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An enhanced real-time routing protocol with load distribution for mobile wireless sensor networks

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ABSTRACT

Mobile wireless sensor network (MWSN) is a wireless ad hoc network that consists of a very large number of tiny sensor nodes communicating with each other in which sensor nodes are either equipped with motors for active mobility or attached to mobile objects for passive mobility. A real-time routing protocol for MWSN is an exciting area of research because messages in the network are delivered according to their end-to-end deadlines (packet lifetime) while sensor nodes are mobile. This paper proposes an enhanced real-time with load distribution (ERTLD) routing protocol for MWSN which is based on our previous routing protocol RTLD. ERTLD utilized corona mechanism and optimal forwarding metrics to forward the data packet in MWSN. It computes the optimal forwarding node based on RSSI, remaining battery level of sensor nodes and packet delay over one-hop. ERTLD ensures high packet delivery ratio and experiences minimum end-to-end delay in WSN and MWSN compared to baseline routing protocol. In this paper we consider a highly dynamic wireless sensor network system in which the sensor nodes and the base station (sink) are mobile. ERTLD has been successfully studied and verified through simulation experiment.

1. Introduction

Wireless sensor networks (WSNs) may consist of a large number of sensor nodes, which are densely deployed in close proximity to the phenomenon. In WSN, sensors gather information about the physical world and the base station or the sink node makes decision and performs appropriate actions upon the environment [1]. A MWSN can be considered as a collection of distributed sensor nodes, which are capable of sensing, moving, communicating within its allowable range. The complete system architecture of a MWSN includes a group of mobile and static sensor nodes, a mobile base station (laptop or PDA), and upper communication network infrastructure [2,3]. As shown in Fig. 1, the sensor nodes are scattered in the target environment and they form a multi-hop mesh networking architecture. Each of these sensor nodes has the capability of collecting data and routing data peer-to-peer to base stations. The mobile sensor node is in fact an enhanced sensor node. It not only has all the capabilities of the static sensor node, but also realizes mobility by adding a robotic base and a driver board. Each mobile sensor node is capable of navigating autonomously or under control of humans. Large numbers of mobile sensor nodes can coordinate their actions through ad-hoc communication networks [3]. A base station or mobile sink is used to bridge the sensor network to another network or platform, such as the Internet. The mobile sink offers many benefits to the network. For instance, it helps to improve scalability, maintain load balance, conserve energy, and prolong the network lifetime [2].

MWSN is very different from traditional networks as it comprises of a large number of nodes that produce a very large amount of data. However, MWSNs are not free of

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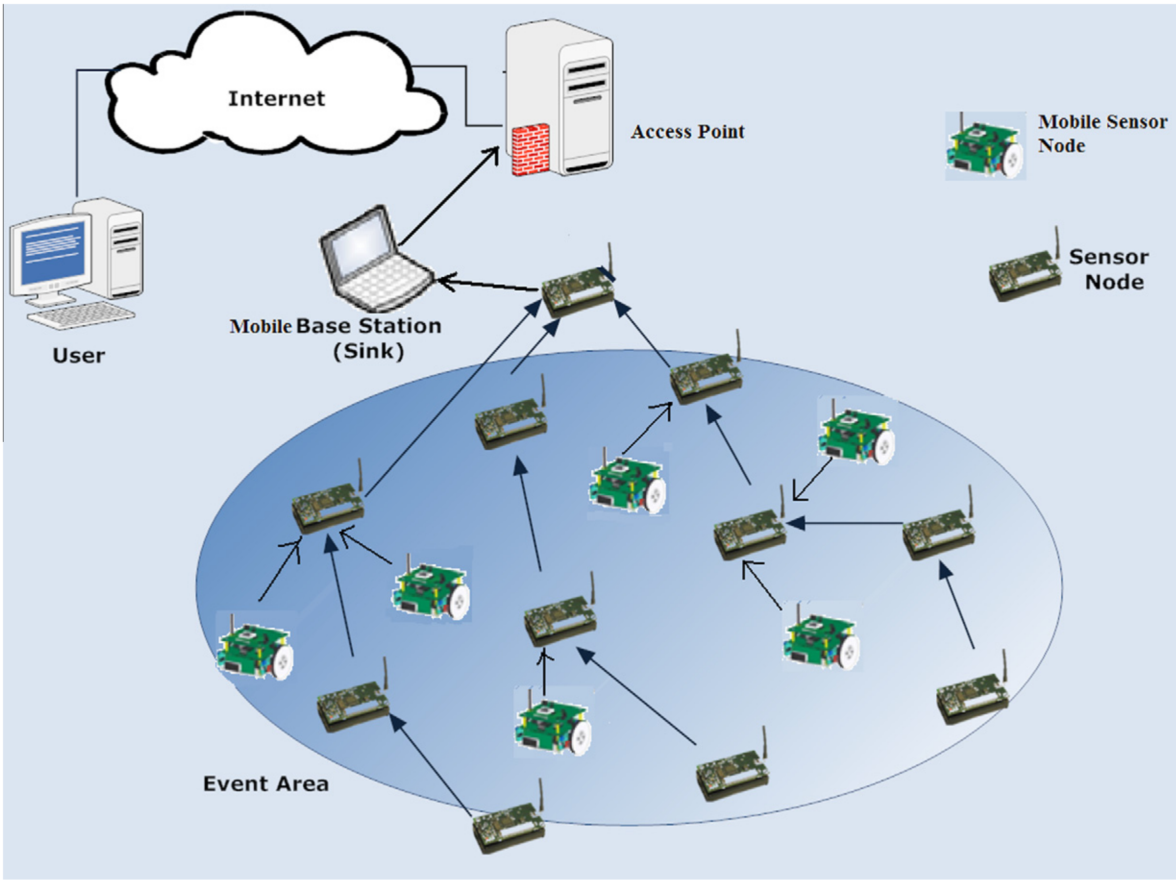


Fig. 1. MWSN architecture.

certain constraints such as power, computational capacities, and memory. Moreover, MWSNs are very data-centric, meaning that the information that has been collected about an environment must be delivered in a timely fashion to a collecting agent or mobile sink. Since a large number of sensor nodes are deployed, neighbour nodes may be very close to each other. Hence, multi-hop routing idea is suitable for MWSN to enable channel reuse in different regions of MWSN and overcome some of the signal propagation effects experienced in long-distance wireless communication [4]. Routing Protocols in MWSN is a greater challenge than routing in WSN due to the following reasons. First, since it is not easy to grasp the whole network topology and it is hard to find a routing path. Secondly, sensor nodes are tightly constrained in terms of energy, processing, and storage capacities. Thus, they require effective resource management policies, especially efficient energy management, to increase the overall lifetime of MWSN.

Real-time communication is necessary in many MWSN applications. For example, in a fire fighting application where appropriate actions should be made in the event area immediately as delay may cause some huge damages further. The sensor data collected and delivered must still be valid at the time of decision making since late delivery of data may endanger the fire fighter's life. Without loss of generality, QoS on a real-time guarantee can be categorized into two classes: hard real-time and soft real-time. In hard real-time system, deterministic end-to-end delay bound should be supported. The arrival of a message after the deadline is considered as a failure of the whole system. While in soft real-time system, probabilistic guarantee can meet requirements and some lateness is tolerable. Hence, supporting real-time in MWSNs means there should be either a deterministic or probabilistic end-to-end delay guarantee. It should be noted that while considering real-time support in MWSNs, energy efficiency should not be ignored [5,6].

This paper reports the following main contributions. Firstly, it proposes an enhanced real-time with load distribution (ERTLD) routing protocol for MWSN. ERTLD is based on our previous routing protocol RTLD [7]. It utilizes corona mechanism as a replacement of location based routing and computes optimal forwarding node based on received signal strength indicator (RSSI), remaining power of sensor nodes and packet delay over one-hop. Since forwarding nodes with the best link quality are chosen, the data throughput is improved. By choosing the forwarding nodes with the maximum packet velocity, the real-time packet transfer is ensured in the MWSN. Additionally, choosing nodes with the highest remaining power level ensures sporadic selection of forwarding neighbour nodes. The continuous selection of such nodes spread out the traffic load to neighbours in the direction of the sink, and subsequently prolonging the MWSN lifetime. ERTLD reports high performance in terms of delivery ratio, end-to-end delay, and power consumption. It has been successfully studied and verified through simulation experiment using Network Simulator-2 (NS-2) [8]. Secondly, it proposes a mobility detection mechanism that used corona architecture based on the position of a mobile sink. Corona architecture divides MWSN area into a dynamic corona based on a mobile sink which is assumed to be in the centre of coronas as it will be explained in Section 3. An acronym table for frequently used terms is shown as Table 1.

