Real Time communication with Power Adaptation (RTPA) in Wireless Sensor Network (WSN)

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Abstract- Wireless sensor network (WSN) has become a hot research area due to its important applications in military, health, home and other commercial areas. WSN is referred to as a group of sensors and base station(s) linked by wireless medium to perform sensing and decision-making tasks. In 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. Sensor nodes are low-cost, low-power, multi-functional devices that communicate unattended in short distances [1]. This paper proposes Real Time communication with Power Adaptation (RTPA), a novel real time routing scheme that provides efficient power consumption and the desired quality of service (QoS) in WSN. A key advantage of RTPA is that it can deliver packets within their end-to-end deadlines, while minimizing the network power consumption by adapting the transmission power based on the timing requirements of the workload and link quality between the source and destination. RTPA uses the IEEE 802.15.4 MAC and physical layers standard. IEEE 802.15.4 is a new standard uniquely designed for low rate wireless personal area networks (LR-WPANs). It targets low data rate, low power consumption and low cost wireless networking, and offers device level wireless connectivity.

I. INTRODUCTION

Wireless sensor network is a wireless ad hoc network that comprises of very large number of sensor nodes which are densely deployed either inside the phenomenon or very close to it. Wireless sensor network enables reliable monitoring and analysis of physical environment and are very different from traditional networks; they are composed of a large number of nodes that are densely deployed, produce very large amounts of data, and are limited in power, computational capacities, and memory. Due to these inherent properties, conventional management schemes are not appropriate to manage sensor networks and thus, a new management scheme is needed [1].

Real-time interaction with physical environments is crucial for many WSN applications. For instance, a surveillance system must notify users within a few seconds after an intruder is detected so that pursuing actions can be initiated in time. Similarly, a fire fighter may rely on timely update of temperatures to remain alert to the surrounding fire conditions. Late delivery of sensor data may endanger the fire fighter. Moreover, different sensor data in a system may have different deadlines. To support such applications, the underlying communication protocols must be able to deliver a packet within its specific end-to-end deadline.

From the above scenarios, the main and critical function of sensor networks is data delivery. There are three types of communication patterns associated with the delivery of data in such networks. First, it is often the case that one part of a network detects some activity that needs to be reported to a remote base station. This mode of communication is called unicast. Secondly, a base station may want to issue a command or query to a specific area in the ad hoc sensor network. For example, it may ask all sensors in the region of a damaged nuclear plant to report radiation readings, or command all lights in a given area to turn on. This type of communication motivates a different routing service where one endpoint of the route may be an area rather than an individual node. We call it area-geocast communication.

Finally, 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.

IEEE 802.15.4 is a new standard uniquely designed for low rate wireless personal area networks (LR-WPANs). It targets low data rate, low power consumption and low cost wireless networking, and offers device level wireless connectivity. In non-beacon enabled mode and under moderate data rate, the new IEEE 802.15.4 standard, compared with IEEE 802.11, is more efficient in terms of overhead and resource consumption. It also enjoys a low hop delay (normalized by channel capacity) on average. In beacon enabled mode, an LR-WPAN can be flexibly configured to meet different needs such as link failure self-recovery and low duty cycle. In both modes, association and tree formation proceed smoothly and the network can shape up efficiently by itself. 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 typically between multiple source nodes and a sink [2].

This paper proposes RTPA which is a real time communication with power consideration and it is designed based on results of the previous researches. RTPA enhances and modifies the previous work and hope to achieve low end-to-end delay, low power consumption, reduced overhead in control packet flow, good throughput, less interference and channel contention. RTPA comprises of six
components: geographical location service, real time forwarding metrics assignment policy, power management, neighborhood management, forwarding management system and handling routing problem as shown in Fig. 1.

The remainder of this paper is organized as follows. Section 2 will present related work on real time communication and power control protocols. Design of RTPA in WSN will be described in Section 3 and Section 4 will describe the simulation implementation of RTPA. Finally Section 5 will conclude the paper.

