Journal of Universal Computer Science, vol. 16, no. 9 (2010), 1215-1233
submitted: 19/1/09, accepted: 22/3/10, appeared: 1/5/10 © *J.UCS*

Position-based Routing Protocol for Low Power Wireless Sensor Networks

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Abstract: We present a table-less position based routing scheme for low power data centric wireless sensor networks. Our proposed scheme is localized, uses greedy forwarding approach, and does not rely on neighborhood information. These characteristics reduce the communication overhead (no neighborhood information exchange), make the protocol highly scalable (no routing tables are maintained and beacons are not exchanged when a node leaves or enters a network), and performs better in mobile environments (as the next hop is non-deterministic and is computed at run time). It also deals with dead end problem by a recovery strategy in a distributed and localized way. The proposed protocol is implemented in the OMNET++ based discrete event simulation environment PAWiS. The results show that the proposed protocol provides guaranteed delivery, extended network lifetime, and a mechanism to route on the basis of end-to-end delay and/or energy consumption.

Keywords: Ad hoc networks, routing protocols, wireless sensor networks, position based routing
Categories: C.2.0, C.2.2

1 Introduction

Wireless Sensor Networks (WSNs) are characterized by restricted energy, processing power, and memory [Akyildiz, 02]. Sensor networks and ad hoc networks are different in many ways. These differences include number of nodes, density of nodes, mode of operation (unattended for WSNs), resource availability, data redundancy, possibly hostile environment, and higher frequency of link failures in WSNs [Ulema, 06], [Raghavendra, 04]. New routing techniques which are energy efficient, memory efficient, and less computational complex are required. The routing protocols for wireless networks can be categorized into geographic and non-geographic [Witt, 05]. Non geographic routing protocols are table driven and routing tables are built at the cost of control packet overhead. Geographic routing protocols perform routing on the basis of location of the source, the next hop, and the destination. Position of the nodes can be obtained from low power GPS (Global Positioning System) receivers or relative coordinates can be found using techniques like signal strength [Stojmenovic, 01], manual registration or as discussed in [Zhang, 08]. Position based routing schemes are highly scalable and exhibit robust behavior against frequent topological changes [Fueßler, 03]. Such protocols can reduce/avoid communication and processing overhead caused by neighborhood information exchange, and can minimize memory usage by not maintaining routing tables.

Two main components of position based routing are *location services* and *forwarding strategy* [Mauve, 01]. Location services translate the identity of a node into its geographic position. In many-to-one communication, the participating nodes must know the position of the sink node (base station). Forwarding strategies can be based on minimizing the number of hop count, geographic distance, delay and/or, energy consumption. In distance based greedy forwarding, a node always forwards a packet to the node with lesser *Euclidean distance* towards the sink node. If a message arrives at a node, which is shorter in distance than all its neighbor nodes and is not within the communication range of the sink node, the node is known as *dead-end* (concave node), e.g., node *F* in Figure 1, and the associated strategy to recover from dead-end problem is called recovery strategy. This paper deals with a dead-end aware Table-less Position based Routing (TPR) scheme for data centric low power WSNs. The development of TPR is driven by a Wireless Container Monitoring System (WCMS) project [Mahlknecht, 07] with WSNs. In WCMS, each sensor node attached to a container comprises a GPS, GSM/UMTS, and short range RF communication system and reports the container data (current location, and sensory data like acceleration, velocity, temperature, and humidity) to the sink node. The availability of positions of nodes drives our motivation to develop a low power position based routing scheme for similar class of applications.

TPR is initiated by the sink node. The sink node broadcasts its current position to all other nodes at fixed time intervals. This broadcast is also used to compute accumulative cost towards the sink node by other nodes. As the nodes may be mobile (e.g., if containers are on a running train), each node save it's position obtained from GPS receiver at the same time intervals at which the sink node saves its position without strict time synchronization requirements. Now these positions are used as relative positions until the updated position of the sink node is broadcasted again. This is in contrast with other position based routing strategies which assume position of destination to be known.

If a node intends to send/relay data packet, it sends it blindly without forwarder's address. All the nodes within the forwarding area *compete* to become the relay node for the transit packet based on *total cost* towards the sink node. The winning node *suppress* the other competing nodes with adaptive transmit power. If a node is a dead-end, it re-routes the data packet based on the *recovery strategy*.

The rest of the paper is organized as follows. In Section 2, an overview of the related work is given. Section 3 discusses TPR in detail. Simulation and results are discussed in Section 4. The paper is concluded by highlighting future work and open research issues in Section 5.

2 Related Work

Based on experimental study [Jain, 01], it is shown that non-geographic routing protocols including AODV [Perkins, 99], DSDV [Perkins, 94] or DSR [Johnson, 96] that do not use location information and are based on exchange of routing information are not scalable as opposed to position based routing strategies. The overhead incurred by maintaining routing tables in such schemes due to mobility and topological changes is "*quadratic in network*" [Stojmenovic, 02]. On the other hand, localized position based routing algorithms only need accurate neighborhood information (i.e., position of neighbor nodes) and position information of the sink node to provide scalable solutions [Stojmenovic, 02]. Even in some cases, for example, our proposed scheme, the positions of the neighbor nodes are also not required. Geographic routing protocols route the packets based on geographic location of source, next hop, and destination nodes. Position of the nodes can be obtained from low power GPS (Global Positioning System) receivers or relative coordinates can be found using techniques based on incoming signal strength, time of arrival, angle of arrival, or a mix of them [Stojmenovic, 01]. Position based routing schemes are highly scalable and robust against frequent topological changes [Fueßler, 03]. They can reduce/avoid communication and processing overhead by minimizing neighborhood information exchange, and can minimize memory usage by not maintaining routing tables.