The rest of this paper is organized as follows: Section 2 will present related work on real-time communication for MWSN. The design of ERTLD will be described in Sections 3 and 4 will describe the simulation study of ERTLD. Finally, Section 5 will conclude the paper.

2. Related work

While most existing wireless sensor network deployments are still terrestrial networks with static sensor nodes, mobile wireless sensor networks have received increasing attention. During the past few years, several mobile wireless sensor networks have been successfully deployed in which sensor nodes are either equipped with motors for active mobility or attached to mobile objects for passive mobility. For example, researchers have attached wireless sensor devices to Micro Air Vehicles [9], bikes [10], vehicles [11,12], and animals [13,14]. In addition, wireless sensors are equipped with motors to move underwater to collect data from static sensor devices [15]. The related research for this paper can be classified into two categories as follows:

2.1. Real-time routing protocol for static WSN

RAP is a real-time architecture and protocols based on velocity [16]. It provides service differentiation in the timeliness domain by velocity-monotonic classification of packets. Based on packet deadline and destination, its required velocity is calculated and its priority is determined in the velocity-monotonic order so that a high velocity packet can be delivered earlier than a low velocity one. Similarly, SPEED [17] is a stateless protocol for real-time communication in WSN. It bounds the end-to-end communication delay by enforcing a uniform communication speed in every hop in the network through a novel combination of feedback control and non-deterministic QoS aware geographic-forwarding. MM-SPEED [18] is an extension to SPEED protocol. It was designed to support multiple communication speeds and provides differentiated reliability. Scheduling messages with deadlines focuses on the problem of providing timeliness guarantees for multi-hop transmissions in a real-time robotic sensor application [19]. In such application, each message is associated with a deadline and may need to traverse multiple hops from the source to the destination. Message's deadlines are derived from the validity of the accompanying sensor data and the start time of the consuming task at the destination. The authors propose heuristics for online scheduling of messages with deadline constraints as follow: schedules messages based on their per-hop timeliness constraints, carefully exploit spatial reuse of the wireless channel and explicitly avoid collisions to reduce deadline misses.

A routing protocol called real-time power control (RTPC) uses velocity with the most energy-efficient forwarding choice as the metrics for selecting a forwarding node [20]. A key feature of RTPC is the ability to send the data while adapting to the power of transmission.

RTLD is a real-time with load distribution for WSN. It computes the optimal forwarding node based on the packet reception rate (PRR), remaining power of sensor nodes and packet velocity over one-hop. It consists of four functional modules that include location management, routing management, power management and neighbourhood management. The location management calculates the sensor node location based on the distance to three predetermined neighbour nodes. RTLD reports high performance in terms of delivery ratio, control packet overhead and power consumption. However, RTPC, MM-SPEED, and RTLD are designed for static WSN and unsuitable for MWSN.

2.2. Real-time routing protocol for MWSN

EAR2 is an expected area-based real-time routing protocol in Wireless Sensor Networks [21,22]. It depends on an Expect Area (EA) of the mobile sink and exploit flooding of real-time data within EA. EAR2 exploits multicasting and one-hop forwarding time. To support a real-time data with a desired time deadline, EAR2 guarantees that the

Table 1
An acronym table for frequently used terms.

Acronym	Full spelling	Acronym	Full spelling
ERTLD	Enhanced Real-time with Load Distribution	CCP	Corona Control Packet
CCP_ID	Corona Control Packet Identity	CD	Corona Discovery
C_ID	Corona Identity	LM	Location Management
LN	Local Neighbour	MWSN	Mobile Wireless Sensor Network
MS	Mobile Sink	NC	Neighbour Discovery
MN	Mobile Node	NS-2	Network Simulator-2
NM	Neighbour Management	NT	Neighbour Table
OF	Optimal Forwarding	PE	Performance Evaluation
PM	Power Management	PRR	Packet Reception Rate
RM	Routing Management	RPH	Route Problem Handler
RSSI	Received Signal Strength Indicator	RTR	Request to Route

Tset_deadline is smaller than the total summation of the unicast forwarding time from a source to the Closest Point (CP) of Expect Zone (EZ) of the mobile sink, the multicast forwarding time from the CP to the grid header of Expect Grids (EGs), and the one-hop forwarding time from the grid head of an EG to the mobile sink. However, the proposed routing in [21,22] has some constraints such as mobility only applied for sink and power consumption is high due to multicast data packet to EZ of mobile sink.

RACE is a network conditions aware geographical forwarding protocol for real-time applications in MWSN [23]. It aims to provide QoS requirements to the application layer by giving priority to real-time messages and also by handling network congestions. Routing is performed node-by-node, where each node calculates a score to choose the best node to forward the message. The score consists of the link quality, the buffer remaining, and the packet velocity. The main feature of RACE is to consider network conditions for calculating the score and has a mechanism to keep knowledge of the buffer situation from the transmitting node to the sink node. Such mechanism provided a considerable improvement in the packet delivery ratio. Simulation experiments show that RACE presents excellent performance in respect to a message delivery ratio and deadline miss ratio. RACE was compared with a well-known protocol which is Real-time Power-Aware Routing (RPAR) [24] and observed that it outperformed RPAR in both metrics. However, RACE is location based and assumed the sink node was static and their positions were previously known. In addition, RACE did not consider load distribution.

Sidewinder is a predictive data forwarding protocol for mobile wireless sensor networks [25]. Like a heat-seeking missile, data packets are guided towards a sink node with increasing accuracy as packets approach the sink. Different from conventional sensor network routing protocols, Sidewinder continuously predicts the current sink location based on distributed knowledge of sink mobility among nodes in a multi-hop routing process. Moreover, the continuous sink estimation is scaled and adjusted to performing with resource-constrained wireless sensors. In addition, the authors show the impact of radio ranges on topology changes when nodes are mobile, concluding that traditional mobile ad-hoc routing protocols do not work well for MWSN. Moreover, the authors give test bed evidence that geographic forwarding-based protocols in MWSN (forwarding based on sensor node location) have poor performance in terms of delivery ratio and end-to-end delay. This is mainly due to geographical forwarding-based protocols have been widely used in static wireless sensor networks, because they only maintain local information to achieve end-to-end routing. However, a common assumption of these geographic forwarding-based protocols is that all intermediate nodes in a routing path know the exact sink location and use it for multi-hop routing. This assumption is reasonable when the sink is static, but leads to poor performance when the sink is mobile. However, Sidewinder does not design for real-time forwarding which required end-to-end delay enhancement to achieve this goal.

TBRP is a Tree-Based Routing Protocol with degree constraint for MWSN [26]. It works in three phases: Tree formation phase, data collection and transmission phase, and finally purification phase. TBRP protocol improves nodes and network life time by moving the node to the next higher level. Simulation results show that the nodes at level 0 consume more energy than at higher levels. When these nodes at a lower level reach a critical level of energy, they move to the next higher level, where energy consumption is less thus improving the lifetime of the nodes and network. Simulation results also show that because of mobility in TBRP energy dissipation is more efficient. However, If nodes in the network die (especially parent nodes in a tree-based routing protocol, where a "funnel" effect results in nodes closest to the base station expending more power more quickly than nodes further from it), the overall coverage and sensing capability of the network will be degraded.

A colour theory based routing protocol is presented in [27]. This protocol works in three phases. This protocol is based on the colour of the geographical area. In this protocol a colour theory based localization algorithm is used to find the position of the sensor node. There are various localization algorithms such as Monte Carlo localization algorithm [28,29] which are used for the localization of the sensor nodes. However, location-based algorithms are unsuitable for MWSN because they provided poor performance in terms of delivery ratio and end-to-end delay MWSN.

The main key features of ERTLD among previous work are using a corona mechanism to provide mobility for MWSN and maintain high performance in terms of delivery ratio and end-to-end delay. ERTLD has backward corona delivery to solve the hole routing problem and to produce more flexibility of forwarding.

3. Design of ERTLD in MWSN

ERTLD is based on our previous routing protocol which is RTLD. The differences between RTLD and ERTLD are as follows:

- **Sensor Location Management:** RTLD is depending on location management to calculate the sensor node location based on the distance to three pre-determined neighbour nodes. However, geographic forwarding-based is suitable for static WSN and leads to poor performance when the sink and/or intermediate nodes are mobile. Hence ERTLD used corona mechanism as a replacement to location based routing.
- **Optimal Neighbour Selection:** RTLD computes optimal forwarding node based on PRR, remaining power of sensor nodes and packet velocity over one-hop. PRR reflects the diverse link qualities within the transmission range and approximately calculated as the probability of successfully receiving a packet between two neighbour nodes [30,31]. If PRR is high that means the link quality is high and vice versa. However, PRR requires extra time, more energy and complexity mathematical calculation based on IEEE 802.15.4/Zigbee RF transceiver. Hence, ERTLD saves calculation time by utilizing RSSI which is a built-in physical layer parameter and does not require any extra calculation.