II. RELATED WORK

Several real-time protocols have been proposed for wireless sensor and ad-hoc networks. At the MAC layer, the EDCF mode of the proposed 802.11e [3] protocol supports packet prioritization based on service classes. Implicit EDF [4] is a collision-free real-time scheduling scheme that exploits the periodicity of WSN traffic. RAP [5] prioritizes real-time traffic through a novel velocity monotonic scheduling scheme which considers both a packet's deadline and distance to the destination. In RTPA, IEEE 802.15.4 MAC layer is used which has low data rate, low power and low cost wireless network [10]. Higher-layer protocols that deal with real time issues also exist. For example, SWAN [6] provides differentiated services on mobile ad-hoc networks through stateless control algorithms. SPEED [7] bounds the end-to-end communication delay by enforcing a uniform communication speed throughout the network. MM-SPEED [8] is an extension to the SPEED protocol and designed to support multiple communication speeds and provides differentiated reliability. A comprehensive review of the challenges and the state of the art of real-time communication in sensor networks can be found in [9]. In general, a distinguishing aspect of this paper is the use of power adaptation as a mechanism to meet packet deadlines and reduce power consumption.

Transmission power control has been studied extensively in the context of wireless ad-hoc networks. The previous work can be roughly classified into two approaches, namely topology control and power-aware routing. Topology control preserves a desirable property of a wireless network (e.g., K-connectivity, maximize throughput) by reducing the transmission power of nodes. A survey on existing topology control schemes can be found in [11]. We review several representative works here. Ramanathan et al. [12] proposes two centralized algorithms to minimize the maximal power used per node to preserve the (bi) connectivity of the network. Li et al. [13] proposes a cone-based topology control scheme in which each node reduces the transmission power to reach one neighbor in each cone. A MST-based topology control scheme is proposed in [14] to preserve the network connectivity and bound node degrees. More recently, an empirical study on MICA2 motes showed that transmission power control can effectively improve the link quality of WSNs [15]. Note that this paper distinguishes itself from the work on topology control by attempting to manage the tradeoff between throughput and delay, sacrificing throughput in favor of low delays. This property makes RTPA particularly suitable for real-time applications with moderate but time critical workload. The goal of power-aware routing is to find energy-efficient routes by varying transmission power. Singh et al. [16] proposes five power-based routing metrics that can minimize power consumption or extend system lifetime. Li et al. [17] proposes an online power-aware routing scheme to optimize system lifetime. Chang and Tassiulas [18] propose a local algorithm to maximize the lifetime of a network with known message rates. Sankar et al. [19] formulated maximum lifetime routing as a maximum concurrent flow problem and propose a distributed algorithm. [16] proposes a linear programming approach to maximize the system lifetime based on the formulation of multi commodity flows. Power aware routing schemes have been implemented on real wireless network platforms [20,21]. Although the above studies demonstrate the effectiveness of transmission power control in reducing power consumption, none of them deal with real-time requirements in WSNs. Different from the aforementioned works that treated real time communication and energy-efficient communication separately; our RTPA approach integrates power adaptation and real time routing to support power-efficient real-time communication.

The most related work to RTPA approach is real time power control (RTPC) [22]. However, the differences between [22] and RTPA approach are described as follows: RTPC uses the velocity requirement as a metric of selection forwarding node but RTPA uses the best value of the product of the velocity requirement and Packet Reception Rate (PRR). The velocity, \( V \), alone does not have the information about link quality and the best link quality usually has low packet loss [23]. Secondly, RTPC does not use the power remaining factor in the choice of the forwarding node while RTPA uses this factor to estimate the lifetime of the forwarding choice to avoid the routing holes problem. Thirdly, RTPC does not introduce complete solution for the routing holes problem but RTPA does. Fourthly, RTPC uses the broadcasting neighbor discovery to solve the problem of failing to find available forwarding choice but RTPA uses the geocasting neighbor discovery since geocasting has less communication overhead. Finally, RTPC uses B-MAC layer [24] but RTPA uses IEEE 802.15.4 MAC layer which has low power consumption.

III. DESIGN OF RTPA IN WSN

RTPA comprises of six components: geographical location service, real time forwarding metrics assignment policy, power management, neighborhood management, forwarding management system and handling routing problem. Fig. 1 shows the general block diagram of RTPA. RTPA is implemented in the network layer of the TCP/IP model. Brief descriptions about RTPA are as follows:

A. Geographical Location Services

RTPA utilizes location information to carry out routing. Because of this, we assume that each node is location aware. Each node in RTPA can use any location information service such as [25,26] to aware its location in WSN area. In addition, the location service of each sensor node has all one hop neighbors’ geographic location.
B. Real Time Forwarding Metrics Assignment Policy

RTPA calculates two real time factors: required velocity from the source to the destination ($V_r$) and packet reception rate (PRR) of the link between the source and the one hop neighbor. $V_r$ can be calculated as follows:

$$V_r(S, D) = \frac{d(S, D)}{\text{end to end deadline}}$$  \hspace{1cm} (1)

where $d(S, D)$ is the Euclidean distance from source node $S$ to the destination node $D$. The end to end deadline is the amount of time left before the deadline expires. The required velocity is computed on each hop. If a packet is late then the required velocity is increased so that the packet may catch up. Conversely, if the packet arrives early the required velocity is decreased. The end to end deadline is included in the header of packet and updated in each hop.

