REAP: ring band-based energy adaptive protocol for information dissemination and forwarding in wireless sensor networks

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Abstract: The design issues related to routing in Wireless Sensor Networks (WSNs) are inherently different from those encountered in traditional mobile ad hoc networks. Routing protocols forad hoc networks usually impose prohibitive demands on scares resources of a sensor node such as memory, bandwidth and energy; therefore, they are not suitable for WSNs. In this paper, we present a novel, energy adaptive data forwarding protocol, referred to as Ring band-based Energy Adaptive Protocol (REAP), in which nodes self-organise into virtual ring bands centred at the Base Station (BS). Packets are automatically delivered to the BS along a path with decreasing ring band number. Furthermore, the proposed probabilistic forwarding mechanism also balances the workload among neighbouring nodes within the same ring band. Simulation study showed REAP exhibits good performance in various network settings even when nodes are in rapid motion.

Keywords: energy efficient; data forwarding; Wireless Sensor Networks (WSNs); ring band; routing.

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1 Introduction

Recent advances in wireless communications, coupled with the convergence of technological and application trends, have resulted in exceptional levels of interests in Wireless Sensor Networks (WSNs). These networks are composed of large number of low-cost, low-power, multifunctional, wireless devices spread over a geographical area. Individually, sensing devices are resource-constrained and, therefore, are only capable of a limited amount of processing and communication. It is the coordinated effort of a large number of these devices, however, that bears promises for a significant impact, not only on science and engineering, but equally importantly on a broad range of civil and military applications, including managing complex physical systems, surveillance and environmental monitoring.

Harnessing the potential of WSNs brings about a number of fundamental challenges, the most critical of which is finding new ways to increase the longevity of these networks. Since sensors will either have to be powered by small non-renewable batteries or by the modest amounts of energy that can be harvested from the environment, developing energy-efficient algorithms and mechanisms to optimise the use of battery power, while satisfying different and often contradictory performance metrics, is the most critical issue in the design of network protocols for WSNs. This is particularly true for the routing problem, which arises naturally in many sensor applications, where data reporting on events flows toward the Base Station (BS).

Routing in WSNs has been the focus of increased research efforts. Sensors collectively self-organise into a wireless ad hoc network and use multihop paths to send data about sensed events back to the BS. A closer look at the characteristics of typical WSN applications reveals unique features of these applications, in terms of data flow, which make the routing problem inherently different from its counterpart in traditional ad hoc networks. Firstly, data collected by multiple collaborating sensors is typically aggregated on its way to the BS. Furthermore, the data exchange is usually of short duration, as short bursts of packets are generated in response to occurring events. Consequently, the establishment of reliable, end-to-end connections is unnecessary and too cumbersome for WSNs. Secondly, in traditional ad hoc networks, data is exchanged between peers. In a sensor network, however, most of the data traffic flows from sensor nodes to the BS, although traffic from the BS to the rest of the network, such as interest broadcasting or reinforcement in Directed Diffusion (DP) (Intanagonwiwat et al., 2000), for example, may occur occasionally. Finally, efficiently gathering data, generated by sensor nodes, on its way to the BS will yield greater gain in system performance.

Although WSNs exhibit few similar features to ad hoc networks, directly applying routing protocols designed for ad hoc networks to forward data from sensor nodes to the BS is inefficient. Most of the routing protocols for ad hoc networks are designed to support communication between peers. As such, these protocols usually require each node to store recently discovered routing paths in its cache. Furthermore, an ad hoc node may resort to some form of flooding to rebuild a broken path after a link failure or discover a new one if such a path is not stored in the cache. Consequently, increased node mobility leads to frequent flooding as broken links invalidate entries in the network nodes' caches.

Other routing protocols designed specifically for sensor networks fail to recognise the asymmetry of the traffic patterns in sensor networks. Efforts are mostly directed towards finding energy efficient paths either to the BS or to a peer. Routing tables are required by these schemes and flooding is inevitable to establish new routes.

In this paper, we propose a novel Ring band-based Energy Adaptive Protocol (REAP), for data forwarding from sensor nodes to the BS. Based on this protocol, nodes self-organise to logically form a set of *ring bands* centred at the BS. These ring bands form a *gradient*, whereby packets are routed automatically from the most outer ring band towards the BS. In moderately mobile WSNs, nodes adjust their ring band information locally, thereby obliviating the need for route discovery. Flooding occurs only during the network initialisation phase when nodes establish their ring band information.

An important issue in the design of network protocols for WSNs is energy consumption, as sensor nodes are often operated by unrenewable batteries or at best rechargeable using very limited energy sources harvested from the surrounding environment. REAP limits its use of flooding, thereby leading to significant energy savings. Furthermore, REAP is robust against node failures, as it does not require creating and maintaining routing tables. Finally, REAP uses a unique probabilistic forwarding mechanism to balance the workload among the sensor nodes, effectively prolonging the network lifetime.

The rest of this paper is organised as follows. Several routing protocols that are related to our work are discussed in Section 2. The basic operations and functionalities of REAP are discussed in Section 3. In Section 4, a simulation study is presented, and the results of multiple experiments to assess the performance of REAP are discussed. We conclude this work in Section 5.

2 Related work

There has been a great deal of research work related to routing in ad hoc and wireless sensor networks. A few representative protocols for traditional ad hoc networks include AODV, DSR and WRP (Johnson and Maltz, 1996, Murthy and Garcia-Luna-Aceves, 1996, Perkins, 1997). These protocols aim at finding the shortest path, usually expressed in number of hops. This is achieved by typically maintaining a routing table, which may require periodical or on-demand flooding to discover new routes or to repair broken ones. These protocols are not scalable and, therefore, are not suitable for WSNs, especially those that involve thousands of mobile nodes.

Hierarchical routing represents a large family of routing protocols (Heinzelman et al., 2000; Li and Znati, 2005; Lindsey and Raghavendra, 2001; Manjeshwar and Agrawal, 2001; Nieberg et al., 2003; Sun and Brodersen, 1992). The basic idea of these protocols is to elect nodes, usually called cluster-heads, to assume specific responsibilities, such as forming clusters and creating routing backbones. Routing information are exchanged and maintained only by these nodes. As such, these protocols can scale to large network sizes. However, if nodes are mobile, the cost of maintaining a cluster-based architecture can become prohibitive, as mobility may frequently disrupt cluster membership.

