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RESEARCH ARTICLE

Probabilistic routing protocol for a hybrid wireless underground sensor networks

Ahmed Adel[1*,†] and Fisal Norsheila[2]

[1] Computer and Communication Department, Faculty of Engineering and Information Technology, Taiz University, Taiz, Republic of Yemen
[2] Telecomminication, University Technology Malaysia, Johor, Malaysia

ABSTRACT

A wireless underground sensor network (WUSN) is defined as a network of wireless sensor devices in which all sensor devices are deployed completely underground (network sinks or any devices specifically for relay between sensors and a sink may be aboveground). In hybrid wireless underground sensor network (HWUSN), communication between nodes is implemented from underground-to-air or air-to-underground, not underground-to-underground. This paper proposes a novel hybrid underground probabilistic routing protocol that provides an efficient means of communication for sensor nodes in HWUSN. In addition, signal propagation based on the shadowing model for underground medium is developed. The proposed routing protocol ensures high packet throughput, prolongs the lifetime of HWUSN and the random selection of the next hop with multi-path forwarding contributes to built-in security. Moreover, the proposed mechanism utilizes an optimal forwarding (OF) decision that takes into account of the link quality, and the remaining power of next hop sensor nodes. The performance of proposed routing protocol has been successfully studied and verified through the simulation and real test bed. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
an optimal node; packet reception rate; path loss exponent; underground routing

***Correspondence**
Ahmed Adel, Faculty of Engineering and information Technology, Telecomminication, Taiz University, Republic of Yemen.
[†]E-mail: engadel2003@hotmail.com

1. INTRODUCTION

Wireless networking has witnessed tremendous development in recent years and it has become one of the fastest growing telecommunication sectors. There has been an explosive growth in integration and convergence of different heterogonous wireless networks in order to ensure effective and efficient communication [1].

The recent technological advancement in wireless communications, micro-electro-mechanical systems (MEMS), and digital electronics have led to the development of low-cost, low-power; multifunctional sensor nodes that are small in size and communicate within short distances [2]. These tiny sensor nodes consist of sensing, data processing and communicating components. The sensor nodes can be interconnected to form a network defined as wireless sensor network (WSN). Sensor networks are currently a very active area of research. The richness of existing and potential applications from commercial agriculture and geology to security and navigation has stimulated significant attention to their capabilities for monitoring various underground conditions.

A wireless underground sensor network (WUSN) is defined as a network of wireless sensor devices in which all sensor devices are deployed completely underground (network sinks or any devices specifically for relay between sensors and a sink may be aboveground) as illustrated in Figure 1. A hybrid wireless underground sensor network (HWUSN) is similar to WUSN; however the communication between nodes is implemented from underground-to-air or air-to-underground, not underground-to-underground. These networks can be utilized to monitor the underground environment, especially soil conditions such as water and mineral content or the presence of toxic substances, as well as certain aboveground events, such as the presence of people or animals overhead which can be determined with the use of pressure sensors [3].

HWUSN devices are thus different from existing underground sensing devices in that they require no wired link to the surface, utilizing only a buried antenna to

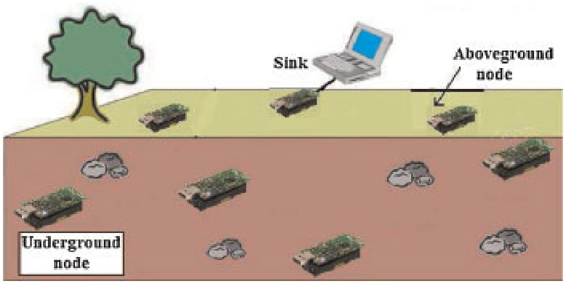

Figure 1. Underground topology.

transmit their sensor data. HWUSNs can therefore provide complete concealment, increased ease of deployment and real-time monitoring of underground data. The unique nature of the physical layer in HWUSNs makes communication amongst underground WSNs an interesting research topic. However, wireless communication with electromagnetic (EM) waves through a dense medium such as soil or rock experiences high levels of attenuation due to absorption of the signal. Overall, the underground wireless channel for EM waves can be characterized by; extreme signal loss, multi-path effects due to the inhomogeneous nature of soil, noise due to electrical ground currents, extended black-out periods after a rainfall due to wet soil.

The amount of signal loss when propagating through soil or rock is dependent upon the properties of the material. Any water in the soil produces significant amounts of attenuation which increase as the water content of the soil increases. Other soil factors which affect attenuation of EM signal propagating through the ground include density, particle size and temperature. The harsh characteristics of the underground channel require re-evaluating existing WSN routing protocols.

The general research challenges for multi-hop routing in HWUSN arise primarily due to the large number of constraints that must be simultaneously satisfied. One of the most important constraints on HWUSN is forwarding sensory data wireless through soil and rock using a buried antenna. Also, finding innovative methods of conserving power in a HWUSN is one of critical importance since devices will likely be difficult to access once they have been deployed underground (making replacement of failed power supplies impractical). Additionally, the unique requirements of underground sensing (e.g. low duty cycle operation) create other interesting challenges for communication protocols in these networks.

Most low-power wireless networks usually have unreliable links with limited bandwidth, and their link quality can be heavily influenced by environmental factors [4,5]. Recent empirical results obtained on the Berkeley mote platform indicate that wireless links are highly probabilistic, asymmetric and the link quality (i.e. packet reception rate, PRR) depends on the transmission power and the distance travelled by a packet [4,6]. Consequently, the link quality between sensor nodes should be considered while designing multi-hop routing in order to achieve high throughput in HWUSN.

This paper reports the following main contributions. First, it proposes a novel hybrid underground routing protocol (URP). URP can efficiently utilize the available physical layer which is based on the IEEE 802.15.4/Zigbee RF transceiver that has a frequency of 2.4 GHz with O-QPSK modulation. In addition, URP will use two types of packet forwarding: geodirection-cast and unicast forwarding based on the quadrant. Geodirection-cast forwarding combines geocast with directional forwarding in order to forward the data packet through a multi-path to destination. URP computes an optimal forwarding (OF) node based on PRR, and remaining power of sensor nodes. Since forwarding nodes with the best link quality are chosen, the network improves the data throughput. Additionally, choosing nodes with the highest remaining power level ensures sporadic selection of forwarding neighbour nodes. The continuous selection of such nodes spread out the traffic load to neighbours in the direction of the sink, hence, prolonging HWUSNs lifetime. URP reports high performance such as the delivery ratio and power consumption. The performance of URP has been successfully studied and verified through the simulation and real test bed. Second, this research measures experimentally the path loss exponents which will be used in the propagation model for HWUSNs. To the best of our knowledge, this is the first work that measures the path loss exponent based on shadowing mode for signal propagation in underground media.

The remainder of this paper is organized as follows: Section 2 will present related work on underground routing. The design of URP will be described in Section 3. Sections 4 and 5 will describe test bed and the simulation results. Finally Section 6 will conclude the paper.

2. RELATED WORK

The behaviour of routing protocol over HWUSN has not been addressed and evaluated by many researchers. The related research to this paper can be classified into three categories as:

2.1. WSN routing protocol

A routing protocol based on link quality is proposed in Ref. [7]. In this research, the expected transmission count metric (ETX) is developed as a metric to select forwarding node. ETX finds paths with the minimum expected number of transmissions (including retransmissions) required to deliver a packet all the way to its destination. This metric predicts the number of retransmissions required using per-link measurements of packet loss ratios in both directions of each wireless link. The primary goal of the ETX design is to find paths with high throughput, despite losses.

However, ETX does not consider the remaining power in the packet forwarding.

