Opportunistic Real-Time Routing in Multi-Hop Wireless Sensor Networks

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ABSTRACT

Wireless sensor networks (WSNs) are subject to significant resource constraints. Particularly, routing protocols for low-rate WSNs suffer from maintaining routing metrics and stable links of paths. Even though opportunistic routing protocols are well-suited to WSNs, they have some weaknesses for supporting real-time data and low power consumption. This paper proposes a new routing protocol called opportunistic real time routing (or ORTR) that guarantees delivery of data under time constraints with efficient power consumption. In order to satisfy time requirements, an area where real-time data must be delivered is defined with effective transmission power and a relay node within the area is selected for the purpose of balancing overall energy levels. We compare existing routing protocols against ORTR through a set of simulation experiments. Our simulation results illustrate that ORTR provides guaranteed real-time service with optimal transmission power without degrading the energy balance.

Categories and Subject Descriptors

C.2.2 [**Network Protocols**]: Routing protocols; C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems

General Terms

Real-time routing

Keywords

Opportunistic real-time routing, Wireless sensor networks

1. INTRODUCTION

Typically, routing schemes are needed in multi-hop wireless networks for the delivery of data. Unlike wired networks, the reliability of link condition in wireless networks fluctuates so that some routing schemes are based on building the most reliable rather than the shortest path between the source and the destination [6]. In order to maximize reliability, a medium access control (MAC) scheme handles the transmission power consumption and a routing scheme selects paths avoiding unreliable links. The delivery of data in a timely fashion is highly related to the reliability of routing paths. Many existing works have studied routing protocols for transferring real-time data in wireless environments [3, 5, 8, 10, 13].

Wireless sensor networks have limited resources for communication. For that reason, sensor networks based on low-rate wireless personal area networks (LR-WPAN) have difficulty managing extra transmission, efficient power consumption, and heavy routing metrics for the delivery of data. The concept of opportunistic routing is well-suited to wireless sensor networks (WSNs) [15] but has some shortcomings toward effective transmission power and timely delivery.

The design of real-time routing schemes in LR-WSNs must consider the following issues. First, there are less additional message transmissions for recognizing the link condition. Even though the link measurements for maintaining routing metrics are useful for the adaptation of dynamic link changes, transmissions based on low-rates can lead to heavy traffic. Second, for time-sensitive WSN applications (e.g., surveillance, tracking), real-time guarantees on message delays must be provided. Third, traffic load has to be balanced. The load of traffic causes queuing delays that can negatively influence the satisfaction of timing requirements and maintenance of energy balance. Fourth, the remaining battery level has to be balanced because routing holes or unrecognizable regions can occur [11]. Although the traffic load distributes evenly, the balance of battery consumption for each node must be considered independently. Finally, transmission power must be effectively consumed. An increase in transmission power can reduce transmission delay, but can increase interference, which means that other nodes utilize the channel less.

In order to meet these requirements, the routing scheme should cooperate with MAC-layer functionalities. The MAC-layer plays a role in the control of wireless link condition and transmission power. Thus, information from the MAC-layer can be used for effective power consumption and for meeting real-time requirements [7]. In fact, discovering an optimal path to achieve both energy efficiency and guaranteed real-time service is an NP-hard problem. The main purpose of real-time routing is to find a feasible path that has sufficient resources to satisfy the time constraints. In this paper, we present a heuristic method called opportunistic real-time

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routing (or ORTR) that integrates routing-layer and MAC-layer functionalities to meet real-time requirements.

For the delivery of real-time data in WSNs, ORTR computes an optimal region that data must be sent for guaranteeing the real-time delivery using effective transmission power. This paper provides some important contribution. First, we compute the smallest transmission power demanded by real-time data and all nodes within the optimal region guarantee it time requirements. Secondly, one of nodes is selected using its remaining battery level so that it leads to balance overall power level. Our simulation study shows that ORTR performs better than existing routing schemes in particularly heavy traffic.

The rest of this paper is organized as follows. In Section 2, we overview past and related research. The key ideas of ORTR is described in Section 3 and the protocol is described in Section 4. In Section 5, we present our simulation results. The paper concludes in Section 6.

