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Energy-Efficient Adaptive Routing Mechanism for Real-Time Wireless Sensor Networks

Sandhya Rachamalla[1] and Anitha Sheela Kancherla[2]
[1]Department of ECE, University College of Engineering, Osmania University, Hyderabad, India.
[2]Department of ECE, University College of Engineering, Jawaharlal Nehru Technological University, Hyderabad, India.

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ABSTRACT

One of the most important and challenging issues in wireless sensor networks (WSNs) is to optimally manage the limited energy of nodes without degrading the routing efficiency. In this paper, we propose an Energy-Efficient Adaptive routing mechanism (EE-ARM) for WSNs which saves energy of nodes by removing the much delayed packets without degrading the real-time performance of the used routing protocol. It uses the adaptive transmission power algorithm which is based on the attenuation of the wireless link to improve the energy efficiency. Integrated in PATH, the well known real-time routing protocol based on two-hop neighborhood information, the results show that the proposed routing mechanism perform good in terms of energy consumption, Deadline miss ratio(DMR) and end-to-end delay.

Introduction

Wireless sensor networks have gained attention of the research community in the recent years because of wide variety of applications that can be supported. Many WSN applications require real-time communication systems and examples of such applications can be found in many military, environment surveillance, disaster management and intelligent transportation systems [1]. Among several aspects of WSNs, energy conservation and delay, supporting Quality of service (QoS) in WSNs is still a largely unexplored research field [2].

Although energy efficiency is the primary concern in WSNs for longer network lifetime, the low latency communication is gaining more importance in new applications. Out-of-date information will be irrelevant, mainly in real-time environments and may lead to negative effects to the systems [3].

Timeliness is important in sending crucial messages in industrial WSNs. And sensor nodes are battery operated for energy supply. Hence energy efficiency and latency are the important design goals in WSNs. Supporting real-time QoS in WSNs can be addressed from different layers and mechanisms [4]. Cross-layer optimization can provide further improvement and above all, routing protocol plays a crucial role in supporting end-to-end QoS [3]. Here, in this paper, the focus is on the timely delivery of packets within deadline and end-to-endQoS i.e. the messages are to be transmitted in time to take prompt actions and energy efficiency.

To reduce the complexity of the systems, most of routing protocols are based on one-hop neighborhood information [5]. However, multi-hop information based routing can perform better as more information about the neighbors of a node in the network is available and that is effectively utilized in broadcast operations, channel access methods etc. [6,7,8].

It is observed from the study that two-hop based routing results in less number of hops from source to sink when compared with that of one-hop based routing [6]. However, it is not attractive to go for three-hop based routing, as it further increases the complexity which may not be affordable for the given network application. Hence in this paper, the proposed routing mechanism is integrated with PATH, the well-known two-hop based real-time routing algorithm for WSNs.

In this paper, an efficient routing mechanism is proposed with the following goals:

- Save more energy of nodes by removing early all much delayed packets or useless packets according to their residual deadline requirements and expected end-to-end delay as in [9].
- Adjust the transmission power based on the attenuation of the wireless link [10] without degrading the real-time flow of packets. It further results in effective utilization of energy.
- To improve the routing performance in terms of real-time QoS with two-hop neighborhood information, with the association of PATH.

The rest of the paper is organized as follows Section II summarizes related routing protocols and their performance measures. Section III presents our proposed mechanism which aims to improve energy consumption and real-time QoS. The performance of the proposed protocol is evaluated in Section IV. Simulations and comparisons are discussed in this section. Section V concludes the paper and possible enhancements are discussed.

Real-Time Routing Protocols for WSNs

Many researchers have provided solutions for real-time routing in WSNs. This section provides the analysis of the various existing real time routing protocols for WSNs emphasizing their strengths and weaknesses and various other challenges. Real time routing is discovering an optimum route from source to destination which meets the real time constraints. Timely and reliable data delivery is very important for positive results as out-dated data may lead to disaster effects.

