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REAL-TIME ROUTING PROTOCOL WITH LOAD DISTRIBUTION IN WIRELESS SENSOR NETWORK BASED ON IEEE 802.11 AND IEEE 802.15.4

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Abstract. In Wireless Sensor Network (WSN), sensors gather information about the physical world, while base station takes decisions and then perform appropriate actions upon the environment, which allows a user to effectively sense and monitor from a distance in real time. This paper proposes a novel real time routing protocol with load distribution (RTLD) that provides efficient power consumption and high packet delivery ratio in WSN. The highlight advantage of RTLD is that it can deliver packets within their end-to-end deadlines, while minimizing the network miss ratio and power consumption. It combines the geocast forwarding with link quality, maximum velocity and remaining power to achieve the real time routing in WSN. The remaining power capability assists WSN to avoid routing holes problem due to power expiration.

Keywords: MICAz sensor node, packet reception rate, remaining power, signal to noise ratio, end to end delay, delivery ratio

Abstrak. Dalam Rangkaian Penderia Tanpa Wayar (WSN), penderia mengumpul maklumat tentang alam fizikal manakala stesen tapak membuat keputusan dan kemudiannya melaksanakan tindakan yang sesuai ke atas persekitaran tersebut. Proses ini membenarkan seseorang pengguna untuk mengesan dan mengawas rangkaian dengan berkesan pada jarak jauh dalam masa sebenar. Kertas kerja ini mencadangkan satu protokol penentuan laluan masa sebenar dengan agihan beban yang baru (RTLD). Protokol ini menyediakan penggunaan kuasa secara efisen dan kadar penerimaan data yang tinggi dalam WSN. Kebaikan yang ketara dalam RTLD ialah boleh menghantar paket dalam tempoh hujung-ke-hujung yang ditentukan sementara dapat meminimumkan nisbah tersasar rangkaian dan penggunaan kuasa. Protokol ini juga menggabungkan konsep maju dengan maklumat geografi berserta dengan kualiti laluan, kelajuan maksimum dan baki kuasa pada nod untuk merealisasikan penentuan laluan masa sebenar dalam WSN. Penentuan baki kuasa nod dapat membantu WSN untuk mengelak masalah ketiadaan nod jiran yang disebabkan oleh ketandusan kuasa pada nod.

Kata kunci: Nod penderia MICAz, kadar penerimaan paket, baki kuasa, nisbah isyarat hangar, lengah hujung-ke-hujung, kadar penghantaran

1.0 INTRODUCTION

Wireless Sensor Network (WSN) is a wireless ad hoc network that consists of very large number of sensor nodes, which are densely deployed either inside an event area

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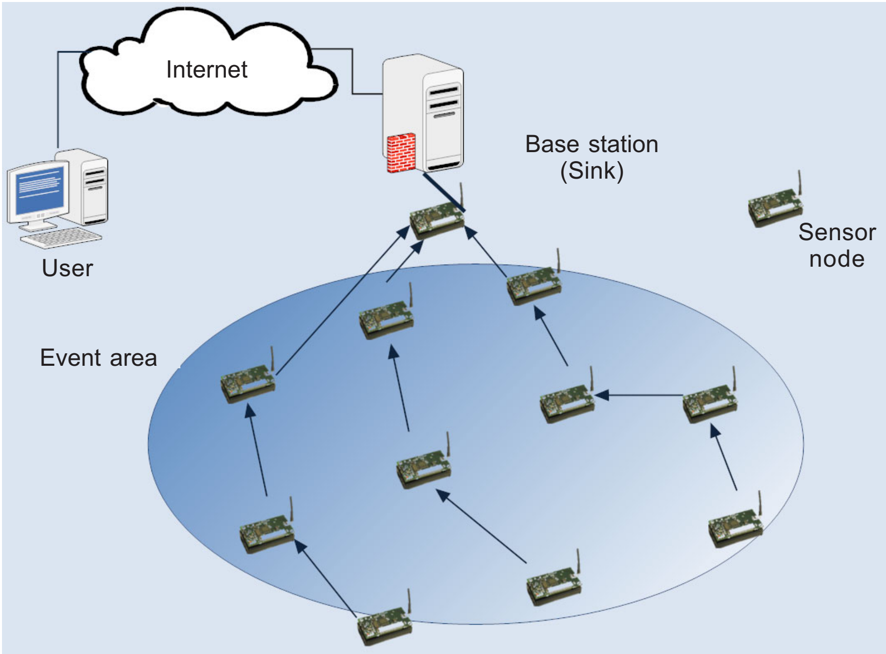


Figure 1 WSN with MICAz motes

or in proximity to the event area as shown in Figure 1. WSN enable reliable monitoring and analysis of the physical environment and are very different from the traditional networks; they are composed of a large number of nodes that produce very large amounts of data, and are limited in power, computational capacities, and memory. Due to these inherent properties, conventional management scheme are not appropriate to manage the sensor networks and thus, a new management scheme is needed [1].

Real-time communication is necessary in many WSN applications. For instance, in a fire fighting application, appropriate actions should be initiated in the event area as soon as possible. Moreover, the sensors data collected and delivered must still be valid at the time of the decision making. Late delivery of the data may endanger the fire fighter's life. On the other hand, if sensors detect a malicious person in an area and transmit that information immediately to the security, the malicious person might be apprehended immediately. Otherwise, the malicious person may be escaped. Moreover, if some sensor nodes pass data to the destination in an energy constrained situation, the communication between the sensor nodes in WSN might be lost. Thus, the main critical factors that determine the performance of sensor networks are data delivery and energy consumption.

There are three modes of communication pattern associated with the delivery of data in WSN [2]; unicast, area-multicast and area-anycast. A unicast mode is implemented when a node in the network detects some activity that needs to be reported to a remote base station. When a base station wants to issue a command or query to a specific area in the ad hoc sensor network, it motivates a different routing service called area-multicast communication. In this case the endpoint of the route is an area rather than an individual node. Since sensors often measure highly redundant information, in some situations it may be sufficient to have any node in an area to respond. We call this routing service as area-anycast communication. However, RTLD proposes new type of communication in WSN called geodirectional-cast forwarding based on quadrant. Geodirectional-cast forwarding combines geocast with directional forwarding to forward the data packet through multiple paths to destination. This forwarding mechanism is discussed in Section 3.2.1.