2. RELATED WORK

Routing protocols in WSNs are classified based on network structure into data-centric, hierarchical and location based protocol [3]. Data-centric protocols are dependent on the naming of desired data so that redundant transmission is reduced. Hierarchical protocols based on node clustering provide the aggregation and reduction of data for saving energy. Location based protocols use the location information to forward data to the desired area instead of entire networks. In addition, routing approaches are based on the scheme for general network flow or for meeting some time requirements.

Opportunistic routing is a scheme to achieve high throughput in lossy wireless links [4]. The scheme extends the concept of location-based routing for specifying broadcasting region [15]. There are pre-existing two issues of the routing scheme: how to define broadcasting region and how to find a best forwarder to reach the destination [14, 15]. In this paper, we address two more issues on the scheme: power consumption for energy effectiveness and guaranteed service for real-time data. In order to achieve both issues, the traditional approach provides how to compute the end to end delay using system resources such as transmission power and channel-state information [5]. However the proposed approach is how to uses the resources for the guarantee of their time requirements.

This paper contributes to the decision of an optimal broadcasting region for real-time data transmission and the selection of a forwarder through the policy of assigning various sizes of backoff exponents (BE) according to the remaining power level (RPL) of the nodes. In this paper, we design a new routing scheme by exploiting the broadcast advantage of wireless networks. For an evaluation, we compare existing routing schemes with ORTR for energy effectiveness and miss ratio under moderate and heavy traffic.

3. OUR APPROACH

Before broadcasting real-time data, a sender computes an expected real-time guarantee region (ERTGR), which describes the geographical region where data must reach for guaranteeing its time requirements (TR). Real-time data with a short TR is assigned relatively more transmission power so that the transmission range is enlarged. The assignment of less power for long TR indicates that the transmission range is reduced, which means that other nodes may be given chances to send data. Thus, our approach is to compute an optimal ERTGR using the most effective transmission power for managing its TR and determine the best forwarder within the ERTGR. After the sender broadcasts real-time data, a forwarder node within the ERTGR is determined through the assignment of different BE values according to its RPL. If the power level is low, a long BE is assigned, which means that a node which has a relatively high power level is able to get a chance to send its packets first. If a node has an extremely low power level, the node does not act as a forwarder. The next ERTGR is determined by the selected forwarder using a new TR, excluding the time consumed by the previous transmission.

3.1 Expected Real-Time Guarantee Region

In order to determine an ERTGR, a node uses its resources – i.e., transmission power and channel state. If the TR is relatively short, the node tries to send data to the particular region that is relatively far away from itself.

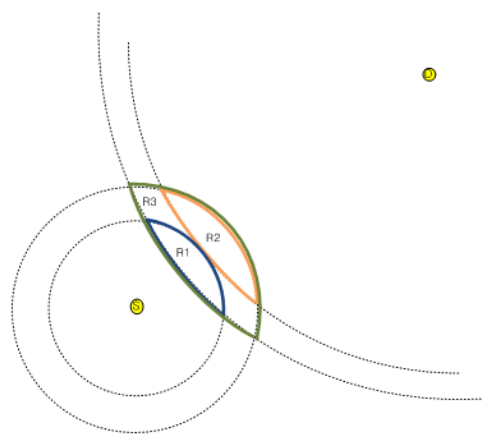

Figure 1: Example ERTGR Calculation

Figure 1 shows an example ERTGR calculation. According to the TR, the region R1 or R2 is determined. The node sends data (by broadcasting) to the region using the control of transmission power. Due to the nature of the broadcast, we do not expect that all nodes within the ERTRG receive the data. The reception of the nodes may be limited due to heavy traffic or interference. Thus, the size of the ERTGR is dependent on the channel state. If the channel state is poor, the larger region R3 is determined. Only received nodes participate in the decision process for selecting a forwarder. Now, the problem is to find an optimal ETRGR.

3.2 The Assignment of Backoff Exponent for the Best Forwarder

IEEE 802.15.4 MAC-layer, which we assume in this work, transmits using the unslotted version of carrier sense multiple access with collision avoidance (CSMA-CA) algorithm [2]. The BE is related to not only network congestion and sharing bandwidth. The proper distribution of BE provides fair and efficient allocation of bandwidth through the competition for the channel [17]. We focus on balancing the power consumption instead of the bandwidth. The idea is to give the chance to send data to a node which has more RPL.