An energy-aware multi-path routing scheme, called as maximum capacity path scheme (MCP scheme), is proposed in Ref. [8]. In the MCP scheme, the sensor network is constructed as a layered network at first. Based on the layered network, every sensor node selects a shortest path with maximum capacity to sink. In order to improve the performance of MCP scheme, a path switching function is added to MCP scheme, denoted as MCP with path switching (MCP–PS) scheme. In MCP–PS, a node can switch the routing path to its neighbours in order to share the traffic. In multi-path routing schemes [9], sensor nodes have multiple paths to forward their data. Each time data is sent back to sink, a sensor node picks up one of its feasible paths based on special constrains such as maximum available energy or minimum delay. However, the mechanisms in Ref. [8,9] are not proposed for underground communication which is the main objective in this paper.

2.2. Underground routing protocol

Joe and Kim [10] propose underground opportunistic routing (UnOR). In UnOR, the neighbourhood nodes are supposed to buffer data through overhearing, as data are passed in the underground. If transmission fails, one of the neighbour nodes of the destination that has a high link quality is in charge of retransmission instead of the source node. The performance of UnOR protocol is superior compared to the traditional routing protocol on the test-bed. Through some test results, they had shown that UnOR protocol can improve the reliability significantly. However, UnOR used data broadcasting based on ETX to measure the link cost. Data broadcasting has a very high overhead and is not scalable to large networks such as HWUSN. In addition, UnOR does not consider load distribution which affected the HWUSN lifetime [11].

Wu *et al*. [12] propose an efficient routing algorithm, called Bounce Routing in Tunnels (BRIT), for underground tunnel WSNs. They study signal propagation and deployment models for data communication in underground tunnel environments. In addition, they propose and describe a hybrid model that combines the free-space and two-ray propagation models adaptively under the cylindrical geometric model. The performance of BRIT was evaluated using network simulator-2 (NS-2) simulations and compared against AODV as a bottom-line. However, BRIT is designed for underground tunnel WSN which means it is not working in HWUSN or WUSN. Also, BRIT does not consider remaining power for next hop node which will decrease the overall WSN performance due to limit the lifetime of WSN.

2.3. Propagation channel model

The main challenge in HWUSN area is the realization of efficient and reliable underground links to establish multiple hops underground and efficiently disseminate data for seamless operation. To this end, the propagation of EM encounters much higher attenuation in soil compared to air, which severely hampers the communication quality. As an example, efficient communication between sensor nodes above and below ground is shown to be possible only at the distance of 0.5 m when the 2.4 GHz frequency is used [13]. In addition, multi-path fading is another important factor in underground communication, where unpredictable obstacles in soil such as rocks and roots of trees make EM waves being refracted and scattered [13].

Li *et al*. [14] proposed advanced channel models to completely characterize the underground wireless channel and lay out the foundations for efficient communication in this environment. They modelled the underground communication channel such as the propagation of EM waves in soil, multi-path, soil composition, water content and burial depth. The propagation characteristics were shown through simulation results of path loss between two underground sensors. Moreover, based on the proposed channel model, the resulting bit error rate was analyzed for different network and soil parameters. The theoretical analysis and the simulation results proved the feasibility of wireless communication in underground environment and highlight several important aspects in this field. However, the proposed channel model in [14] is simulation work and it requires experiment verification. Stuntebeck *et al*. [13] examined the packet error rate and the received signal strength of received packets for a communication link between two underground sensors and between an underground sensor and an aboveground sensor. They found that the communication between two underground sensors nodes at the same depth is impossible. Hence, they focus on communication between one underground sensor node and one aboveground. However, path loss exponent based on shadowing model which is useful to predict the signal propagation does not considered. Lin *et al*. [15] proposed a WUSN based solution for monitoring the water distribution network for the purpose of leakage detection. They focus on the physical layer of WUSN, i.e. radio propagation and the determination of appropriate path loss models. In addition, they addressed the propagation measurement concerns and described how to overcome the fast fading effect. The results in Ref. [15] show that 2.4 GHz has a better path loss performance than 868 MHz for a sensor node buried at shallow depths (less than 40 cm). However, further measurements are needed in order to determine an empirical channel model for the underground to above ground scenario.

There has been some work focusing on the EM wave propagation through soil and rock for ground-penetrating radars [16–18]. In Ref. [18], a review of the principles of the surface-penetrating radar is provided. More specifically, an overview of the empirical attenuation and relative permittivity values of various materials, including soil, at 100 MHz is presented. In Ref. [17], it has been shown that the soil composition has significant effects on the ground penetrating radar (GPR) detection of landmines. Further-more, in Ref. [18], communication through soil is regarded as an EM wave transfer through the transmission line and microwave analysis methods are exploited to provide a propagation model. The results of this work focus on the frequency range of 1–2 GHz. Although significant insight in EM wave propagation through soil can be gathered from these works, none of the existing work provides a complete characterization of underground communication. More specifically, neither the channel characteristics nor the multi-path effects due to obstacles in soil have been analyzed before.

3. DESIGN OF URP IN HWUSN

In order to develop routing mechanism in HWUSN, the wireless link quality at the physical layer is studied to predict the communication between sensors. In addition, the remaining power is estimated to spread all traffic load distribution during path forwarding to the destination. In Figure 2, URP consists of four functional modules that include location management, routing management, power management and neighbourhood management. The location management in each sensor node calculates its location based on the distance to three pre-determined neighbour nodes. The power management determines the state of transceiver power and the transmission power of the sensor node. The neighbourhood management discovers a subset of forwarding candidate nodes and maintains a neighbour table of the forwarding candidate nodes. The routing management computes the OF choice, makes forwarding decision and implements routing problem handler.

3.1. Operation of URP

The overall flowchart diagram of URP is shown in Figure 3. Initially, the location management module is invoked in order to determine the sensor node location using three pre-determined nodes extracted from the neighbour table.

If the neighbour table is empty, the neighbour discovery is invoked to discover one-hop neighbour nodes. If the source node does not receive a reply from any node, the routing problem handler will be invoked. Once the location is determined, the routing management is summoned to calculate the OF node. The routing management selects the forwarding mechanism and requests the power management to adjust power transceiver for packet transmission. Besides, the routing management replies the broadcasting packet if the sensor node is in same direction of the sink.

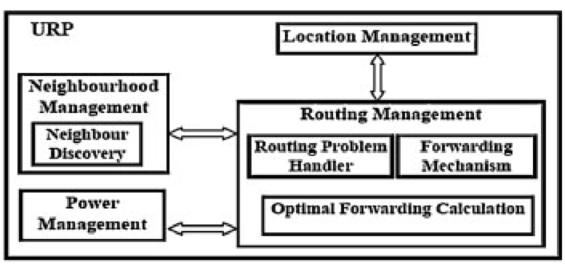

Figure 2. Block diagram of URP routing protocol.

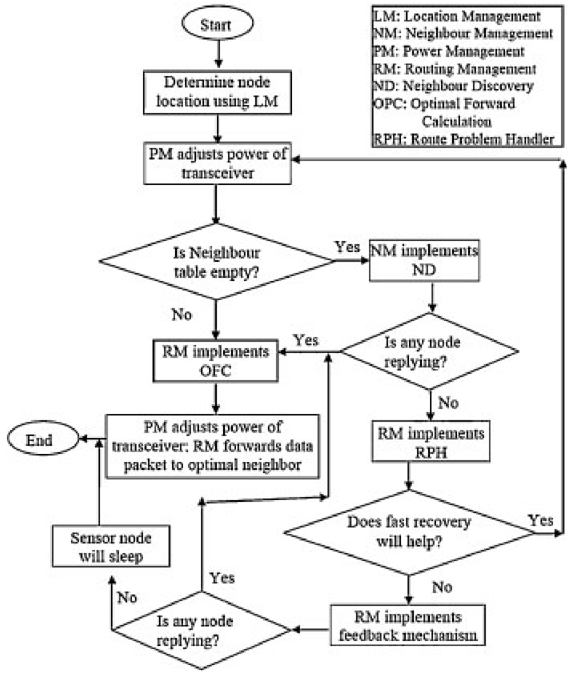

Figure 3. Flowchart diagram of URP.

