An Interference Aware Heuristic Routing Protocol for Wireless Home Automation Networks

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Abstract—Wireless Home Automation Networks consist of battery powered sensors and actuators that communicate with each other over wireless channels. The sensor nodes collect environmental information such as temperature, light intensity, humidity, and pressure to provide context-aware services and to facilitate smart home control. However, resource limitations, unpredictable topology changes, and interference introduce a number of challenges to the design of home automation protocols. One of the challenging tasks is developing energy efficient routing protocols to prolong the network lifetime. This paper proposes an interference aware heuristic routing protocol which determines the forwarding path between sensors and the base station using a heuristic function and a heuristic search algorithm. On the basis of local and global distance, longevity factor (LF), and link quality (LQ), the heuristic function generates a heuristic value for each node and this value is used in A* search algorithm to determine the efficient route. Simulation results show that the proposed routing scheme outperforms GAHR and AODV_{jr} protocols in terms of network lifetime, energy consumption, and message throughput. Furthermore, it achieves up to 15% increase in packet delivery ratio over GAHR protocol in a noisy environment.

Index Terms—A* search, heuristic function, home automation networks, interference, link quality, longevity factor

I. INTRODUCTION

RAPID advances in microsensor technology and wireless communications have expanded the application domains of wireless sensor networks (WSNs) including industry control, structural health monitoring, strategic surveillance, and wireless home automation. Among the wide variety of WSN applications, wireless home automation networks (WHANs) have gained considerable attention both in academia and industry over the past few years. Moreover, recent research indicates that it will be one of the fastest growth sectors in consumer electronics over the next five years [1].

A WHAN consists of a number of sensors and actuators that sense and forward collected information to the base station in order to monitor and control devices in a home network. As depicted in Figure 1, the WHAN contains a gateway server (GS), a base station (BS), and sensor nodes (SNs). The SNs are spread over the house to collect various data and send them to the BS via other nodes within one hop distance. The BS is responsible for the

Figure 1. An example of wireless home automation network

maintenance of entire network, whereas the GS connects the BS with end user in order to provide external controls. Compared to battery operated SNs, the BS has more computation, memory, and energy resources. Although battery powered SNs are easy to install, they need to be replaced or recharged on a regular basis. Statistics show that in about 50% of in-home displays (IHD), batteries do not get replaced when they run out of power [2]. Therefore, energy efficient routing protocol is essential to improve the lifetime of WHANs.

Many routing protocols have been proposed for WHANs to extend network lifetime [3], [4]. These protocols reduce total energy consumption by sacrificing uniform energy use in the network and thus result in quick network partitions. In addition, WHAN is subject to interference due to presence of numerous devices and networks in home environment such as WiFi, Bluetooth, smart meter, cordless phones, and microwave ovens [5]. However, very few protocols consider interference as one of the important parameters in a WHAN routing protocol design in contrast to routing protocols in wireless sensor networks.

This paper proposes an interference aware heuristic routing (IAHR) scheme to determine the efficient route

between a SN and the BS. The main contributions of this paper are two-fold. First we present IAHR, a heuristic routing protocol based on both local and global knowledge that significantly improves the network performance. Furthermore, instead of considering interference as a binary event (i.e., yes or no), IAHR protocol quantizes the level of interference of each link and uses the value as one of the routing parameters. Thus, the protocol takes every opportunity of delivering data packets using low-interference links and keeps the network functional. Finally, we investigate the effects of random changes in topology and compare performance of the proposed algorithm with standard specifications.

The rest of the paper is organized as follows. Section II describes related works. Section III details the network architecture, and routing procedure of the proposed protocol with three different scenarios. Section IV presents experimental results and performance analysis of the proposed protocol. Finally, Section V concludes the paper.