To address these shortcomings, new features are introduced to deal with various aspects of sensor networks, such as node mobility and the fact that sensor nodes have limited energy supply. An extensive survey of routing protocol for WSNs can be found in Akkaya and Younis (2005). SSA uses signal stability as the indicator of a neighbour's mobility (Dube et al., 1996). In SSA, nodes with mild or no motion are selected to be included in the routing table. Toh independently developed a similar idea in Toh (1996), GAF (Xu et al., 2001), SPAN (Chen et al., 2001) and PAMAS (Singh and Raghavendra, 1999) strategically identify redundant nodes which are then required to turn off their radio transceivers to save energy. This strategy is based on the observation that WSNs are usually densely deployed. Consequently, carefully selecting nodes to go to sleep does not reduce significantly the connectivity of the WSN. These protocols, however, do not take into consideration the impact of turning off radios on the routing cost, as the sensor nodes, which go to sleep, are likely to invalidate active nodes' routing tables. Consequently, subsequent routing requests result in extra routing overhead.

Other novel protocols take different approaches to reduce the amount of overhead required to route data between the sensor nodes and the BS (Barrett et al., 2003; Braginsky and Estrin, 2002; Haas et al., 2001; Li et al., 2001; Zussman and Segall, 2003). Braginsky and Estrin (2002) emulates the rumor spreading phenomenon. Event agents are created when certain events happen. Interest agents are used to intercept these event agents to bring back the information to interested parties. Barrett et al. (2003) and Haas et al. (2001) use probabilistic approach to flood a network with minimum overhead. The works in Zussman and Segall (2003) and Li et al. (2001) model routing in WSNs as a flow problem and use linear programming to maximise certain attributes. These types of protocol often require flow information a priori, which may not be available at the time the network is deployed.

DD is among the first few data-centric protocols designed to collect and forward data towards a BS (Intanagonwiwat et al., 2000). The BS periodically broadcasts its interests to the whole network. The interest broadcast packet builds up an *interest gradient* along the way. Data are gathered from sensor nodes in the reverse direction of the gradient back to the BS. Similar work can be found in PULSE (Younis et al., 2004). An extension work of DD is presented in Schurgers and Srivastava (2001). In these protocols, if the gradients of a multiple candidate nodes for next hop are the same, selection of one node among these candidates can be performed either randomly, based on the residual energy of the node or its current workload.

A cost-based routing protocol, which uses a similar approach as REAP, is described in Ye et al. (2001). Based on this protocol, the BS initially broadcasts a packet to the rest of the network. Nodes compute the cost for this packet to reach them, append this information to the packet header and rebroadcast the packet. At the end of this phase, each node discovers the minimum cost to transmit a packet from itself to the BS. In subsequent communications, each packet carries the minimum cost of the sending node and the cost to send this packet. A node only relays a packet if its minimum cost value matches the difference between the two values carried in the received packet. No route information, except the minimum cost, is cached at any node. This scheme suffers several shortcomings, including the risk of fast energy depletion of nodes which lie on critical routing paths and the inability to deal efficiently with mobility as the minimum cost status of each node changes when nodes move.

GRAB (Ye et al., 2005) extends the work in Ye et al. (2001). In this protocol, a 'credit' field is added to the cost field. Nodes whose cost is less than the sum of the budget and the credit are allowed to forward received packets. The addition of credit increases the number of nodes participating in data forwarding. Consequently, it is more robust than the original scheme. GRAB, however, still relies on periodical refreshment to handle excessive packet losses due to link or node failures, making it unsuitable in mobile sensor networks.

EAR (Shah and Rabaey, 2002) is a variation of DD. In DD, lowest energy paths are always used. EAR shows that probabilistically using suboptimal paths can help in prolonging the lifetime of the network. ReInForm (Deb et al., 2003) achieves robustness through multiple paths. A sender decides how many copies of a packet to be sent out based on the distance, between itself and the sink, and the error rate of the channel. It chooses the next hop with a bias towards nodes with less hop numbers toward the sink. However, ReInForm uses the number of hops to the sink as the routing performance metric. This limits significantly its applicability to WSNs with mobile nodes.

REAP takes a different approach from the ones taken by the above protocols, and establishes a ring band-based structure for data forwarding. Based on this structure, each node only maintains information about which ring band it belongs to. Packets are relayed automatically from the outer ring bands to the inner ring bands, until they eventually reach the BS. As there could be multiple relaying candidates in the next ring band, a number of these candidates can turn off their radio without disrupting the data forwarding process. No route-discovery-related flooding is necessary even when links break. Nodes dynamically adjust their membership to a given ring band as they move within the network. This is achieved either implicitly based on overhearing or explicitly based on the exchange of local queries and responses between neighbouring nodes, thereby making the scheme highly scalable. Furthermore, nodes adopt a probabilistic forwarding strategy in relaying a packet based on their residual energy. This results in a balanced load among relaying nodes, which in turn results in a longer network lifetime.

3 REAP: architecture and data forwarding

The basic idea of REAP revolves around the concept of ring bands. Nodes in REAP self-organise into a structure of ring bands, centred around the BS, in a way such that each node belongs to one ring band. Based on this organisation, traffic is forwarded from an outer to an inner ring band until it reaches the BS. In the following sections, a formal definition of a ring band is provided, along with a detailed description of REAP functionalities and operations.

3.1 Ring band formal definition

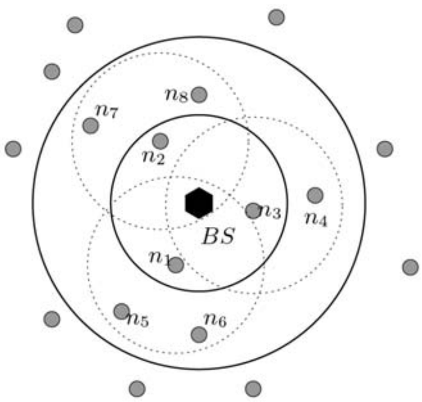
Based on REAP, a ring band is a collection of sensor nodes located within the same number of hops from the BS. The initial ring band is initiated by the BS and includes all sensor nodes, which reside within the transmission coverage of the BS. These nodes are considered to be one hop away from the BS, and as such they belong to ring band 1. This process continues recursively until every node in the network identifies the ring band to which it belongs. Formally, the concept of ring band can be defined as follows.