RTPA calculates the PRR for both analysis and simulation as in (2). The PRR in RTPA uses the link layer model derived in [10] and uses the same calculation but with different representation for the transmission data as derived in [27].

$$\text{PRR} = 1 - \left( 1 - \left( 1 - \frac{d}{d_0} \right)^{16 \sum_j \exp \left[ 20 \gamma(d_j) \left( \frac{1}{16} - 1 \right) \right] \right)^{-76}$$  \hspace{1cm} (2)

where $\gamma(d)$ is Signal to Noise Ratio (SNR) and it can be calculated as follows:

$$\text{SNR} = \gamma(d) = P_t - PL(d) - S_r$$  \hspace{1cm} (3)

where $P_t$ is the transmitted power in dBm, $S_r$ is the receiver's sensitivity in dBm-95 dBm in CC2420 which is used in MICAz. $PL(d)$ is the path loss model which can be calculated as follows:

$$PL(d) = PL(d_0) + 10n \log \left( \frac{d}{d_0} \right) + X_o$$  \hspace{1cm} (4)

where $d$ is the transmitter-receiver distance, $d_0$ is the reference distance, $n$ the path loss exponent (rate at which signal decays) which depends on the specific propagation environment. For example, in free space, $n$ is equal to 2 and when obstructions are present, $n$ will have a larger value. $X_o$ is a zero-mean Gaussian distributed random variable in (dB) with standard deviation $\sigma$ (shadowing effects in dB).

RTPA also estimates the one hop delay of each neighbor as follows:

$$\text{Delay}(S, N) = \frac{\text{cont} + \text{transm} + \text{timeout}}{\text{PRR}(S, N)}$$  \hspace{1cm} (5)

In (5), $\text{PRR}(S, N)$ represents the packet reception rate of the link between $S$ and its neighbor $N$. $1/\text{PRR}(S, N)$ is the expected number of retransmissions before successfully forwarding the packet to $N$. The delay of each retransmission includes the time it takes for $S$ to obtain the wireless channel (denoted by $\text{cont}$), the time to transmit the packet (denoted by $\text{transm}$) and a timeout that indicates a transmission failure. Since $\text{transm}$ and the $\text{timeout}$ are constants determined by packet size and node bandwidth, the main function of the delay estimator is to monitor the PRR of each link and the contention delay.

For each one hop neighbor, RTPA calculates PRR and available velocity from source node $S$ to neighbor node $N$ ($V_a$) and stores the values in the neighborhood table. The available velocity can be calculated as follows:

$$V_a(S, N) = \frac{d(S, N)}{\text{Delay}(S, N)}$$  \hspace{1cm} (6)

C. Power Management

RTPA focuses on minimizing the energy to transmit packet which is only a part of the total energy consumption of a network. To further minimize the energy consumption, a WSN needs to integrate real time communication with a power management protocol that reduces the energy wasted by idle listening. However, low-power wireless networks usually have unreliable links and limited bandwidth. Furthermore, link quality can be heavily influenced by environmental factors [28]. Moreover, many WSN applications must remain operational for months or years without wired power supplies. RTPA designed for WSNs must therefore balance real-time performance with power efficiency. For example, transmitting a packet using high power may increase the communication range and/or improve link quality [27] and hence reduce the communication delay; it may also increase the power consumption. In this project, MICAz with ZigBee wireless interface is used. ZigBee has eight steps programmable output power from approximately -25 dbm to 0 dbm with current consumption from 8.5mA to 17.5mA. The power remaining in WSN node also can be monitored. RTPA achieves both desired communication delays and low power consumption under medium workload by dynamically adapting the transmission power based on packet deadlines and network conditions.
The MICAz has an accurate internal voltage reference that can be used to measure battery voltage ($V_{\text{bat}}$). Since the eight-channel ADC on the 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) is monitored to determine the ADC full-scale (ADC_FS) voltage span which corresponds to $V_{\text{bat}}$ [29].