II. RELATED WORKS

A number of standard solutions have been proposed for WHANs such as ZigBee, Z-Wave, INSTEON, Wavenis, Bluetooth, WiFi, and UWB (Ultra-Wideband) [6], [7]. The ZigBee model enables multihop data delivery, where the routes are created by using either Ad hoc On-demand Distance Vector (AODV) or simplified AODV (AODV_{jr}) routing protocol for point-to-point communication [8]–[10]. On the other hand, the ZigBee PRO solution facilitates many-to-one communication and thus is more suitable for WHANs. In Z-Wave, a controller maintains the entire network topology and determines the routes for every SN [11]. When a packet is required to transmit, the controller includes the path to reach the destination node. Unlike ZigBee and Z-Wave, INSTEON uses a different multihop routing approach (simulcast), where SNs within the same radio range are allowed to transmit messages simultaneously [12]. Wavenis [13] is a wireless protocol stack that constructs a four-level virtual hierarchical tree. The root node works as the BS or gateway and gathers data packets from lower level nodes. Compared to these technologies, Bluetooth and UWB support very low communication range and limited number of nodes, therefore, are not suitable for large-scale WHANs [7]. Similarly, WiFi is not feasible for WHANs due to high energy consumption.

One of the drawbacks of these protocols is that very few of them consider link quality as a routing metric. For example, Z-Wave, INSTEON, Bluetooth, and UWB are susceptible to interference and is not suitable for the applications communicating over noisy channel. Similarly, Wavenis uses Received Signal Strength Indicator (RSSI) value to estimate link quality which may be inaccurate because of multipath and interference [6]. Another drawback is that most of these WHAN architectures (ZigBee, INSTEON, and UWB) implement flooding-based routing protocols that are subject to high energy consumption and

high probability of collision in the MAC (media access control) layer.

Relative Direction based Sensor Routing (RDSR) [3] divides the entire home area into a number of sectors and assigns a manager node to each sector. The manager nodes receive data from the SNs and send them to the BS. However, node energy and link quality are not considered in this protocol. As a result, it may not find the efficient route and may result in high energy consumption and high delay. Furthermore, RDSR protocol does not support node mobility.

Base-station Centric Data Gathering Protocol (BCDGP) [4] is a cluster-based hierarchical routing algorithm proposed for home automation applications. The protocol uses relay nodes for each room of the house to receive information from sensor nodes. However, cluster-based approach is not suitable for WHANs since it consumes significant amount of energy to build and maintain efficient cluster structure. In addition, link quality is not considered in this protocol.

A Location-Based self-Adaptive Routing (LBAR) protocol is proposed to extend network lifetime in WHANs [14]. The protocol limits route discovery flooding to a cylindrical request zone. Experimental results show that LBAR protocol performs better than AODV_{jr} in terms of routing overhead and packet delivery ratio. However, the protocol is not energy efficient and is not suitable for a noisy channel.

A Greedy and A* Heuristic Routing (GAHR) algorithm based on Euclidean distance is proposed for WHANs [15]. The algorithm uses greedy forwarding to limit the number of hops required for data transmission. Furthermore, the protocol implements A* search algorithm to overcome unpredictable topology changes and local minimum problems. In GAHR, every SN maintains a neighbor table that keeps a record of interfered links. When a SN detects data transmission error, it marks the forwarding node as *temporarily unstable* and sets the timer. The temporarily unstable node waits to return to stable state until the timer expires. The number of recoveries from temporarily unstable state to stable state is also recorded. When the recovery count is greater than a threshold value, the corresponding link is marked *unstable*. This protocol has a number of limitations. First, since the node energy is not used in route selection procedure, low energy SNs can be selected as forwarding nodes and may run out of energy fast. Second, the greedy forwarding selects the same route until a node on that path exhausts its energy. Thus, the protocol results in network partitions. Third, if a SN is marked *unstable* then it will never return to *stable state*. For example, a microwave oven is a source of radio interference in home network. In an office, the oven is used several times to heat or cook food during office hours. Hence, the SNs near a microwave oven will be affected many times and hence may be marked as unstable. It is more likely that there will be no interference at night or on a public holiday. Therefore, GAHR protocol is unable to deal with interference problems effectively.