This paper proposes RTLD which is a real time routing protocol with power consideration. RTLD enhances and modifies the previous work by [2-5] in order to achieve high delivery ratio with low power consumption. In this paper, the performance of RTLD is evaluated through simulation based on a realistic radio model of MICAz motes. Currently RTLD is experimentally studied using MICAz motes.

MICAz is a radio sensor board with transceiver interface using IEEE 802.15.4 MAC sub layer. IEEE 802.15.4 is a new standard uniquely designed for low rate wireless personal area networks (LR-WPANs). It offers low data rate, low power consumption and low cost wireless networking, at device level connectivity. Like most protocols designed for wireless networks, 802.15.4 uses CSMA-CA mechanism for channel access. However, the new standard does not include the request-to-send (RTS) and clear-to-send (CTS) mechanisms, in consideration of the low data rate used in LR-WPANs. RTS packets plus CTS packets increase the overhead packets sent in IEEE 802.11 and this is not applicable to IEEE 802.15.4. However, the RTS/CTS overhead proves to be useful when the traffic load is high, but obviously too expensive for low data rate applications as of the case of LR-WPANs for which IEEE 802.15.4 is designed [6]. In non-beacon enabled mode and under moderate data rate, the new 802.15.4 standard is more efficient in terms of overhead and resource consumption compared to 802.11. It also enjoys a low hop delay (normalized by channel capacity) on average [6]. Both 802.15.4 and 802.11 support multi-hop network topology and peer-to-peer communications. However, 802.15.4 also supports star communication where traffic is typical between multiple source nodes and a sink [6].

The remainder of this paper is organized as follows. Section 2 presents the related work on real-time communication and power control protocols. The design procedure for RTLD in WSN is described in Section 3 while Section 4 describes the simulation implementation of the RTLD. Finally, Section 5 concludes the paper.

2.0 RELATED WORK

A comprehensive review of the challenges and the state of the art of the real-time communication in sensor networks can be found in [7]. In this paper, the most common work to WSN routing protocol is presented. Reactive routing protocols such as Ad Hoc on Demand Distance Vector Routing (AODV) maintain only the routes that are currently in use, thereby reducing the burden on the network when only a small subset of all available routes is in use at any time [8]. Since routes are only maintained while in use, it is typically required to perform route discovery. Route discovery in AODV can lead to significant delays in a sensor network with a large network diameter (measured in multiples of radio radius). In addition, a node in AODV protocol uses flooding to discover new paths. In sensor networks where thousands of nodes communicate with each other, broadcast storms may result in significant power consumption and possibly a network meltdown [9]. This limitation makes on-demand algorithms less suitable for real-time applications.

The routing protocol in WSN based on IEEE 802.11 MAC and the reason why the transmission is at a high data rate can be explained as follows: Real-time architecture and protocols (RAP) prioritizes real-time traffic through a novel velocity monotonic scheduling scheme, which considers both a packet's deadline and distance to the destination [3]. SPEED 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 [2]. MM-SPEED is an extension to the SPEED protocol [4]. It was designed to support multiple communication speeds and provides differentiated reliability.

The routing protocol based on a low data rate such as B-MAC can be explained as follows: Real-time power control in WSN (RTPC) uses the velocity with the most energy efficient forwarding choice as the metric for selecting forwarding node [5]. A key feature of RTPC is its ability to send a data while adapting to the power of transmission.

RTPC, RAP, SPEED and MM-SPEED depend on the velocity metric to forward data packet towards the destination. In RTLD, the best values of velocity, Packet Reception Rate (PRR) and remaining power mechanism are used as the metric for selecting forwarding node. Velocity alone does not give the information about the link quality. The best link quality usually had low packet loss and hence high energy efficient [10]. Another novel feature of RTLD is employing remaining power parameter in selecting the forwarding candidate node. The remaining power assists the source node to distribute the forwarding load to all available forwarding candidates and hence avoid routing holes problem. RTLD can adapt to geocast and unicast forwarding, which has better packet delivery with minimum communication overhead. On the other hand, RTPC uses minimum hop count as a metric to provide energy efficient forwarding. However, the minimum hop count affects the delivery ratio [11].

3.0 DESIGN PROCEDURE FOR RTLD IN WSN

RTLD routing protocol consists of several features that include: geographical location management, power management, neighborhood management, and routing

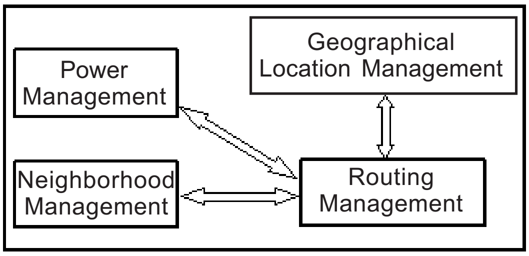


Figure 2 RTLD routing protocol architecture

management as shown in Figure 2. In this figure, the geographical location management in each sensor node calculates its location based on three pre-determined neighbor nodes and its distance to those neighbors. The power management determines the remaining power and the power level of transmission in the sensor node. The neighborhood management discovers a subset of forwarding candidate nodes and maintains a neighbor table of the forwarding candidate nodes. The routing management computes the optimal forwarding choice based on the neighbor table information. It makes forwarding decision, neighborhood discovery and routing problem handler. The following section describes in details RTLD components.

3.1 Geographical Location Management

RTLD utilizes localized information to carry out routing. It is assumed that each node has a location aware mechanism such as in [12, 13] to obtain its location in WSN area. In [12], the location service uses at least three signal strength measurements extracted from the "hello" messages that are being broadcast by pre-determined nodes at various intervals. Distance of the unknown node to the pre-determined nodes will be determined from the signal strength received based on a propagation path loss model of the environment. If the distance and location of these pre-determined nodes are known, unknown nodes can triangulate their coordinates. The system to be developed will not require additional hardware since it uses the existing wireless communication hardware.