Definition: *A node i is said to belong to ring band j if and only if there exists some node k which belongs to ring band $j-1$, such that node i is within the transmission range of node k.*

Definition: *Let d_i be the distance, expressed in terms of hops, between node i and the BS. A ring band j $(j \geq 1)$ is a collection of nodes i such as $d_i = j$. Ring band 1 is the set of nodes within one hop from the BS.*

The recursive process of ring band formation is depicted in Figure 1. The process is initiated by the BS, which leads to the formation of ring band 1. This ring band includes nodes n_1, n_2 and n_3. These nodes are within the transmission coverage of the BS. Nodes n_5 and n_6 are within the transmission range of node n_1, whereas node n_7 and n_8 are within the transmission range of node n_2 and node n_4 is within the transmission range of n_3. Since nodes n_1, n_2 and n_3 belong to ring band 1, node n_i, $4 \leq i \leq 8$ are by definition in ring band 2.

Figure 1 Recursive ring band formation process



3.2 REAP basic operations

To carry out its functionalities and basic operations, REAP defines a set of packet types. The generic format of a given packet is depicted in Figure 2. Every packet is identified by its type, as indicated in the type field of the packet. The description of each field in the packet header is provided in Table 1.

The maximum number of ring bands depends on the number of sensor nodes as well as the distance between the farthest node and the BS. If k is the maximum number of bits allocated for the 'ring band' field, the farthest node in the network can reside at a maximum number of 2^k hops. The Packet Number field contains the sequence of the number of the packet. This number is generated by the source node and wraps back to 0 after $2^s - 1$ packets are generated. This field is used to detect duplicate packets. Notice that type 4 packets are used exclusively when there is a need for peer communications between sensor nodes. The details of how these packets are routed are omitted since the main focus is on forwarding data traffic to the BS, which accounts for the majority of the traffic in WSNs.

Figure 2 (a) A packet and (b) header formation

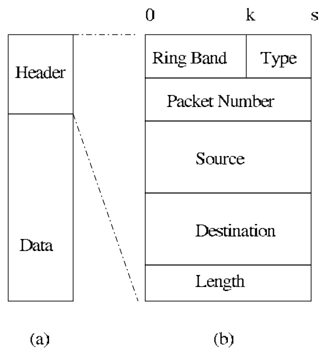


Table 1 Packet header

Field	*Meaning*
Ring band	Sender ring band
Type	Packet type
0	Ring band initialisation
1	Data
2	Ring status inquiry
3	Reinitialisation request
4	Routing Request (RR)
5	Response to RR
6	Dummy Packet
Packet Number	Source generated packet number
Source	Source address
Destination	Destination address
Length	Data field length

3.3 REAP network initialisation

Each node maintains a local variable L to record its own ring band number. Originally, the value of L is set to 0 and reflects the fact that the node does not currently belong to any specific ring band. During the network initialisation phase, the BS broadcasts a type 0 packet with the ring band field set to 1. Upon receiving a type 0 packet, a node examines the value of the ring band field carried by the packet to determine the action to be undertaken. If current value of the node's variable L is set to 0, the node copies the received ring band number into its own variable L, thereby signifying its joining of the ring band identified in the ring band field of the received packet. The receiving station also overwrites its own ring band variable, L, with the value, V, carried in the ring band number field of the received packet, if L is greater than V. This is necessary as a node may receive multiple type 0 packets in a random order, causing the node to incorrectly associate itself with the wrong ring band. In both cases, the node increases the value contained in the ring band field of the received packet by one and rebroadcasts this packet. If the current value of the node's variable is lower than V, the packet is simply discarded.

At the completion of the initialisation phase, all nodes correctly associate themselves with the proper ring band. Consequently, the local ring band variable of each node contains the minimum number of hops between itself and the BS. Furthermore, the set of ring bands form a virtual, layered structure which provides a backbone for data forwarding.

3.4 REAP data forwarding

Upon discovering the ring band to which it belongs, each node is responsible for relaying packets from outer to inner ring bands. To achieve this goal, REAP uses a power-aware strategy, whereby nodes make local decisions on whether or not to forward a received packet, taking into consideration their current residual energy and the number of attempts to forward the packet. More specifically, upon receiving a packet, a given node, n, attempts to forward the received packet with a probability, $\Gamma(e, t)$, where e is the residual energy level of n and t is the number of unsuccessful attempts made by n to forward the packet.

3.4.1 Data forwarding probability

To ensure that some node, n, within a ring band eventually forwards the received packet, the value of $\Gamma(e, t)$ must be 1 when t, the number of attempts made by n to forward the packet, reaches the maximum number of attempts, T. Consequently, the value of $\Gamma(e, t)$ must increase as t increases. Furthermore, $\Gamma(e, t)$ must be such that, within a ring band, nodes with higher residual energy levels, are more likely to forward a packet than those with lower energy levels. Formally, these constraints can be summarised as follows:

$$0 \leq \Gamma(e, t) \leq 1 \tag{1}$$

$$\Gamma(e, t+1) \ > \ \Gamma(e, t) \tag{2}$$

$$\Gamma(e, t) \ > \ \Gamma(e', t), \ e > e' \tag{3}$$

$$\Gamma(e, T) \ = \ 1 \tag{4}$$

$$\Gamma(e, 1) = P \tag{5}$$

where P is the initial packet forwarding probability.