Most Forward within Radius (MFR) [Takagi, 84] forwards packets based on the notion of *progress*. Given a destination *D*, source *S* forwards the packet to the neighbor which is nearest to *D* and is within the transmission radius *R* of node *S* (for example, node "*A*" in Figure 1). Nearest Forward within Radius (NFR) [Hou, 88], transmits a packet to the nearest neighbor (node "B" in Figure 1) of the *S* which is in direction of *D*. NFR reduces the number of collisions (by lowering the transmit power to restrict signal propagation to a confined area) as opposed to MFR where the number of hop count is reduced. Compass routing [krankis, 99] forwards packets to the next node that forms the smallest angle to the line connecting *S* and *D* (node "A" in Figure 1). Compass routing may create loops [Stojmenovic, 01] under special conditions. Randomized compass routing algorithm, [Ara06, p. 22] a variant of compass routing, tries to avoid loops by taking randomized routing decisions (node "A" or node "B" in Figure 1).

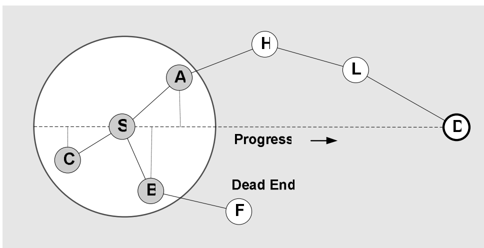

Figure 1: Position based routing strategies

GEographic DIstance Routing (GEDIR) [Stojmenovic, 01] is a position based greedy algorithm which can be differentiated from other greedy algorithms in situations when the sending node itself is a local minimum (dead-end). For example, in Figure 1, assume source node *F* wants to send a message to destination node *D*, such that *F* and *D* are not within the transmission range of one another. In this case *F* is a *dead-end*, but according to GEDIR, node *F* will still forward message to node *B*, hoping that *B* may have another neighbor which is closest to the destination *D*. GEDIR is proved to be loop free algorithm, although local loops may be created which can be dealt with by dropping the message by limited memorization.

Greedy Perimeter Stateless Routing (GPSR) [Karp, 00] is a routing strategy based on combining two different forwarding strategies: greedy forwarding and right hand rule. GPSR uses greedy forwarding approach by using only neighborhood information. When greedy forwarding becomes impossible (if a packet arrives at a dead end), then the forwarding strategy is switched to the right hand rule, where the packet is forwarded along the FACE of the planar graph [Araújo, 05]. The basic assumption of considering a planar graph can be computational complex when considering nodes in a 3 coordinate system (having different altitudes). GPSR results in large number of beacons to maintain routing table which results in communication and processing overhead [Witt, 05]. GPSR performs well in dense networks where the average network degree is greater than 20 but performance deteriorates with a decrease in the density of networks [Zou, 05].

Distance Routing Effect Algorithm for Mobility (DREAM) [Basagni, 98] is designed keeping in view the node mobility and distances between nodes. In each node, the routing table maintains network-wide location information. Each node sends its location information to every other node using control packets. Though it is claimed in [Basagni, 98] that DREAM is a loop free routing algorithm, it is shown in [Stojmenovic, 01] that it is not loop free with a counter example. Location Aided Routing (LAR) [Vaida, 00] is a routing strategy for mobile ad hoc networks (MANETs) where location information is used to enhance the performance by reducing flooding overhead of protocols where flooding is used for route discovery (for example, reactive routing protocols). LAR and DREAM reduce the communication overhead to some extent by using directional flooding but still paths are maintained between communication pairs. The enhancement that is achieved is to restrict the flooding to a particular zone as done in DREAM. All the routing schemes discussed above are based on maintaining routing tables as opposed to TPR.

The work that is most related to the proposed routing protocol is Implicit Geographic Routing (IGF) [Blum, 03], Contention Based Routing (CBR) [Fueßler, 03], and Blind Geographic Routing (BGR) [Witt, 05]. The basic idea of IGF is to "*non-deterministically route packets by allowing next hop candidates to 'compete' in the forwarding process*". IGF is a combined routing-MAC scheme which uses the 802.11 DCF MAC[1] scheme. The forwarding zone is defined by an angle (30 degrees in this case) with a line connecting the source and destination. It also introduces energy aware and distance aware metrics to facilitate routing decisions. The energy related metric is based on local information only and would experience problems as discussed in section 3.1. Communication failures because of dead-ends in the

[1] standards.ieee.org/getieee802/802.11.html accessed on August 27, 2007.

forwarding zone are identified but not explained. In CBR, the routing scheme is divided into the *selection* process and the *suppression* (area based suppression and active suppression) process. In the selection process, the next hop is determined by means of contention while in the suppression process, if a node is selected as a forwarding node; other nodes within the same transmission radius are suppressed from being selected. The timers used for contention can be based on progress. The dead end problem is not solved in the paper and it is mentioned that one of the existing schemes can be used as a recovery strategy. BGR, in principle a variant of IGF and CBR, forwards the packets in a greedy manner and is table-less. It focuses on minimizing duplicate packets. TPR is different from the aforementioned schemes in the definition of the Forwarding Area (FA), the recovery strategy, and by considering the network wide energy aware cost towards the sink node which is considered by none of the above schemes. A novel distributed algorithm is presented in [Zou, 05] for the dead end problem in location based routing but requires neighborhood tables to be maintained and cannot be used with TPR.

3 Table-less Routing Protocol Description

Table less position based routing (TPR) is divided into different phases which are discussed in the following sections.