Our previous work on Energy Aware Heuristic-based Routing (EAHR) protocol [16] proposed a simple heuristic function to find the efficient route between a SN and the BS. The protocol determines optimal path between source and destination nodes using local and global distance when the nodes have a sufficient amount of energy. If the energy level goes below the threshold limit then it uses energy as a routing parameter to find alternative path to reach the BS. However, the protocol has few limitations. First, it does not consider link quality although performance of home automation network is highly affected by interference. Second, no experiment is done to evaluate the impacts of node mobility in the network. Since a home network also contains mobile devices, the effectiveness of the protocol is unknown. Finally, EAHR takes energy level in consideration when nodes are already in critical conditions. Thus, the protocol is unable to take full advantages of energy balanced routing. To overcome these problems, we have proposed a new interference aware heuristic routing protocol with improved adaptability to changes in topology. Furthermore, we have conducted extensive experiments to evaluate the effectiveness and performance of IAHR protocol in home environments.

III. INTERFERENCE AWARE HEURISTIC ROUTING PROTOCOL

This section presents the network model, radio model, and the proposed IAHR protocol in details.

A. Network Model

It is assumed that WHAN comprises of a number of SNs, a BS, and a GS. Further, the following assumptions are considered to define the network model.

- Every SN has a unique node ID and the node is aware of the location of the BS as well as its own. The location of the static nodes can be determined during network deployment using either physical devices (e.g., Global Positioning System) or topology discovery algorithms [17] whereas the BS broadcasts its location to all SNs.
- SNs periodically send remaining energy and link quality values to their neighbor nodes. To adapt to the changes in topology caused by intermittent interference and energy consumption, every SN collects local information from its neighbour nodes at the beginning of each round.
- SNs are equipped with limited batteries, whereas the BS has sufficiently large power. Since SNs are operated by battery power, they have limited energy. On the other hand, the BS is supported with powerful resources and extra capabilities as it connects a WHAN to a wired network.
- The network consists of both stationary and mobile nodes and the energy consumption is not uniform for every SN.

B. Radio Model

The energy consumption model for radio communication is assumed similar to Heinzelman et al. radio model [18]. We have used the multipath propagation model which is based on the distance between the transmitter and the receiver. In order to receive k -bit message and transmit k -bit message over the distance d , the radio hardware dissipates energy as per following equations respectively.

$$E_{Rx}(k) = k \epsilon_{elec} \quad (1)$$

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

where, ϵ_{elec} and ϵ_{amp} denote electronics energy and amplifier energy respectively, and γ represents the path-loss exponent. The value of γ is set to 3, which is typical for home and office environments [19].

C. The IAHR Protocol

WHAN may have both static and mobile nodes. Every SN exchanges the longevity factor and location information with its neighbor nodes during the network setup phase. However, the network is considered interference free at this stage and thus the LQ value is set to zero for all SNs initially. In order to adapt to the changes in the network topology, the SNs share the LF and LQ value at the beginning of every round with their neighbor nodes. Since WHAN is a small network, the overhead for exchanging local information is reasonable.

Node mobility is another critical issue in WHANs. It is quite likely that the number of mobile nodes is smaller compared to the static nodes in home network. In IAHR protocol, the static nodes keep separate records of the mobile nodes and they usually do not select mobile nodes to route data packets. When a mobile node has to transmit data packets, it sends a 'Hello' message to discover the neighbor nodes within its communication range. Upon receiving the reply messages with location information, the mobile node selects the neighbor node with closest distance to forward data packets. However, static nodes may use mobile nodes if and only if there is no route available to reach the BS through static sensors. Thus, IAHR protocol makes every effort to keep the network functional.