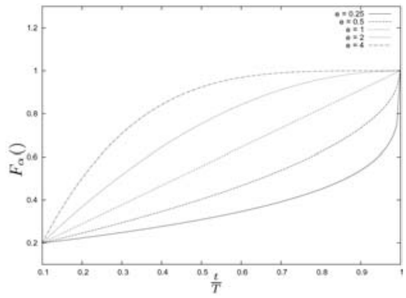
Theorem 3.1: *The family of functions described in Equation (6) satisfies the constraints 2–4.*

$$F_\alpha\left(\frac{t}{T}\right) = 1 - \alpha\left(1 - \frac{t}{T}\right)^e \quad 1 \leq t \leq T \tag{6}$$

Proof: It is easy to show that $F_\alpha(t/T)$ is an increasing function of t and e. Furthermore, the remaining constraint can be verified by substituting t with T in Equation (6).

An instance of $F_\alpha()$, for $\alpha = 1$, is illustrated in Figure 3. As shown in the figure, for a given value of t/T, the value of $F_\alpha()$ increases as e increases. For a fixed value of e, however, the value of $F_\alpha()$ increases as t increases. Furthermore, the value of $F_\alpha()$ reaches 1, when t equals T. It is worth noting that $F_\alpha()$ increases at a faster rate towards 1 as the value of e increases.

Figure 3 $F_\alpha(t/T)$ for different values of e ($\alpha = 1$)



Theorem 3.2: $\Gamma(e, t) = F_\alpha(t/T)$ *satisfies constraints 1 and 5 when* $\alpha = (1 - P)(T/T - 1)$.

Proof: Constraint 1: $\Gamma(e, t) = 1 - \alpha(1 - t/T)^e = 1 - (1 - P)(T - t/T - 1)^e$, since $0 \leq (1 - P) \leq 1$ and $0 \leq (T - t/T - 1)^e \leq 1$ when $0 \leq t \leq T$, $0 \leq \Gamma(e, t) \leq 1$. Constraint 5: $\Gamma(e, T) = 1 - (1 - P)(1 - T/T)^e = 1 - (1 - P) = P$.

Based on the above discussion, the forwarding probability of a given node, n, is defined in Equation (7).

$$\Gamma_n(e_n, t_n) = 1 - (1 - P_n)\left(\frac{T - t_n}{T - 1}\right)^{e_n} \quad 1 \leq t_n \leq T \tag{7}$$

where P_n is the initial forwarding probability, t is the current number of attempts since the arrival of the packet and e is a measure of the residual energy level.

The parameter e_n in Equation (7) is a function of the current energy level of node n. When the node has a low energy level, e_n should be low, which forces the forwarding probability to increase at a slow rate. On the other hand, when the node has a high energy level, e_n must be high: thus, forcing the forwarding probability to increase at a higher rate. It should be noted that, for a mid-range energy level, the increase of the forwarding probability is almost linear with the number of attempts. For a given node, n, the parameter e_n can be derived from the n's current relative energy level as follows:

$$e_n = 2^{4(E_n - 0.5)} \tag{8}$$

where E_n is the relative energy level (normalised to full energy) of node n.

The parameter E_n is equal $r_n/E\max_n$, where r_n represents the current residual energy level of node n and $E\max_n$ is the maximum energy level of node n. The parameter P_n, which defines the initial forwarding probability, can be set to E_n. Note that, within a ring band, nodes with higher energy residue levels are more likely to forward the packet at the first attempt than their neighbouring nodes with lower energy residue levels.

3.4.2 Data forwarding process

For each received packet from a higher ring band, a node computes its packet forwarding probability, $\Gamma_n(e_n, t_n)$, to determine if it is responsible for relaying the packet towards the BS. The node stores the received packet in a received queue, Q_r, until it either successfully forwards the packet to a lower ring band or it determines that a neighbouring node within its ring band has assumed the responsibility to transmit the packet. In the latter case, the node drops the packet.

If the node forwards the packet to a lower ring band, it keeps track of the forwarded packet in a sent queue, Q_s, until it determines that the packet has been successfully received by the lower ring band or a timeout occurs. The node confirms that the packet is successfully received by the lower ring band, if it overhears that it is being forwarded by a lower ring band node towards the BS. The main steps of the data forwarding process, executed by node n, can be summarised as follows:

- If the node overhears a packet transmission from a lower ring band, the packet number, source address and destination address are examined and compared to the packets in Q_s. A match indicates that the packet has been successfully received by a lower ring band node and it is being relayed towards the BS. In response, the node deletes the corresponding entry in Q_s. If there is no match, the node ignores the overheard transmission.
- If the node overhears a packet coming from its own ring band, the node checks the packet header against packets in its own Q_r. A match indicates that a peer node has assumed the responsibility of forwarding the packet. The node terminates its own packet forwarding process and clear the packet from its Q_r. If no match occurs, the node ignores the overheard transmission.
- If the packet comes from outer ring band, a node stores the received packet in its Q_r and initiates the packet forwarding process by computing $\Gamma_n(e_n, t_n)$. This process continues until either the node successfully forwards the packet or overhears the transmission from another node within its own ring band. If the node forwards the packet, a record of the forwarded packet is created and stored in Q_s, until the receipt of this packet by the lower ring band is confirmed, or a timeout occurs.

The pseudo-code description of the data forwarding process is depicted in Algorithm 3.4.2. It is worth noting that the BS always acknowledges every packet it receives to eliminate unnecessary attempts to continue forwarding the packet. This is particularly useful if the packet is being forwarded by a mobile node, which travelled within the vicinity of the BS.

Procedure 1 Packet_Processing

Define:
p: The received packet.
D: The maximum delay of a packet before it is forwarded at one node.
t: The current number of packet transmission attempts.
G: The node current ring band number.
g: The sender's G carried in p.
Q_r: Queue for packets received from higher ring band nodes.
Q_s: Queue for packets sent.

Packet_Processing: for each data packet, p, received

```
  if g < G then
    if Match(Q_s,p) then
      Remove p from Q_s.
    end if
    Drop p.
end if
if g = G then
  if Match(Q_r,p) then
    Remove p from Q_r.
    Terminate p forwarding process.
  end if
end if
if g > G then
  Compute Γ(e_n, t_n) and continue p's forwarding process.
  if p is forwarded then
    Put p in Q_s.
  end if
end if
```

The probabilistic packet forwarding process provides the basis for power-aware load balancing among nodes within the same ring band. REAP is robust against node failure, as the probabilistic packet forwarding scheme allows multiple nodes as candidates to forward a data packet. The probabilistic nature of the scheme increases the likelihood of involving multiple nodes in the packet forwarding process, but limits the responsibility of forwarding a packet to the node with the highest residual energy. This energy-awareness aspect of the scheme prolongs the lifetime of the network.