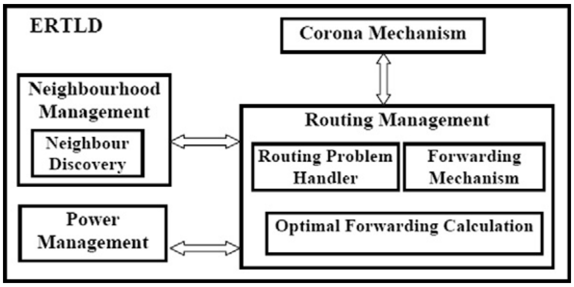


Fig. 2. Block diagram of ERTLD routing protocol.

- **Routing Problem Handler:** in ERTLD, if a mobile sensor node cannot forward data packets to the next-hop neighbour, it backwards the data packet to any node in high corona level and it will inform its parent to stop sending data. The parent will select new forwarding candidate. Hence, the backward mechanism guarantees to prevent dropping of data packet at the mobile node or its parent. This flexibility is not founded on RTLD.

In Fig. 2, ERTLD consists of four functional modules that include corona mechanism, routing management, power management, and neighbourhood management.

The corona mechanism calculates the sensor node corona level based on the distance to the sink. The power management determines the state of the transceiver and the transmission power of the sensor node. The neighbourhood management discovers a subset of forwarding candidate nodes and maintains a neighbour table of the forwarding candidate nodes. The routing management computes the optimal forwarding choice, makes a forwarding decision and implements a routing problem handler.

3.1. Corona mechanism

In order to determine corona ID (C_ID) for all sensor nodes in MWSN, MS can broadcast packets periodically to one hop neighbours which they forward this broadcast to next hop neighbours. Fig. 3a features MWSN immediately after deployment in which MS is assumed to be in the middle of MWSN. Corona is a concentric circle at the sink. For the sake of simplicity, it is assumed that the corona width is equal to the sensor transmission range r, and hence the (outer) radius r_i of corona C_i is equal to $r * i$. The main task of corona mechanism is to impose a coordinate system of MWSN in such a way that each sensor belongs to exactly one corona (the identity of the corona in which it lies) as illustrated in Fig. 3b. coronas concentric to MS; (c) MS after travelling and changing of MWSN coordinate system.

Since MS can travel to any random position, the coordinate system of MWSN and the C_ID of sensor nodes are changed accordingly as shown in Fig. 3c. This figure also shows the forwarding of data packet from the mobile node (MN) to the mobile sink (MS). The data travels from MN that is at a high level of corona to MN in a low level of corona. In case MN does not have any candidate in the neighbour table with low level corona, data packet will be forwarded to MN that has the same value of corona.

The algorithm of corona mechanism is depicted in Fig. 4. In this figure, corona mechanism starts at the MS which will broadcast corona control packet (CCP) to all one-hop neighbours (local neighbours). The main fields in CCP are C_ID (initial value is 0) and CCP_ID. If MN receives CCP, it will fetch CCP_ID and C_ID. Then, MN will check CCP_ID whether it has already received the CCP or not. If it has received CCP, MN will discard it. On the other hand, if CCP has not been received, MN will increase C_ID field in CCP and save the new value of C_ID as its corona level. After that, MN will broadcast CCP to the local neighbour. It is interesting to note that MS the only one can produce CCP. If MN does not receive CCP (because MN was in a sleep mode or a way out of the hidden problem), it will utilize the old C_ID value. If C_ID value is equal to zero, MN will change its status to idle mode and wait until it gets new C_ID. Moreover, in order to respond to the dynamic topology change in MWSN, MS will periodically broadcast CCP and the previous scenario will be repeated.

3.2. Routing management

The routing management consists of three sub functional processes; forwarding metrics calculation, forwarding mechanism and routing problem handler. Specifically, the chosen optimal nodes rely on RSSI, the delay per hop and the remaining battery level of the forwarding nodes. The routing problem handler is used to solve the routing hole problem due to hidden sensor nodes in MWSN. Unicast is used to select the way to forward data.

3.2.1. Optimal forwarding determined

In order to carry out the optimal forwarding calculation, the routing management calculates three parameters namely packet velocity, RSSI as link quality and remaining power (remaining battery) for every one hop neighbours. Eventually, the router management will forward a data packet to the one-hop neighbour that has an optimal forwarding. The optimal forwarding (OF) is computed as follows:

$$OF = \max\left(\lambda_1 * \frac{RSSI_{\max}}{RSSI} + \lambda_2 * \left(\frac{V_{batt}}{V_{mbatt}}\right) + \lambda_3 * \left(1 - \frac{D}{D_{ETE}}\right)\right)$$

where

$$\lambda 1 + \lambda 2 + \lambda 3 = 1 \qquad (1)$$

where $RSSI_{max}$ is the signal strength at reference point 1m which equals −45 dBm; V_{mbatt} is the maximum battery voltage for sensor nodes and equals to 3.6 V [32]. D is the average one hop delay and D_{ETE} is end-to-end delay for real-time which was setting to 250 ms. The values of $\lambda 1, \lambda 2$ and $\lambda 3$ are estimated by exhaustive search using Network Simulator-2 (NS-2) simulation such that $\lambda 1 + \lambda 2 + \lambda 3 = 1$ as illustrated in [33]. In [33], the number of possible values for each λ is 11 (from 0.0 to 1.0) and the number of trials for the event $\lambda 1 + \lambda 2 + \lambda 3 = 1$ is 66. The optimal trial from the 66 trials has been determined using NS-2 simulation with four types of grid network topology which are low density, medium density, high density with one source and high density with several sources. In each