3.1 Location Service and Setup Phase

All the participating nodes in the network update their current location after time interval T, and use this location information until the next location update at $2T$. The value of T can be set based on application requirements. For example, for containers being transported by trains, the update can be done less frequently as the relative position of the containers do not change as long as they are on the train. The sink node initiates the setup by sending a broadcast message (m_{setup}). m_{setup} contains the current location of the node, the minimum and the maximum State of Charge (SOC_{min} and SOC_{max}), and the cost to the sink (C_{sink}) which is set to zero by the sink node. Each node N_i computes its own state of charge (SOC_i) which is given by Q/Q_{max} where Q is the remaining battery capacity and $Q_{\max}$ is the initial battery capacity. The remaining battery capacity can be computed by the Rakhmatov battery model [Rakhmatov, 03]. Initially, N_i initializes its SOC_{min} and SOC_{max} to SOC_i. N_i may receive different SOC ranges from multiple sources but stores only the maximum and the minimum SOC. If SOC_i is less or greater than the received SOC_{min} or SOC_{max} respectively, it updates m_{setup} before forwarding it. Ni also stores the location of the sink node and the accumulative cost towards the sink node. At the end of each setup, every node knows the network wide minimum and maximum SOC, sink location, and C_{sink} (without neighborhood or next hop information). Whenever the sink issues a new setup message m_{setup} it tags it with a different identifier Id_{setup}. Each node receiving m_{setup} checks the message for setup updates. Whenever a node updates its setup information, it forwards m_{setup}. A setup update occurs when Id_{setup} changes, when the received cost is lower than the saved one, or when SOC_{min} or SOC_{max} changes. Whenever Id_{setup} changes the node drops all setup information and reinitializes its setup state based on currently received data.

This cost is then used in response timers which are used by nodes to become the relaying nodes for transit traffic. The intuition to use the accumulative cost towards the sink node is as follows. Assume that node *S* intends to send a packet to node *D* as shown in Figure 2. The percentage values on each node represent the remaining battery capacity, for example, 90% for node *A*. Now if the decision is based only on the remaining battery capacity of the node and not the accumulative cost towards the sink node, node *A* will become the relay-node based on high energy reserve (low cost). The message will then reach the destination *D* via node *B* and *C* which are low remaining energy nodes and would soon become depleted nodes. The network lifetime (the time it takes for the first node to become dead node is considered as the network lifetime) can be increased by using the accumulative cost towards the sink node which would select node *E*. A dead node is the one with negligible remaining energy. The aforementioned principle also applies to other parameters such as delay or congestion.

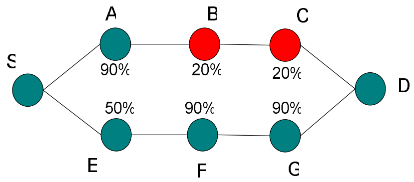

Figure 2: Routing decision based on accumulative cost vs. local cost

3.2 Forwarding Area, Contention, and Suppression

The Forwarding Area (FA) is defined by an angle α drawn at a line connecting the sender node *S* and destination node *D* as well as the transmission range (*R*) of the sender. The angle α can be selected based on the density of the network, i.e., the denser the network, the smaller the angle, for instance, [Blum, 03] considers 30 degrees. All the nodes that are within the transmission range *R* and within an angle α are considered to be inside the FA.

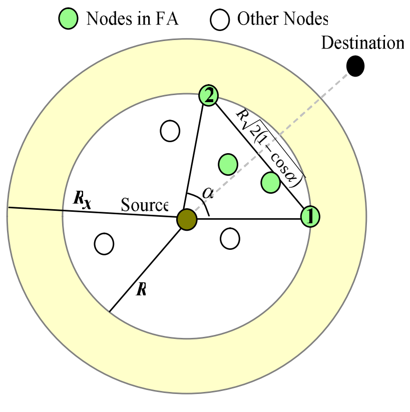

Figure 3: Forwarding area

For example, in Figure 3, green nodes are considered to be in the FA for the given source and destination pair. One of the nodes in FA becomes relay-node for the transit packet and sends an ACK message back to *source*. This ACK message is also used to *suppress* the other nodes which are competing to become relay nodes. The transmission range covered by the ACK message is R_x which is the maximum possible distance between two nodes, for example, node 1 and node 2 in Figure 3 are at R_x) within the FA and is given by,

$$R_x = \max\left(R, R\sqrt{2(1-\cos(\alpha))}\right) \qquad (1)$$

The second term in the equation 1 is given by the law of cosines as shown in Figure 4 .

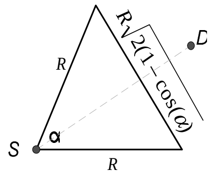

Figure 4: Law of cosines

Assuming $\alpha = 90°$, the transmission range of nodes for data packets would be R (inner circle in Figure 3) while that for ACK messages would be $R_x = \sqrt{2}R$. Alternatively to reduce the transmission range and hence the interference range as in [Hou, 88], the original message can be sent with a range of $R/\sqrt{2}$ and the ACK can be sent back with a transmission range of R (e.g., $\alpha = 90°$). The maximum value of α can be restricted to 90 degrees which would make sure that all the nodes selected in FA would result in positive progress towards the destination. The value of α can be adjusted depending upon the network density, for example, in high density networks, smaller angles must be used to reduce the number of nodes selected in the FA. Thus, adaptive transmission power control along with positions of the source node, relay node, and the destination node are used to define the FA.

3.3 Response Timers

A response timer (T_r) is used by nodes which are competing to become relay nodes in the Forwarding Area (FA). T_r is given by,

$$T_r = T_{\max}\left(\eta C_d + (1-\eta)C_e\right) \qquad (2)$$

In equation 2, $T_{\max}$ is the maximum possible value of the T_r (maximum delay) defined by the user where $0 \le \{\eta C_d + (1-\eta)C_e\} \le 1$ as well as $0 \le \{\eta, C_d, C_e\} \le 1$. η is a factor to assign weight to C_d and C_e. T_{max} can have significant impact on the delay and is dependent on node density [Wit05, Fue03]. C_d is the time attributed to T_r based on positive progress that is made towards the sink node. The higher the progress made by the competing node, the lesser is the time added to T_r. C_d is given by

$$C_d = 1 - \frac{\overline{SN_i}}{R} \qquad (3)$$

In equation 3, $\overline{SN_i}$ is the Euclidean distance between sender node S and any competing node N_i. Assuming $\overline{SN_i} = R$ would result in maximum possible progress and hence attributing no time to T_r. C_e is the time attributed to T_r based on the total energy cost towards the sink node. The higher the cost to reach the destination, the higher is the time added to the T_r. C_e is given by,