1) *Heuristic Function*: The heuristic function guides the search procedure by providing a good estimate of how far the destination node is from the current node. It derives a numerical value for every SN by combining different routing parameters. The following parameters are used in the heuristic function of IAHR protocol.

a) *Local and Global Distance*- The local and global information on network topology helps to find an efficient route. Since the use of only local or global information may lead to network partition and local minimum problems, IAHR protocol uses the distance traversed so far (i.e., local distance) as well as estimated distance between a SN and the BS (i.e., global distance) to guide the search procedure in the right direction.

Figure 2. Impacts of greedy forwarding technique

b) *Longevity Factor*- Remaining energy is an important routing metric that can help to extend network lifetime by avoiding low energy nodes during route selection process. The IAHR protocol derives longevity factor (*LF*) for every SN from remaining energy as per following equation:

$$LF = \frac{T \times E_{res}}{E_{init}} \quad (3)$$

where, T is sustainable time of a SN, E_{res} and E_{init} are remaining energy and initial energy of that SN respectively. The *LF* metric is used to maximize the value of the heuristic function to avoid low energy nodes from being selected repeatedly.

Figure 2 presents a network topology with nine SNs and a BS. Let the SNs send information to the BS using greedy forwarding algorithm proposed in GAHR protocol. The greedy forwarding technique uses global distance between SNs and the BS to select the forwarding nodes. Suppose, the global distance between *node 4* and the BS is 25, whereas the distance is 22 for *node 5*. Hence, the packets from *node 1-3, 8, and 9* will go through *node 5* in this method. As a result, *node 5* will deplete its energy and *node 8* and *node 9* will be disconnected from the network. Even the use of A^* search algorithm fails to overcome the situation if the route '*node 5 – node 6 – BS*' is better than the route '*node 4 – node 7 – BS*'. The proposed protocol overcomes this problem by using longevity factor in addition to local and global distance. Since the decrease in the energy level of a node increases the heuristic value of that node, the probability of selecting alternative nodes is very high in IAHR protocol. For example, the heuristic value of *node 5* will be increased with the decrease in remaining energy. Therefore, the packets from *node 1-3* will go through *node 4* instead of *node 5* when the heuristic value of *node 4* is smaller than that of *node 5*.

c) *LQ Metric*- Link quality in WHANs is highly affected by interference. Interference leads to packet retransmissions and thus wastes significant amount of energy. However, the existing protocols always consider

interference as a binary event. But, the real fact is that it has a continuous degree of impact on reception of packets depending on Signal-to-Interference-and-Noise Ratio (*SINR*) [20].

Most of the network models assume that a packet is received correctly if the *SINR* value is above the threshold level. However, research indicates that the *SINR* threshold is not a constant value and it mainly depends on transmitter hardware and signal strength [21]. For example, experimental results on Mica2 sensor mote find the following *SINR* thresholds for successful packet reception: $SINR_{LOW} = 2\text{dB}$; $SINR_{HIGH} = 6\text{dB}$. The $SINR_{LOW}$ threshold level indicates that if the *SINR* is equal to or less than 2dB then the packet cannot be decoded. On the other hand, if the *SINR* value is equal to or greater than 6dB, the packet will be received successfully. It is noted that the probability of successful packet reception increases with the increase of the *SINR* value. As an example, if the *SINR* value is 5dB then there is more than 80% probability that a packet will be decoded correctly, whereas the probability is about 10% for 4dB *SINR* [21]. IAHR protocol takes the advantage of this *SINR* characteristic and quantifies *SINR* level in such a way that the value can directly be used in route selection procedure.

In IAHR protocol, the receiver node calculates the level of interference using the geometric *SINR* model [22] at each round. For example, if *node v* sends data packets to *node u*, then *node u* measures the *SINR* of link '*u-v*' as follows:

$$SINR(uv) = \frac{S_{vu}}{I_{vu} + N} \quad (4)$$

where, S_{vu} denotes the signal strength of sender v , I_{vu} is the total signal power received from other nodes except v and N is noise power. The value of S_{vu} is the product of path gain (G_{vu}) and power (P_v) whereas I_{vu} is the sum of the signal power of other nodes, i.e., $I_{vu} = \sum G_{wu} P_w$, for $w \neq v$. On the basis of *SINR* value, each node is assigned a numerical value which presents the quality of link between the sender and the receiver. For example, if $SINR \geq 6\text{dB}$, the link is not affected at all. In contrast, the link is completely down when $SINR \leq 2\text{dB}$. Thus, the effect of interference and noise on a link ($u-v$) is defined as per following equation:

$$LQ(u-v) = \begin{cases} 0 & ; SINR(uv) \geq 6 \\ 100 & ; SINR(uv) \leq 2 \\ (SINR_{HIGH} - SINR_{uv})^2 & ; otherwise \end{cases} \quad (5)$$

The *LQ* value is set to 100 if the *SINR* is equal to or less than the lower threshold. This is done to increase the heuristic value of the interfered links so that the link becomes unavailable for the current round. Similarly, the closer the *SINR* value is to the upper threshold, the less the *LQ* value is used to represent it. As an example, if the *SINR* of a link is 5dB, then the *LQ* value will be $(6 - 5)^2$, i.e., 1. Thus, the proposed protocol represents the interference using different weights on the basis of link quality. Now, combining the four parameters, *node v*

Algorithm 1: Pseudocode of A* search algorithm

INPUT: *start_node*, *goal_node*
OUTPUT: *path_list*
STEPS:
open_list = {*start_node*} ; list of explored nodes
closed_list = { $\emptyset$ } ; list of visited nodes, initially empty
path_list = { $\emptyset$ } ; list of selected nodes, initially empty
while *open_list* $\neq \emptyset$ **do**
 select the node with lowest *f*-value in *open_list*
 make it *current_node* and remove from the *open_list*
 if *current_node* is *goal_node* **then**
 return *path_list*;
 else
 add the *current_node* to the *closed_list*
 for each neighbor of *current_node* **do**
 if the neighbor is in the *closed_list* **then**
 continue
 end
 compute the sum of local distance, LF and LQ
 if the neighbor is in the *open_list* & *new_sum* < *old_sum* **then**
 update the *parent_info* in the *path_list*
 update the *sum* and *f*-value of the neighbor
 end
 if the neighbor is not in the *open_list* or *closed_list* **then**
 add the neighbor in the *open_list*
 add the *parent_info* in the *path_list*
 end
 end
 end
end

computes the heuristic value of *node u* as follows:

$$f_v(u) = g(u) + h(u) + 100/LF(u) + LQ(u - v) \quad (6)$$

where, $f_v(u)$ is the heuristic value of *node u*, $g(u)$ and $h(u)$ are local and global distance respectively, $LF(u)$ is the longevity factor, and $LQ(u-v)$ is the quality of link between *node u* and *node v*. The inverse of LF is multiplied by 100 to increase the heuristic value of low energy nodes in the equation.

2) *A* Search Algorithm:* A* search combines best-first-search and Dijkstra's algorithm to find the efficient route between source and destination nodes. This is a leading path-finding algorithm used in real-world applications such as the Warcraft III game, and road networks [23]. A* search is more efficient than other conventional shortest path algorithms such as Bellman-Ford and Dijkstra's algorithms. The conventional search algorithms are not applicable in WHANs due to long delay, trapping in blind alley, and computational complexity. Moreover, it is difficult for them to adapt with frequent changes in network topology. However, A* search overcomes these problems effectively. To efficiently compute the optimal solution, it combines features of both pure heuristic search and uniform cost search.