Tele:
E-mail addresses: reddysandhya28@gmail.com

AODV [11] is an on-demand routing protocol which builds route between the nodes only when the source node demands for routing the sensed data. And as long as required by the source node the routes are maintained. This routing algorithm provides the tree formation connecting the multicast members. It uses the sequence numbers to ensure the freshness of the routes resulting in loop-free routing. The main advantage of this protocol is that it is a reactive protocol and routes are established on-demand i.e. whenever source wants to deliver the sensed data to destination then only the path is established. *Sequence numbers* are used to find the latest routes to the destination. The disadvantage is that the intermediate nodes can lead to inconsistent routes if the sequence number is old. Also periodic beaconing leads to unnecessary bandwidth consumption. Also it does not repair a broken path locally. The connection setup delay is less, but control overhead is heavy. This is a reactive protocol which maintains the routing information for a small subset of destinations, namely for those in use. If there is no route for a new destination, a *route discovery* process is invoked, which leads to the significant delays in sensor networks. This limitation makes this on- demand algorithm less suitable for real-time applications.DSR [12] protocol is a reactive protocol and another on-demand routing protocol. Unlike AODV, it is designed to restrict the bandwidth consumed by the control packets in WSNs. It eliminates the periodic updating of routing tables as it is *beacon- less.* The main advantage of this reactive routing protocol is that there is no need for the update of the messages. The route cache information in the intermediate nodes efficiently reduces the overhead. The disadvantage is that it cannot repair broken link locally as the complete path is originated from the source node. In case of broken link, the source node finds the new route only after receiving the *Route Error* from the node adjacent to the broken link. Also route cache information may result in inconsistent route setup. The connection setup delay is high. Due to the source routing mechanism, considerable routing overhead is involved which is directly proportional to the path length. Delay in discovering new routes and considerable connection set up delay makes this protocol less suitable for real time applications.

RAP [13] is the first real-time communication architecture that handles the deadline issues pertaining to large scale WSNs. It uses the high level query and event services and the *velocity monotonic scheduling* (VMS) policy to schedule packets. Geographic forwarding is used in RAP and hence the scalability is possible. One of the performance metrics of this architecture is *mobility.* The notation of the velocity is exploited in real-time communication protocols on sensor networks by this architecture. The key constraints in sensor networks, namely end-to-end dead line and communication distance are the factors considered in this protocol. This kind of routing protocol cannot handle long term congestion where diversion of routing is necessary away from hotspot. The protocol hence provides convenient services for the application layer programs that require real-time support.

SPEED [14] protocol is an important real-time communication protocol to route packets with the desired speed for sensor networks. This protocol provides the real-time communication services, such as real-time unicast, real-time area-multicast, real-time area-anycast. The SPEED is a localized and stateless protocol which carries minimal control overhead. This protocol is provisioning the efficiency in real-time communication with the desired speed being maintained across the network for the data packets from source to the destination through a novel combination of *feedback control* and *non-deterministic QoS aware geographic forwarding*. However, the protocol maintains single speed for packet delivery throughout the network, which is not suitable for sending various types of data packets having different deadline. It doesn't consider the energy metric. MMSPEED [15] extends the SPEED protocol to support different velocities and level of reliability for multiple probabilistic QoS guarantee in WSNs. The QoS provisioning is performed in two quality domains, namely *timeliness* and *reliability*. Unlike the SPEED, this protocol provides the multiple network wide options to obtain the QoS in terms of timeliness. For timeliness, this protocol provides multiple layers of network wide speeds augmented by the two novel techniques: *Virtual isolation* and *dynamic compensation*. This protocol provides the desirable properties such as scalability for large scale networks, self adaptability to the network dynamics, and works well for both urgent non-periodic and periodic packets. Many features of MMSPEED may lead to more energy consumption and frames with large overhead.

RPAR [16] is the advance version of RAP. It is the only protocol that is designed to support the real time routing for WSNs with power control. Application specific communication delays are handled in this protocol by dynamically adapting transmission power and routing decisions based on the workload and packet deadlines. RPAR uses forwarding policy with power awareness and neighborhood manager that efficiently discovers eligible neighborhood node to forward the packet in wireless sensor networks. The key feature of this protocol is its adaptability, i.e. for tight deadlines, it trades energy and capacity to meet the desired time constraints, and for loose deadlines, it lowers the transmission power to increase the throughput. The proposed power adaption and neighborhood mechanisms are on-demand and hence this protocol is a reactive protocol. This reactive approach help in discovering neighbors quickly with low control overhead. This protocol addresses important practical issues like broken links, scalability and bandwidth constraints and performs well in terms of energy consumption and deadline miss ratio.