The robustness and reliability of REAP in forwarding packets can be further enhanced by using limited flooding. This is particularly useful if no nodes currently exist within the lower ring band of the sender. This situation may cause the sender to eventually time out. To remedy this situation, the sender may initiate a route discovery process. The ring band number at each node can be used to limit the scope of the routing request flooding by confining the traffic towards the direction of the BS. To this end, the sender initiates a routing request by generating a type 4 packet, which includes its ring band number. Any node receiving a type 4 packet, with the BS as the destination, forwards the routing request packet using the following probability:

$$P = \begin{cases} 1 & \text{if the receiver's ring band number is less} \\ & \text{than or equal to the initiator's;} \\ 2^{-l} & \text{if the receiver's ring band number is greater} \\ & \text{than the initiator's and } l \text{ is the absolute} \\ & \text{value of the ring band number difference.} \end{cases}$$

Based on the above expression, the probability of forwarding a routing request is halved each time the packet moves one ring band away from the BS. Flooding is limited in the upper level ring bands in the belief that the route to the BS will be most likely discovered by the nodes in the same ring bands and below.

3.5 Adjust ring band status

Due to the mobility of the sensor nodes, their distance to the BS may change. In the ideal case, nodes only hear transmissions from other nodes in its own ring band, the ring band above and the ring band below its own. If a node hears any transmission other than these, it initiates an inquiry to adjust its ring band status by sending out a type 2 packet.

Consider the scenario when a node N, initiates an enquiry to adjust its ring band status. All the neighbouring nodes that hear node N's type 2 packet, respond with a type 6 dummy packet. Node N collects these responses and counts the number of responses from each ring band. Node N sets its ring band to be the middle ring band among three consecutive ring bands that include the majority of the responses. For example, let the number of responses received by node N be: 2 from ring band r_1, 3 from ring band r_2, 3 from ring band r_3, 5 from ring band r_4 and 1 from ring band r_5. Node N would set its ring band to be r_3, since it is the middle ring band among three consecutive ring bands (r_2, r_3 and r_4) that include the majority of the responses. In the cases when, there is more than one choice or there are less than three consecutive ring bands (e.g. in the outermost regions of the network), node N always chooses the higher ring band as its current ring band.

REAP also includes a mechanism for dealing with unstable ring bands. Since nodes gather their ring band status from the environment, it may be the case that the ring band information is incorrect. A possible scenario may involve a region (containing mobile nodes from different ring bands) in the network that experiences a prolonged silent period after which a node finally sends out a packet. This causes the nodes in the region to notice the abnormality in the ring band formation and no correct inference can be drawn. In this scenario, a node can send out a type 3 packet to ask the BS to initiate another initialisation process. Notice though, that according to REAP, a node can still send data to the BS even if it is not maintaining the correct ring band status as long as there is a connected route from the node in question and the BS with consistent decreasing ring band gradient.

Using the knowledge of their relative position to the BS, nodes can relay packets without consulting a routing table. Consequently, REAP can save energy by avoiding the cost associated with routing table construction and update, which is common to other protocols. Furthermore, nodes' willingness to relay packets is proportional to their residual energy and the workload is balanced among neighbouring nodes. Additional energy savings can be achieved by combining REAP with other protocols such as SPAN that allow us to strategically turn off redundant nodes within the same ring band according to node density and application requirements.

3.6 Adaptive sleep

A major source of energy expenditure in wireless communications is overhearing. It is especially true in WSNs because a WSN is usually densely deployed. Many energy efficient protocols save energy by strategically switching off the radio of redundant nodes. This scheme, however, does not account for the fact that turning off the radio of a sensor node may invalidate the routing table entries that are currently in use, and thus increase the routing overhead. REAP, on the other hand, is naturally amicable to such energy-saving techniques. Nodes in REAP can make local decisions on whether or not to go to sleep based on the neighbourhood connectivity without disrupting the routing process.

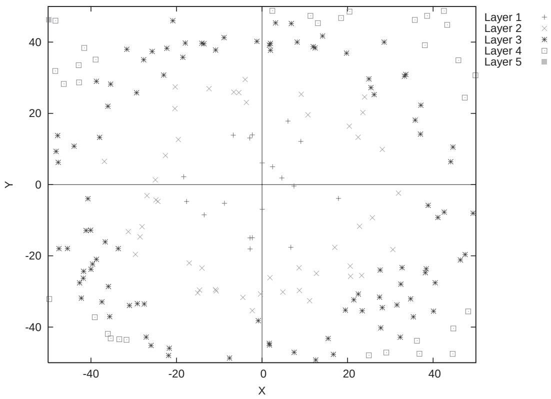
A node roughly serves a $2R \times R$ area, where R is the transmission range of a node. To ensure network connectivity, we require that a node can go to sleep only after it perceives that a certain number of its neighbouring nodes are awake within its ring band. More specifically, a node switches on its radio when it has data to report to the BS. The node remains awake until it hears a packet transmission from at least two nodes within its ring band. This node, then compares its energy level with its neighbours and goes back to sleep, if it has the lowest residual energy; otherwise, it instructs the neighbour with the lowest residual energy to go to sleep. Letting the node with the lowest residual energy switch off its radio can prolong the lifetime of the sensor network.

4 Simulation study

4.1 Simulation set-up

In all simulation experiments, 200 nodes are randomly placed on a $[-50, 50]$ m $\times$ $[-50, 50]$ m square field. Different values of transmission ranges are used to simulate different network densities.[1] Small transmission ranges lead to a higher number of ring bands than larger ones. For example, using a radio transmission range of 15, leads to a network of five ring bands at the end of the initialisation phase. The resulting network virtual ring band structure is shown in Figure 4.