A* search algorithm maintains an *open_list* and a *closed_list* as shown in Algorithm 1, where the *open_list*

initially contains the *start_node* and the *closed_list* is empty. Then it removes the first node from the *open_list* and makes it the *current_node*. After that, the algorithm explores all neighbors of the *current_node*, computes their heuristic values, and adds them to the *open_list*. The *open_list* is then sorted in ascending order with respect to heuristic value and the *current_node* is added to the *closed_list* as well as in the *path_list*. The *path_list* is an array that keeps track of the valid path by updating the traversed nodes accordingly. Now, it again removes the first node from the *open_list*, makes it the *current_node*, and follows the same procedure until the goal state is found. In a nutshell, A* search follows a path of the lowest known heuristic cost and also maintains a priority queue of alternative path segments along the way. Thus, it is not trapped in an infinite loop and reduces delay, and complexity. Since WHAN consists of resource-constrained SNs, A* heuristic search algorithm is more suitable compared to conventional algorithms.

3) *Routing Procedure:* As mentioned earlier, the heuristic function of the proposed IAHR protocol uses four parameters to calculate the heuristic value f of a node: the distance traversed to reach current node from source node (g), the Euclidian distance between current node and the BS (h), the longevity factor (LF), and the link quality (LQ). As an example, Figure 3 depicts a network topology with 15 SNs and a BS. The communication range of the SNs is presented by dotted circles, whereas the dotted lines represent the communication links between two nodes. Every node computes the route to reach the BS using A* search algorithm. In order to understand the impacts of remaining energy and interference in WHANs, three different cases are explained for the proposed protocol.

The first case assumes that all SNs have same level

Figure 3. An example of WHAN topology

of energy and there is no interference in the network. Suppose, *node 6* has to find the route to reach the BS and the initial parameters of its neighbor nodes are as follows: [$g(5) = 1$, $g(7) = 3$]; [$h(5) = 10$, $h(7) = 11$]; [$eng(5) = eng(7) = 0.5$ J]; [$LQ(5-6) = LQ(7-6) = 0$]; $T = 50$ minutes for both nodes. First, *node 6* computes its f -value via *node 5* and *node 7* as follows: $f(5) = 1 + 10 + 2 + 0 = 13$, $f(7) = 3 + 11 + 2 + 0 = 16$. Since the f -value via *node 5* is smaller than that of *node 7*, *node 6* selects *node 5* as its forwarding node. Upon receiving the information, all the neighbor nodes update their f -values with respect to *node 6*. During the next hop selection process, *node 5* calculates the f -value to reach the BS via *node 7* and *node 4*. Let, the values are: $f(4) = 11$; $f(7) = 15$ respectively. Hence, *node 4* is selected as the next hop as well as the f -value and g -value of *node 7* is also updated. In this way, the route of *node 6* is constructed to reach the BS.

The second case assumes that the SNs have different level of energy and the network is still interference free. Suppose, after time t , the energy level of *node 5* and *node 7* degrades to 0.1 J and 0.25 J respectively. At this stage, the new f -values of *node 5* and *node 7* are: $f(5) = 1 + 10 + 100/((0.1 - 50)/0.5) + 0 = 21$ and $f(7) = 3 + 11 + 100/((0.25 - 50)/0.5) + 0 = 18$ respectively. Since the heuristic value of *node 7* is smaller than that of *node 5*, *node 7* will be selected to forward the data packets of *node 6*. It means that IAHR protocol avoids low energy nodes when there exists alternative routes. Thus, the protocol ensures energy balanced routing in WHANs.

The third case explains the effects of both remaining energy and interference. Consider, the following parameters of *node 5* and *node 7*: [$eng(5) = 0.2$, $eng(7) = 0.5$]; [$LQ(5-6) = 0$, $LQ(7-6) = 4$]. Using the values, *node 6* computes the heuristic values as follows: $f(5) = 1 + 10 + 100/((0.2 - 50)/0.5) + 0 = 16$ and $f(7) = 3 + 11 + 100/((0.5 - 50)/0.5) + 4 = 20$. Although *node 7* possesses more energy than *node 5*, it will not be allowed to forward data packets. It indicates that IAHR protocol effectively handles the interference problem and minimizes the number of packet retransmissions.