To compute the battery voltage, the following steps were taken:

- Program the application code to measure ADC channel 30 – the Internal Band gap Voltage reference.
- Compute battery voltage, $V_{\text{bat}}$, from ADC reading (ADC_Count) by:
  \[
  V_{\text{bat}} = \frac{V_{\text{ref}} \cdot \text{ADC_FS}}{\text{ADC_Count}}
  \]  
  \[ (7) \]

where $V_{\text{bat}}$ is battery voltage, ADC_FS is equal to 1024, $V_{\text{ref}}$ (internal voltage reference) is equal to 1.223 volts and ADC_Count is Data from the ADC measurement of Internal Voltage reference. The TinyOS component that is VoltageM.nc can be wired into an application to provide this measurement capability. The reserved keyword TOS_ADC_VOLTAGE_PORT is mapped to ADC Channel 30 in the MICAz.

D. Neighborhood Management

The design goal of the neighborhood manager is to discover a subset of forwarding candidates (neighbor-power pairs) and maintain a neighborhood table containing the forwarding candidates. Due to the limited memory space and the large number of combinations of neighbors and power levels, the neighborhood table must keep a small set of forwarding candidates that are most useful in meeting the current velocity requirements with the best PRR.

The neighborhood table will include at least the following field:

- Node ID: the IP address of the neighbor node.
- Power remaining: the power remaining of the neighbor node.
- Available velocity ($V_v$): the available velocity from source node to neighbor node.
- Packet reception rate (PRR): represents the packet reception rate of the link between the source and neighbor node.
- Expire Time: used to timeout the neighborhood table entry. If a neighbor entry is not refreshed after a certain timeout, it will be removed from the neighbor table.

E. Forwarding Policy

In general, high PRR corresponds to low packet loss and between half to 80% of communication energy is wasted on repairing lost transmission [28]. RTPA forwards a packet using the most energy efficient forwarding choice that meets the deadline as explained in the following algorithm:

**Step 1:** Check RTPA real time forwarding condition ($V_v \cdot \text{PRR} \leq V_v \cdot \text{PRR}$) in neighborhood table for the nodes that have same quadrant (direction) with destination.

**Step 2:** Check the power remaining for each forwarding candidates that implement step 1 in neighborhood table.

**Step 3:** Select the optimal forwarding choice with the highest power remaining.

**Step 4:** if no neighbor satisfies the forwarding condition, RTPA will use power adaptation algorithm and it will repeat this algorithm from step 1 to step 3.

**Step 5:** if RTPA cannot find a viable forwarding choice after increasing the link powers through the power adaptation scheme, it will use the neighbor discovery algorithm and it will repeat this algorithm from step 1 to step 3.

The forwarding policy may fail to find a forwarding node when no neighbor currently in the neighborhood table forwards the packet closer to the destination or when no forwarding choice in the table meets the forwarding condition. RTPA has two options to recover from these failures; they are Power Adaptation and Neighbor Discovery.

Power Adaptation

This scheme increases the transmission power to improve the velocity provided by the neighbors already in the neighbor table when the forwarding condition is not met. On the other hand, when the forwarding condition is met, it attempts to improve the energy efficiency by decreasing the transmission powers. A multiplicative increase and linear decrease scheme is used by the power adaptation process as discussed in the following. First, we consider the case when the forwarding policy cannot identify a forwarding choice that meets the forwarding condition. RTPA first determines which neighbor's power should be increased. We call a neighbor eligible for power adaptation if it is beneficial to increase the transmission power of the link to it. Specifically, a neighbor is eligible if (i) the estimated PRRs of all existing forwarding choices associated with the neighbor are below a threshold; and (ii) all transmission powers in the existing forwarding choices associated with the neighbor are below the maximum power. RTPA implements the binary search to find the optimal power level to satisfy the forwarding choice. The binary search
The process continues until a forwarding choice can meet the forwarding condition for the current packet or the maximum power has been reached for all nodes in the neighbor table. The power adaptation can also be triggered to decrease the transmission power to improve the energy efficiency of RTPA. When the forwarding choices of incoming packets consistently lead to local velocities with PRR higher than required, RTPA decreases the power of the most energy efficient forwarding choice by using binary search until one of the following conditions is satisfied: (i) the minimum power has been reached; (ii) the PRR of the link drops below a threshold. The power adaptation scheme provides a mechanism for fast adaptation to changing environments. A key benefit of this scheme is that it utilizes the data packets and does not incur any communication overhead.