$$C_e = \frac{(1 - SOC_{scaled})^{\sigma} + C_{\min}}{HC} \qquad (4)$$

where, SOC_{scaled} is SOC of the node scaled in the range SOC_{max} *and* SOC_{min} in equation 4. C_{min} is the minimum cost and HC is the hop count to towards the sink node. σ is an empirical value to increase the cost non linearly or linearly depending upon the remaining energy of the node (see next paragraph for details). The use of SOC_{scaled} is to reduce the adverse effect encountered because of the lower differences between SOC values, i.e., the lower the difference between SOC values, the lower is the time attributed to T_r and hence, the higher the number of duplicate packets. Additionally, by using a scaled SOC, T_r will not degrade to large timeouts (resulting in higher delays) caused by comparatively more drained batteries. C_{min} is the minimum cost received by competing nodes in the setup phase or as piggybacked information in ACKs. For example, if any node N_i receives packet from any node N_j and node N_k, then,

$$C_{min} = \min(C_{ij}, C_{ik})$$

Motivated from [Mah06], the cost based on remaining battery capacity is varied in three ways that is linear, quadratic, and cubic. The cut-off values which are set empirically are selected from [Mah06]. For $Q \geq 80\%, \sigma = 3$, for $20\% \leq Q < 80\%, \sigma = 2$ while for $Q < 20\%, \sigma = 1$. This make sure that nodes with less energy would increase their cost non-linearly and hence attribute more time to T_r. HC is the hop count along the minimum cost path that is stored by each node N_i. Every node saves the value obtained from equation 4 to attribute time to T_r while forwarding the accumulative cost (cost obtained before dividing it by HC), so that values of C_e are normalized between 0 and 1 as required by the equation 2. It should be noted that the time attributed by C_e would not result in energy optimal routing but energy aware routing as the cost propagates slowly between two consecutive setup phases. Also the mobility of nodes would affect the total cost based routing decisions adversely.

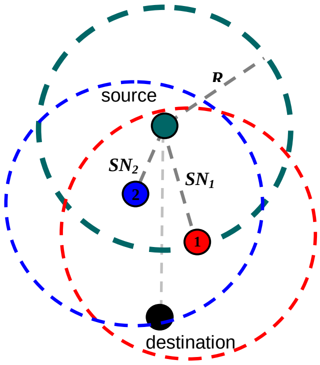

Figure 5: Progress based time attribution to response timer

Let's consider an example to explain the time attributed by the C_d to the T_r. In Figure 5, for a given source-destination pair, node 1 provides progress $SN_1 = R$, while node 2 provides progress SN_2. Based on equation 3, node 1 will attribute 0 time to T_r while node 2 will attribute $1 - \frac{\overline{SN_2}}{R}$ time to T_r.

The value η is selected to be 0 or 1. If $\eta=1$ represents progress aware routing while $\eta = 0$ represents energy aware routing. One way is to select η dynamically. The strategy to select η dynamically is as follows: initially, the value of η is selected either 0 or 1, let's say 1 (this value can be initiated to either values in the start but when a new node joins a network, it normally has good energy reserve, therefore η can be initiated with 1). This means that the forwarding nodes compete on the basis of progress they can provide to the source node. For instance, in Figure 5, node 1 and node 2 will start their timers based on progress and node 1 being nearer to destination will be selected as forwarding node. Whenever source node sends data, node 1 is selected as the forwarding node. After some time, node 1 will have consumed more energy than node 2. Now to dynamically shift η from 1 to 0, each node checks the difference between its SOC_{max} and SOC_{min}, and if SOC_{max} minus $SOC_{min} > \gamma$, it shifts from progress aware to energy aware routing. γ is an empirical value and its optimal value can be computed by checking the network lifetime for different values of γ. The value of γ can be optimized to enhance performance as is done in section 4, page 11.

After sometime, the energy utilized by node 1 and node 2 would become equal as energy aware routing always selects the node which has more energy. Once the energy balance is achieved, the timers of both competing nodes will start expiring at the same time and hence it would result in duplicate packets. Whenever a node receives a duplicate packet, that indicates that one of its neighbor has the same energy as itself, so it shifts from energy aware to progress aware routing and hence the value of η is changed dynamically.

3.4 Routing Strategy

Assume that in Figure 6, sender *S* wants to send a message *m* to destination *D*. *S* will blindly forward *m* and only nodes *C* and *B* being in FA would compete to become the forwarding nodes. Both node *C* and node *B* would start their response timers. As soon as a timer of one of them expires, lets say node *B*, it would send back an ACK message to *S*. Now node C would also hear the ACK message which carries the message ID of message *m* and thus would cancel its timer. In this way, the node whose timers expire first wins and becomes the forwarding node. It should be noted that nodes *S* after sending the message *m* also starts its ACK timer whose value is $T_{\max}$ plus some additional random time (to account for unprecedented delays, e.g., caused by the MAC layer). If the ACK timer expires, a recovery strategy is initiated which is discussed in the following section.

3.5 Dead-End Problem and Recovery Strategy

A node which is nearest to the sink node in comparison to all its neighbors and not within the transmission range *R* of the sink is a *dead end*. This is because only those nodes are selected in FA which would result in positive progress. These nodes are called as *dead* nodes while the others as *live* nodes. In Figure 6, assume that node *F* has either a self generated packet or transit packet to forward to the destination node *D*. Node *F* will forward the message *m*, and other nodes if any in the FA will process the message. At the same time, it will start the ACK timer.