3.2 Routing Management

In order to carry out this policy, RTLD calculates three parameters to select the optimal forwarding choice: maximum velocity, PRR and remaining power (remaining battery voltage) for every one-hop neighbors. The delay to one-hop neighbor (Delay(S, N)) can be calculated as follows:

$$Delay(S, N) = \frac{Round\ Trip\ Time}{2} \tag{1}$$

The maximum velocity (V) to one-hop neighbor is calculated from the one-hop distance divided by minimum Delay(S, N). RTLD does not need synchronization timer in all sensor nodes. The transmission time is inserted in the header of the control packet. The PRR in RTLD uses the link layer model derived in [11, 14, 15]. In order to simplify the mathematical equation, this paper assumes there is no interference effects and considers Signal-to-Noise ratio (SNR) only. In this work, the physical layer is based on IEEE 802.15.4/Zigbee RF transceiver, which has a frequency of 2.4 GHz with O-QPSK modulation. It is based on a chip rate R_c of 2000 kc/s, a bit rate R_b of 250 kb/s and a codebook of M=16 symbols. Conversion from SNR to bit noise density (E_b/N_0) assuming matched filtering and half-sine pulse shaping [15] is given by:

$$\frac{E_b}{N_0} = \frac{0.625 R_c}{R_b} SNR = \frac{0.625 \times 2000000}{250000} SNR = 5.0 SNR \tag{2}$$

The conversion from E_b/N_0 to symbol noise density (E_s/N_0) [15] is

$$\frac{E_b}{N_0} = \log 2(M) \frac{E_b}{N_0} = 4 \frac{E_b}{N_0} \tag{3}$$

Symbol error rate P_s is computed for non-coherent MFSK [16] as:

$$P_s = \frac{1}{M} \sum_{j=2}^{M} (-1)^j \binom{M}{j} \exp\left(\frac{E_s}{N_0} \left(\frac{1}{j} - 1 \right) \right) \tag{4}$$

Finally, conversion from P_s to bit error rate (BER) P_b is given as:

$$P_b = P_s \left(\frac{M/2}{M-1} \right) = P_s \left(\frac{8}{15} \right) \tag{5}$$

Rolling these together produces the BER function as:

$$P_b = \left(\frac{8}{15} \right) \left(\frac{1}{16} \right) \sum_{j=2}^{16} (-1)^j \binom{16}{j} \exp\left(20 SNR \left(\frac{1}{j} - 1 \right) \right) \tag{6}$$

The PRR is calculated from the BER as: let P_i be a Bernoulli random variable, where P_i is 1 if the packet is received and 0 otherwise. Then, for r transmissions, the PRR is defined by $\frac{1}{r} \sum_{i=1}^{r} P_i$. Since all packets are independent and identically distributed (i.i.d.) random variables, by the weak law of large numbers PRR can be approximated by $E[P_i]$, where $E[P_i]$ is the probability of successfully receiving a packet [17]. Hence, the PRR conditioned for m bits in one packet is as follows,

$$PRR = (1 - P_b)^m \tag{7}$$

Since the average frame length for IEEE 802.15.4 is 22 bytes [14], m is 176. From Equations (6) and (7), PRR is determined by

$$PRR = \left[1 - \left(\frac{8}{15}\right)\left(\frac{1}{16}\right)\sum_{j=2}^{16}(-1)^j \binom{16}{j} \exp\left(20\gamma(d)\left(\frac{1}{j} - 1\right)\right)\right]^{176} \tag{8}$$

where $g(d)$ is SNR and it can be calculated as follows [16, 18],

$$SNR = g(d) = P_t - PL(d) - S_r \tag{9}$$

where P_t is the transmitted power in dBm (maximum is 0 dBm for MICAz), S_r is the receiver's sensitivity in dBm (–95 dBm in MICAz) [19]. $PL(d)$ is the path loss model which can be calculated as follows [16]

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{10}$$

where d is the transmitter-receiver distance, d_0 is the reference distance, n is the path loss exponent (rate at which signal decays) which depends on the specific propagation

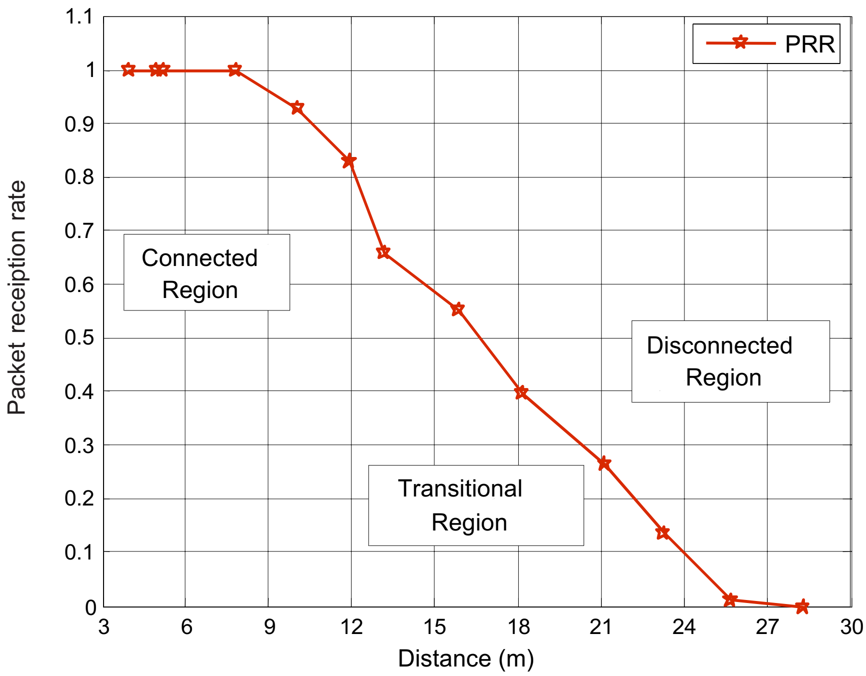


Figure 3 PRR vs. Distance

environment. For example, n is equal to 2 in free space and will have larger value in the presence of obstructions. X_σ is a zero-mean Gaussian distributed random variable in (dB) with standard deviation σ (shadowing effects in dB). Equation (8) was simulated in NS2 simulator and the results are as shown in Figure 3. The figure shows the effect of PRR as the distance is increased. The PRR is high when the distance is less than 15 m and goes to 0 when the distance is more than 18 m.

To compute the remaining power in the battery of the sensor node, MICAz has an accurate internal voltage reference that can be used to measure the battery voltage (V_{batt}). Since the eight-channel ADC on the microcontroller of MICAz (ATMega128L) uses the battery voltage as a full scale reference, the ADC full scale voltage value changes as the battery voltage changes. In order to track the battery voltage, the precision voltage reference (band gap reference) V_{ref} is monitored to determine the ADC full-scale (ADC_FS) voltage span which corresponds to V_{batt} [20]. The battery voltage is computed as follows:

$$V_{batt} = \frac{V_{ref} * ADC\_FS}{ADC\_Count} \tag{11}$$

ADC_FS equals 1024 while V_{ref} (internal voltage reference) equals 1.223 volts and *ADC_Count* is the ADC measurement data at the internal voltage reference.