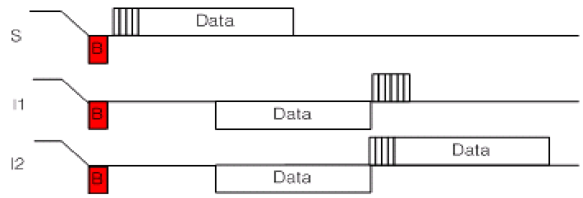

Figure 2: Data Transmission of Forwarder in MAC

Figure 2 shows the decision making sequence of a forwarder using MAC-layer functionalities. The main goal of the ORTR protocol is to define an ERTGR and find a best forwarder to guarantee real-time data delivery and maintain the energy balance in WSNs.

4. THE ORTR PROTOCOL

In order to design the ORTR protocol, we define our system model according to the specification of chipcon CC2420 [1]. In this section, the process of deciding the ERTGR and the selection scheme of a forwarder are described based on the transmission power and the receiver sensitivity of CC2420.

4.1 System model

A node broadcasts a real-time data over LR-WPAN for each node pair (a, A) according to an expected delivery time matrix, $F^i(t) = F^i_{a,A}(t)$ subject to one-hop delivery time of link i, where a is a node and A is a group of nodes within the particular region.

$$F^i(t) = T^i_{TransTime} + T^i_{RelayTime} + T^i_{PropagationTime} \quad (1)$$

$$\sum_{i=i}^{EHC} \cdot F^i(t) \leq TR \quad (2)$$

, where EHC is an expected hop count and i is a link between a and A. We can calculate the expected end-to-end delivery time using Equation 2. If Equation 2 is less than or equal to the TR from the source node, real-time delivery is guaranteed. $T^i_{RelayTime} + T^i_{PropagationTime}$ is a constant time. Thus, we focus on $T^i_{TransTime}$.

$$T^i_{TransTime}(l, m, n) = T^i_{DataTransTime}(l, m) + T^i_{MaxWaitTime}(n) \quad (3)$$

,where m is the bit rate, l is the size of the physical-layer service data unit (PSDU), and n is a backoff exponent (BE).

$$T^i_{DataTransTime}(l, m) = \frac{(l + SHR + PHR) \cdot 8}{m \cdot 10^3} = \frac{(l + 6) \cdot 8}{m \cdot 10^3} \quad (4)$$

$$T^i_{MaxWaitTime}(n) = [(2^n - 1) \cdot aUnitBackoffPeriod + CCA] \quad (5)$$

Including the 6 byte packet overhead (preamble and start of frame delimiter SHR and frame lengh PHR) to the MAC protocol data unit, and given the modulation and the length of PSDU [2], we can calculate the data transmission time as shown in Equation 4. The clear channel assessment(CCA) detection time is defined as 8 symbol periods.

Table 1: Transmission Power Consumption of Chipcon CC2420

Transmission Power(dBm)	Power Consumption (mA)
0	17.4
-1	16.5
-3	15.2
-5	13.9
-7	12.5
-10	11.2
-15	9.9
-25	8.5

$aUnitBackoffPeriod$ is defined as 20 symbol periods (1 symbol period is equal to 16 μs). BE are dependent on the RPL.

LEMMA 1. *Given a P^i_r, the satisfaction of TR is determined by P^i_t, where P^i_t is the transmission power and P^i_r is the reception power of link i.*

PROOF. According to Equation 2, TR is determined by EHC. Given d_{total}, which indicates the distance between the source and destination, EHC is defined as $\lceil \frac{d_{total}}{d^i} \rceil$. Thus, TR is determined by d^i, i.e., the distance of link i. The relationship between power and distance is well known as Friis Transmission Model [9] of $d^i = \sqrt{\frac{P^i_t}{P^i_r}} \cdot \frac{\lambda}{4\pi}$. Therefore, whether or not TR is guaranteed is determined by P^i_t. □

If P^i_t is increased under the boundary of Table 1, EHC is decreased. P^i_r is the RF sensitivity of a receiver. The sensitivity is defined empirically on the distribution of nodes. If the nodes are densely distributed, the sensitivity is relatively small. If the nodes are distributed less densely, EHC is increased so that P^i_t depends on the TR according to Lemma 1. We assume that link i represents all links to compute the EHC based on broadcast nature. It is difficult to determine exactly the future condition of all links. Even if we attempt to precisely anticipate a link condition, real-time transmission may not be guaranteed based on that condition because it is frequently outdated.