3.2. Routing management

The routing management consists of three sub functional processes; forwarding metrics calculation, forwarding mechanism and routing problem handler. The OF calculation is used to calculate next hop based on the forwarding metrics that include PRR, and remaining power. The routing problem handler is used to solve the routing hole problem due to hidden sensor nodes in HWUSN. Unicast and geodirectional-cast are the mechanisms used to select the way to forward data. In URP, communication between two sensor nodes buried underground is possible only through relay node because communication between two nodes buried underground is shown to be possible only at the distance of 0.5 m when the 2.4 GHz frequency is used [13]. However, communication between two buried underground nodes at distance 0.5 m is costly and impractical solution. Note that neighbourhood management, power management, location management, routing problem handler and forwarding mechanism are described in details in Ref. [11]. Consequently, OF calculation will be described in this paper.

3.2.1. Optimal forwarding determined.

In order to carry out the OF calculation, the routing management calculates two parameters, which are link quality and remaining power (remaining battery) for every one hop neighbours. Eventually, the router management will forward a data packet to the one-hop neighbour that has an OF. The OF is computed as follows:

$$\mathrm{OF} = \max\left(\lambda_1 \times \mathrm{PRR} + \lambda_2\left(\frac{V_{\mathrm{batt}}}{V_{\mathrm{mbatt}}}\right)\right) \quad \text{Where} : \lambda_1 + \lambda_2 = 1 \tag{1}$$

where V_{mbatt} is the maximum battery voltage for sensor nodes and equals to 3.6 V [19]. The determination of PRR, and V_{batt} is elaborated in the following section. The values of λ_1 and λ_2 are estimated by exhaustive search using NS-2 simulation such that $\lambda_1 + \lambda_2 = 1$ as illustrated in Ref. [20]. In Ref. [20], the number of possible values for each λ is 11 (from 0.0 to 1.0) and the number of trials for event $\lambda_1 + \lambda_2 = 1$ is 11. In order to determine the optimal trial from 11 trials, comprehensive NS-2 simulation is implemented. The simulation carried using one source node with four types of grid network topology which are low density, medium density, high density and high several sources with high density. In each type of topology, three types of traffic load (low, moderate and high) are examined. The finding in Ref. [20] shows that the trial with 0.6, and 0.4 for λ_1 and λ_2 experiences high performance in term of delivery ratio and power consumption. Therefore, Equation (1) can be written as:

$$\mathrm{OF} = \max\left(0.6 \times \mathrm{PRR} + 0.4\left(\frac{V_{\mathrm{batt}}}{V_{\mathrm{mbatt}}}\right)\right) \tag{2}$$

In designing URP routing protocol, the link quality is considered in order to improve the delivery ratio and energy efficiency. It should be noted that the link quality is measured based on PRR to reflect the diverse link qualities within the transmission range. PRR is approximated as the probability of successfully receiving a packet between two neighbour nodes [21,22]. If PRR is high that means the link quality is high and vice versa. The PRR uses the link layer model derived in [21,23] as;

$$\mathrm{PRR} = \left[1 - \left(\frac{8}{15}\right)\left(\frac{1}{16}\right)\sum_{j=2}^{16}(-1)^j\binom{16}{j}\exp\left(20\gamma(d)\left(\frac{1}{j}-1\right)\right)\right]^{176} \tag{3}$$

where $\gamma(d)$ is SNR and it can be calculated as:

$$\mathrm{SNR} = \gamma(d) = P_{\mathrm{t}} - \mathrm{PL}(d) - S_{\mathrm{r}} \tag{4}$$

where P_{t} is the transmitted power in dBm (maximum is 0 dBm for TelosB), S_{r} is the receiver's sensitivity in dBm (−95 dBm in TelosB) [24]. PL(d) is the path loss model which can be calculated based on shadowing mode as:

$$\mathrm{PL}(d) = \mathrm{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{5}$$

where d is the transmitter-receiver distance, d_0 the reference distance and n is the path loss exponent (rate at which signal decays) which depends on the specific propagation environment. X_σ is a zero-mean Gaussian distributed random variable in (dB) with standard deviation σ. Path loss exponent measurement will be explained in the next section. The battery voltage is computed as follows:

$$V_{\mathrm{batt}} = \frac{V_{\mathrm{ref}} \times \mathrm{ADC\_FS}}{\mathrm{ADC\_Count}} \tag{6}$$

where ADC_FS is ADC full-scale and equals 1024 while V_{ref} equals 1.223 V and ADC_Count is the ADC measurement data at internal voltage reference [19,24].

3.2.2. Forwarding mechanisms.

The routing management proposes two different types of forwarding in URP: unicast forwarding and geodirectional-cast forwarding towards the destination based on quadrant. URP uses unicast forwarding as a default forwarding mechanism. However, if an application requires better delivery ratio, geodirectional-cast forwarding will be automatically switched by setting forward mechanism bit in the configuration file. The forwarding based on quadrant can be calculated relative to the source node as in Ref. [25]. In unicast forwarding, the source node checks the forward flag of each neighbour in the neighbour table. The forwarding flag can be determined by comparing neighbour node's quadrant with destination node's quadrant relative to the source node. The forwarding flag is used to check the direction of neighbour node. If the forward flag is one (neighbour- and destination node are in the same quadrant), the neighbour node is in the direction to destination. In case of forwarding flag is one for any node in neighbour table, the source node will check the OF metrics and compute forwarding progress as in Equation (2). This procedure continues until the OF choice is obtained. If there are no nodes in the direction to the destination, the source node will invoke the neighbour discovery. Once the OF choice is obtained, the data packet will be unicast to the selected node. This procedure continues until the destination is one of the selected node's neighbours.

Directional forwarding is defined as forwarding to the next nodes that have the best progress towards the destination. In geodirectional-cast forwarding, if a node wants to forward a data packet to a specific destination in a specific geographical location, it will broadcast the packet in the first hop to all neighbours. Then the selected neighbouring node will use unicast forwarding to forward the packet towards the destination. Therefore, if the neighbouring nodes are in the same quadrant as the destination and if the distance to the destination is less than the distance from source to destination, nodes will forward the packet using unicast forwarding. Otherwise, the packet will be ignored. Since nodes have information of its neighbours, it will not only forward but also select a neighbour that has the OF progress towards the destination. If the destination receives multiple copies of the same packet, it will accept the first packet delivered and ignore the others.

The geodirection-cast mechanism is a modification of our previous work done on Q-DIR [26]. In Q-DIR, all forwarding nodes broadcast the packet without knowing the distance. However, in the proposed mechanism, source

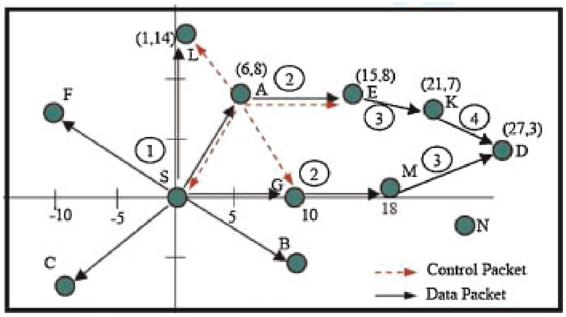

Figure 4. Geodirectional-cast forwarding based on quadrant.