Figure 4 Network status after initialisation



A first-order radio model is used to simulate the radio transceiver. On the basis of this model, where the path loss factor is set to 2, the energy expended by a sensor to transmit a k-bit message over a distance, d, is expressed as:

$$E_{Tx}(k, d) = E_{\text{elec}} \times k + \epsilon_{\text{amp}} \times k \times d^2$$

To receive a message of the same length over the same distance, the energy expended by the sensor can be expressed as

$$E_{Rx}(k) = E_{\text{elec}} \times k$$

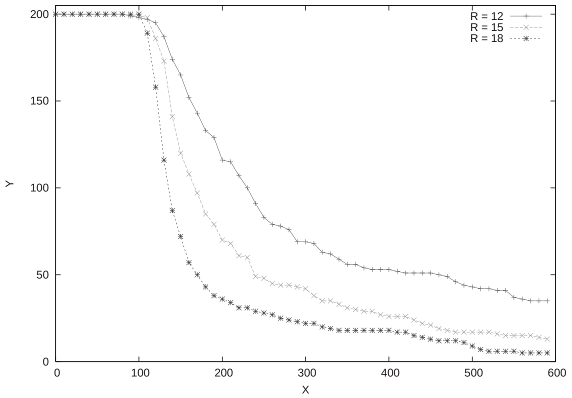
Each node within the simulated field reports one packet at a random time within a 5-sec time interval. In all experiments, all packets are assumed to be of equal length. Consequently, to receive a packet, a node expends 0.5 units of energy, while transmitting a packet over a distance of 10 m costs the sensor node one unit of energy. Energy consumption to transmit a packet over different distances can be computed based on these two values according to the radio model described above. Each node is initially configured with 4000 units of energy reserve.

Node mobility is simulated using the *random waypoint* model. Based on this model, a three-element tuple (pause-time, min-speed, max-speed) is used to describe the movement of a node. A node randomly chooses a destination within the simulated field and moves in the direction of the destination at a speed uniformly drawn from the (min-speed, max-speed) interval. After it reaches its destination, the node stays there for a time duration equal to pause-time before it chooses the next destination. Careful selection of the model's variables lead to different patterns of mobility, including stationary node behaviour. The latter can be simulated by setting the pause-time to $+\infty$.

4.2 REAP performance study

The first experiment focuses on assessing the impact of the radio transmission range on REAP's performance. The results depicted in Figure 5 show the impact of different values of *R* on the lifetime of the system, when all nodes of the network are stationary.

Figure 5 Impact of radio range on network lifetime



The simulation results show that for large radio transmission ranges, nodes expend more energy on transmission and overhearing. As a result, the energy reserves of the nodes deplete rapidly, leading to reduced network lifetime. However, since larger values of *R* extend the radio transmission range to cover larger number of nodes, energy consumption is more evenly distributed among the nodes within the same ring band. Consequently, the energy reserves of the nodes deplete at approximately the same time, resulting in a sharp drop in the number of alive nodes alive.

The focus of the second experiment is on studying the impact of node adaptive sleep on the network lifetime, expressed in terms of the number of nodes, which remain alive. The results of the experiment are depicted in Figure 6. Overall, the results show adapting network nodes to alternate between sleep and active modes increases the network longevity. The results also indicate that when a node goes to sleep with only two neighbours to remain awake, nearly half of the packets are lost. The large packet loss is due to the fact that the network becomes too sparse, which in turn, makes it difficult for active nodes to find a path with descending ring band gradient leading back to the BS. Forcing a network node not to go to sleep unless at least four of its neighbours remain awake yields both satisfactory network longevity and acceptable level of reliable packet delivery. These results are depicted in Figure 7.

Figure 6 Effect of adaptive sleep on network longevity

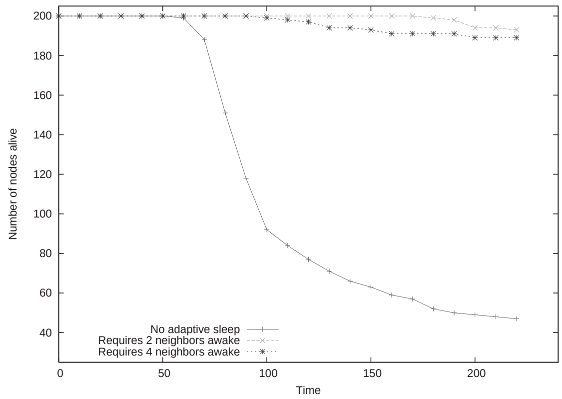
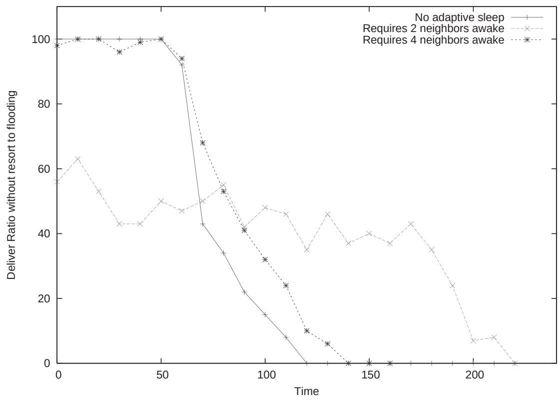


Figure 7 Packet delivery ratio without flooding



The next set of experiments focuses on studying the impact of node mobility on REAP's performance. In this set of experiments, the radio transmission range is fixed to be 15. Figure 8 shows the remaining number of alive nodes, for different node mobilities. The results reveal that node mobility disrupts the ring band memberships resulting from the initialisation phase. As nodes move, it becomes difficult to forward packets along the decreasing ring band gradient. REAP overcomes the disruption of the ring band memberships using limited scope flooding. As node mobility increases, the need to resort to scoped flooding increases, which, in turn, decreases the longevity of the network.

Further examination of the simulation results reveals that as nodes move within the simulated field, they change ring bands and rely on overhearing their current neighbouring nodes' transmissions to determine the ring band number where they are currently located. If a high level of node mobility persists in the network, nodes may carry wrong information about their ring band membership, the boundaries between ring bands blur and the number of ring bands changes frequently. Figure 9 depicts a snapshot of the network ring band structure for a radio transmission range $R = 15$ and a motion vector (5, 5, 40), after 100 sec of simulation time elapsed. It is worth noting, however, that REAP exhibits a high level of robustness to frequent network topology changes and partially wrong ring band membership by allowing nodes to still forward packets to the BS. This is due to the fact that, as long as a node can forward traffic across a decreasing ring band gradient towards the BS, no flooding is necessary.