RTLD forwards a data packet to the optimal forwarding choice that has high forwarding progress. The forwarding progress (*FP*) is computed as follows:

$$FP = \lambda 1 * PRR + \lambda 2 * V_{batt} / V_{mbatt} + \lambda 3 * V / V_m \tag{12}$$

Where: $\lambda 1 + \lambda 2 + \lambda 3 = 1$ and $\lambda 1 = 0.6, \lambda 2 = 0.2, \lambda 3 = 0.2$

Where V_{mbatt} is the maximum battery voltage for sensor nodes and is equal 3.6 volts [20]. V_m is the maximum velocity of the radio frequency signal which is equal speed of light over the distance between the packet transmitter and receiver.

We proposed two different types of forwarding in RTLD: (i) unicast forwarding and (ii) geodirectional-cast forwarding towards the destination based on quadrant. Figure 4 shows the flow chart diagram of the RTLD algorithm with unicast forwarding. In the unicast forwarding, the source node checks for the forward flag of each neighbor in the neighbor table. If the forward flag is 1, the source node will check the RTLD real-time forwarding metrics and compute the forwarding progress as in equation (12). This procedure continues until the optimal forwarding choice is obtained. If there are no nodes in the direction to the destination, the source node will implement neighborhood discovery, which will be explained in Section 3.2.2. Once the optimal forwarding choice is obtained, the data packet will be unicast to the selected node. The selected forwarding node will then select the next forwarding node if the destination is not one of its neighbors. This procedure continues until the destination is one of the