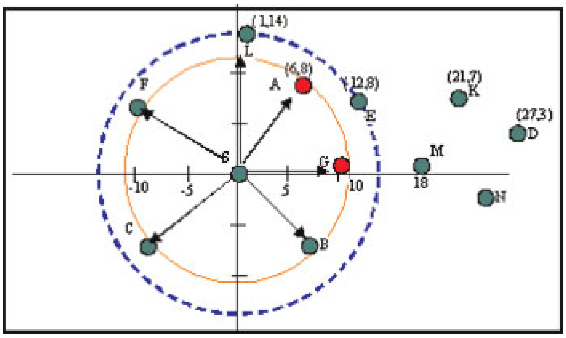

Figure 5. Fast recovery of routing hole problem.

node only broadcasts the packet to one hop neighbour. This modification of Q-DIR will save power usage, reduce packet flooding and minimize collision.

Figure 4 shows an example of geodirectional-cast forwarding of 12 nodes in a global coordinate system based on quadrant system. In this figure, S considers D to be in the first quadrant. First step, S broadcasts the data packet to its neighbours. Nodes B, C, F, and N ignore the forwarding request because they are not in the same quadrant as D. Node L also ignores the forwarding request because its distance to D is greater than the distance between S and D. On the other hand, nodes A and G are in the first quadrant and the distance from them to D is less than the distance from S to D. Second step, A and G implement neighbour discovery in order to select OF node (we assume A will select E and G will select M). A and G will participate and forward the data packet to E and M, respectively. It is interesting to note that nodes A and G will use unicast forwarding to forward the data packet to E and M rather than broadcast. This procedure continues until the data packet received at D.

The forwarding policy may fail to find a forwarding node when there is no neighbour node currently in the direction of destination. The routing management recovers from these failures by using routing problem handler as described in the following section.

3.2.3. Routing problem handler.

A known problem with geographic forwarding is the fact that it may fail to find a route in the presence of network holes even with neighbour discovery. Such holes may appear due to voids in node deployment or subsequent node failures over the lifetime of the network. Routing management in URP solves this problem by introducing routing problem handler which has two recovery methods; fast recovery using power adaptation and slow recovery using feedback control packet.

The fast recovery is applied when the diameter of the hole is smaller than the transmission range at the maximum power. The routing problem handler will inform neighbour discovery to identify a maximum transmission power required to efficiently transmit the packet across the hole as shown in Figure 5. In this figure, if nodes A and G are failures due to some problems such as diminishing energy of sensor node or due to unreliable connection, S will use maximum transmission power (0 dBm in IEEE 802.15.4) to send request-to-route (RTR). Therefore, node E will receive RTR from S and will reply using maximum transmission power. Hence, node E will be used as OF node. If the fast recovery cannot avoid routing hole problem, the slow recovery is applied. In the slow recovery, candidate OF node will send feedback packet to its parent. The feedback packet will inform the sensor node parent to stop sending data packet toward OF sensor node. When the parent received feedback control packet, it will calculate OF again for all candidates as depicted in Figure 6. In this case, node G has a hole routing problem. Therefore, node G sends feedback to node S that will select node A as OF.

3.3. Location management

The proposed location management determines localized information of sensor nodes. It assumes that all sensor nodes are in a fixed position. Since the channel model for different burial depth was estimated in this paper, the network coordinate system was assumed as two dimensions because the depth is ignored (between 0 and 20 cm). It also assumes that the sink node is at the origin (0,0) and at least two of its neighbours are location aware. The

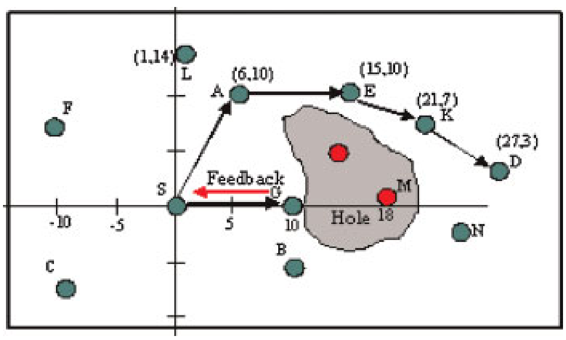

Figure 6. Feedback mechanism in routing problem handler.

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location management is used to determine the sensor node location in a grid of HWUSN. It assumed that each node has a location aware mechanism such as in Refs. [27,28] to obtain its location in the HWUSN area. The location mechanism uses at least three signal strength measurements extracted from RTR packets broadcasted by pre-determined nodes at various intervals. Each pre-determined node (relay or sink) broadcasts RTR packet and inserts its location in the packet header. The distance of the unknown node from the pre-determined nodes is determined from the signal strength received based on the proposed propagation path loss model of the environment. If the distance and location of these pre-determined nodes are known, unknown nodes can trilaterate their coordinates as explained in Refs. [27,28]. The accuracy in the proposed location system is between 0.5 and 1 m as illustrated in the simulation result. In Figure 7a, a HWUSN network grid of 25 sensor nodes (12 buried underground has yellow colour) is simulated to implement location management algorithm. Node 24 is the source and node 0 is the sink. Three pre-determined nodes 0, 10 and 13 are assumed known and the locations of remaining nodes are determined based on the location management mechanism. Figure 7b shows the results of location management mechanism for remaining node in the grid. Each line shows the angle from NCS, sensor node address and the coordination of sensor node.

The developed location management does not require additional hardware such as GPS since it uses the existing wireless communication hardware. In addition, GPS does not behave correctly when working underground.

3.4. Neighbourhood management

The design goal of the neighbourhood manager is to discover a subset of forwarding candidate nodes and to maintain neighbour table of the forwarding candidate nodes. Due to limited memory and large number of neighbours, the neighbour table is limited to a small set of forwarding candidates that are most useful in meeting the one-hop end-to-end delay with the optimal PRR and remaining power. The neighbour table format contains node ID, remaining power, one-hop end-to-end delay, PRR, forward flag, location information and expiry time. The proposed system manages up to a maximum store of 16 sensor nodes information in the neighbour table.

3.4.1. Neighbour discovery.

The neighbour discovery procedure is executed in the initialization stage to identify a node that satisfies the forwarding condition. The neighbour discovery mechanism introduces small communication overhead. This is necessary to minimize the time it takes to discover a satisfactory neighbour. The source node invokes the neighbour discovery by broadcasting RTR packet. Some neighbouring nodes will receive the RTR and send a reply. Upon receiving the replies, the neighbourhood management records the new neighbour in its neighbour table.

3.5. Power management

The main function of power management is to adjust the power of the transceiver and select the level of transmission power of the sensor node. It significantly reduces the energy consumed in each sensor node between the source and the destination in order to increase node lifetime span. To minimize the energy consumed, power management minimizes the energy wasted by idle listening and control packet overhead. The transceiver component in TelosB consumes the most energy compared to other relevant components of the TelosB. The radio has four different states: down or sleep state (1 μA) with voltage regulator off, idle state (20 μA) with voltage regulator on, send state

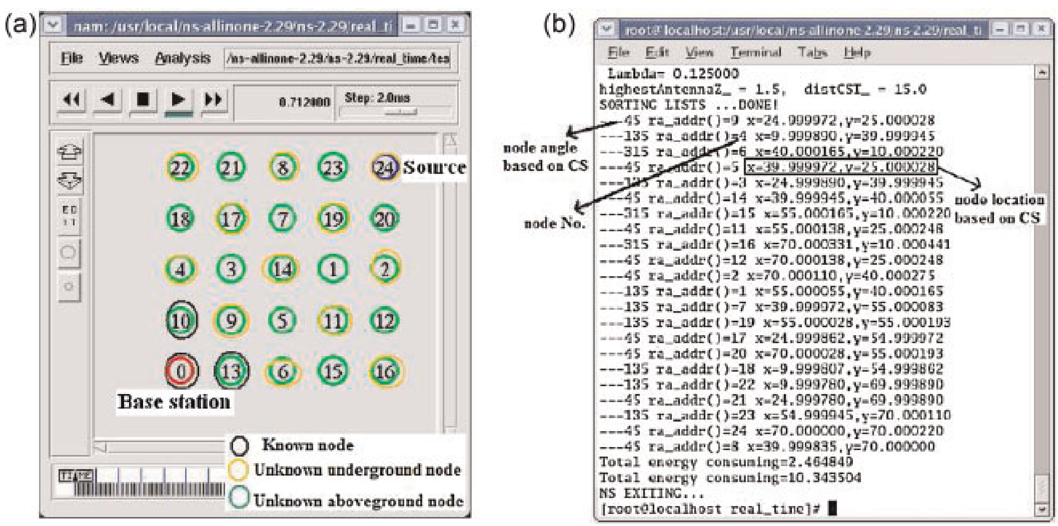

Figure 7. Location management of 25 sensor nodes in HWUSN.