Figure 8 Network longevity for different mobility models

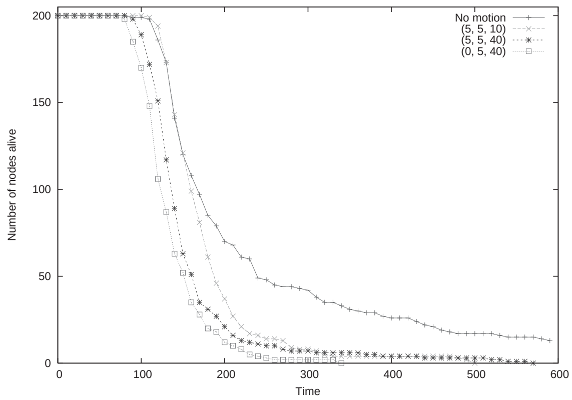
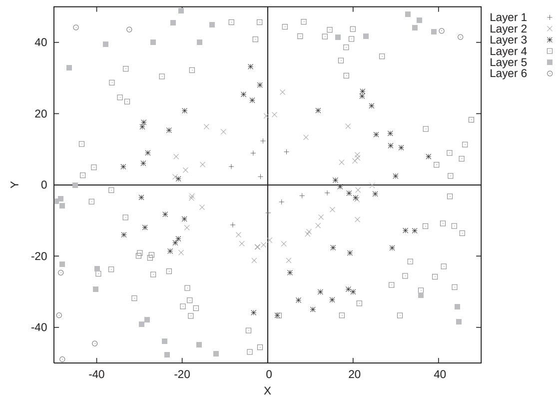
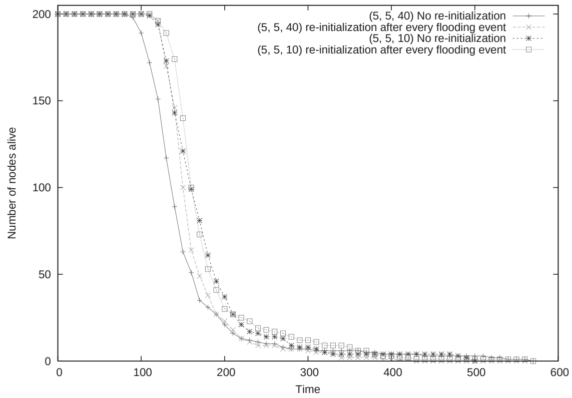


Figure 9 Nework snapshot showing blurred layer boundaries caused by node mobility



The next experiment focuses on the impact of reinitialisation on the performance of REAP. To illustrate the need for reinitialisation, consider the case where a node becomes unable to forward a packet towards the BS. This situation may occur as a result of a disconnected network or the absence of a decreasing ring band gradient toward the BS. In case of a disconnected network, which isolates the BS from a number of sensor nodes, packet forwarding data traffic becomes physically impossible. In the absence of a decreasing ring band gradient towards the BS, limited flooding can be used to forward traffic to the BS. Although the scope of flooding can be reduced in REAP by utilising ring band information, the cost of limited flooding can still be high. An alternative approach to limited flooding would be to engage the network node into a reinitialisation phase in order to restore accurate information about ring band membership. A threshold can be set in a way such that when the number of flooding packets received by the BS exceeds this threshold, a reinitialisation process is initiated by the BS. At the completion of this phase, nodes determine their correct ring band membership. Figure 10 shows the effects of reinitialisation on the performance of REAP.

Figure 10 The effects of network reinitialisation

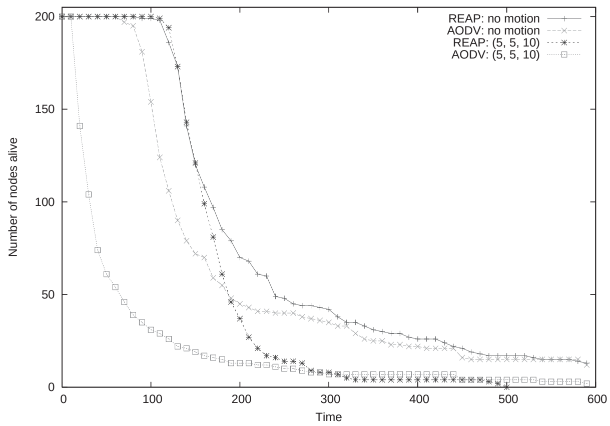


The results show that REAP, augmented with the reinitialisation process, outperforms its REAP counterpart for different mobility profiles. The results also show that the impact of reinitialisation on REAP performance is stronger when nodes move faster.

4.3 REAP comparison with AODV and GRAB

In this section, the performance of REAP is compared with that of AODV. In this simulation study, the radio transmission range is set to be 15. Figure 11 shows the network longevity profile for REAP and AODV.

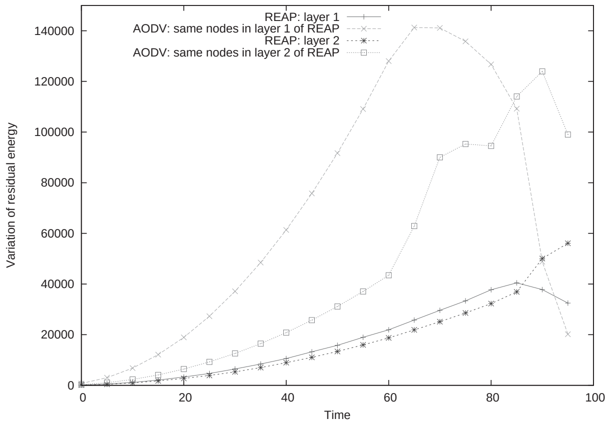
Figure 11 REAP and AODV network longevity



As illustrated in Figure 11, REAP consistently performs better than AODV, especially when nodes are in rapid motion. The performance of AODV deteriorates rapidly, while the performance of REAP is not affected significantly. This is due to the fact that when node mobility is slow or when nodes are stationary, a node is chosen to be the relay based on its residual energy reserve. Consequently, nodes expend energy in a balanced manner. When nodes are in rapid motion, however, REAP not only achieves load balancing but also manages to deliver packets without resorting to flooding. When flooding becomes necessary, REAP limits the scope of the flooding by utilising ring band information. Rapid motion just caused the collapse of the AODV routing protocol, as nodes consume a significant amount of their energy reserves trying to find a route to the BS.