4.2 Guaranteeing Real-Time Service with Efficient Power Consumption

Even if we calculate a distance for guaranteeing time requirements using the minimum transmission power, due to harsh wireless environments, the real-time delivery of data based on broadcasting may not be guaranteed. An ERTGR would be located in a transitional region with unreliable links. Therefore, we need to know how the channel and radio determine the transitional region. The relationship between P^i_r and P^i_t with distance r_x is given by [19]:

$$P(r_x)^1 = P(r_0) + 10\log_{10}(\frac{r_x}{r_0}) + X_\sigma \quad (6)$$

$P(r_x)$ is the amount of the degradation under link i. We need to calculate the maximum and the minimum value of r_x with the same P^i_t and the P^i_r, which is defined as the range between the minimum sensitivity of node and the consumed signal strength in one hop. P^i_r adapts the distribution of nodes.

[1] r_0: reference distance, σ: shadowing effects

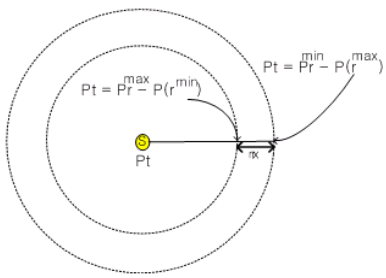

Figure 3: Definition of Expected Progress of Transmission

THEOREM 1. *Given a TR and P_r^i, all nodes within an ERTGR composed of the range of r_x determined in the following Equation 7 guarantee the TR:*

$$P(r_x) = P_t^i - P_r^i \tag{7}$$

$$subject\ to\ \lceil \frac{d_{total}}{r_x} \rceil \cdot F^i(l,m,n) \leq TR.$$

PROOF. In order to compute the average distance in the range between two r_x values illustrated by Figure 3, we have the range of the expected progress of transmission according to Equation 8 [16].

$$g(x) = \int_{r_{min}}^{r_{max}} x \cdot P_x(Progress\ is\ x) \cdot dx \tag{8}$$

$g(x)$ indicates the average distance of the transmission for one-hop. If P_t^i derived from Equation 7 satisfies the transmission in the TR through $\lceil \frac{d_{total}}{g(x)} \rceil \cdot F^i(l,m,n) \leq TR$, all nodes on the boundary of $g(x)$ guarantee TR.

The ERTGR illustrated by Figure 4 is calculated as:

$$\begin{aligned} ERTGR &= r_{max}^2 \arccos(\frac{r_{mac} + r_{min}}{2 \cdot r_{max}}) \\ &+ (d_{total} - r_{min})^2 \arccos(\frac{2 \cdot d_{total} - r_{max} - r_{min}}{2(d_{total} - r_{min})}) \\ &- d_{total} \cdot \sqrt{r_{max}^2 - (\frac{r_{max} + r_{min}}{2})^2} \end{aligned}$$

Therefore,

$$g(x) = \int_{r_{min}}^{r_{max}} \frac{2 \cdot (d_{total} - x) \arccos(\frac{2 \cdot d_{total} - r_{max} - x}{2(d_{total} - x)})}{ERTGR} dx \tag{9}$$

Thus, P_t^i gives the minimum power consumption, satisfying the TR. □

The proposed scheme is suitable for real-time applications with various TRs. The application notifies its time requirements to the MAC-layer and then P_t^i adapts its time requirements.

4.3 Balancing Power Level

The second step of the proposed protocol is to select a forwarder for balancing the power level within the defined ERTGR. We assume that nodes in the ERTGR share a carrier sensing area. The idea is that a node with a short BE has a higher chance to transmit data. BE indicates how many backoff periods a node will have to wait before attempting to access a channel. The transmission delays for the completion of backoff periods is in the range 0 to $2^{BE} - 1$ [2]. Assigning short BE allows the node to access the CCA more frequently. This leads to a higher probability for successful transmission [12]. The approach is to assign successive BE according to Table 2 for the intermediate nodes.