(17 mA) at 1 mW power transmission and receive state (19.7 mA) [19]. According to the data sheet values, the receive mode has a higher power consumption than the all other states.

In URP, the sensor node sleeps most of the time and it changes its state to idle if it has neighbour in the direction of destination (forwarding flag is 1). In addition, if the sensor node wants to broadcast RTR, it changes its state to transmit mode. After that, it changes to receive mode if it waits replies or data packet from its neighbour.

Since the time taken to switch from sleep state to idle state takes close to 1 ms [22], it is recommended that a sensor node should stay in the idle state if it has neighbours with forward flags equal to 1. Thus, the total delay from the source to the destination will be decreased. The power management also proposes that a sensor node should change its state from idle to sleep if it does not have at least one neighbour in the neighbour table that can forward data packet towards the destination.

3.5.1. Built-in security in URP.

URP is a routing protocol that takes advantage of location based routing, multi-path forwarding and random selection of next hop. The random selection of next hop in URP provides some measure of security in HWUSN. Since the random selection of next hop depends on PRR and remaining power, which are totally dependent on the physical parameters. These parameters cannot be changed by other sensor node and thus ensures probabilistic selection chance of next hop node.

URP constructs the routing topology on demand using only localized interactions and information. Because traffic is naturally routed towards the physical location of a sink, it is difficult to attract it elsewhere to create a sinkhole attack. A wormhole is most effective when used to create sinkholes or artificial links that attract traffic. Artificial links are easily detected in location based routing protocols because the neighbouring nodes will notice the distance between them is well beyond normal radio range [30,32]. Probabilistic selection in URP of a next hop from several acceptable neighbours can assist to overcome the problem of wormhole, sinkhole, and Sybil attacks. Hence, URP can be relatively secure against wormhole, sinkhole and Sybil attacks. However, the main remaining problem is that location information advertised from neighbouring nodes must be trusted. A compromised node advertising its location on a line between the targeted node and a sink will guarantee it is the destination for all forwarded packets from that node.

Even through URP is resistant to sinkholes, wormholes and the Sybil attack, a compromised node has a significant probability of including itself on a data flow to launch a selective forwarding attack if it is strategically located near the source or a sink. A compromised node can also include itself on a data flow by appearing to be the only reasonable node to forward packets to the destination in the presence of routing hole problem. Multi-path forwarding in URP can be used to counter these types of selective forwarding attacks. Messages routed over n paths whose nodes are completely disjoint are completely protected against selective forwarding attacks involving at most n compromised nodes and still offer some probabilistic protection whenever n nodes are compromised. In addition, URP allows nodes to dynamically choose a packet's next hop probabilistically from a set of possible candidates which can further reduce the chances of an adversary gaining complete control of a data flow.

Major classes of attacks that are not countered by URP are selective forwarding and HELLO flood attacks. Defence mechanisms that are more sophisticated are needed to provide reasonable protection against selective forwarding and HELLO flood attacks.

4. EXPERIMENTAL RESULTS OF URP ROUTING

The URP routing protocol has been realized in real test bed using 17 TelosB sensor nodes. Figure 8 shows the picture of sensor nodes configuration and code uploading into the sensor through USB port. The code size of URP in TelosB is 32.7 KB in ROM bank and 1.2 KB in RAM bank.

4.1. Path loss exponent determination

The PRR test bed measured signal strength of TelosB transceiver in an underground field of University Technology Malaysia (UTM). This test bed consists of a sink and four TelsoB radio sensor nodes. The sink is a laptop with TelosB attached to the USB port. It is placed in the centre of HWUSN as shown in Figure 9. In this figure, the radio sensor nodes are distributed in different orientations (north, south, east and west) and different depths (0, 10 and 20 cm). TelosB consists of a low power transceiver based on CC2420 ChipCon chip that employs IEEE 802.15.4 physical and MAC layers specifications. It is interested to note that the soil type in test bed area is a clayey soil.

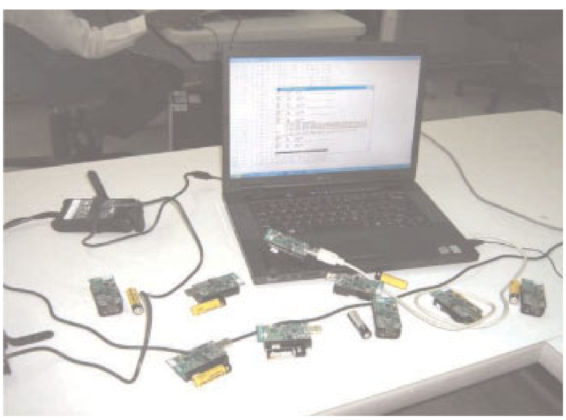

Figure 8. Programming sensor node.

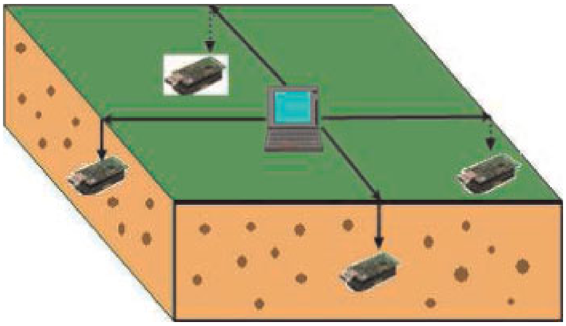

Figure 9. Path loss exponent model.

The experiment was conducted at a coverage radius between 1 and 10 m and three levels of depth (0, 10 and 20 cm) in the underground. At each specified point, 100 samples of the signal strength readings were recorded for each point and the average was used. Then the average of four different orientations was used in the same level of underground depth. Figure 10 shows the result of the program that collects signal strength in the sink node. As it can be seen in Figure 10, the signal strength between two sensor nodes is measured based on an asymmetric link which means the signal strength reading is measured in both sides of a communication link.

Figure 11 illustrates the signal strength varies with a logarithm of distance. It shows the variation due to the orientation of the receiver with the three levels of underground depth. The results show a signal strength variation up to 14 dBm between 0 and 20 cm depth of the underground at the same distance from the sink.