IV. EXPERIMENTS AND ANALYSIS

The proposed protocol is implemented in the OM-NET++ simulator and compared with AODV_{jr} and GAHR protocols. AODV_{jr} is a widely used standard for WHANs, whereas GAHR uses similar routing parameters like IAHR protocol. It incorporates interference in addition to node mobility, local and global distance. Five performance metrics are chosen to evaluate and compare the efficiency and reliability of IAHR, GAHR, and AODV_{jr} protocols. They are Packet Delivery Ratio (PDR), Remaining Energy, Network Lifetime, Routing Overhead, and Average Packet Delay. The simulation parameters used in the experiments are listed in Table I.

TABLE I.
SIMULATION PARAMETERS

Parameters	Value
Network Grid	(0, 0) to (100, 100)
Location of BS	(50, 50)
Initial Energy	2 J
Transmission Range	20 m
Data Packet Size	128 bytes
Broadcast Packet Size	24 bytes
ϵ_{elec}	50 nJ/bit
ϵ_{amp}	10 pJ/bit/m ²
γ	3 (lossy medium)

A. Simulation Scenarios

Two different scenarios are designed to evaluate the performance of the proposed protocol. The number of mobile nodes in both scenarios is two, whereas the number of interferer nodes is two in the first scenario and three in the second scenario. To observe the impacts of increased network connectivity, the experiments are performed for 50, 60, and 70 nodes respectively. Furthermore, the simulation is performed for 500 times for every experiment to compute the average value.

B. Simulation Results and Analysis

1) *Performance comparison*: The *Scenario 1* is designed to investigate the message throughput, network lifetime, and total energy consumption in IAHR, GAHR, and AODV_{jr} protocols. This scenario uses two mobile nodes and two interferer nodes. The speed of both mobile nodes is set to 0.5 meter/second. One interferer node generates random level of interference by varying its transmission power from -10dB to 2dB whereas the transmission power of the other node is fixed to -10dB.

Figure 4. Comparison of packet delivery ratio (Scenario 1)

Figure 4 shows the packet delivery ratios for different number of sensor nodes. It can be seen that IAHR protocol achieves higher level of PDR than the other two protocols. GAHR protocol mainly uses greedy search algorithm to construct the routes. Since greedy forwarding results in quick network partition, many SNs are disconnected

Figure 5. Comparison of remaining energy

and unable to reach the BS. This does not happen in IAHR protocol since it maintains a balance in energy consumption of the SNs. The heuristic function of IAHR protocol maximizes the heuristic values of energy critical nodes and thus finds alternative route to send data packets. On the other hand, the AODV_{jr} protocol floods the route request packets to the entire network that leads to heavy contention and collisions in the MAC layer. The SNs in AODV_{jr} deplete their energy quickly and partition the network. The graph also indicates that the PDR is increased with the increase of SNs. Since the network area is fixed, the growth in node density increases network connectivity as well as the total number of delivered packets.

Figure 5 shows the amount of remaining energy in IAHR, GAHR, and AODV_{jr} protocols until the network becomes non-functional. The network is considered non-functional when 10% of the total nodes run out of power. It can be seen that the amount of remaining energy is maximum in GAHR protocol. This remaining energy is wasted since at that time the network is down and unable to continue its operation. GAHR protocol does not consider node energy to compute forwarding path. Hence, the protocol may use critical nodes to transmit data packets until they exhaust their energy. Therefore, the nodes dependent on critical nodes to send information to the BS are quickly disconnected from the network although they have sufficient remaining energy. The graph also shows that the amount of remaining energy in AODV_{jr} is lowest among all. However, this result does not indicate the energy efficiency of AODV_{jr} protocol. The reason is that SNs in AODV_{jr} waste significant amount of energy because of flood-based route discovery mechanism. The frequent packet collisions and retransmissions are mainly responsible for energy drainage in AODV_{jr} protocol. Therefore, it is obvious that IAHR protocol makes better use of node energy than the other two protocols. Since IAHR protocol implements energy balanced routing, nodes remain alive for more rounds and consumes more energy due to increased volume of data transmissions compared to GAHR and AODV_{jr} protocols.