**Neighbor discovery**

When RTPA cannot find a viable forwarding choice after increasing the link powers through the power adaptation scheme discussed earlier, the neighbor discovery component is invoked to find new neighbors. The goal for neighbor discovery is to identify a node that achieves the forwarding condition. The neighbor discovery mechanism should introduce 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 occurred on node S when routing a packet destined for D that has a velocity requirement Vr. S starts the neighbor discovery by geocasting a request to route (RTR) packet at some power p. Some neighbor node (N) hears the RTR and replies. Upon receiving the reply, RTPA inserts in its neighbor table the new neighbor node (N, p). When RTPA did not receive a reply from any node, RTPA will geocast a RTR at the default power level. Otherwise, the RTR will geocast at the maximum power. This ensures that far away nodes which may provide high delivery forwarding condition may reply to the RTR. Hence from this description, the forwarding policy enables RTPA to meet the packet's deadline while reducing the energy consumption.

Note that the neighbor discovery and power adaptation mechanisms provide adaptation at two different time scales: power adaptation only needs local power adjustments and is used for fast recovery while neighbor discovery involves communication between neighbors and is used for slow recovery.

**F. Geocasting Forwarding based on Quadrant**

Geocasting in RTPA is used in two situations: firstly, if the sink wants to send the monitoring request to some sensor nodes in the certain area and secondly, if a node wants to do neighbor discovery operation. Quadrant-based Geocasting and Forwarding (QGF) Strategy in Mobile Ad Hoc Network [30] will be used in RTPA. In this method of geocasting the sender broadcasts the packet to all its neighbors and we assume the packet contains the location of destination and each node knows its location. If the neighbor is in the same quadrant as the destination, it will forward the packet otherwise it ignores it. RTPA modifies [30] as follows: we assume the sender knows all its neighbors' location, therefore RTPA will select and unicast the identified neighbor that has the most progress towards destination. This modification will save power usage, low end to end deadline and reduce packet flooding.

**G. Handling Routing Problem**

A known problem with geographic forwarding is that it may fail to find a route in the presence of network holes. Such holes may appear due to voids in node deployment or subsequent node failures over the life-time of the network. RTPA partly solves this issue by reading remaining power of its neighbors and if the diameter of the hole is smaller than the transmission range at the maximum power, then RTPA will identify a transmission power that is sufficient to transmit the packet across the hole.

**IV. SIMULATION IMPLEMENTATION OF RTPA**

RTPA will be implemented in NS-2 version 2.28. NS-2.28 will simulate IEEE 802.15.4 MAC and physical layers which can give us real results in WSN. In non-beacon enabled mode and under moderate data rate, the new IEEE 802.15.4 standard compared to IEEE 802.11, is more efficient in terms of overhead and resource consumption. It also enjoys a low hop delay (normalized by channel capacity) on average [2].

Table 1 shows the simulation parameters that using to simulate RTPR. In this table, 802.15.4 MAC and physical layers are used with low power transmission.

<table>
<thead>
<tr>
<th>Table 1: Simulation Parameters</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>Propagation Model</td>
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<td>path loss exponent</td>
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<td>shadowing deviation (dB)</td>
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<td>reference distance (m)</td>
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<td>seed for RNG</td>
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<td>phyType</td>
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<td>RXThresh</td>
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<td>freq</td>
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<td>Power transmission</td>
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<td>Traffic rate</td>
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![Fig. 2: WSN with MICAz motes](image-url)
Fig. 3: Calculation receiving threshold value for MICAz motes

Fig. 4: Distances vs. PRR

Fig. 2 shows the WSN architecture which implemented in NS-2. Fig. 3 shows receiving threshold calculation. If the power received of one frame is below the threshold value, the Mac layer will discard it. Fig. 4 implements equation 2. In this figure, the PRR becomes zero when the distance increases. This paper selects MICAz motes which has ZigBee wireless interface as the preferred sensor node. The simulation work is progressing and will be published hereafter.

V. CONCLUSION

This paper presents the RTPA design for WSN. RTPA enhances and modifies previous works to achieve low end-to-end delay, low power consumption, reduced overhead in control packet flow, good throughput, less interference and channel contention. The work in RTPA is still in process and will be published eventually.

REFERENCES