In order to calculate the path loss exponent, the curve fitting of the data recorded for each depth was calculated. The curve-fitting line of the average value is calculated based on minimized total error R^2 as follows [29]:

$$R^2 = \sum_{i=1}^{m} (y_i - (ax_i + b))^2 \quad (7)$$

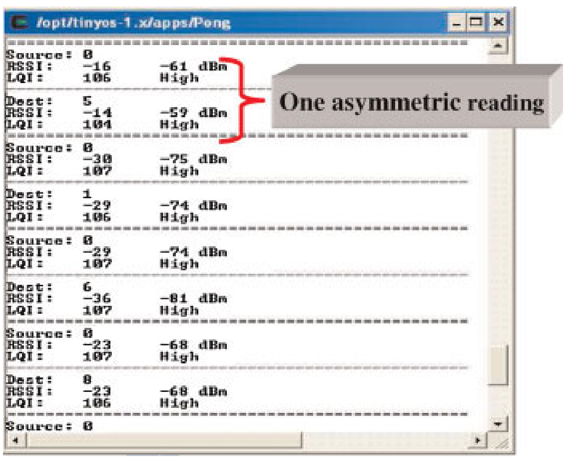

Figure 10. Asymmetric signal strength reading.

where y_i is PL(d), a is $10n$, b is PL(d_0) when compared to Equation (5). The condition for R^2 to be a minimum is that:

$$\frac{\partial(R^2)}{\partial a} = 0 \text{ and } \frac{\partial(R^2)}{\partial b} = 0 \quad (8)$$

However, b is constant in Equation (7) and equals to 51.5, 60 and 65 for 0, 10 and 20 cm underground depth, respectively. In this test bed, $d_0 = 1$ m so we do not need partial derivatives for b. From Equations (7) and (8), we have:

$$\frac{\partial(R^2)}{\partial a} = -2\sum_{i=1}^{m} [y_i - (b + ax_i)]x_i = 0 \quad (9)$$

Equation (9) is simplified to become:

$$a = \frac{\sum_{i=1}^{m} xy - b\sum_{i=1}^{m} x}{\sum_{i=1}^{m} x^2} \quad (10)$$

From the test bed and MATLAB calculation, the values of n are 3, 3.1 and 3.3 for 0, 10 and 20 cm underground depth, respectively, as derived from Equation (10).

4.1.1. PRR determination.

The above section shows the calculation of the path loss exponent which can be used to substitute in Equation (5) to get PL(d). Hence, SNR can be calculated based on P_t which is 0 dBm in this experiment. Figure 12 shows the result for three underground test beds. In this figure, the test bed with touch ground experiences highest PRR in comparison to the underground test beds. This is mainly due to EM waves do not propagate well in underground due to absorption by soil, rock and water which causes signal losses.

Figure 12 also shows that PRR is decreased when the depth of sensor nodes is increased. This is primarily due to the signal attenuation.

4.2. Applying URP in HWUSN

The running of URP routing protocol in HWUSN test bed has been verified. The test bed performance in term of packet delivery ratio is analysed. The results are compared with the simulation output.

Many-to-one traffic pattern is used in URP routing protocol in the case of unicast forwarding mechanism. One-to-many traffic pattern is used in the geodirection-cast forwarding mechanism. In this work, 17 nodes are distributed in a 20 m × 20 m region and the distance between two nodes in any straight line is 5 m as shown in Figure Figures 13 and 14.Node numbered as 0 is the sink and the rest nodes are sources. The traffic has been assumed to be constant bit rate (CBR) and locations of all nodes are known. Also, two different types of node are assumed relay node and underground node. The relay node touches ground and underground node is placed 10 cm underground as illustrated in Figure 14. Figure 13 shows also two types of routing scenario: from underground node to relay node and from relay node to underground node. For

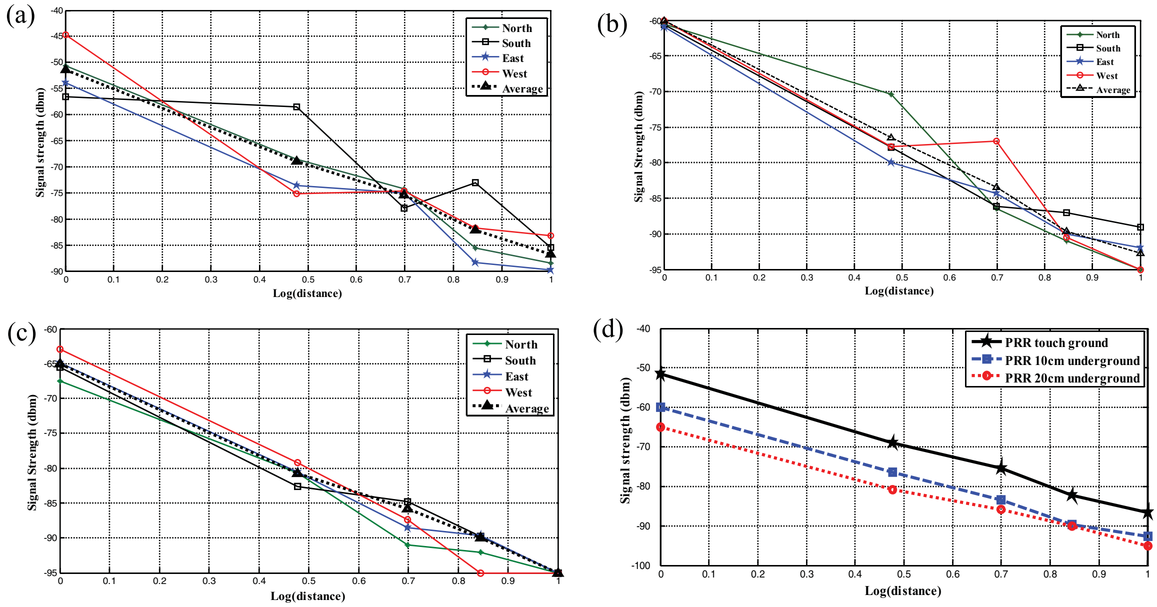

Figure 11. Variation of signal strength for HWUSN (a) 0 cm; (b) 10 cm; (c) 20 cm and (d) average.

example routing can occur from node 1 to 2 then to the sink or from node 16 to 13 then to the sink.

4.3. Results of URP routing protocol in test bed

The network in the test bed has been configured similar to the network in the simulation study. In real test bed, the experiment time were fixed at 100 s, respectively. The traffic load is varied from 0.2 to 2 packet/s to emulate low data rate for IEEE 802.15.4. The results in Figure 15 show that URP routing protocol in the simulation environment experiences slightly higher delivery ratio (about 10%) compared to the real test bed implementation. This may be due to the propagation model in the simulation differs from the real test bed environment. In practice, many parameters in the propagation model affect the signal strength including due to absorption by soil, rock and water in the underground. Signal losses are highly dependent on numerous soil properties such as soil makeup (sand, silt or clay) and density, and can change dramatically with time (e.g. increased soil water content after a rainfall) and space (soil properties change dramatically over short distance). In addition, it has been recommended by Crossbow Technology Inc. that the threshold packet rate for TelsoB should be set to 0.5 packet/s for multi-hop communication because higher packet rates can lead to congestion and or overflow of the communication queue [31].

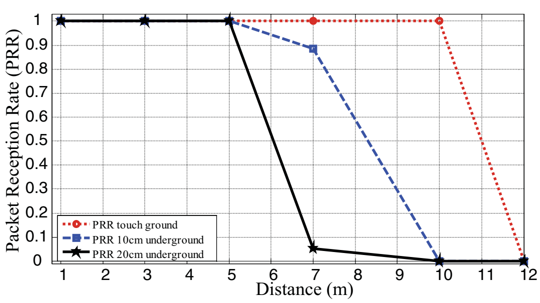

Figure 12. PRR for HWUSN.