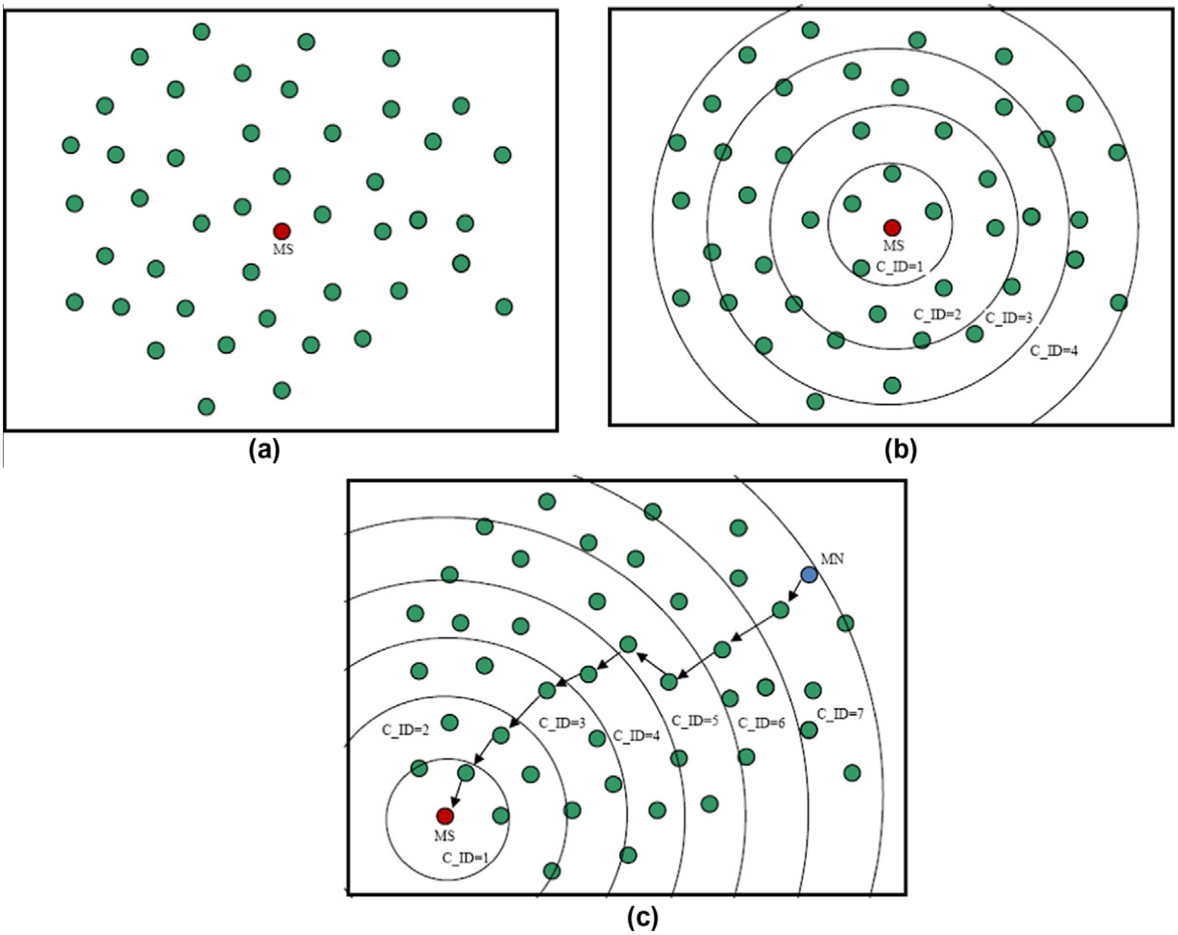


Fig. 3. Corona mechanism in MWSN (a) MWSN immediately after deployment; (b) MWSN model using coronas concentric to MS; and (c) MS after travelling and changing of MWSN coordinate system.

```
Input: CCP; MS; LN; NM and MN;
Output: MN will get new C_Id;
        Algorithm
  C_Id=0;
  MS broadcasts CCP;
  for all MN receive CCP from MS do
  {
        If (CCP is new)
            {
              C_Id of MN=C_Id of CCP+1;
              MN broadcasts adjusted CCP;
            }
        else
            CCP will discard;
  }
        If (CCP of MN ==0 or MN is travelling)
              (if MN does not receive ND request)
                 MN will be in Idle mode;
               else
                 {
                   MN will broadcast CD packet to LN;
                   C_Id of MN=avg(replied LN C_id)
                 }
        else
            MN will participate in data forwarding;
        End
```

Fig. 4. Algorithm of Corona mechanism.

type of topology, three types of traffic load are examined. The finding in [33] shows that the trial with 0.6, 0.2 and 0.2 for $\lambda 1, \lambda 2$ and $\lambda 3$ experiences high performance in term of delivery ratio and power consumption. Therefore, Eq. (1) can be written as;

$$OF = \max\left(0.6 * \frac{RSSI_{\max}}{RSSI} + 0.2 * \left(\frac{V_{batt}}{V_{mbatt}}\right) + 0.2 * \left(1 - \frac{D}{D_{ETE}}\right)\right) \tag{2}$$

The battery voltage is computed in NS-2 as follows:

$$Vbatt = \begin{cases} PPT * Txtime & for\ packet\ transmision \\ PPR * Rxtime & for\ packet\ receiving \end{cases} \tag{3}$$

where P_{PT} is energy usage for packet transmission and P_{PR} is energy usage for packet receiving.

The average delay to one hop neighbour (N) from the source (S) can be calculated as follows:

$$D = Avg\_delay(S, N) = \frac{Round\_trip\_time}{2} \tag{4}$$

It is interested to note that the average delay calculation does not require synchronization timing because transmission time is inserted in the header of request to route (RTR) packet. When receiving node N replies to sensor node S, it inserts the RTR transmission time in its reply. Once S receives the reply, it subtracts the transmission time from the arrival time to calculate the round trip time. In designing ERTLD routing protocol, the link quality is considered in order to improve the delivery ratio and energy efficiency. It should be noted that the link quality is measured based on RSSI to reflect the diverse link qualities within the transmission range. The most widely used signal propagation model is the log-normal shadowing model. RSSI can be estimated as in [33–35]:

$$RSSI(d) = Pt - PL(d0) - 10\beta \log\left(\frac{d}{d0}\right) + X\sigma \tag{5}$$

where P_t is the transmit power in dBm (maximum is 0 dBm or 1 mW for TelosB [36]), $PL(d_0)$ is the path loss for a reference distance d_0, d transmitter–receiver distance, β is the path loss exponent (rate at which signal decays) which depends on the specific propagation environment. For example, β equals to 2 in free space and will have a larger value in the presence of obstructions. This work estimates the value of β to be in between 2.4 and 2.8 as calculated in [34,35]. X_σ is a zero-mean Gaussian distributed random variable in (dB) with standard deviation σ.

3.2.2. Forwarding mechanisms and ERTLD operation

Fig. 5 shows the forwarding algorithm of ERTLD that uses unicast forwarding to route data packet from MN towards the destination which is assumed to be always MS. In unicast forwarding, the source node checks the C_ID of each neighbour in the neighbour table. If the C_ID of any neighbour node is less or equal to source node C_ID, the optimal forwarding algorithm will be invoked to choose the optimal neighbour. If there is no node in neighbour table has C_ID less or equal to source node's C_ID, the source node will invoke the neighbour discovery. Once the optimal forwarding choice is obtained, the data packet will be unicast to the selected node. This procedure continues until the MS is one of the selected node's neighbours. The forwarding policy may fail to find a forwarding node when there is no neighbour node currently in the direction of the destination. The routing management recovers from these failures by using a routing problem handler as described in the following section.

3.2.3. Routing problem handler

A known problem with routing in a wireless network is the fact that it may fail to find a route in the presence of network holes even with neighbour discovery. Such holes may appear due to voids in node deployment or subsequent node failures over the lifetime of the network. Routing management in ERTLD solves this problem by introducing routing problem handler which has two recovery methods; fast recovery using power adaptation and slow recovery using backward corona mechanism.

The fast recovery is applied when the diameter of the hole is smaller than the transmission range at the maximum power. The routing problem handler will inform neighbour discovery to identify a maximum transmission power required to efficiently transmit the packet across the hole as shown in Fig. 6. In this figure, if nodes A and G are failures due to some problems such as diminishing energy of sensor node or due to unreliable connection, S will use the maximum transmission power (0 dBm in IEEE 802.15.4) to send RTR. Therefore, node E will receive RTR from S and will reply using maximum transmission power. Hence, node E will be used as OF node. If the fast recovery cannot solve routing hole problem, the slow recovery is applied.

Fig. 7 shows the slow recovery in ERTLD. In this figure OF node A has data packet from parent node D, however, MN A cannot cross over the hole routing problem using fast recovery. Hence, MN A will search in its neighbour table about higher corona (C_ID of MN + 1) and will select OF from different candidates. So data packet will be sent backward one corona. In Fig. 7, we assumed MN A sends data packet to MN C and will also inform MN D to stop sending data packet toward itself. This mechanism is called backward corona mechanism. When D received backward control packet, it will implement routing management again. During the time that MN D search about new OF candidate, MN A will forward data packets backward to MN C. In this scenario, MN D has two chooses C or E.

3.3. Neighbourhood management

The design goal of the neighbourhood manager is to discover a subset of forwarding candidate nodes and to maintain neighbour table of the forwarding candidate nodes. Due to the limited memory and a large number of neighbours, the neighbour table is limited to a small set of forwarding candidates that are most useful in meeting the one-hop end-to-end delay with the optimal PRR and remaining power. The neighbour table format contains node ID, corona ID (C_ID), remaining power, one-hop end-to-end delay, RSSI, corona control packet ID (CCP_ID), location information and expiry time. The proposed system manages up to a maximum store of 16 sensor nodes information in the neighbour table.

```
Input: LM, PM, NM, ND, RM, RPH, C_Id;
Output: Neighbour node with OF;
        Algorithm
Receive forward or send data request;
        If (NT is empty)
          {
            MN will implement ND;
            For (all replies) do
              {
                  if( C_Id of MN<=C_Id of replied MN)
                      MN calculates OF;
                  else
                      MN will discard Neighbour reply
              }
            if (No replies)
            MN will implement RPH;
              }
        }
        else
        if( C_Id of MN<=C_Id of MN in NT)
          MN calculates OF;
        }
    MN select the OF Neighbour
        End
```

Fig. 5. Unicast forwarding in ERTLD based on corona mechanism.

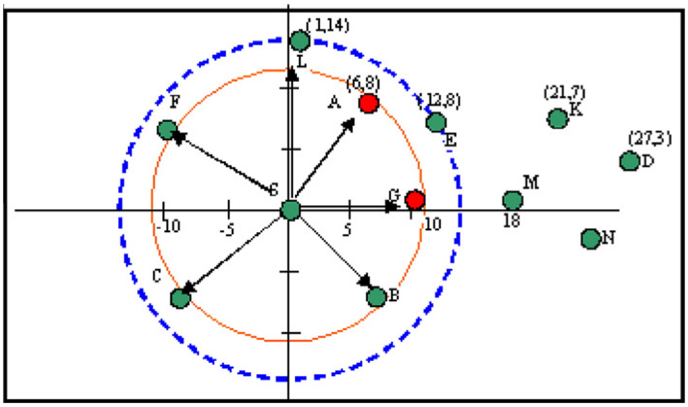


Fig. 6. Fast recovery of routing hole problem.