If the ACK timer expires, before ACK arrives, node *F* assumes that there is no neighbor node with positive progress towards the destination node *D*. Node *F* will declare itself a *dead* node and broadcast the message $m_{reverse}$ with a field indicating reverse message. Being a *reverse* message, all the neighbor nodes which are out of FA will compete in a similar way to relay the message. In this case node *B* will get hold of message $m_{reverse,}$ convert it to a message *m* and would forward the message as in normal routine. As node *F* has already declared itself *dead,* it would not compete to become the relay node. The whole process will be repeated until message reaches node *S* and ultimately to *D* via node *C* and *E*. When node *F* hears a message from a *live* node, which is nearer to the destination than itself, it would convert itself into a *live* node and would take part in competing to become a relay node as long as it is a *live* node.

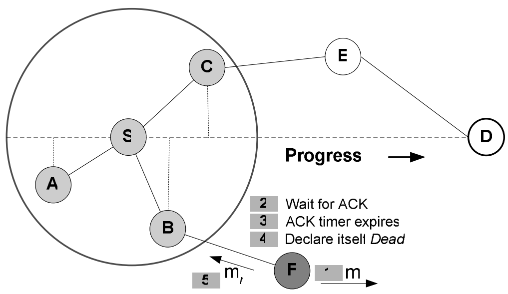

Figure 6 : Dead end problem and recovery strategy

4 Simulation, Results, and Discussion

TPR is simulated in the OMNet ++ based discrete event simulation framework PAWiS [Glaser, 08], a special tool to simulate low power sensor networks. An unobstructed unit disc graph is considered for simulation. A first order radio model to transmit and receive messages is adopted from [Hienzelman, 00]. The amount of energy consumed to transmit a packet (E_{TX}) is given by,

$$E_{TX} = E_{electronics} \times k + E_{amplifier} \times k \times R^2 \qquad (5)$$

where $E_{electronics}$ is the energy consumed to run the transceiver circuitry, k is the size of the packet in bits, $E_{amplifier}$ is the energy consumed by the amplifier to achieve an acceptable *SNR* (Signal to Noise Ratio) and R is the transmission range. The energy consumed to receive a packet (E_{RX}) is given by,

$$E_{RX} = E_{electronics} \times k \; . \qquad (6)$$

As in [Heinzelman, 00], $E_{electronics}$ = 50 nJ/bit, $E_{amplifier}$ = 100 pJ/bit/m^2, and k = 512 bits and 100 bits for data packet and acknowledgement packets respectively. $E_{electronics}$ for receiving and transmitting a packet is assumed to be equal[2]. The MAC (Medium Access Control) layer is implemented as a simple CSMA (Carrier Sense Multiple Access) scheme. As the communication is done hop by hop, and end to end reliability is not important, the transport layer is not implemented. The application layer is abstracted by probabilistic period sampling (for example, if the change in value is greater than 20%, a data packet is sent to the sink). T_{max} is set to 45 milliseconds as done in [Fueßler, 03]. Decreasing the value of T_{max} would result in increased number of collisions while increasing it would result in increased delays. The value of T_{max} needs to be dynamically set based on node density. Selective[3] random topologies based on the uniform distribution function[4] of OMNeT ++[5] are used.

Figure 7 shows the network lifetime for different values of gamma (γ). The value of γ is varied from 5% to 50%. It is visible from Figure 7 that the γ within the range of 20% to 40% gives better results while if the value of γ is decreased below 20% or increase above 40% than the network lifetime starts decreasing. For the given scenario, the optimal value of γ is 20% as shown in Figure 7 and this value is used for the rest of simulation.

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[2] This is a realistic assumption, for example, for the CC2400 radio, receive current consumption is 25mA while transmit current consumption is 19mA. The values are taken from http://focus.ti.com/docs/prod/folders/ print/cc2400.html accessed on May 09, 2007.

[3] Whenever a topology was generated with the random distribution of the OMNeT ++, the topologies that were visually connected were selected while those with many disconnected nodes were not used.

[4] The uniform distribution functionality uses Mersenne Twister random number generation mechanism.

[5] www.omnetpp.org.

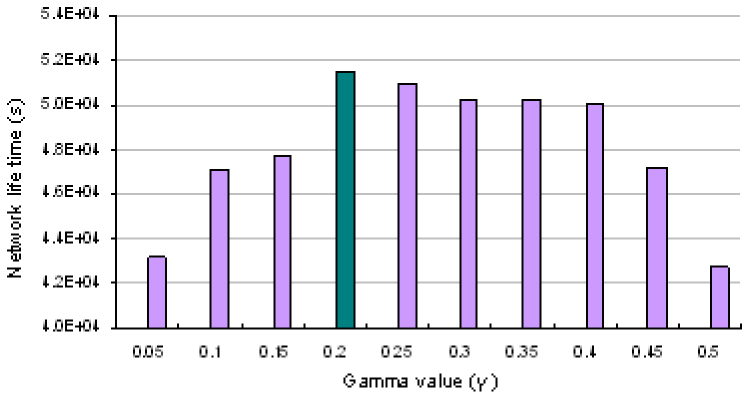

Figure 7 : Value for gamma versus network lifetime

Figure 8 shows the network lifetime for different values of η. It is surprising to see that the network lifetime for η = 0 (energy aware), is less than the network lifetime for η = 1 (progress aware).

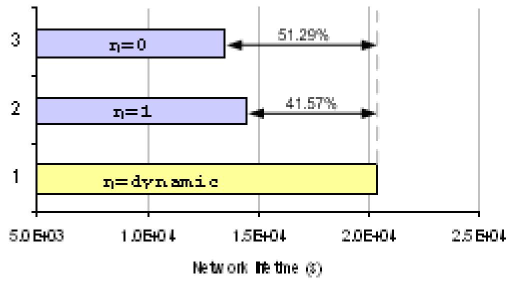

Figure 8 : Network lifetime for different values of η

The basic reason for this is that for η = 0, the nodes always try to balance the energy consumption across the nodes. When this balance is achieved, the timers of the competing nodes always expire at almost the same time resulting in duplicate packets. Although, it ensures the balanced energy consumption across node, the resulting duplicate packets utilizes radio resources redundantly and hence results in decreased network lifetime. For dynamic η, the increase in network lifetime is more than 50% and 40% compared to progress aware and energy aware strategies respectively.