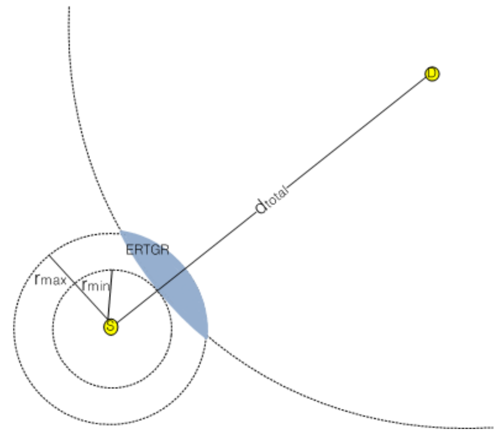

Figure 4: An ERTGR

Table 2: Policy for BE assignment

$macMinBE$	$macMaxBE$	$RPL(\%)$
2	4	∽ 90
3	5	∽ 70
4	6	∽ 50
5	7	∽ 25
6	8	∽ 10

4.4 Algorithm Description

We now describe the algorithm that is performed at each node at the MAC-layer. We use the following definitions to facilitate the algorithm description:

Algorithm 1

NB: the Number of Backoff
BE: Beacon Exponent
$macMinBE$: Minimum BE in MAC
$macMaxBE$: Maximum BE in MAC

1. NB=0;
2. Set BE = macMinBE according to table 2;
3. Calculate an ERTGR,
If TR on any power is not satisfied,then fail;
4. Delay for random $(2^{BE} - 1)$ unit backoff periods;
5. Perform CCA on backoff period boundary;
6. If Channel Idle then transmission;
Else NB=NB+1; BE=min(BE+1,$macMaxBE$);
7. If $NB > macMaxCSMABackoffs$ or receive the same frame then fail, Else goto step 3;

Each node maintains NB and BE for each transmission attempt. NB is initialized to 0 before each new transmission attempt. BE is initialized to the value of macMinBE according to RPL. A random number between $2^{BE} - 1$ and 0 is selected as a backoff period. After the backoff time is over, a node performs CCA to check if the channel is busy or not. If the channel is idle, the transmission is attempted. If the same frame that the node tries to send is received, the frame is discarded because the node realizes that relatively a short BE is assigned to another node within the ERTGR. Otherwise, the node calculates a new ERTGR again using a new BE.

5. SIMULATION STUDY

The goal of our simulation study is to demonstrate real-time delay guarantees and effective power consumption related to TR and the balanced power of participating nodes as a forwarder. Our simulation is conducted in a simple topology composed of evenly distributed 45 and 100 nodes with or without heavy traffic. We define that heavy traffic means that all nodes are involved to data transmission for the simulation. We compare four protocol schemes including Real-time Power Aware Routing (RPAR) [5], Geographic Opportunistic Routing (GOR) [18], Multipath Multi-SPEED protocol (MMSPEED) [10, 8], and our proposed scheme (ORTR). We used the NS2 simulator based on IEEE 802.15.4. The data transmission rate is 250Kbps and the initial power level for each node is 1.

5.1 Effect of Guaranteed Real-Time Service on Transmission Power

We simulated ORTR under moderate and heavy traffic and measured the miss ratio (defined as the fraction of data packets that missed its TR) and the average power consumption per packet. The moderate traffic provides less channel contention when transmitting real-time data so that the miss ratio based on its TR is reduced. Figure 5 shows that the four schemes have similar miss ratios. RPAR, MMSPEED, and ORTR select similar paths to deliver real-time data because of involving the scheme for controlling TR from 100 to 300(ms). Also, GOR yields the same miss ratio because it selects the forwarder that is closer to the final destination. However, in a heavy traffic environment, ORTR outperforms because a forwarder of nodes that successfully receives data is selected through one broadcast. Additionally, even if some nodes are involved in the ERTGR under heavy traffic, they may not receive the broadcast data due to the traffic. Evidently, the nodes are exempt from forwarding so that it leads to balanced traffic. Figure 6 shows the miss ratios of TR under heavy traffic.