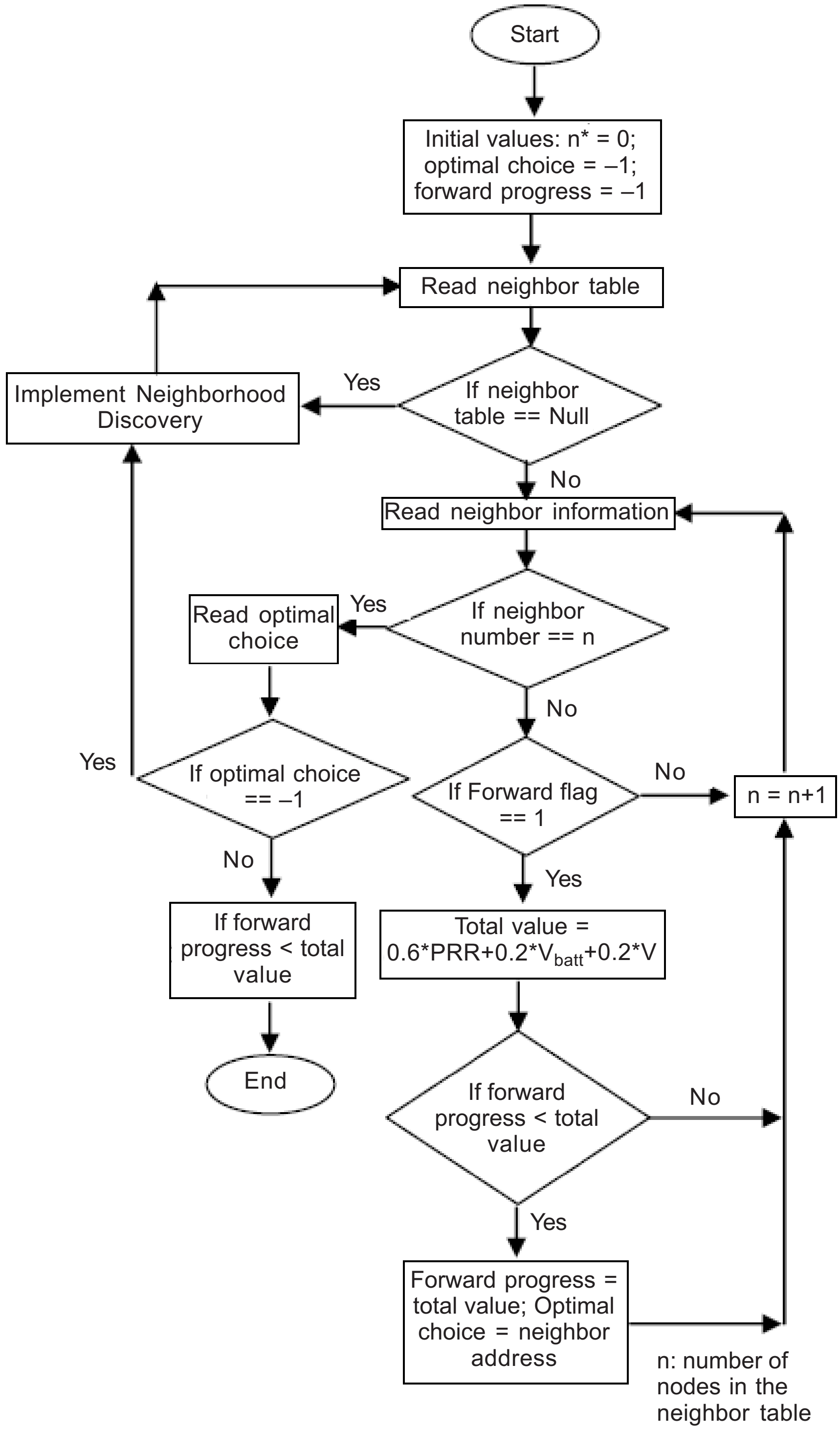


Figure 4 Flow chart diagram of RTLD forwarding policy

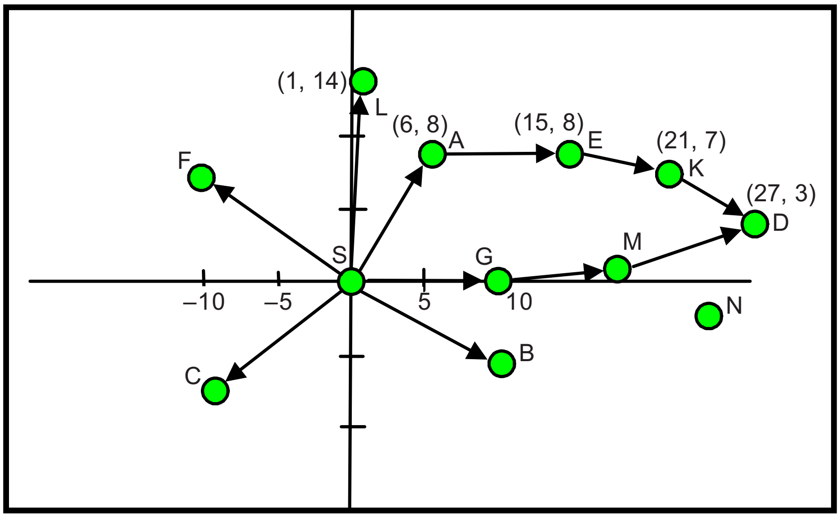
selected node's neighbors. At this instance, the data packet will be unicast directed to the destination.

3.2.1 Quadrant Based Geodirectional-cast and Unicast Forwarding

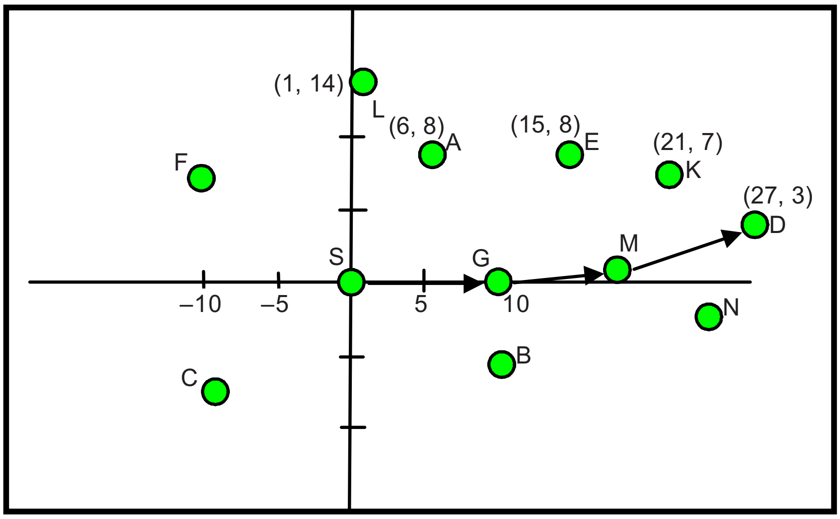
Directional forwarding is forwarding to the next node that have the best progress towards destination Quadrant-based Directional Routing (Q-DIR) [21] which is used in RTLD with some modification. In RTLD geodirectional-cast forwarding, if a node wants to forward a data packet to a specific destination in a specific geographical location, it will broadcast the packet to all neighbors. We assume that each node can calculate its location from three neighbors in its neighbor table as explained in [12, 13]. Therefore, at all neighboring nodes, nodes will decide to forward the packet using unicast forwarding if they are in the same quadrant as the destination and if the distance to the destination is less than the distance from the source to the destination. Otherwise, the packet will be ignored. Since nodes have information of its neighbors, it will not only forward but also select a neighbor that has the best forwarding progress towards the destination. If the destination receives multiple copies of the same packet, it will accept the first packet delivered and ignore the others. This is the modification work done on Q-DIR where neighbors will select the forwarding node and unicast the data packet and also calculate its distance to the destination. In Q-DIR, all forwarding nodes will broadcast the packet and no distance calculation.

Figure 5(a) and Figure 5(b) show the implementation of geodirectional-cast and unicast forwarding of 12 nodes in a global coordinate system. In Figure 5(a), the source node (S) broadcasts the data packet to its neighbors. S considers the destination (D) to be in the first quadrant. Nodes B, C, F and N ignore the forwarding request because they are not in the same quadrant as D. Node L also ignores the forwarding request because its distance to D is greater than the distance between S and D. On the other hand, nodes A and G are in the first quadrant as D and the distance between them to D is less than the distance between S and D. Hence A and G will participate and forward the data packet to E and M respectively. It is interesting to note that nodes A and G will use unicast forwarding to forward the data packet to E and M rather than broadcast. This modification of Q-DIR will save the power usage, reduce the packet flooding and minimize the collision.

In Figure 5(b), S checks the forward flag. The forward flag is 1 if S considers the optimal choice to be in the same quadrant as D and the distance between the optimal choice and D is less than the distance between S and D. The same reasons as explained in figure 5(a) applies to why nodes B, C, F, N and L have forward flag equals 0. On the other hand, the forward flag for nodes A and G is 1, therefore S selects the optimal from A and G based on Equation (12). This procedure continues until the data packet is delivered to D.



(a) Geodirectional-cast forwarding a data packet to the destination



(b) Unicast forwarding a data packet to the destination

Figure 5 Directional and unicast forwarding based on quadrant

The forwarding policy may fail to find a forwarding node when there is no neighbor node currently in the direction of destination. RTLD recovers from these failures by using neighborhood discovery method as described in the following section.

3.2.2 Neighborhood Discovery

If RTLD cannot find a viable forwarding choice, the neighborhood discovery mechanism is invoked to find one-hop neighbors. The goal of the neighborhood discovery is to identify a node that satisfies the forwarding condition. The neighborhood discovery mechanism introduces small communication and energy overhead while minimizing the time it takes to discover a satisfactory neighbor. In the following discussion we assume that a routing failure has occurred at the source node when routing a packet destined for the destination node. The source node invokes the neighbor discovery by broadcasting a request to route (RTR) packet. Some neighbor nodes (N) will receive the RTR and send a reply. Upon receiving the reply, RTLD inserts the new neighbor into its neighbor table. RTLD will broadcast the RTR at the default power level. However, if the source node does not receive a reply from any node, RTLD will broadcast again the RTR but at the maximum power level. This ensures that far away nodes reply to the RTR.

3.2.3 Routing Problem Handler

A known problem with geographic forwarding is that it may fail to find a route in the presence of network holes even with the neighborhood discovery. Such holes may appear due to voids in node deployment or subsequent node failures over the life-time of the network. RTLD partly avoid this issue by using the remaining power as a parameter of forwarding to distribute the load to all forwarding candidate. In addition, if the diameter of the hole is smaller than the transmission range at the maximum power, then RTLD will identify a maximum transmission power that is sufficient to transmit the packet across the hole.