Figure 9 shows simulation results for 12 nodes uniformly distributed over area of 200 x 200 m^2. The remaining energy of all the nodes is checked after 15 hours of simulation time. Although the remaining energy of many of the nodes with η = 1 is higher but the energy consumption is not evenly distributed among nodes which is clear from certain peaks and off peaks in Figure 9. The remaining energy of nodes with η = 0 is comparatively balanced but much lower than that of η = 1. For dynamic η, the energy consumption across all the nodes in evenly distributed. Also remaining energy in this case is greater than those for η = 0, because in the later case, extra energy is consumed to treat duplicate packets.

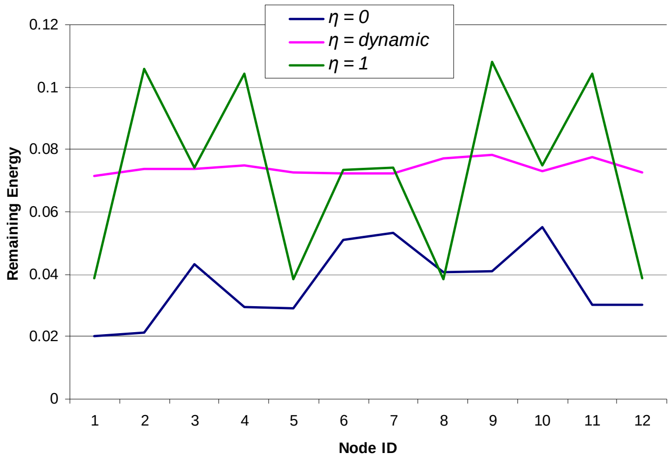

Figure 9 : Remaining energy

Figure 10 shows the end to end delay for different values of η. The results show lower end to end delay for η = 1 because it always selects the node that provides maximum progress. For η = 0, the delay initially is high because the timer of all the nodes expire at the same time because of same energy level. Consequently, the time consumed in contention resolution at the MAC layer contributes to increased delay.

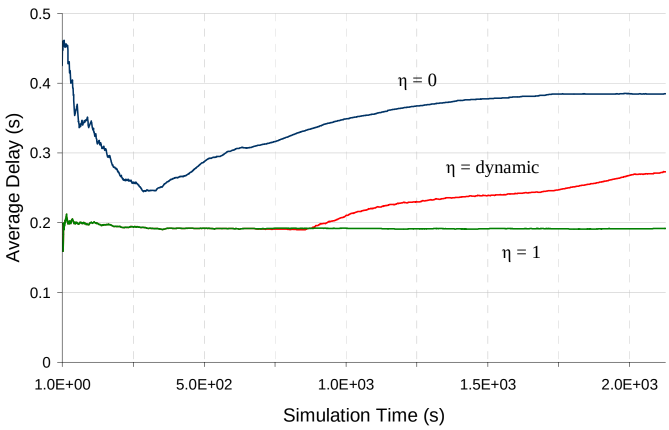

Figure 10 : Average end to end delay for different values of η

For, η = 1 and η = dynamic, the end to end delay is almost the same. At times, for η = dynamic, the results show increased delays, because the strategy shifts from progress to energy aware and may also results in some limited number of duplicate packets before it shifts back.

Figure 11 shows the delivery ratio for different values of η. It is clear from the figure that the protocol promises guaranteed delivery. A delivery ratio of higher than 1 indicates packet duplicates. For η = 1, the delivery ratio is near to the optimal value. As the value η is decreased, the delivery ratio increases. The reason for this is that for lower values of η, such as η = 0, the protocol always tries to balance the energy consumption across the network. Once the remaining energy of nodes have negligible difference, the difference between the timers of contending nodes also becomes negligible, and the transit packet is processed before node receives the ACK message.

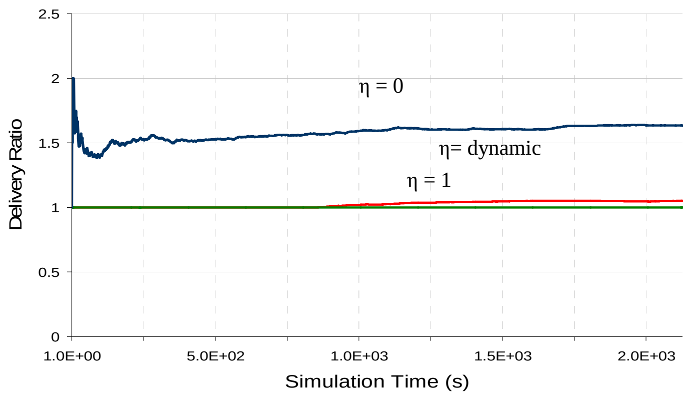

Figure 11 : Delivery ratio of different values of η

Figure 12 shows the average end to end delay for static sink against a mobile sink. Mobility in wireless networks comes with many challenges. A detailed study on trends in mobility management can be found in [Siddiqui, 04].

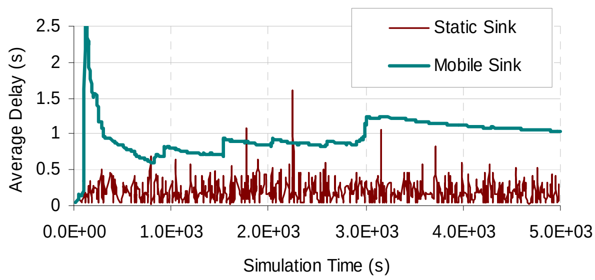

Figure 12 : Average end to end delay for static and mobile sink

In our simulation, instead of moving the normal sensor nodes, we moved only the sink node to reduce computational complexity and therefore simulation time. A higher delay and a few abrupt changes indicate some potential forwarding nodes become dead-nodes when the sink nodes move out of their transmission range. The peaks for static sink are very few and may have caused because of probabilistic nature of MAC scheme.