THVR [3] is a two-hop neighborhood information-based routing protocol for real time wireless sensor networks proposed to support the QoS in terms of real-time packet delivery along with better energy efficiency. In this protocol, two-hop information is used to determine the required velocity and routing decisions are made based on the two-hop velocity with probabilistic packet dropping mechanism for energy balancing. The key features of this protocol is that it achieves low deadline miss ratio along with the high energy efficiency by using novel two hop information based routing. This real time protocol also considers the efficient energy utilization that has not been addressed in SPEED and MM-SPEED.

PATH [17] is a newly proposed real-time protocol which uses the two-hop neighbor information for routing decisions. The real-time performance is improved by means of reducing the packet dropping in routing decisions. Dynamic adjustment of transmission power is adopted to reduce the probability of packet dropping thereby increasing the number of transmission packets that can meet their deadline. In THVR and SPEED, the main cause of packet dropping is that there is no eligible forwarding choice in the neighborhood table for packet forwarding. But PATH provides the service differentiation and serves different data traffic using *dynamic velocity assignment* and control trade-off between energy and delay constraint with *dynamic power control*. Hence, packet dropping is reduced with dynamic performance improving the real-time routing in WSNs.

JiTS [18] shows that shortest path routing provides better performance than geographic routing and explores several policies for non-uniformly delaying data at several intermediate nodes for contention-free transmission. It does not require low layer support and node synchronization and performance metrics are deadline miss ratio and packet drop ratio. EARTOR [19] aims to maximize the number of requests in the network and route requests are designed with specified latency constraints. Cross layer design is adopted in EARTOR along with the mechanism for each relay node that takes into consideration residual energy, location information and relay node priority. EEOR [20] improves the throughput by allowing nodes that overhear the transmission to participate in forwarding the packet. The nodes are prioritized and low priority forwarder will discard the packet if the packet has been forwarded by high priority forwarder. The selection of forwarder list and prioritizing is a challenging task in it to have optimized energy consumption.

In our proposed mechanism, we adopt the approach of identifying the slow packets, which are useless and cannot meet the prescribed deadline, and remove those packets from the queue of intermediate nodes located near to the sink. This conserves energy and improves the network lifetime. It also implements the adaptive transmission power algorithm, which dynamically changes the transmission power to be used in forwarding metric, instead of fixed transmission power as in THVR. Though power adaption scheme is used in PATH, it is invoked when it cannot find suitable two-hop neighbor and when it has sufficient choice of forwarding pair. In our paper, each time the transmission power is adjusted according to the location of the receiver and the quality of the wireless link. This further improves energy efficiency. The forwarding metric is same as used in PATH, finding the suitable next forwarding pair based on the novel two-hop velocity integrated with energy balancing mechanism which maintains the routing efficiency without degrading the real-time behaviour of the protocol.It is therefore named as Energy-Efficient Adaptive routing mechanism (EE-ARM).The proposed routing mechanism details are given in the next section.

Design of EE-ARM for RT-WSN

The proposed mechanism route the packets in three stages: (i) Identification and Removal of much delayed packets (ii) Adaptive transmission power algorithm and (iii) Forwarding metric.

Identification and Removal of much delayed packets

Not all the packets routed for transmission have the chance to reach their destination because of insufficient deadline. The deadline information is exploited in the proposed routing mechanism and the much delayed packets or slow packets are removed from the queue of intermediate nodes near the sink as it is useless to traverse those packets towards destination, thereby saving the energy of nodes. The queue is now maintained to have only packets with sufficient residual deadline. To identify the slow packet from the queue, EE-ARM calculates the expected delay for the current packet to reach the destination and decides whether to remove or not, the current packet based on this expected delay.

(1) Expected delay: The expected delay for the current packet *p* at the current node *x* to reach the destination *d* is $Txd(p)$ and is given by the formula (1).

