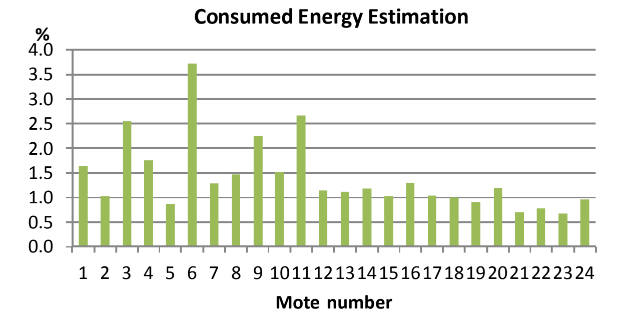

Fig. 8. Consumed Energy Estimation of each mote using ETX link metric OF

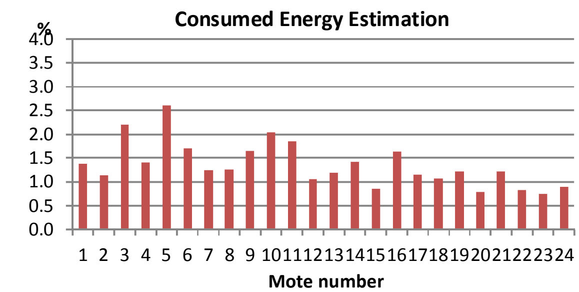

Fig. 9. Consumed Energy Estimation of each mote using mote energy metric objective function

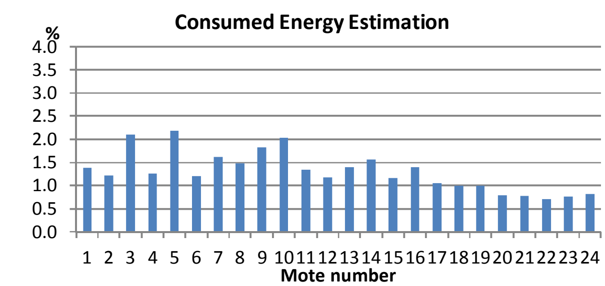

Fig. 10. Consumed Energy Estimation of each mote using both ETX link metric and with best value K=256.

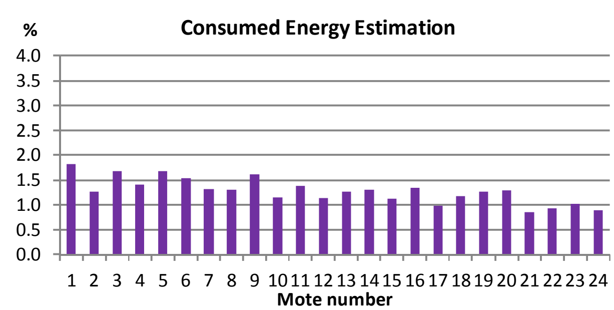

Fig. 11. Consumed Energy Estimation of each mote using ETX path metric plus path energy metric function with best value K=256.

We can see that OF3 - ETX+e2eEnergy gives the best energy balance compared to the other objective functions. The ratio of highest EE and lowest EE among 24 motes for each case OF ETX, OF1, OF2, OF3 is decreasing from 3.72/0.67 to 2.60/0.74, then to 2.10/0.77 and reduced to 1.83/0.85 respectively.

Figure 12 shows the total energy for OF (ETX), OF1, OF2 and OF3 after 30 minutes of simulation time being 31%, 32%, 32% and 33% respectively. This means that the three designed OFs have equivalent performance on total energy consumption to OF ETX. Our designed methods give better energy balancing by choosing routing paths with good PDR and less energy consumption but maintaining good performance on consumed energy compared to OF (ETX).

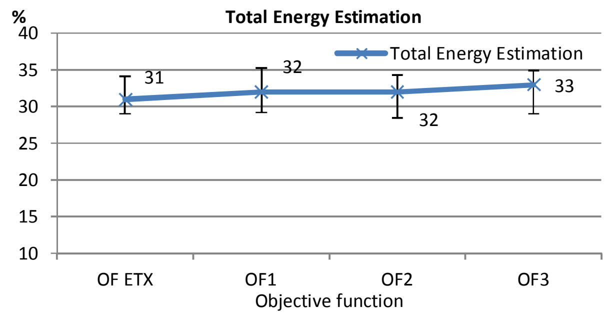

Fig. 12. Total energy estimation of each OF

Figure 13 shows PDR of the network in each case in the same order: ETX link metric (OF ETX), Energy mote metric (OF1), ETX and single mote energy metric (OF2), ETX and path energy metric (OF3) functions after 30 minutes of simulation time. The mean PDR is 57%, 57%, 58% and 61% for OF ETX, OF1, OF2, and OF3 respectively. This means that the three designed OFs have comparable performance on PDR to the OF ETX, seen the confidence intervals. These PDRs are due to the lossy links of the network.

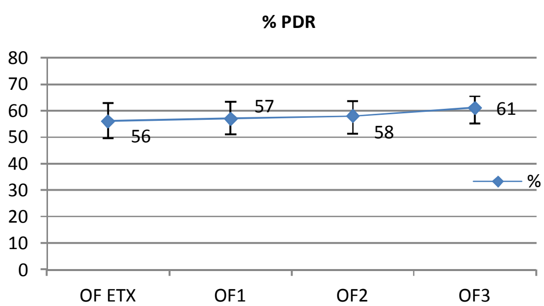

Fig. 13. Percentage of PDR of each objective function

Our approach takes care of path energy for routing decision, targeting at balancing energy consumption of motes. Motes with high number of packets waiting to be forwarded to the sink will share the load with other low traffic motes. Thus it reduces the number of retransmissions and is more adaptive in routing decision in terms of energy balance and packet successful delivery rate.

We supposed that using energy metric in routing decision helps to distribute traffic more evenly. Therefore, it could help to reduce the traffic concentration at some "hot spot" which might create traffic congestion and packet drops. That can bring equivalent network reliability and energy efficiency in our approaches compared to ETX OF. Further investigation in the future work should be done.

VI. Conclusion

We proposed and evaluated three objective functions involving the energy consumption estimation scheme (EE), which is independent of mote type and does not involve extra messages. Those objective functions use combination of ETX and EE routing metrics. Simulations show that our methods achieve better energy balance while keeping good energy efficiency and PDR.

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