Figures 7 and 8 show the average energy consumption per packet transmission under moderate and heavy traffic, respectively. Since GOR and MMSPEED do not consider transmission power consumption, they consume more energy than the other schemes. Under heavy traffic, ORTR outperforms in terms of average energy consumption per a packet transmission because it does not require extra control transmissions for finding reliable paths.

5.2 Effect of Forwarder Selection on RPL

In order to evaluate the balanced power level, we deployed 45 nodes as a 5 by 9 matrix. Nodes 1, 3, and 5 send data to nodes 41, 43, and 50. The disadvantage of broadcasting is that nodes that are not related to data transmission consume energy. However, senders and forwarders have a merit in terms of power level in harsh environments.

Figure 9 shows the remaining power level of each node after data transmission. In GOR and ORTR, other nodes that

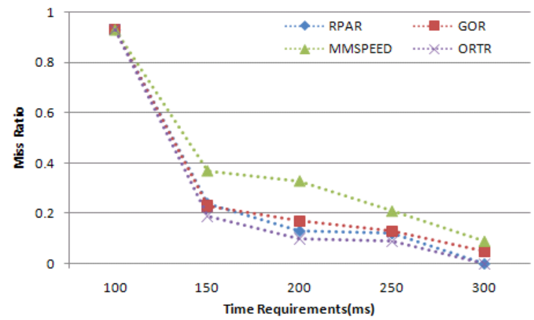

Figure 5: Miss Ratio on Variable TR under Moderate Traffic

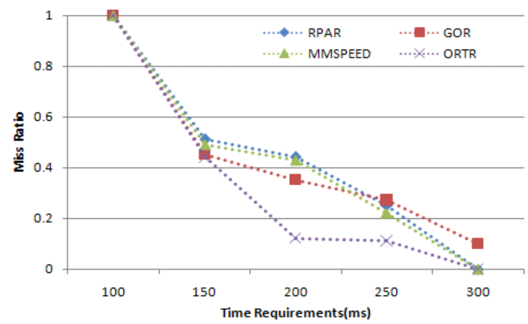

Figure 6: Miss Ratio on Variable TR under Heavy Traffic

do not participate in forwarding consume more energy than the other schemes because of the penalty of broadcasting. However, relatively, overall energy is balanced. Particularly, node 23 shows that its energy is balanced with its neighbor nodes. In the meantime, RPAR, GOR, and MMSPEED suffer from more energy consumption for maintaining routing metrics and paths. These schemes are originally implemented with IEEE 802.11 MAC. In our simulation study, they operated on IEEE 802.15.4 instead of IEEE 802.11 for a fair comparison.

5.3 Discussion

Our simulation results show that ORTR achieves both guaranteed real-time service and effective power consumption in multi-hop WSNs. Additionally, the best forwarder node is selected for balancing the power level. The opportunistic routing protocol takes advantage of broadcasting and the differentiated distribution of backoff exponents. The main objective of ORTR is to determine an optimal ERTGR. However, the ERTGR depends on interference and attenuation, which can influence the sensitivity of reception. Small ERTGR may not be able to exploit the advantages of broadcasting. Thus, an exact loss estimation scheme is needed for the implementation. However, in order to do that, this scheme needs to exchange extra transmissions, which may result in some loss of its performance. Therefore, we are developing a test-bed based on IMote2 for modeling reception signals in the real world. Through channel sensing, the results of modeling can show how to adapt to a reception power.

ORTR is not suited to support periodic real-time data.