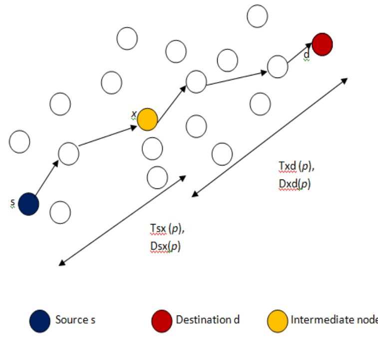

Fig 1. Expected delay estimation.

$$Txd(p) = \frac{Dxd(p)}{Dsx(p)} * Tsx(p) \tag{1}$$

As shown in Fig 1, $Dxd(p)$ denotes the remaining geographic distance that the current packet *p* from current node *x* to the destination *d*, $Dsx(p)$ is the geographic distance travelled by the packet *p* from source *s* to current node *x*.$Tsx(p)$ gives the delay for the packet to reach to the current node *x*.

(2) Removal of much delayed packets : After having the expected delay for the current packet *p* at current node *x*, it is to be decided whether the packet can be retained or not in the queue of intermediate node. The distance between source *s* and destination *d*, Dsd(*p*)and progressive distance PD(*p*), the distance that the packet *p* progressed towards the destination, are used in the decision rule. Figure 2 shows the PD(*p*).The complete algorithm for the *identification and removal of slow packets* at each intermediate node is given in Algorithm 1.

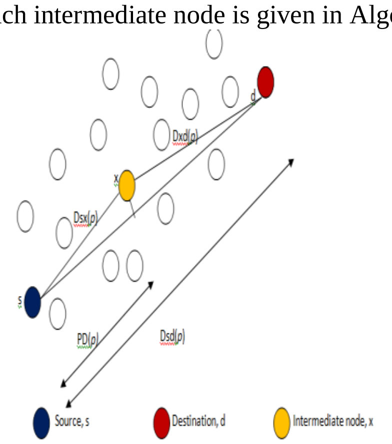

Fig 2. Illustration of Progressive distance PD(*p*).

The algorithm1 is as follows:

Algorithm 1

Identification and Removal of slow packets

1. For each current packet p at the current node x,

2.Calculate expected delay $Txd(p)$;

$Txd(p)$ is the expected delay for the packet p to reach the remaining distance until destination d.

#PD(p) is the distance that the packet p progressed towards the destination d.

Dsd(p) is the distance between source s and destination d.

#α is the parameter chosen according to the application, it must be close to 1 for real-time applications and close to 0 for energy-efficient applications.

Packet removal decision rule.

3. If PD(p) > α * Dsd(p) then
4. If $Txd(p)$ > deadline (p) then
5. Remove packet p from the queue of current node x
6. Endif
7. Else
8. If $\frac{PD(p)}{\alpha * Dsd(p)} * Txd(p)$ > deadline (p) then
9. Remove packet p from the queue of current node x
10. Endif
11. Endif

The PD(p) is calculated as shown in formula 2.

PD(p) = (2)

$$\begin{cases} \frac{D^2sx(p) - D^2xd(p) + D^2sd(p)}{2 * Dsd(p)} & \text{if } Dsx(p) < Dsd(p) \\ Dsd(p) & \text{otherwise} \end{cases}$$

The algorithm 1 explains the procedure to identify and remove the unwanted slow packets from reaching the destination because of insufficient deadline and to preserve energy of the nodes by not forwarding them towards the destination. After calculating the expected delay as shown in formula 1, the packet removal decision rule is applied as shown in algorithm 1. While simulating the proposed algorithm, the parameter α is chosen 0.5.So, the packet is tested only when it is progressed more than 50 % of the total distance. i.e. if PD(*p*) is greater than 0.5 * Dsd(*p*), then the expected delay for the packet *p*, $Txd(p)$,is compared with the required deadline, deadline (*p*), which is set according to the application requirements. If the packet *p* cannot meet the deadline requirement then it is removed from the queue of the current or intermediate node *x*. Otherwise, more chance is given to the packet *p* to reach the destination with $Txd(p)$ multiplied with $\frac{PD(p)}{\alpha * Dsd(p)}$ and compared with given deadline. If the value exceeds the deadline, then the packet is removed.