3.3.1. Neighbour discovery

The neighbour discovery procedure is executed in the initialization stage to identify a node that satisfies the forwarding condition. The neighbour discovery mechanism introduces small communication overhead. This is necessary to minimize the time it takes to discover a satisfactory neighbour. The source node invokes the neighbour discovery by broadcasting RTR packet. Some neighbouring nodes will receive the RTR and send a reply. Upon receiving the replies, the neighbourhood management records the new neighbour in its neighbour table.

3.4. Power management

The main function of power management is to adjust the power of the transceiver and select the level of transmission power of the sensor node. It significantly reduces the energy consumed in each sensor node between the source and the destination in order to increase node lifetime span. To minimize the energy consumed, power management minimizes the energy wasted by idle listening and control packet overhead. The transceiver component in TelosB consumes the most energy compared to other relevant components of the TelosB. The radio has four different states: down or sleep state (1 μA) with voltage regulator off, idle state (20 μA) with voltage regulator on, send state (17 mA) at 1 mW power transmission and receive state (19.7 mA) [32]. According to the data sheet values, the receive mode has a higher power consumption than the all other states.

In ERTLD, the sensor node sleeps most of the time and it changes its state to idle if it has neighbour in the direction of the destination. In addition, if the sensor node wants to broadcast RTR, it changes its state to transmit mode. After that, it changes to receive mode if it receives replies or data packet from its neighbour.

Since the time taken to switch from sleep state to idle state takes close to 1ms [37], it is recommended that a sensor node should stay in the idle state if it has neighbours. Thus, the total delay from the source to the destination will

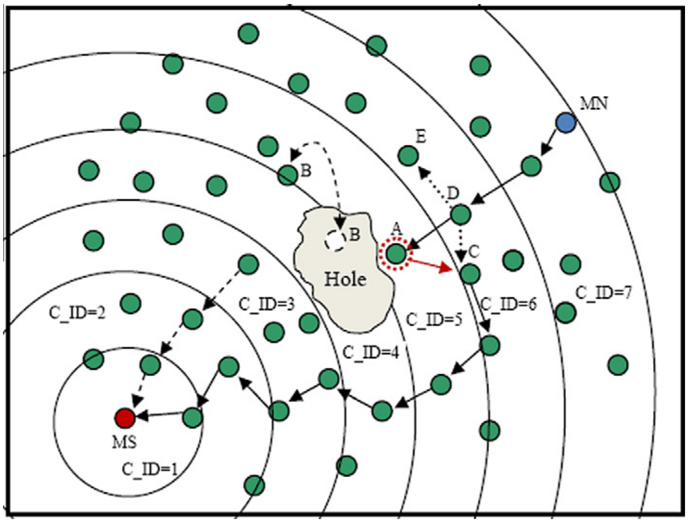


Fig. 7. Feedback mechanism in routing problem handler.

be decreased. In addition, a sensor node should change its state from idle to sleep if it does not have at least one neighbour in the neighbour table that can forward data packets to the destination.

4. Simulation implementation of ERTLD

The NS-2 simulator has been used to simulate the ERTLD routing protocol. IEEE 802.15.4 MAC and physical layers are used to reflect the real access mechanism in MWSN.

4.1. Model and assumptions

In order to create a realistic simulation environment, the ERTLD has been simulated based on the characteristics of the TelosB mote from MEMSIC. Table 2 shows the simulation parameters that used to simulate ERTLD in NS-2. Many-to-one traffic pattern is used. This traffic is typical between multiple MN and single MS. In this work, 100 MN are distributed in a random manner (150 m × 150 m) as shown in Fig. 8a. To increase the hop count between the source and the sink, the source node was selected from the rightmost and the sink from the left most of the topology. Therefore, a node numbered as 18 is MN and node 0 is MS. We assume that the MS has an ability to communicate with the outside world (the Internet, local LAN, etc.) via WLAN interface card and can communicate with mobile sensor node via a low-power transceiver based on a CC2420 ChipCon chip that employs IEEE 802.15.4 physical and MAC layers specifications. In the following simulation study; ERTLD utilizes on demand neighbour and corona discovery scheme. When the periodic beacon scheme is employed, the data packets will transmit after 10 s to allow neighbour table forwarding metrics to be initialized. It is important to note that in this scenario, the data packet travels between 10 and 15 hops to reach the sink and it can travel further more hops if the distance between sink and source nodes is big. We assume the traffic used is constant bit rate (CBR). Fig. 8a and b show the change of simulated network topology and random paths that created using ERTLD during the discovery stage.

Table 2
Simulation parameters.

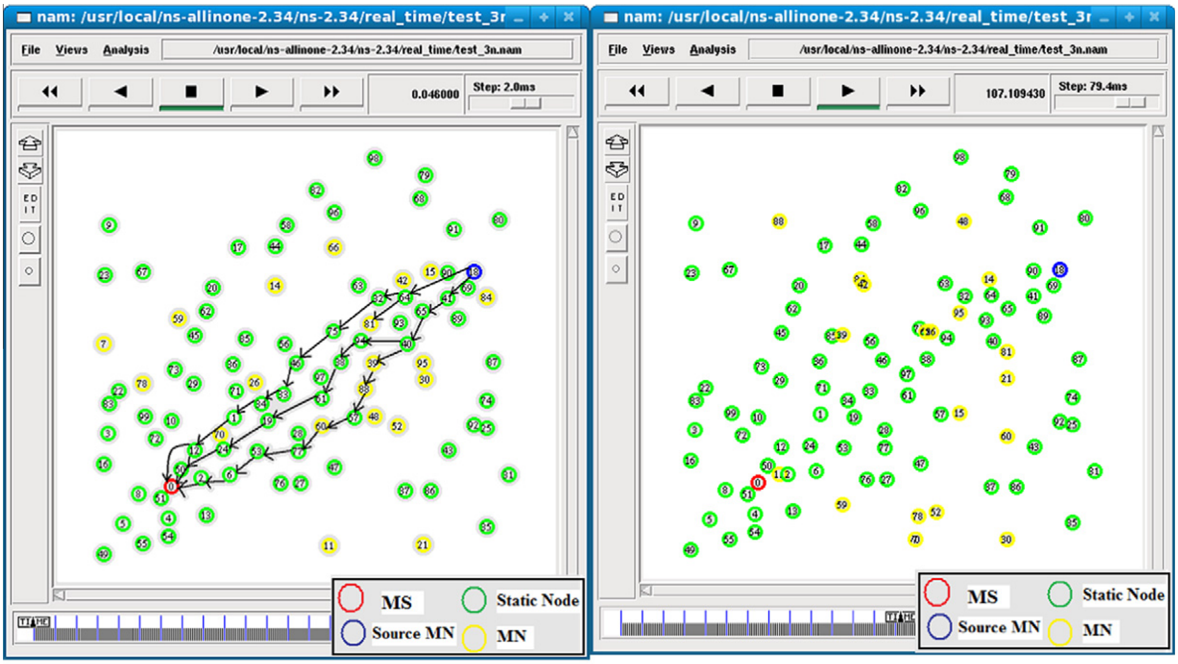
Parameter	IEEE 802.15.4
Propagation Model	Shadowing
Path loss exponent	2.5
Shadowing deviation (dB)	4.0
Reference distance (m)	1.0
Packet size	70 bytes
phyType	Phy/WirelessPhy/802_15_4
macType	Mac/802_15_4
freq_	2.4e+9
Initial Energy	3.3 J
Transmission Power	1 mW

ERTLD is compared with three other baseline protocols that consider multiple packet speeds (MM-SPEED), packet velocity with link quality and buffer remaining (RACE) and RTLD. MM-SPEED and RTLD are mainly designed for static WSN; however, RACE is designed for MWSN. The feedback control and differentiated reliability in MM-SPEED routing protocol have not been taken into account in this work because they require modification to the MAC layer protocol. The simulation evaluates the performance of all forwarding policies in a situation whereby the neighbour table at each node does not have forwarding choices. Packet delivery ratio, normalized power consumption, normalized control packet overhead and average end-to-end delay are the metrics used to analyze the performance evaluation (PE) of all routing protocols. The PE for ERTLD compared to anyone in the baseline routing can be calculated as:

$$PE = \frac{\sum_{i=0}^{n}(Y_{ERTLD}(i) - Y_R(i))}{\sum_{i=0}^{n}(Y_R(i))} \tag{6}$$

where Y_R is the performance of baseline routing and n is a set of traffic load points.

All metrics are defined with respect to the network layer. The packet delivery ratio is the ratio of packets received at the destination to the total number of packets sent from



(a) (b)

Fig. 8. Network simulation model; (a) initial state; (b) after MNs travel.