3.3 Neighborhood Management

The design goal of the neighborhood manager is to discover a subset of forwarding candidate nodes and maintain a neighbor table of the forwarding candidate nodes. Due to limited memory and large number of neighbors, the neighbor table must keep a small set of forwarding candidates that are most useful in meeting the one-hop end-to-end delay with the best PRR and remaining power. The neighborhood table contains node id, remaining power, one-hop end-to-end delay, PRR, forward flag, location information and expiry time.

3.4 Power Management

RTLD focuses on minimizing the energy spent in each sensor node between the source and destination to avoid the failure. To further minimize the energy consumed, a WSN needs to integrate real-time communication with a power management protocol to minimize the energy wasted by idle listening. However, low-power wireless networks usually have unreliable links, limited bandwidth and the link quality is heavily influenced by the environmental factors [10]. Thus, RTLD has designed to balance real-time performance with power efficiency. On the other hand, transmitting a packet using high power may increase the communication range and/or improve link quality and hence reduce the communication delay [11]. Since the remaining power in WSN nodes can be monitored, RTLD distributes the forwarding load to the forwarding candidates in the neighbor table. RTLD updates the neighborhood table after a certain timeout and the previous optimal choice may not be selected because the link quality, velocity and the remaining power will change. It is interested to note that the remaining power of forwarding nodes decrease which means that the probability to be selected again for the next period time is decreased. Hence, the load of forwarding is distributed to many intermediate nodes.

4.0 SIMULATION IMPLEMENTATION OF RTLD

NS2 simulator has the ability to simulate IEEE 802.11 and IEEE 802.15.4 MAC sub layer, which reflect real access mechanism in WSN. RTLD had simulated in both IEEE 802.11 and IEEE 802.15.4 MAC sub layer environment. To create a realistic simulation environment, we had simulated RTLD based on the characteristics of the MICAz mote from Crossbow. According to the data sheet of MICAz motes RF transmission power is programmable from 0 dBm (1 mW) to –25 dBm. Lower transmission power can be advantageous by reducing interference and dropping radio power consumption from 17.5 mA at full power to 8.5 mA at the lowest power [20]. Table 1 shows the simulation parameters used to simulate RTLD in both IEEE 802.15.4 and IEEE 802.11. In this table, IEEE 802.15.4 and IEEE 802.11 MAC and physical layers are used with default power transmission. Many-to-one traffic pattern is used which is common in WSN applications. This traffic is typical between multiple source nodes and a base station. In this work, 121 nodes are distributed in a 100 m × 100 m region as shown in Figure 6. Node 120, 110, 100 and 90 are the source nodes and node 0 is the base station node (sink). To increase the hop count between sources and the base station (sink), we choose the sources from the leftmost grid of the topology and the sink on the middle of the grid. We assume the traffic used is having constant bit rate (CBR), thus there is no retransmission. The packet delivery ratio and energy consumption are assigned as the metrics for studying the performance of RTLD. All metrics are defined with respect to the network layer. The packet delivery ratio is the ratio of packets successfully received to the total packets sent in the network layer. The energy consumption is the total energy consumed in each sensor node during the simulation task. RTLD is compared with three baseline protocols that consider energy consumption and velocity with energy efficiency. One of the most common protocols is AODV, which is a reactive routing protocol. The other protocol, Maximum remaining Power (MAXP) integrates a geographic forwarding policy with energy consumption. It selects next hop based on the most energy forwarding choice. RTPC

Table 1 Simulation parameters

Parameter	IEEE 802.15.4	IEEE 802.11
Propagation Model	Shadowing	Shadowing
path loss exponent	2.5	2.5
shadowing deviation (dB)	4.0	4.0
reference distance (m)	1.0	1.0
seed for RNG	0	0
phyType	Phy/WirelessPhy/802_15_4	Phy/WirelessPhy
macType	Mac/802_15_4	Mac/802_11
CSThresh_	1.10765e-11	2.78242e-10
RXThresh_	1.10765e-11	2.78242e-10
freq_	2.4e+9	2.4e+9
Power transmission	1mW= 0dBm	25mW= 14dBm
Traffic	CBR	CBR

protocol is a geographic routing protocol, which forwards packet to the most energy efficient forwarding choice that meets the packet's velocity [5]. All the above baseline protocols including RTLD operate at a default transmission power level of 0 dBm (1 mW) for MICAz as in IEEE 802.15.4 and 14 dBm (25 mW) in IEEE 802.11 [14].

Table 1 shows the receiving threshold which reflects the specification of IEEE 802.15.4 and IEEE 802.11 MAC sub layer. If the power received for a frame is below the threshold value, the MAC sub layer will discard it. The simulation evaluates the performance of the all forwarding policies in the case when the neighbor table of each node does not