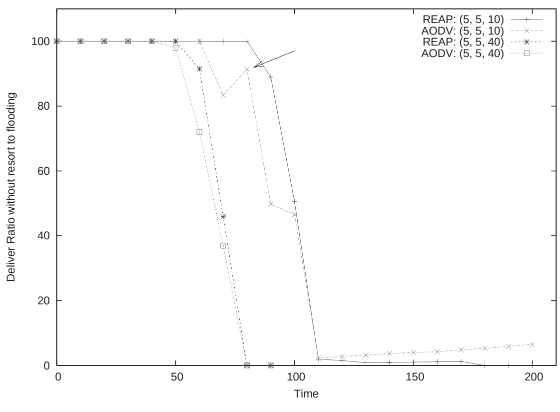
To assess the effect of load balancing on REAP and AODV performance, the variation of residual energy of nodes residing in ring band 1 and 2 when REAP is used is compared to that of the corresponding nodes in AODV, assuming no node mobility. Only results obtained when most of the nodes are alive are depicted in Figure 12.

Figure 12 REAP and AODV residual energy variation



It is evident from Figure 12 that REAP effectively balances workload among the nodes residing in one layer. Consequently, a longer lifetime is achieved as shown in Figure 11. Conversely, in AODV, nodes residing on critical path are heavily used. As a result, the energy reserves of these nodes deplete rapidly, while other nodes preserve much of their energy by not participating in the routing activity. Figure 13 shows the ratio of packets delivered by REAP and AODV without resorting to flooding, using two different motion profiles.

Figure 13 REAP and AODV packet delivery ratio



As shown in the figure, REAP can reduce the number of routing requests by 20%, in comparison to AODV. Further examination of simulation data reveals that when flooding happens, REAP involves about 30% less nodes than AODV does. These two facts explain the nearly 700% increase in the network longevity achieved by REAP in comparison to AODV, as illustrated in Figure 11, assuming nodes are mobile. The fluctuation pointed by the arrow is caused by a few routing request, which occurred during time interval [70, 80].

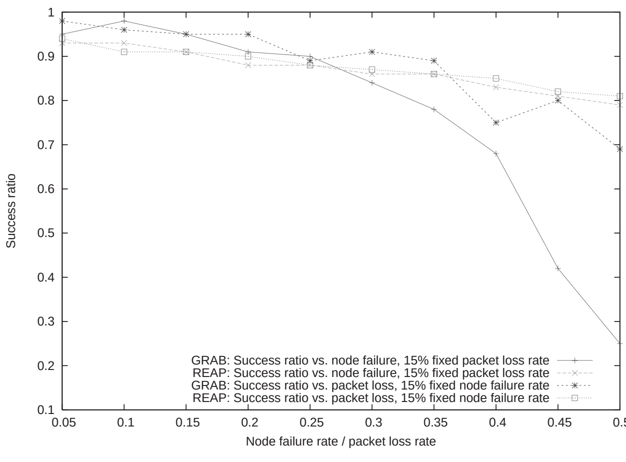
New routes are established. However, nodes on these new discovered routes die very rapidly because of the excessive involvement in forwarding packets towards the BS.

Comparing Figures 11 and 13, it can be observed that although more than 50 nodes remain alive in both protocols after 100 sec of simulated elapse, only less than 40% of the messages are delivered to the BS. Simulation data shows that most of these 50 alive nodes are far away from the BS. This observation suggests that nodes must be deployed densely around the BS and a sleeping schedule must be in place to allow nodes to take turn in sleeping and forwarding data traffic.

In the study comparing the performance of REAP with GRAB, the setting of the simulation parameters was based on the values used in the study described in Ye et al. (2005). In this experiment, 1200 nodes are spread over a 150 $\times$ 150 m^2 field with the sink and a source node residing in opposite corners. The node's transmission range is 10 m.

Figure 14 shows the ratio of packet delivery without resorting to flooding. It can be seen that REAP achieved comparable deliver ratio as GRAB. Node failure rate has almost the same effect as that of packet loss ratio, since in REAP the receiver has to acknowledge the sender when a packet is successfully received. Notice that this performance is achieved without any control overhead after the network initialisation. GRAB, on the contrary, needs periodic refreshing when the node failure or packet loss rates are high.

Figure 14 Packet delivery and node failure ratios



5 Conclusions

In this paper, we present REAP, a novel REAP for data forwarding in wireless sensor networks. In REAP, sensor nodes self-organise themselves in a *virtual ring band* centred at the BS. Instead of a routing table, nodes in REAP only maintain the ring band number of the ring to which they belong. Updates are less frequent and only involve one-hop neighbours. Packets are relayed automatically from nodes in outer ring bands to nodes in inner ring bands and eventually to the BS. The decision to forward a packet from one ring band to another is based on a probabilistic forwarding scheme that takes into consideration the residual energy of the sensor nodes. This ensures that the workload is evenly distributed among the nodes within the same ring band.

REAP requires minimal overhead to maintain paths, even if the neighbouring nodes move out of radio range. REAP can potentially prolong network lifetime as compared to other protocols by balancing the workload and by substantially reducing routing requests. Energy saving techniques frequently used in WSNs, such as adaptive sleeping, can corrupt routing tables, as nodes alternate between active and sleep states. REAP deals with this behaviour in an intrinsic, natural fashion without any disruption to the routing process.

Simulation study showed REAP exhibits good performance in various network settings, even when the nodes in the network are in rapid motion.

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Note

[1] In this work, node density is defined as the number of nodes covered by a radio transmission range, as opposed to the number of nodes per unit area.