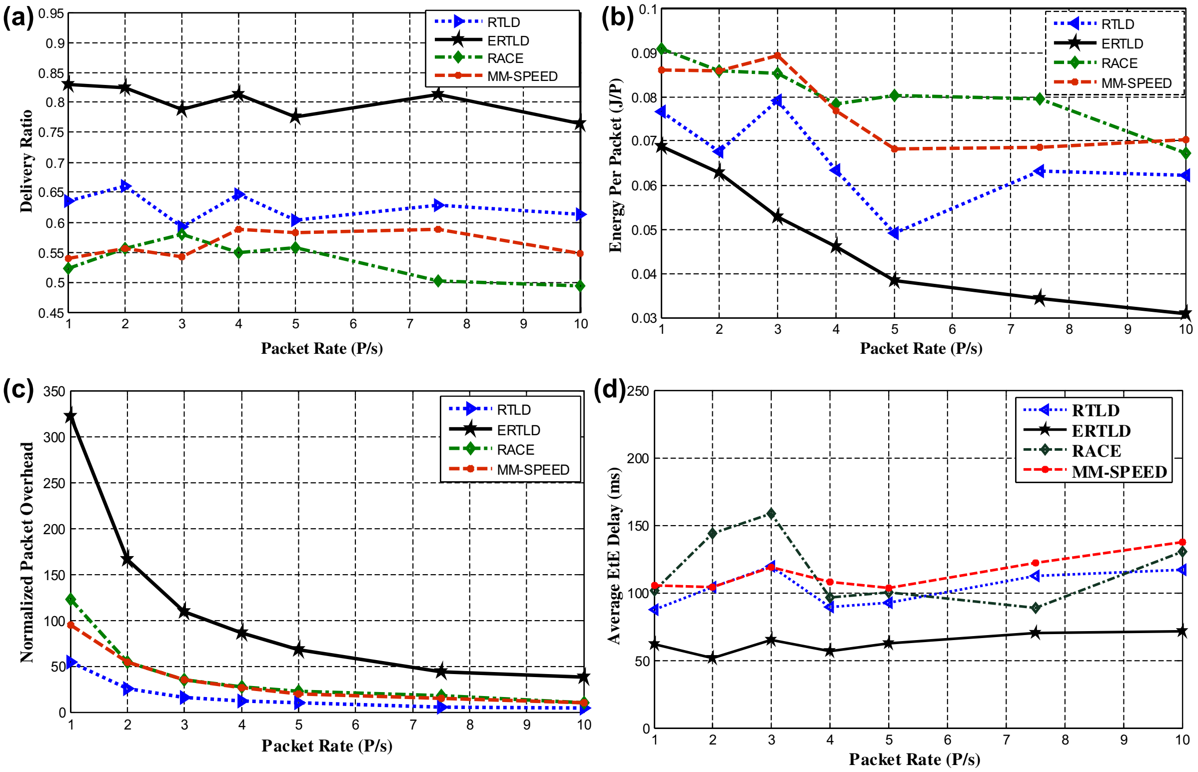


Fig. 9. Comparison between ERTLD and baseline routing protocols in static WSN (a) delivery ratio; (b) energy per packet received; (c) normalized packet overhead; and (d) average end-to end delay.

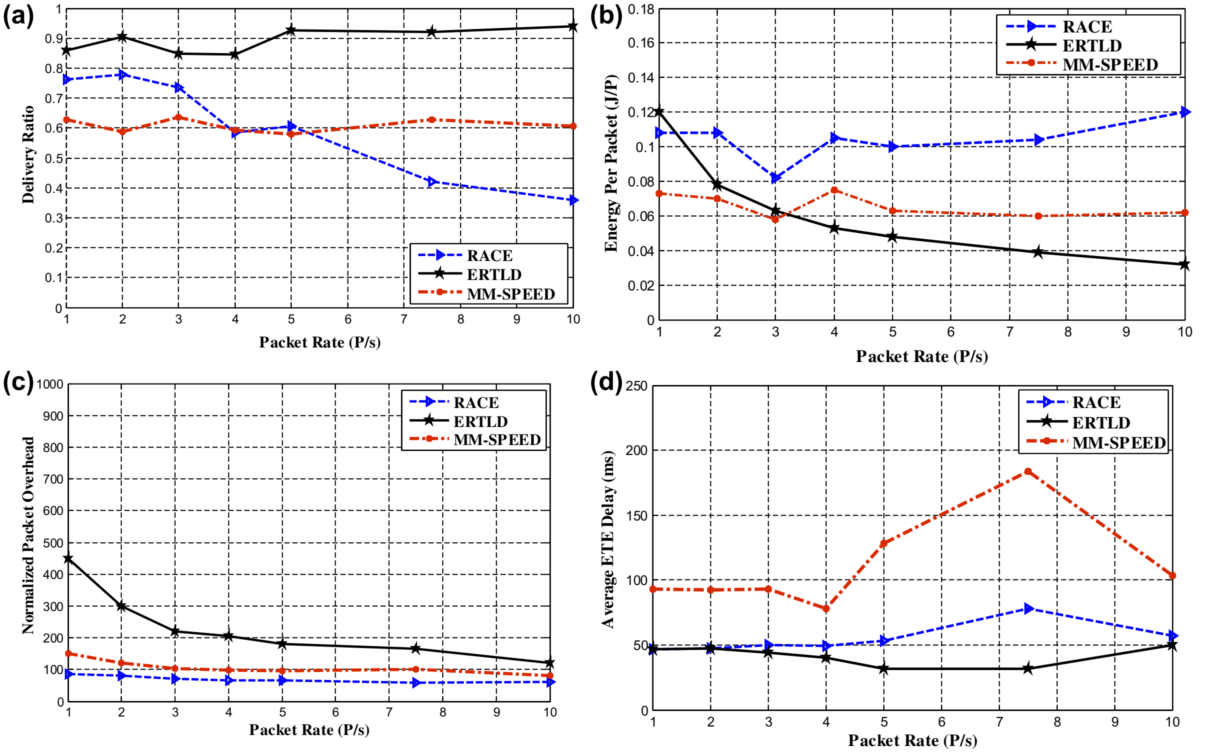


Fig. 10. Comparison between ERTLD, MM-SPEED and RACE on MWSN (a) delivery ratio; (b) energy per packet received; (c) normalized packet overhead; and (d) average end-to end delay.

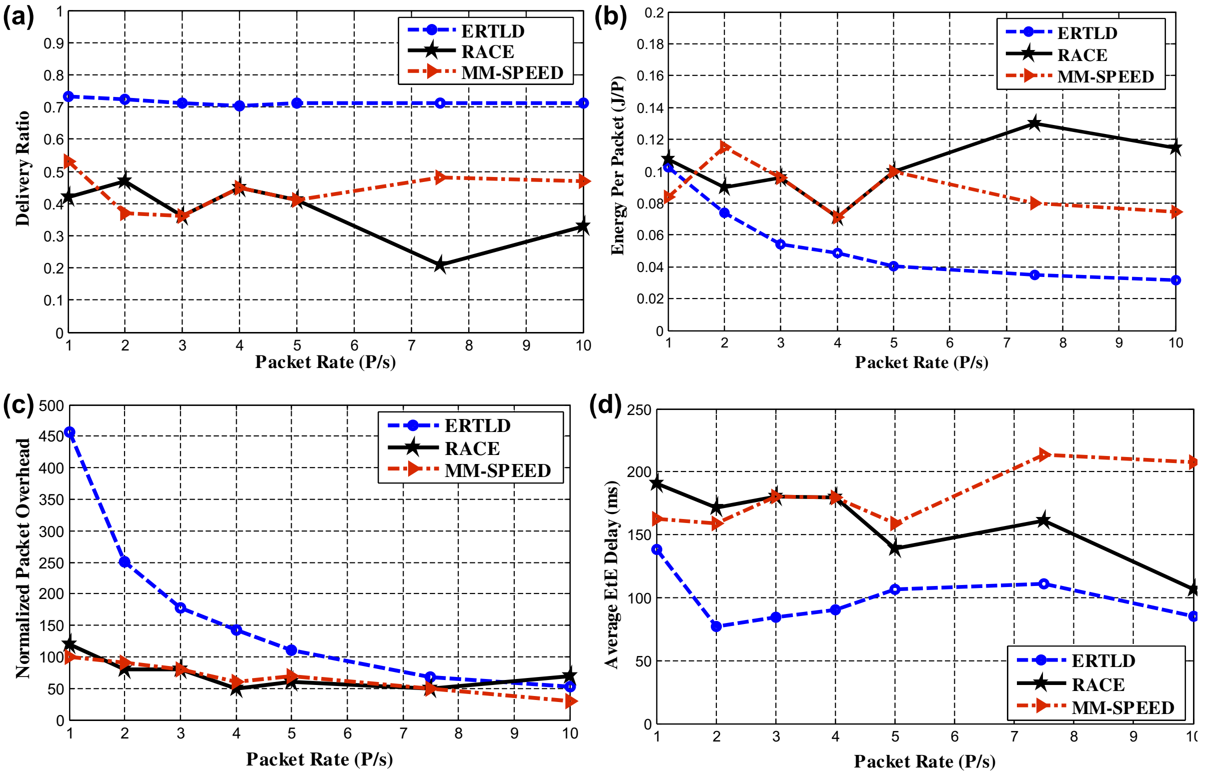


Fig. 11. Effect of mobile sink on ERTLD, MM-SPEED and RACE (a) delivery ratio; (b) energy per packet received; (c) normalized packet overhead; and (d) average end-to end delay.