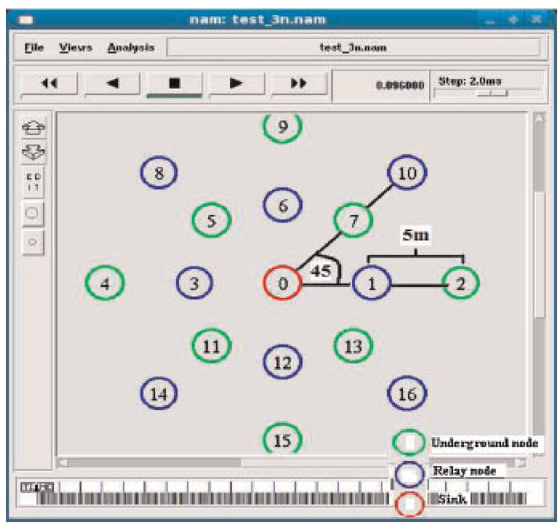

Figure 13. Network simulation grid.

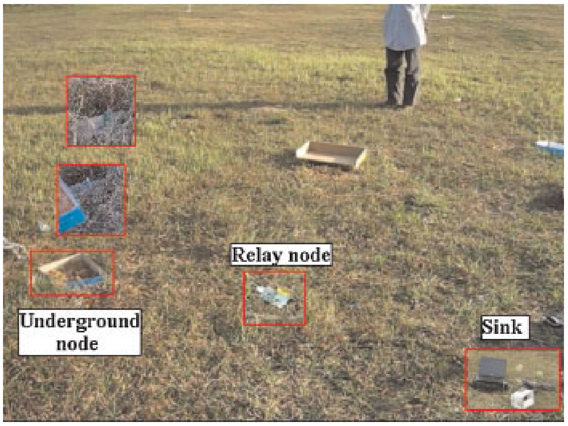

Figure 14. Network test bed field.

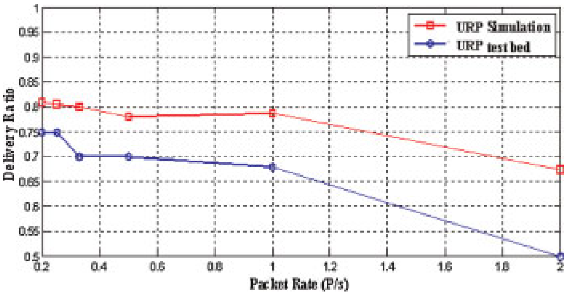

Figure 15. Performance of URP test bed and simulation at different packet rate.

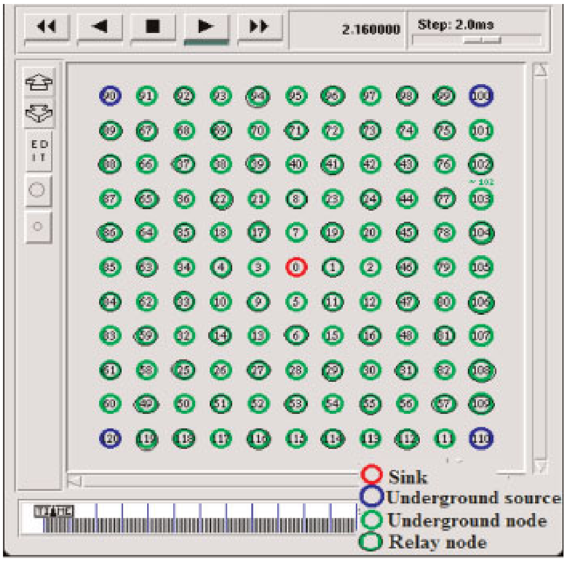

Figure 16. Network simulation model.

5. SIMULATION IMPLEMENTATION OF URP

NS-2 simulator has been used to simulate URP routing protocol. IEEE 802.15.4 MAC and physical layers are used to reflect real access mechanism in HWUSN. To create a realistic simulation environment, the URP has been simulated based on the characteristics of the TelosB mote from Crossbow [24]. Table I shows the simulation parameters used to simulate URP in NS-2. Many-to-one traffic pattern is used. This traffic is typical between multiple underground source nodes and aboveground sink. In this work, 121 (60 underground, 60 relay aboveground and 1 sink) nodes are distributed in a 100 m × 100 m region and the distance between two nodes is 10 m as shown in Figure 16. Nodes numbered as 120, 110, 100 and 90 are the underground source nodes and node 0 is sink. To increase the hop count between sources and the sink, the source nodes from the leftmost grid of the topology and the sink in the middle of the grid were selected. Also, the traffic has been assumed to be CBR. In the following simulation study, URP utilizes on demand neighbour discovery scheme. When the periodic beacon scheme is employed, data packets will transmit after 10 s to allow neighbour table forwarding metrics to be initialized. It is important to note that the data packet travels between 5 and 10 hops to reach the sink. Moreover, two sensor buried underground can only be communicated through relay node because communication between two nodes buried underground is shown to be possible only at the distance of 0.5 m when the 2.4 GHz frequency is used [13].

Table I. Simulation parameters.

Parameter	IEEE 802.15.4
Propagation model	Shadowing
Path loss exponent	Depend on the depth of node
Shadowing deviation (dB)	4.0
Reference distance (m)	1.0
Packet size	70 bytes
phyType	Phy/WirelessPhy/802_15_4
macType	Mac/802_15_4
Frequency	2.4E+9
Initial energy	3.3 J
Transmission power	1 mW

5.1. Impact of varying network load

In this simulation, the packet rates were varied from 1 to 8 packet/s to emulate low data rate in IEEE 802.15.4 and the distance between sensor nodes is varied from 5 to 10 m. This simulation compares three underground depth scenarios: 0, 10 and 20 cm. The path loss exponents for the three scenarios are 3, 3.1 and 3.3, respectively. The simulation time was fixed at 100 s.

5.1.1. Ten meters distance between nodes.

The simulation results in Figure 17a show that URP with touch ground (0 cm) experiences higher delivery ratio than

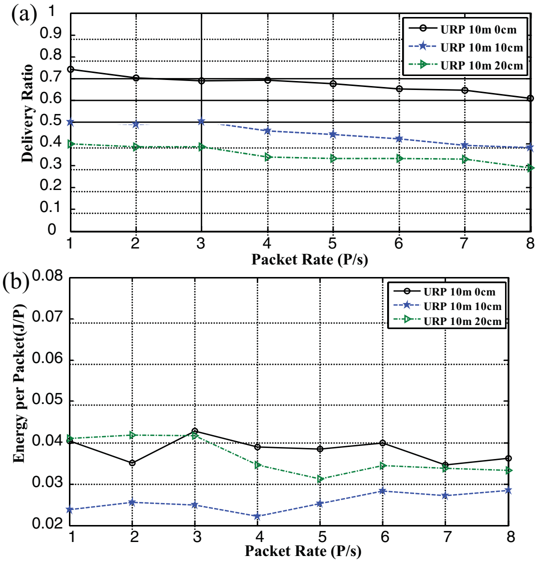

Figure 17. Comparison between URP scenarios at 10 m distance at different packet rates (a) delivery ratio (b) energy consumption.

10 cm depth by 40% and 10 cm depth experiences higher delivery ratio than 20 cm depth by 20%. This is because of soil factors (includes density, particle size, water content and temperature) which decay EM signal propagating through the underground.

Figure 17b demonstrates that URP in 10 cm underground consumes less power compared to other scenarios due to it spends less packet overhead. In addition, 10 cm forwards less data packet than 0 cm depth. This is primarily due to variation of the link quality which affects the forwarding of packets from the source to destination in 10 cm depth. However, 20 cm does not get response from neighbours, which makes sensor node issues neighbour discovery periodically.

5.1.2. Five meters distance between nodes.

The simulation results in Figure 18a show that URP with touch ground (0 cm) experiences highest delivery ratio than the other scenarios and 10 cm depth experience higher delivery ratio than 20 cm depth. Figure 18a also shows that the delivery ratio in 5 m scenario is better than 10 m scenario. This is mainly due to soil factors that affect signal propagating through the underground.