Figure 13 shows the delivery ratio of a static sink and a mobile sink in the simulation topology. It is clear from the figure that the delivery of a message is guaranteed even if the sink node is moving. Higher delivery ratio for the mobile sink is because of increased reverse message transmissions due to mobility of the sink node as well as failure to suppress duplicate message transmission.

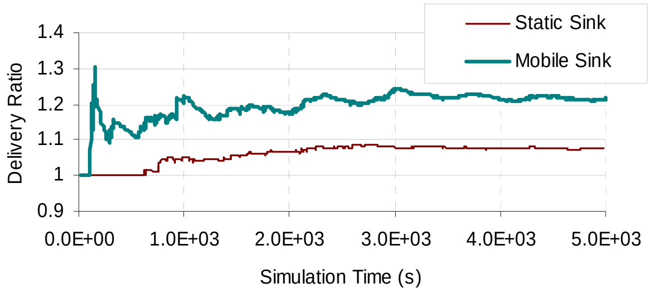

Figure 13 : Delivery ratio for static and mobile sink

The average end to end delay values in order of seconds do not reflect the absolute values. These values can be minimized to greater extent by using optimized value of T_{max}. The delivery ratio of 1 indicates guaranteed delivery while delivery ratio of greater than 1 indicates packet duplication. The only reason for packet duplication is either the competing nodes have almost the same energy level or they provide more or less the same progress towards the destination. The usage of η between the range of 0 to 1 and not the both extremes will eliminate the problem to some extent; by reducing the probability to have both the value in the same range.

Figure 14 shows the remaining network energy for three different schemes, flooding, simplified version of EADV (Energy Aware Distance Vector Routing) [Mahlknecht, 06], and TPR. This test was conducted to see the results of TPR against a table driven protocol. The network remaining energy is the energy consumed by all the nodes with time. It is clear from the figure that the network energy consumed by TPR is far less than that of EADV and flooding. The simulation was stopped when the remaining energy reached to 0.1J to reduce the simulation time.

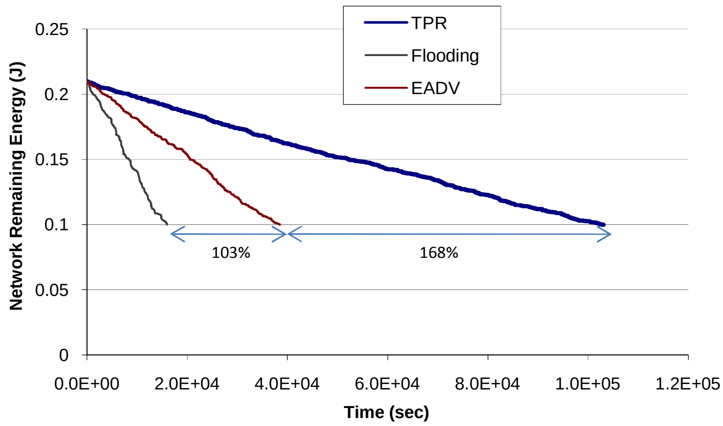

Figure 14 : Remaining network energy

Although, TPR, results in extended network lifetime and reduced energy consumption as compared to other routing protocols like EADV and flooding; for end-to-end delay, EADV and flooding outperforms TPR as shown in Figure 15. Therefore, it is always a trade off between end to end delay and is dependent on the application to go for low energy consumption at the cost of higher end to end delay or vice versa.

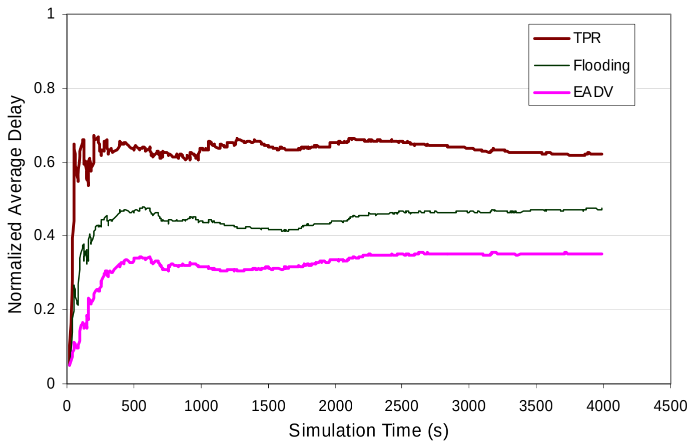

Figure 15 : End to end delay comparison

5 Conclusion and Future Work

We have shown that TPR is well suited for low power wireless networks of embedded devices. It exhibits reduced message overhead, guaranteed delivery, and an adjustable delay-energy aware metric which can be adapted to extend the network lifetime or decrease the end to end delay. The dynamic shifting between progress and energy aware strategy has extended the network lifetime by more or less 50%. TPR is highly scalable as no routing tables are maintained. Setting up response timers is a challenging issue specifically when the competing nodes provide same progress and/or same remaining energy based cost and requires further research. Future work also includes an adaptation of the currently used forwarding acknowledgement scheme to a CTS/RTS like approach to reduce the data packet duplicates at the cost of increasing control packet duplicates. Additionally a method to dynamically control weight parameters (progress or energy aware) during network lifetime is currently under development. We also intend to use obstructed graph models in future to see the robustness of protocol in such environments. Further testing and extensive simulation to compare TPR with similar class of protocols with detailed modeling of MAC layer and Radio will be done. Extensive simulations and performance evaluation would be followed by implementation of TPR on a real sensor node.

Acknowledgements

We would like to thank FIT- IT, Austria, and Higher Education Commission of Pakistan for proving support for this work.

References

[Akyildiz, 02] Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, A survey on sensor networks, IEEE Commun. Mag. 40 (8) (2002) 102--114.

[Araújo, 05] F. Araújo, "Position-based distributed hash tables," Ph.D. dissertation, University of Lisbon, Lisbon, Portugal, 2005.