Figure 6. Network lifetime comparison

The simulation result on network lifetime comparison of IAHR, GAHR, and AODV_{jr} protocols is illustrated in Figure 6. The results indicate that the network (with 50 nodes) remains functional for 713 rounds in IAHR protocol, whereas the number is 634 and 119 for GAHR and AODV_{jr} protocols respectively. The similar trend is observed for networks consisting of 60 and 70 nodes respectively. Furthermore, the graph shows that the network lifetime decreases with the increase of number of nodes in the network. The reason is that the increased number of nodes results in increased volume of data traffic, which leads to a high probability of collisions in the network. Even in this situation, IAHR protocol outperforms the other two protocols. Every node in IAHR protocol is aware of link quality and remaining energy of its 1-hop neighbours at the beginning of each round. This local information helps the protocol to avoid unsuccessful data transmission through high-interference links. Furthermore, exclusion of low energy nodes in route selection process delays network partitions. Therefore, nodes remain alive for more rounds in IAHR than the other two protocols.

2) *Performance comparison in presence of high interference:* In *Scenario 2*, the experiments are performed to measure the PDR, routing overhead and average packet delay. The AODV_{jr} protocol is not evaluated since it does not use link quality in route selection procedure. However, this scenario uses three interferer nodes where two nodes have the same properties defined in *Scenario 1*. The third node is mobile and generates random level of interference.

Figure 7 indicates that IAHR protocol achieves 10-15% more PDR gain compared to GAHR protocol in noisy communication environment. In IAHR, every SN is aware of the link quality of its neighbors and can easily select alternative path to avoid the interfered links. If the interfered links are recovered then the information is provided to the corresponding node at the beginning of new round. Therefore, the links can again be used in forwarding data packets. On the other hand, GAHR protocol marks a link permanently unstable if it exceeds the threshold level of recovery count. This approach

Figure 7. Comparison of packet delivery ratio (Scenario 2)

reduces node connectivity and thus many packets are unable to reach the BS.

Table II represents routing overhead and average packet delay of IAHR and GAHR protocols. It can be seen that GAHR protocol sends more control packets compared to IAHR protocol. GAHR protocol follows greedy forwarding technique and restarts the route discovery process using A^* search algorithm to overcome the local minimum problem. Furthermore, since the protocol detects the interference in real time, it has to find new routes to avoid interfered links. Therefore, GAHR protocol has to send more control packets than IAHR protocol. For the same reason, the average packet delay in GAHR is also higher than that of IAHR protocol. Instead of marking a node *unstable*, IAHR protocol quantizes the level of interference in order to use the low interfered links for data transmission. In the presence of mobile interferers, this strategy significantly minimizes delay since the affected links become functional as soon as they recover from the interference.

TABLE II.
COMPARISON ON ROUTING OVERHEAD AND LATENCY

Protocols	Total Nodes	Routing Overhead	Avg. Packet Delay (s)
IAHR	50	1611	0.0207
	60	1783	0.0236
	70	2276	0.0254
GAHR	50	1634	0.0317
	60	1857	0.0343
	70	2388	0.0392

V. CONCLUSION

This paper proposed an interference aware heuristic routing protocol for WHANs to extend network lifetime. The proposed scheme uses A^* search algorithm to find an efficient route on the basis of a number of routing parameters. In IAHR protocol, every SN is aware of local and global distance, remaining energy, and link quality of its neighbor nodes before starting the route selection process. Therefore, the low energy nodes and

high-interference links are avoided when selecting the routes. Thus, the network lifetime improves over that of GAHR and AODV_{jr} protocols by a factor upto 1.84 and 6.36 respectively. Similarly, the throughput of IAHR protocol is increased by maximum of 10% and 25% over GAHR and AODV_{jr} protocols respectively. Although IAHR protocol is designed for WHANs, it can be used in large-scale WSN applications because of its self-adaptation characteristic. The future work will focus on a real world implementation of the protocol in a home environment.

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