Figure 18b demonstrates that URP in 20 cm underground consumes less power compared to other scenarios due to data packet got dropping in the intermediate node which will save power of nodes that in the forwarding path but experience less delivery ratio.

5.2. Influence of multi-path forwarding

URP routing that uses geodirectional-cast forwarding is defined as (URP_G) while URP routing that uses unicast

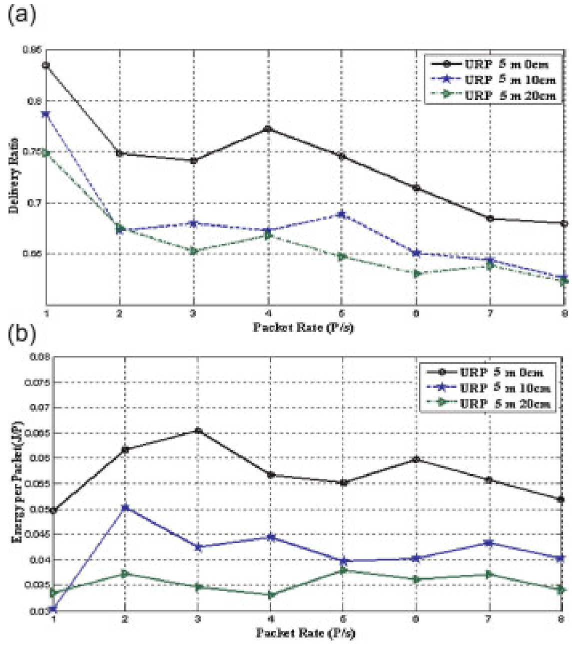

Figure 18. Comparison between URP scenarios at 5 m distance at different packet rates (a) delivery ratio (b) energy consumption.

forwarding is termed as (URP_U). Simulation study on the influence of the forwarding mechanism is carried out using parameters configured in Table I. The packet rates were varied from 1 to 8 packet/s and simulation time was fixed at 100 s. The simulation results in Figure 19a show that the URP_G increases delivery ratio by 20% compared to URP_U. This is due to multiple paths forwarding in URP_G.

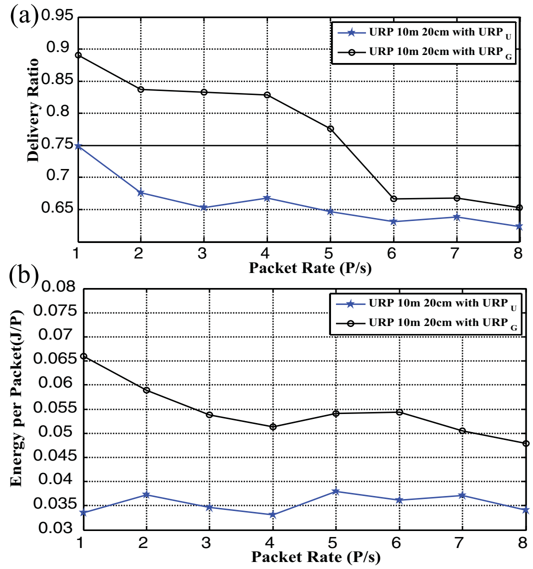

Figure 19. Performance of URP_G and URP_U at different packet rates (a) delivery ratio and (b) energy consumption.

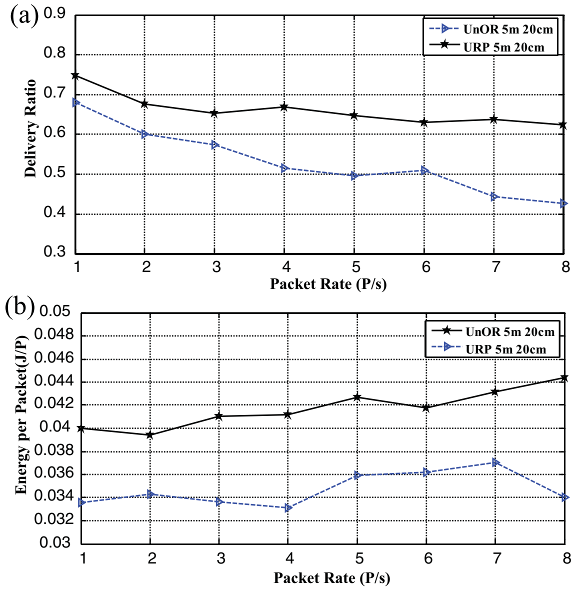

Figure 20. Comparison performance of URP and UnOR at different packet rates (a) delivery ratio and (b) energy consumption.

However, URP_G drops sharply when the traffic load is high mainly due to congestion in the network. Moreover, the IEEE 802.15.4 MAC is designed for low traffic rate and does not work well with high traffic load [23]. The flooding in the direction to the destination causes congestion near the source of the data packet, channel contention and interference.

Figure 19b shows URP_G consumes between 85 and 45% more power compared to URP_U to achieve high delivery ratio. This is largely due to its forwarding strategy spending more packets overhead for the initial broadcasting of packets.

5.3. Comparison with UnOR underground routing protocol

In this simulation, URP is compared with UnOR. UnOR selects next hop based on link quality which means the neighbour node that has a high link quality is in charge of forwarding packet on behalf of the source node. The packet rates were varied from 1 to 8 packet/s while the simulation time was fixed at 100 s. The distance between sensor nodes is 5 m and depth is 20 cm. The simulation results in Figure 20a show that the URP experiences higher delivery ratio than UnOR by 8–20%. This is because UnOR used data broadcasting based on ETX to measure the link cost. Data broadcasting caused congestion and low delivery ratio specially when traffic load becomes high (4–8 packet/s) as shown in Figure 20a In addition, UnOR does not consider load distribution which avoid hole problem around source node.

Figure 20b shows UnOR consumes 18% more power compared to URP. This is largely due to its forwarding strategy spending more packets overhead due to broadcasting of data packet. The reduced power consumption in URP is as a result of sending and distributing the load throughout the neighbouring nodes. URP distributes the load to forwarding candidates to overcome routing holes problem and hence, balancing the load among the neighbouring nodes and maintains the delivery ratio and power consumption to a comparable level.

6. CONCLUSION

Recently, many routing protocols have been proposed for aboveground WSN. However, none of the existing work provides a complete characterization of underground communication. This paper presents a novel hybrid URP that selects optimal nodes based on PRR and remaining power to forward packets to the destination. Since forwarding nodes with the best link quality are chosen, the network improves the data throughput in terms packet delivery ratio. Additionally, choosing nodes with the highest remaining power level ensures sporadic selection of forwarding neighbour nodes. The continuous selection of such nodes spread out the traffic load to neighbours in the direction of destination, hence, prolonging the HWUSN lifetime. Moreover, random selection of the next hop node using location aided routing and multi-path forwarding contributes to built-in security measure. URP has been successfully studied and verified through simulation and real test bed implementation. This work will lead to open up for future work to further improve the wireless communication and the realization of HWUSN.

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AUTHORS' BIOGRAPHIES:

Adel Ahmed received his B.Sc. in Computer Engineering from Cairo University, Egypt in 2001. M.Sc. and Ph.D. degrees in Telecommunication Technology from University of Technology Malaysia, Malaysia in 2005 and 2008, respectively. He did his Post Doctoral in University Technology Malaysia 2008. Currently, he is senior lecturer at Taiz University.

Norsheila Fisal received her B.Sc. in Electronic Communication from the University of Salford, Manchester, U.K. in 1984. M.Sc. degree in Telecommunication Technology, and Ph.D. degree in Data Communication from the University of Aston, Birmingham, U.K. in 1986 and 1993, respectively. Currently, she is the Professor with the Faculty of Electrical Engineering, University Technology Malaysia and Director of Telematic Research Group (TRG) Laboratory.

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