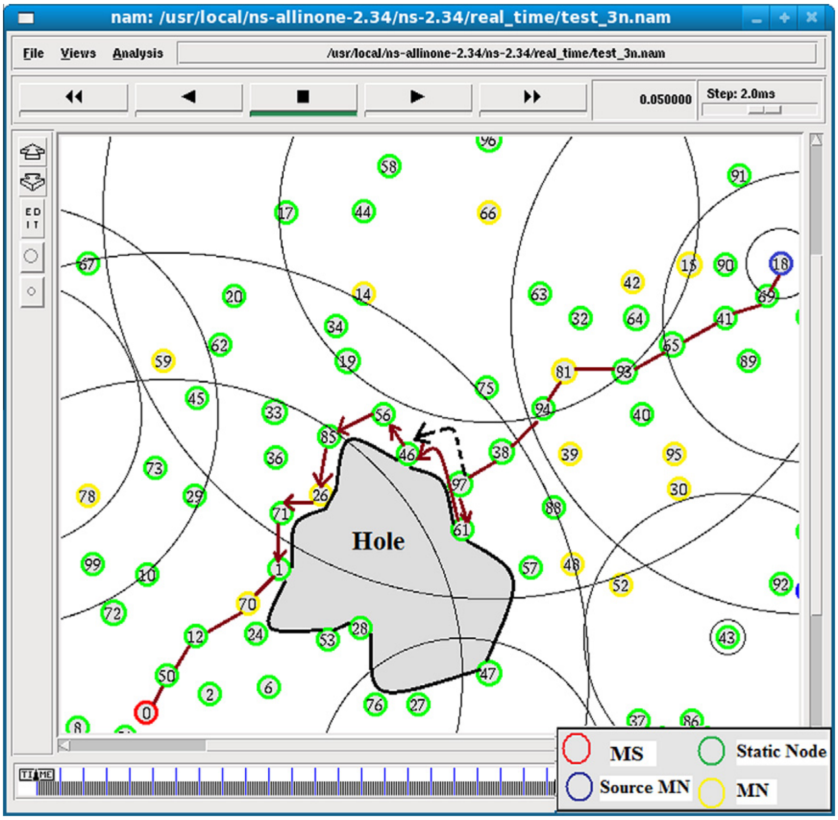


Fig. 12. Network simulation model at presence of hole problem.

the source in a network layer. Normalized energy consumption is the energy consumed in each sensor node for each packet delivered and normalized control packet overhead counts the number of control packets sent in the network for each data packet delivered while end-to-end delay is the total delay from the source to the destination.

4.2. Comparison between ERTLD and baseline routing protocol

The real-time transfer requires that each packet reaches its destination within the deadline period. The deadline delimits the lifetime of a packet traversing the MWSN. Simulation study of the influence of the forwarding mechanism is carried out using parameters configured in Table 2. The packet rate is varied from 1 to 10 packet/s while the simulation time is between 1000 and 5000 s. The distance between sensor nodes is varying between 5 m and 20 m.

4.2.1. Static network topology

In this simulation, 50 mobile nodes are simulated as static nodes and the simulation time is 1000 s. The simulation results in Fig. 9a show that the ERTLD experiences higher delivery ratio than a baseline by 28%. This is primarily due to the ERTLD forwarding strategy that used corona and optimal forwarding mechanism which not depend on location management. In the location based routing protocol, some data packets miss the deadline because of time taken to estimate a position of MN and MS. In addition, the forwarding mechanism in ERTLD is more flexible than a baseline because it implements backward corona to recover from a route hole problem. Fig. 9b demonstrates that ERTLD consumes 84% less power compared to a baseline routing protocols because of constraints in baseline such as directional and location calculation that expend more energy per packet forwarding. Moreover, Fig. 9c shows that ERTLD spends a large number of packets overhead compared to baseline routing protocols. This is largely due to two types of discoveries which are neighbour discovery, and corona discovery. Furthermore, the location management packet overhead in the baseline was not considered. Corona discovery is invoked every 8s. Fig. 9d shows that ERTLD possesses short average delay which is 65% less compared to RTLD routing protocols because of the convergence corona forwarding mechanism in ERTLD. Besides that, Fig. 9d shows the maximum average end-to-end packet delay is around 60 ms. Beyond this, the packet delivery ratio remains unchanged from the maximum throughput. It is important to note that the data packet travels between 5 and 10 hops to reach the sink.

4.2.2. Dynamic network topology

In this simulation, 100 sensor nodes have been simulated while 20% of MNs (20 nodes) have been changed their position randomly using fixed speed at 5 m/s. In order to test the load distribution on ERTLD, RACE and MM-SPEED, the simulation time was increased to 5000 s. The simulation results in Fig. 10a show that the ERTLD experiences higher delivery ratio than RACE by 42%. This is mainly due to the location management in RACE and MM-SPEED leads to poor performance if the topology of MWSN is changed. Location management required extra time to estimate the new position of the MNs. In contrast, MS in ERTLD periodically broadcasts CCP that assists to determine C_ID of MN which will be used to forward data packet even if the topology changes. In addition, Fig 10b shows ERTLD consumes 39% less power per packet received compared to RACE routing protocol between 4 and 10 P/S. This is because the number of lost packet using RACE and MM-SPEED is high which dissipates the power of MNs. Moreover, Fig. 10c shows that ERTLD spends large number of packet overhead compared to RACE and MM-SPEED routing protocols. This is largely due to two types of discoveries which are neighbour discovery, and corona discovery. Furthermore, the location management packet overhead in RACE and MM-SPEED was not considered. However, this large of control packet overhead is essential to achieve high performance in dynamic topology. Fig. 10d shows that ERTLD possesses short average delay which is 31% compared to RACE and MM-SPEED routing protocol because of the flexibility of forwarding mechanism in ERTLD.

4.2.3. Impact of mobile sink on MWSN

In this simulation, 50 mobile nodes are simulated; MS and 20% of mobile nodes have been changed their position randomly using fixed speed 5 m/s. Also, the simulation time is 1000 s.The simulation results in Fig. 11a show that ERTLD experiences higher delivery ratio than RACE and MM-SPEED by 63% according to Eq. (6). This is essentially due to the change of MS position which caused many data packets loss their destination. Moreover, Fig. 11b shows ERTLD consumes 38% less power per packet received compared to RACE and MM-SPEED routing protocol. This is because the number of lost packet using RACE and MM-SPEED is high which dissipates the power of MNs. In addition, Fig 11c that ERTLD spends large number of packet overhead compared to RACE and MM-SPEED routing protocols. However, this large of control packet overhead is essential to maintain high performance in dynamic topology. Moreover, Fig. 11d shows that ERTLD possesses short average delay which is 43% compared to RACE and MM-SPEED routing.

4.2.4. Effect of hole problem on ERTLD

The hole problem was created due to many reasons such as mobility of intermediate nodes; power problem; and duty sleep cycle. In order to simulated hole problem between the MN and the MS, the random topology at initial state will be changed to include some holes as shown in Fig. 12. In Fig. 12, the route between MN (18) and MS (0) is disconnected at nodes 61 and 28. However, ERTLD has a recovery mechanism that can recover from hole problem using the backward corona mechanism. The following simulation will compare the effect of hole problem on ERTLD, MM-SPEED and RACE.