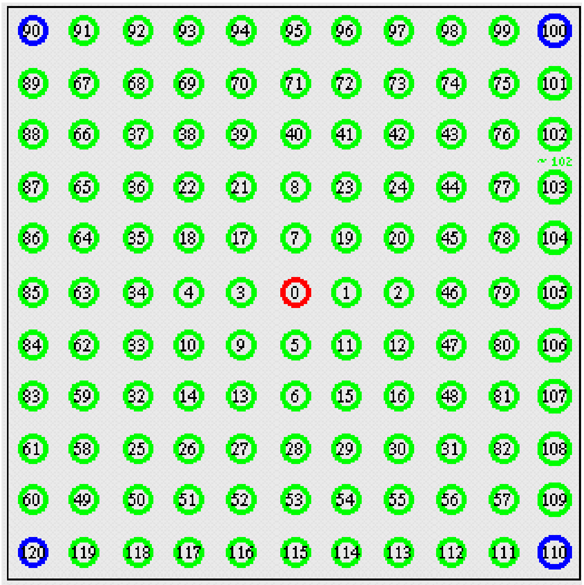


Figure 6 Simulation grid

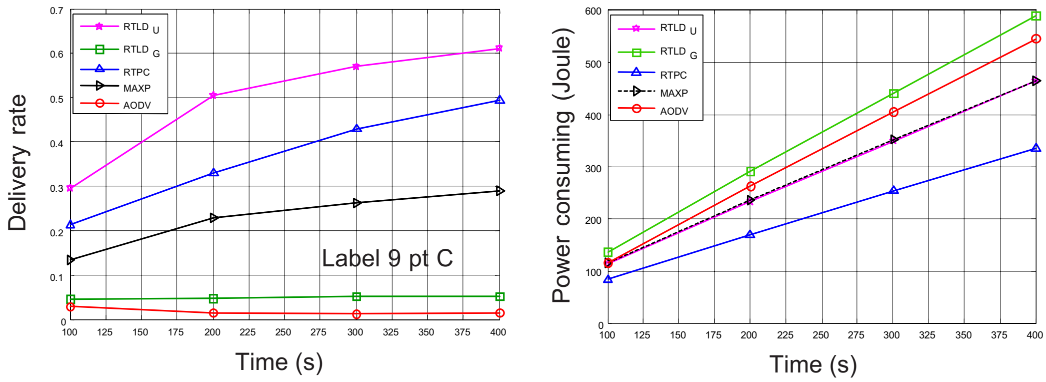
have forwarding choices. The link quality of each forwarding choice is estimated online according to Equation (8).

4.1 Performance at Fixed Workload

The simulation is designed to evaluate the performance of the forwarding policies running in conjunction with the neighborhood management policies. In the following simulations, RTLD uses on demand neighborhood discovery scheme as described in Sub section 3.2.2. In all experiments, each node updates its neighbor table every 20 s. When the periodic beacon scheme is used, data packets start to be transmitted after 10 s to allow for the neighbor table forwarding metrics to be initialized. The neighborhood management of the RTLD protocol is designed to maintain those nodes that have good link quality in the neighbor table. Other information about these neighbors is also stored. In both experiments, the simulation time was varied to analyze the effects of the simulation time on the delivery ratio and the total power consumed with a fixed end-to-end deadline of 250 ms and a fixed packet rate. RTLD has simulated with two different type of forwarding methods: RTLD with geodirectional-cast forwarding ($RTLD_G$) and RTLD with unicast forwarding ($RTLD_U$).

In the first simulation, the IEEE 802.11 MAC sub layer is used and the protocols evaluated are AODV, RTPC, MAXP, $RTLD_G$ and $RTLD_U$ as shown on Fig. 7. In this figure, the packet rate is high and equals to 25 packet/s and the simulation time changes from 100 s to 400 s. Figures 7(a) and 7(b) indicate that the $RTLD_U$ provides the highest delivery ratio with acceptable energy consumption. This is mainly due to its forwarding strategy that considers the deadline based on the link quality. The packet delivery ratio in AODV drops more packets than $RTLD_G$ in the face of congestion because it floods the network with a control packet. The congestion is not only the reason for packet dropping in AODV and $RTLD_G$. Packet loss may also be due to the miss deadline under heavy workload. The energy constraint is vital for sensor nodes to minimize energy consumption in radio communication to extend the lifetime of the sensor networks. Figure 7(b) shows the energy consumption for all routing protocols. RTPC has the lowest energy consumption because its forwarding strategy uses minimum number of hops between the source and the destination. However, the minimum number of hop used in RTPC forwarding strategy affects the delivery ratio more than 10% compared to the $RTLD_U$ as shown in Figure 7(a).

In the second simulation, the MAC sub layer were changed to IEEE 802.15.4 and the packet rate is fixed at 3 packets/s while the end-to-end deadline is maintained at 250 ms. We have used a much lower packet rate since the IEEE 802.15.4 does not work well in heavy workload [6]. The protocols evaluated are MAXP, RTPC, $RTLD_G$ and $RTLD_U$ as shown on Figure 8. It is interested to note that AODV is not simulated in Figures 8 and 10 because AODV in IEEE 802.15.4 is designed to work with two-ray ground radio propagation model but the simulation in this paper depends on shadowing propagation model.

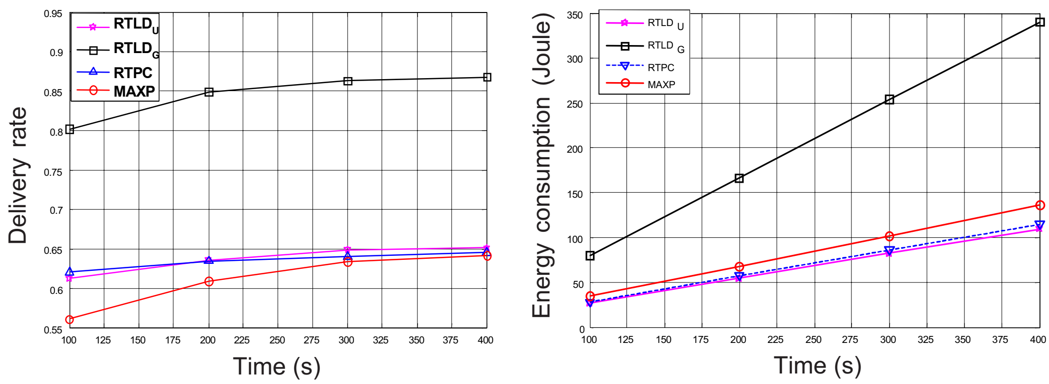


(a) Delivery ratio at 25 packet/s (b) Energy consumption at 25 packet/s

Figure 7 Performance of baseline protocols at fixed packet rate in IEEE 802.11

Figure 8(a) indicates that the $RTLD_G$ provides the highest delivery ratio. However, MAXP does not perform well in real time routing because its forwarding does not care about the end to end deadline. Figure 8(b) shows the energy consumption in each protocol. $RTLD_G$ consumes the highest energy because its forwarding strategy broadcasts the data packets. RTPC has delivery ratio and energy consumption similar to $RTLD_U$ due to low traffic load.

In general, the finding concludes that if the data rate is fixed, $RTLD_U$ experiences high delivery ratio with acceptable power consumption compared to RTPC. $RTLD_G$ has high throughput in low traffic load and consumes more power in favor of meeting end to end deadline because the original sources broadcast the data packet to one-hop neighbor.