Adaptive Transmission Power algorithm

The queue of the current node now contains the useful packets after the removal of useless packets. The transmission power of each packet is adaptively varied based on the quality of wireless link and this power is used in forwarding metric for choosing the next candidate. In path loss model, the transmit power falls as $1/d^n$, where *d* is the distance between the sender and receiver and *n* is the path loss exponent, this idea is exploited in the proposed routing mechanism. The remaining energy is only considered in THVR [thvr] in forwarding metric. In PATH [path], both the forwarding energy and remaining energy are considered. The adaptive transmission power algorithm is described as follows.

Algorithm 2

Adaptive Transmission Power algorithm

1. While forwarding a packet *p* in a queue of intermediate node, the transmission power *P*(*x*) is given by formula (3)

$$P(x) = t.d^n + C \quad (3)$$

Where *d* is the distance from current node to the next forwarding node. *n* is the path loss exponent and depends on the quality of wireless link ($n \geq 2$).*C* is the system processing cost and *t* is prediction threshold.

2. The quantity of energy required to send a packet is proportional to the transmission power of the current node. The transmission energy *E(x)* is given

$$E(x) = P(x) * T(x) \quad (4)$$

Where $T(x)$ is the transmission time, the time required to send a packet by a node.

In the proposed routing mechanism, the transmission power is varied based on the geographic position of next choice and is useful in saving the energy instead of fixed transmission power as used in THVR[3]. In PATH[17], the power adaptation scheme is used but it is invoked only when there is no suitable forward choice or when more than one forwarding choice exist. While simulating the proposed protocol, the path loss exponent *n* is chosen to be 2 and system processing cost *C* is assumed to be 0.

Forwarding metric

The forwarding metric used in the proposed mechanism utilizes the two-hop neighborhood information of the network as in THVR and PATH, which improves the routing performance when compared with that of one-hop neighborhood information. The proposed routing mechanism is integrated with PATH [17] protocol and the same forwarding metric, which is based on velocity and energy metric, is used to select next forwarding pair for the packet *p* to get routed towards destination. But the transmission energies are adaptively calculated, as shown in formula 4, based on the distance between sender and receiver. This improves the energy efficiency and better forwarding pairs are selected in routing the packets.

Performance Evaluation

The proposed routing mechanism EE-ARM is simulated in Network Simulator-2.35[21]. The Network simulator is used to simulate TCP, routing and multicast protocols over wired/wireless networks, from application to communication layers. It provides simple and realistic radio propagation and MAC models. We set the parameters close to practical WSN according to MicaZ motes[22] with MPR2400(2.4 GHz) radio. These motes are used for enabling low-power , wireless sensor networks with globally compatible ISM band (2.4 GHz to 2.48 GHz). Nodes are randomly distributed in a 500m X 500m area. We considered one source and one destination. The source node is chosen at the left-lower corner of the sensing area fixed at the location (95m,50m), while the destination node is fixed at the location(430m,475m) at right-top corner of the sensing area.

The proposed mechanism EE-ARM is investigated and compared with THVR and PATH protocols. The source generates CBR traffic at 10kbps rate with packet frame size 64 bytes (including header and CRC fields).

The performance metrics are (i) ECPP(energy consumption per packet), which is defined by the total energy expended divided by the number of successfully transmitted packets, (ii) DMR (deadline miss ratio), which is defined as the ratio of packets that miss the predefined deadline, and (iii) E2E delay(end-to-end delay), the total delay of the packet being transmitted from source to the sink till the last bit of it (includes propagation delay, transmission delay, queuing delay and processing delay). The proposed EE-ARM is compared with two-hop based routing protocols THVR and PATH for the same network scenario and simulation settings as shown in Table 1. The deadline requirement is varied from 400 ms to 1100 ms and in each run DMR and ECPP are calculated for the three protocols THVR, PATH and EE_ARM. The E2E delay for the three protocols is also verified.

The results show that the proposed mechanism offers better energy efficiency than the other two protocols as shown in Fig 3.