[Basagni, 98] Basagni, S., Chlamtac, I., Syrotiuk, V. R., and Woodward, B. A. 1998. A distance routing effect algorithm for mobility (DREAM). 4th Annual ACM/IEEE international Conference on Mobile Computing and Networking, October 25 - 30, 1998.

[Blum, 03] B. Blum, T. He, S. Son, and J. Stankovic. IGF: A state-free robust communication protocol for wireless sensor networks. Technical Report CS-2003-11, Department of Computer Science, University of Virginia, 2003.

[Fueßler, 03] H. Fueßler, J. Widmer, M. Mauve, and H. Hartenstein. A Novel Forwarding Paradigm for Position-Based Routing (with Implicit addressing). In IEEE Computer Comm. Workshop (CCW 2003), 2003.

[Glaser, 08] J. Glaser, D. Weber, S. Madani,, S. Mahlknecht, "Power aware simulation framework for wireless sensor networks and nodes", Eurasip journal of embedded systems 2008.

[Heinzelman, 00] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. Hawaii International Conference on System Sciences Jan. 2000.

[Hou, 88] Ting-Chao Hou; Victor Li, “Transmission Range Control in Multihop Packet Radio Networks”, IEEE Transactions on Communications, Vol.34, Iss.1, Jan 1988.

[Jain 01] R. Jain, A. Puri, and R. Sengupta, “Geographical Routing Using Partial Information for ireless Ad Hoc Networks,” IEEE Pers. Commun., Feb. 2001, pp. 48–57.

[Johnson, 96] D. B. Johnson and D. A. Maltz, “Dynamic source routing in ad hoc wireless networks”, Mobile Computing, Kluwer, 1996.

[Karp, 00] Karp, B. and Kung, H. T. 2000. GPSR: greedy perimeter stateless routing for wireless networks. 6th Annual international Conference on Mobile Computing and Networking, August 2000.

[Ko, 00] Ko, Y. and Vaidya, N. H. 2000. Location-aided routing (LAR) in mobile ad hoc networks. Wirel. Netw. 6, 4 , Jul. 2000.

[Kranakis, 99] E. Kranakis, H. Singh and J. Urrutia, Compass routing on geometric networks, Proc. 11th Canadian Conference on Computational Geometry, Vancouver, August, 1999.

[Mahlknecht, 06] Mahlknecht, S., Madani, S.A., Roetzer, M., “Energy Aware Distance Vector Routing Scheme for Data Centric Low Power Wireless Sensor Networks”, 5th IEEE International conference on industrial informatics, 2006.

[Mahlknecht, 07] S. Mahlknecht, S. Madani, “On architecture of low power wireless sensor networks for container tracking and monitoring application”, fifth IEEE international conference on industrial informatics, July 2007.

[Mauve, 01] Martin Mauve, Jörg Widmer, and Hannes Hartenstein. A survey on position-based routing in mobile ad-hoc networks. IEEE Network Magazine, November 2001.

[Omnet, 08] www.omnetpp.org

[Perkins, 94] C. E. Perkins and P. Bhagwat, “Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers”, Comp. Commun. Rev., Oct. 1994.

[Perkins, 99] C. Perkins and E. Royer, “Ad hoc On demand distance vector routing”, Proc. 2nd IEEE Wksp Mobile Comp. Sys. & Apps., Feb 1999.

[Raghavendra, 04] C.S. Raghavendra, Krishna M. Sivalingam and Taieb Znati, “Wireless Sensor Networks”, Kluwer Academic Publishers, 2004.

[Rakhmatov, 01] Rakhmatov, D. N. and Vrudhula, S. B. “An analytical high-level battery model for use in energy management of portable electronic systems”. IEEE/ACM international Conference on Computer-Aided Design, 2001.

[Shah, 02] Rahul C. Shah and Jan M. Rabaey. Energy aware routing for low energy ad hoc sensor networks. In Proc. IEEE Wireless Communications and Networking Conference (WCNC), Orlando, FL, March 2002.

[Siddiqui, 04]Farhan Siddiqui, Sherali Zeadally, Mobility management across hybrid wireless networks: Trends and challenges, Computer Communications, Volume 29, Issue 9, , ICON 2004 - 12th IEEE International Conference on Network 2004, 31 May 2006, Pages 1363-1385.

[Stojmenovic, 01] I. Stojmenovic and Xu Lin, “Loop-free Hybrid Single-Path/Flooding Routing Algorithms with Guaranteed Delivery for Wireless Networks,” IEEE Trans. Parallel Dist. Sys., vol. 12, no. 10, 2001.

[Stojmenovic, 02] I. Stojmenovic, "Position-based routing in ad hoc networks," IEEE Commun. Magazine, vol. 40, pp. 128--134, July 2002.

[Takagi, 84] H. Takagi and L. Kleinrock, “Optimal transmission ranges for randomly distributed packet radio terminals,” IEEE Transactions on Communications, vol. 32, no. 3, pp. 246–257, March 1984.

[Ulema, 06] Ulema, M., Nogueira, J. M., and Kozbe, B. 2006. Management of Wireless Ad Hoc Networks and Wireless Sensor Networks. J. Netw. Syst. Manage. 14, 3, Sep. 2006.

[Witt, 05] Witt, M.; Turau, V., BGR: blind geographic routing for sensor networks, Third International Workshop on Intelligent Solutions in Embedded Systems, 2005.

[Zhang, 08]L. Zhang, Q. Cheng, Y. Wang, and S. Zeadally, "A Novel Distributed Sensor Positioning System Using the Dual of Target Tracking", IEEE Transactions on Computers, Vol. 57, No. 2, February 2008.

[Zou, 05] Zou, L.; Lu, M.; Xiong, Z., A Distributed Algorithm for the Dead End Problem of Location Based Routing in Sensor Networks, IEEE Transactions on Vehicular Technology, Vol.54, Iss.4, July 2005.