(a) Delivery ratio at 3 packet/s (b) Energy consumption at 3 packet/s

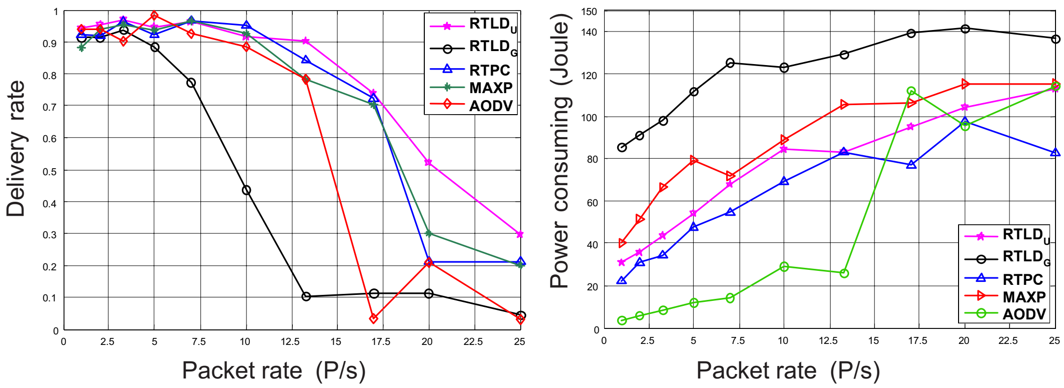
Figure 8 Performance of baseline protocols at fixed packet rate in IEEE 802.15.4

4.2 Impact of Varying the Workload

Further simulations were carried out on both the IEEE 802.11 and 802.15.4 MAC sub layer but this time the packet rates were varied while the end-to-end deadline and simulation time are fixed at 250 ms and 100 s respectively.

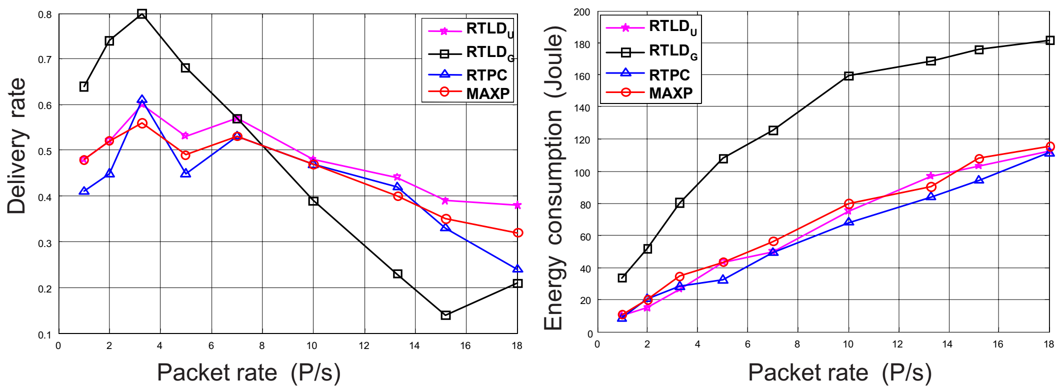
For the IEEE 802.11 simulation, the traffic load is varied from 1 to 25 packet/s. On the other hand, in IEEE 802.15.4 simulation, the traffic load is varied from 1 to 18 packet/s to emulate low data rate in IEEE 802.15.4.

The results in Figure 9 show that $RTLD_U$ experiences a high packet delivery ratio with acceptable power consumption compared to RTPC when the traffic load is varied. However, the packet delivery ratio of RTPC drops more sharply in the same range. The packet delivery ratio of AODV and $RTLD_G$ drops more sharply in the high



(a) Delivery ratio at different packet rate (b) Energy consumption at different packet rate

Figure 9 Performance of baseline protocols at different packet rate in IEEE 802.11



(a) Delivery ratio at different packet rate (b) Energy consumption at different packet rate

Figure 10 Performance of baseline protocols at different packet rate in IEEE 802.15.4

traffic load because the congestion is high due to the broadcasting. Figure 10 shows the delivery ratio and energy consumption of MAXP, RTPC, $RTLD_G$ and $RTLD_U$ for the IEEE 802.15.4 MAC, when the workload changes from 1 to 18 packet/s. At lower packet rate of 3 packets/s, $RTLD_G$ experiences the highest packet delivery ratio. $RTLD_U$ experience slightly higher power consumption compared to RTPC because $RTLD_U$ provides a highest delivery ratio which is important for real-time performance. $RTLD_G$ consumes more power to achieve high delivery ratio. Table 2 summarizes the performance of all routing protocols based on IEEE 802.11 and IEEE 802.15.4.

Table 2 Performance analysis

Parameters	**IEEE 802.11**		**IEEE 802.15.4**	
Delivery ratio of 25 packets/s	$RTLD_U$	highest	It does not work well in heavy workload because it designed for low rate wireless network.	
	RTPC	higher		
	MAXP	higher		
	$RTLD_G$	lower		
	AODV	lowest		
Energy consumption of 25 packets/s	$RTLD_G$	highest		
	AODV	higher		
	MAXP	lower		
	$RTLD_U$	lower		
	RTPC	lowest		
Delivery ratio of varying work load	$RTLD_U$	highest	$RTLD_G$	highest
	$RTLD_G$	higher	$RTLD_U$	higher
	RTPC	higher	RTPC	Medium
	MAXP	lower	MAXP	Medium
	AODV	lowest		
Energy consumption of varying work load	$RTLD_G$	highest	$RTLD_G$	highest
	MAXP	higher	$RTLD_U$	lower
	$RTLD_U$	Medium	MAXP	lower
	RTPC	lower	RTPC	lowest
	AODV	lowest		
Delivery ratio of low data rate 3 packets/s		$RTLD_G$	highest	
		$RTLD_U$	higher	
		RTPC	Medium	
		MAXP	lowest	
Energy consumption of low data rate 3 packets/s		$RTLD_G$	highest	
		MAXP	higher	
		RTPC	Medium	
		$RTLD_U$	lowest	

5.0 CONCLUSION

This paper presents the $RTLD_U$ and $RTLD_G$ design for WSN. RTLD is proposed to enhance the previous work in term of the delivery ratio. The finding shows that $RTLD_U$

experiences a high packet delivery ratio and consumes slightly higher power consumption compared to RTPC in IEEE 802.11 and IEEE 802.15.4. $RTLD_G$ maintains a high delivery ratio when there is no congestion. It consumes more power to achieve a high throughput. The significant feature of RTLD is that it distributes the load of forwarding to all forwarding candidate to avoid packet dropping due to power expiration in specific forwarding candidate. In the future RTLD will be evaluated through real experiment based on radio model of MICAz motes.

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