TABLE 1. SIMULATION SETTINGS FOR EE-ARM

Parameters	***value***
Area size	500 m X 500m
Mac	IEEE 802.11
Simulation time	10 s
Traffic source	CBR
Packet size	64 bytes
No. of nodes	50 (Random distribution)
Range	100m

This is due to the adaptive transmission power algorithm and the novel method of removal of slow packets thereby saving the energy of nodes in the network.

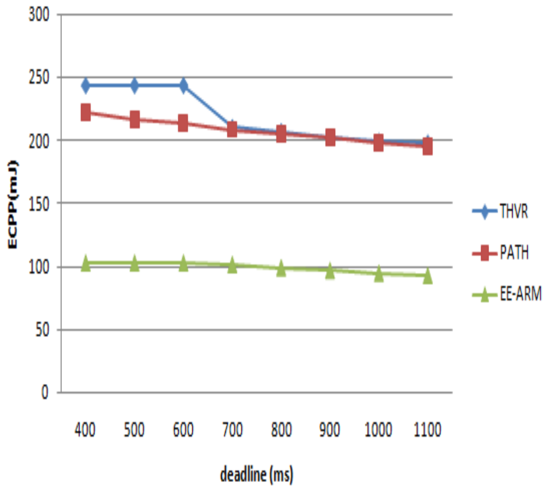

Fig 3. ECPP comparison of THVR, PATH and EE-ARM.

The DMR is also improved in EE-ARM as shown in Fig 4, because of the removal of much delayed packets at intermediate nodes and preventing them to reach the destination with large delay. In THVR and PATH, the packets are given chance to progress and initiative drop controller is invoked to decide whether a packet should be drop or not. In EE-ARM, the drop controller is not used as in PATH and THVR. Instead the novel method of removal of much delayed packets is employed. This method helps in the removal of slow packets from the queue and only the packets which have sufficient residual deadline are retained for routing. Also the efficient utilization of energy results in better forwarding choice and the packets are routed effectively which further reduces DMR.

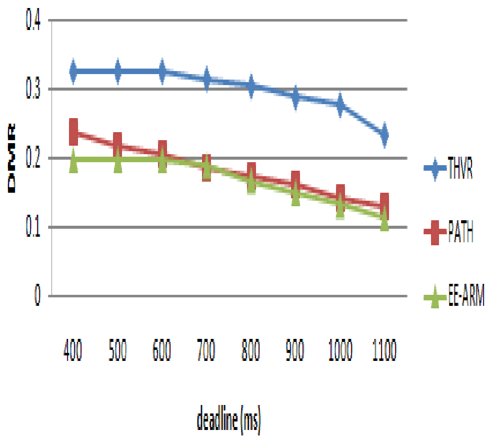

Fig 4. DMR comparison of THVR, PATH and EE-ARM

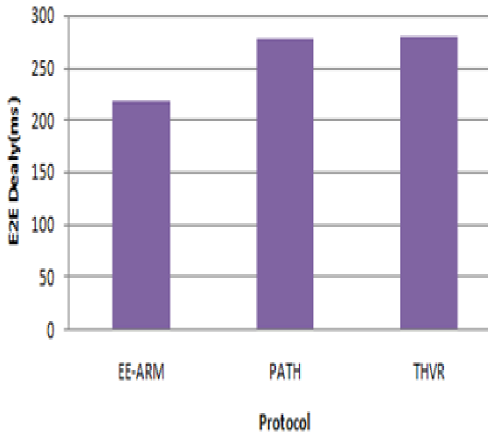

Fig 5. E2E Delay comparison for the Protocols THVR, PATH and EE-ARM.

The average E2E delay of all the packets is also less in EE-ARM, as shown in Fig 5, as slow packets are removed and only useful packets with sufficient deadline are allowed to reach the sink.

Conclusion and Future Scope

In this paper, an adaptive routing mechanism based on two-hop neighborhood information of the network is proposed. It is integrated with a novel real-time power aware two-hop based protocol PATH. It employs a novel method of removal of much delayed packets and also the efficient adaptive transmission power algorithm to achieve better energy efficiency without degrading the real-time performance in WSNs. This integration reduces the energy consumption and improves deadline miss ratio better than THVR and PATH. Our future work will consider multiple sources there by increasing the traffic intensity in the network and the performance of the proposed mechanism is observed.

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