In this simulation, 20% of mobile nodes (20 nodes) have been changed their position randomly using fixed speed 5 m/s. The packet rates were varied from 1 to 10 packet/s

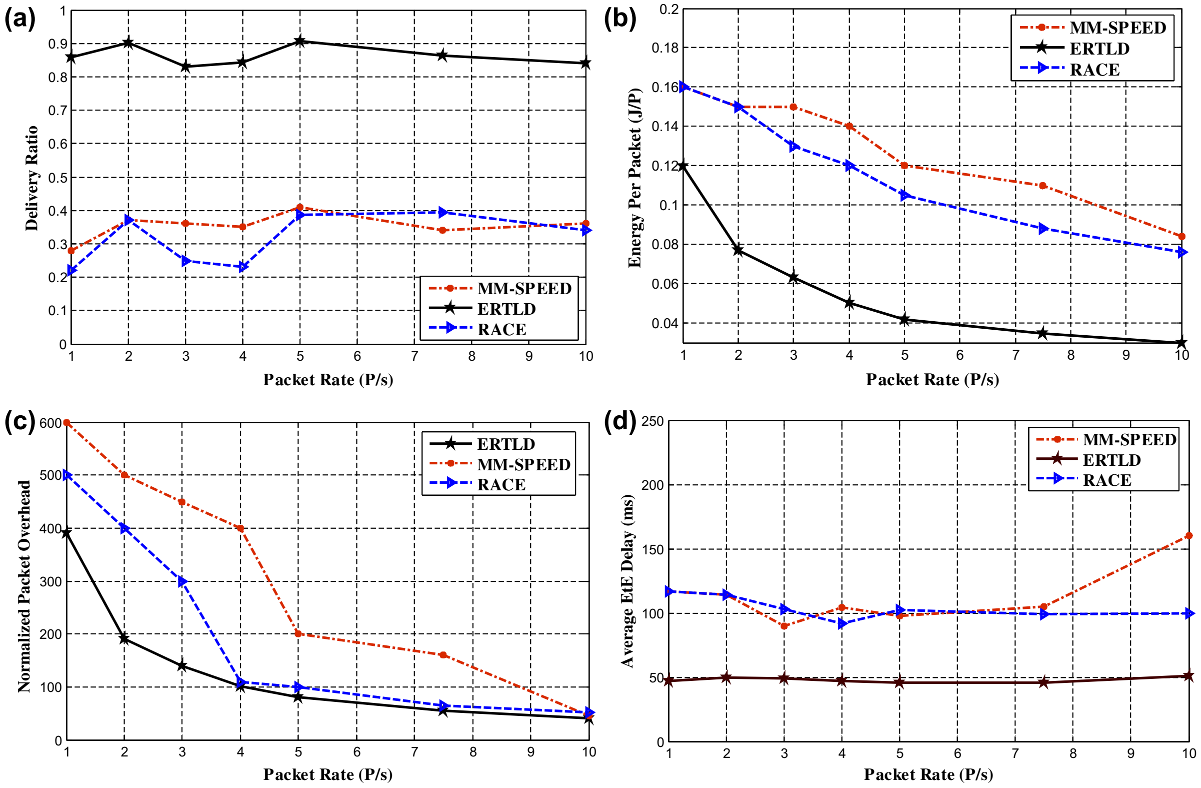


Fig. 13. Influence of hole problem on performance of ERTLD, RACE and MM-SPEED (a) delivery ratio; (b) energy per packet received; (c) normalized packet overhead; and (d) average end-to end delay.

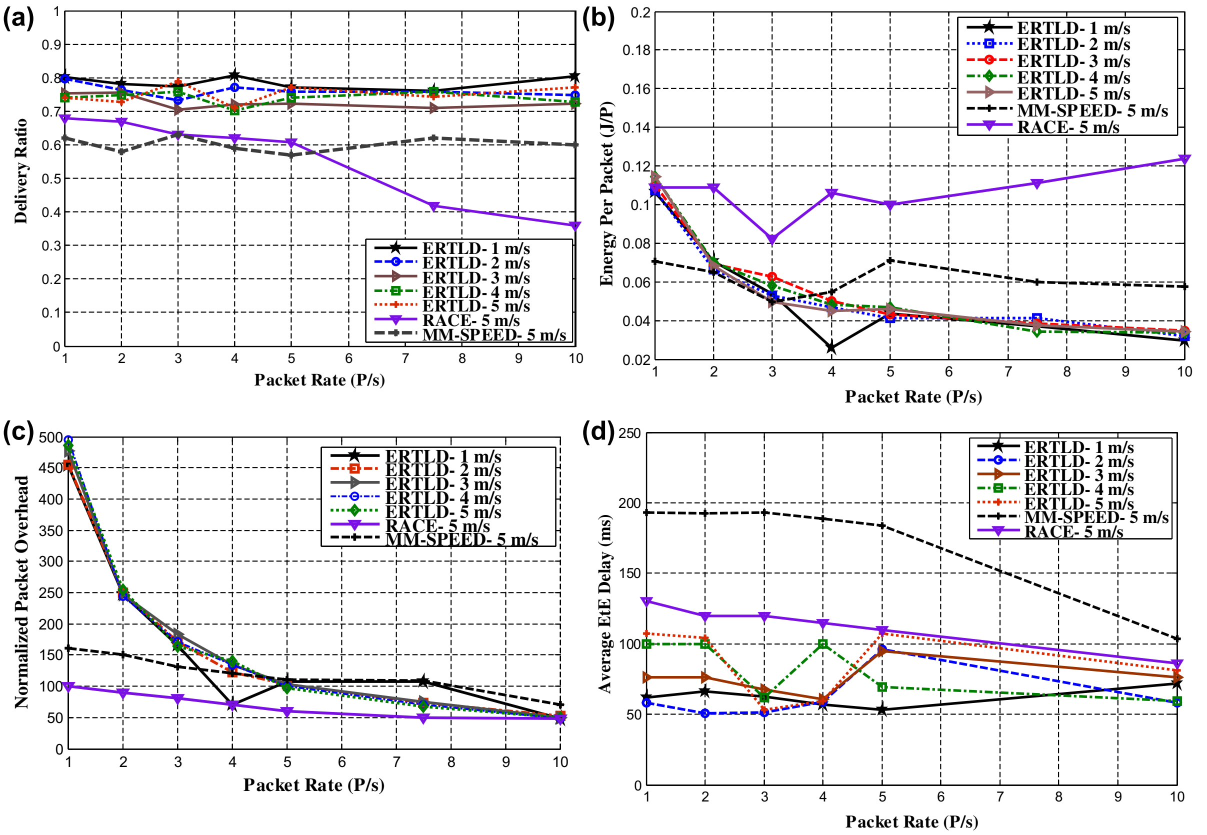


Fig. 14. Comparison between ERTLD, MM-SPEED and RACE at different mobile node speed of ERTLD (a) delivery ratio; (b) energy per packet received; (c) normalized packet overhead; and (d) average end-to end delay.

while the simulation time was 5000 s. The simulation results in Fig. 13a shows that ERTLD higher delivery ratio than MM-SPEED and RACE by more than 100% at the presence of hole problem between the MN and the MS. This is basically due to the consideration of hole problem in MN 61 that uses ERTLD which will redirect the packet to MN in the backward corona (MN 46). In addition, MN 61 will inform its parent (MN 97) at higher corona level to select new path. Hence, the arrived packets at MN 61 will not be dropped. In contrast MM-SPEED has backpressure re-routing scheme which will drop all packets in MN 61 and inform MN 97 to choose a new path. In Fig. 13b and c, ERTLD consumes very less power and packet overhead per packet received compared to RACE and MM-SPEED routing protocol. This is mainly because of high packet drops in RACE and MM-SPEED. Moreover, Fig. 13d shows that ERTLD possesses short average delay compared to RACE and MM-SPEED routing protocol because the recovery mechanism in ERTLD has rapid adaptation technique to find new path.

4.2.5. Influence of varying mobile node speed

In this simulation, 50 mobile nodes are simulated and 20% of mobile nodes have been changed their position randomly using varying speeds between 1 and 5 m/s. The main reason for selecting low speed is IEEE 802.15.4 support short-range radio frequency transmissions. Moreover, if the MN increases mobility speed, it will affected by periodic handover. The simulation results in Fig. 14a show that ERTLD with 1 m/s speed experiences slightly higher delivery ratio than all other including RACE and MM-SPEED. This is basically due to topology does not change quickly so most of data packet will be forwarded to MS. In addition, Fig. 14b–d show small variances between all speeds of MNs and these reflect the stability of ERTLD. In addition, ERTLD experiences higher performance than RACE and MM-SPEED because of the reasons mentioned in the previous section.

5. Conclusion

Most of the existing real-time routing protocol designed for WSN and they did not consider the real-time routing for mobile WSN. This paper introduces an ERTLD routing protocol for MWSN. It is based on our previous work which is RTLD routing protocol for WSN. ERTLD is based on corona mechanism which is a replacement to location based routing in RTLD. It computes the optimal forwarding node based on RSSI, remaining power of sensor nodes and packet velocity over one-hop. The finding concludes that location based routing is not suitable for MWSN and corona mechanism in ERTLD enhances the total performance, reliability and flexibility of data forwarding mechanism in MWSN. The proposed mechanism has been successfully studied through simulation work and in the future it will be evaluated in real test bed network based on radio model of Telosb motes.

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