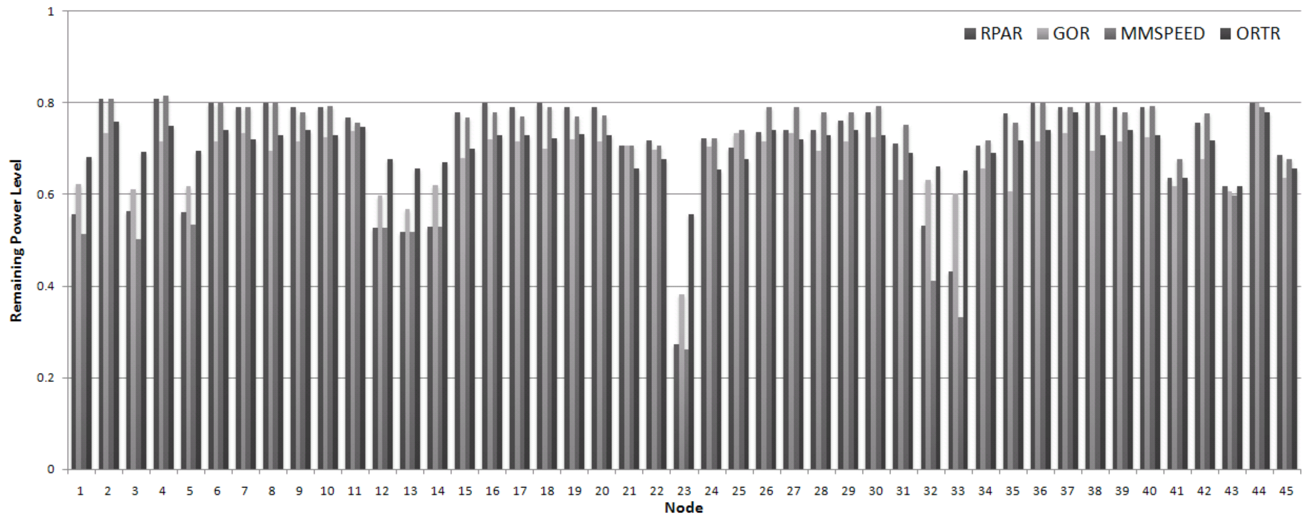

Figure 9: Remaining Power Level of Each Node

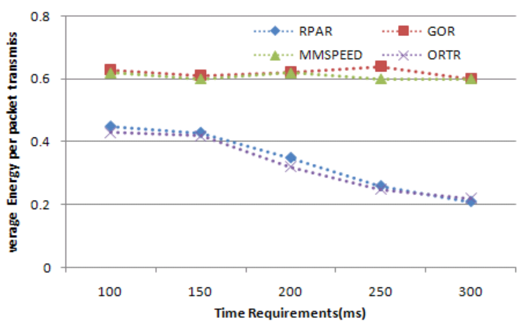

Figure 7: Power Consumption per Packet on Variable TR under Moderate Traffic

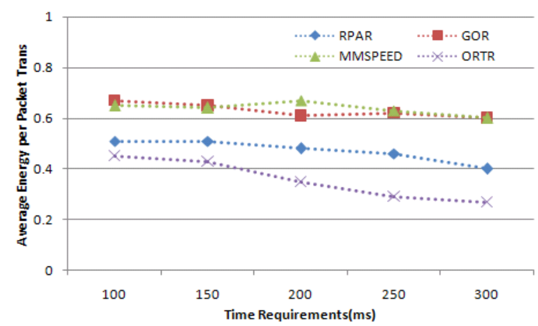

Figure 8: Power Consumption per Packet on Variable TR under Heavy Traffic

Practically, due to low bandwidth in the application layer, LR-WPAN cannot control video and audio data. Our simulation study based on periodic data illustrates that its power consumption is not effective, when compared to traditional routing schemes, because of frequent broadcasts. In fact, we have considered target tracking systems as a motivating application of ORTR so that it works effectively on non-periodic real-time data with variable time requirements.

We have not considered the effect of mobility and the random distribution of nodes. As a future task, our scheme will be tested on both mobile environments and arbitrary node distributions.

6. CONCLUSIONS

In this paper, we propose a novel real-time routing protocol called ORTR for WSNs to achieve guaranteed service using effective power consumption and balance overall power level. Our approach is to define an optimal geographical region that real time data must reach for guarantee and select one of nodes within the region based on remaining power level.

Our simulation results show relatively lower miss ratio of about 20% to 10%, depending on heavy traffic and more effective power consumption of about 10%. Particularly, the remaining power level of overall nodes indicates that energy for each node varies in 10% for balanced energy consumption.

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