Abstract—WSANs are becoming a solution for implementation of control applications. Sensors and actuators can be deployed forming a large or dense network to monitor and control physical parameters or systems. Reliable data transmission and real time constraints are the most significant challenges in WSAN implementation for control applications in addition to basic challenges such as scalability, network topology, energy efficiency and connectivity. Control applications will have some Quality of Service (QoS) requirements from the sensor network, such as requiring a very low packet loss rate, minimum delay and guaranteed delivery of packets. An in-depth review of previous research to date in the area of reliability and real time implementation for WSANs was carried out and a novel routing technique is proposed to improve reliable and real time communication within the sensor network based on a link quality aware and minimum path length routing mechanism. The success of this research will go a long way to address reliability issues relating to guaranteed data delivery within the wireless network, thereby potentially moving WSAN’s for critical control applications on a path to wireless implementation.

Keywords - WSAN; WSN; Zigbee; LQAR; HTR; QoS; WPAN

I. INTRODUCTION

Advancement in wireless microelectronic and embedded systems (MEMS) and very large scale integration (VLSI) has made wireless sensor actuator networks (WSAN) a reality. WSANs are becoming a solution for implementation of control applications. Sensors and actuators can be deployed forming a large or dense network to monitor and control physical parameters or systems. Wireless sensor/actuator networks consist of sensor and actuator nodes which are untethered (no wired links between them). The nodes are small computing devices equipped with sensors, a wireless transceiver, a processor, and an autonomous power supply (battery). Sensor networks require some form of self configuration to effectively route data between nodes in the network. The power of the sensor network lies in the ability of nodes to configure themselves and also re-configure themselves as node parameters change or unwanted occurrences such as node failure. Control applications will have some Quality of Service (QoS) requirements from the sensor network, such as requiring a very low packet loss rate, minimum delay and guaranteed delivery of packets. Packet loss and time varying delay can seriously degrade the control performance and cause instability. For instance, in a time or safety critical control system, large packet losses and delay occurring during the course of data transmission is not acceptable. A lot of work has been done in wireless sensor networks (WSN) research including node deployment [2], power efficiency [3], network topology [4], link quality analysis [5], MAC and routing protocols [6]. However, WSN's and WSANs are different because a WSAN is a heterogenous network and are not mere infrastructures for transporting or collating data but may also have to process each others data locally or forward data towards specific nodes. WSANs are designed to gather information about the state of a physical system and perform actions on physical systems. From an end users perspective, real world WSAN applications have their specific requirements on the QoS of the underlying network infrastructure [1]. As communication plays a central role in distributed systems, it is important that communication protocols or frame works are developed to ensure service is given by a system to an end user in a reliable and efficient manner. The amount of research in WSAN for industrial applications has increased in the last few years. IEEE 802.15.4 [17] is a standard used for low rate personal area networks (PANs). It defines the physical and MAC layer specification of WSNs for low rate PANs. The standard aims to provide a low-power, low-cost and reliable protocol for wireless connectivity. The typical operating range of 802.15.4 is approximately 10 to 20 meters, and the raw data rate is 250kb/s in the 2.4GHz band. Most wireless personal area network (WPAN) platforms have adopted the ZigBee communication protocols for interoperability purposes. ZigBee supports both mesh and hierarchical tree routing (HTR) and adopts the IEEE 802.15.4 standard as its physical (PHY) and medium access control (MAC) layers. The mesh routing is an adhoc on demand vector AODV like protocol and is used to discover the shortest routing path to each destination. The AODV protocol requires more time to establish a connection and the initial communication required to establish a route adds to the delay experienced in the routing. The ZigBee tree routing does not require memory for
calculation of routes. Routing paths are determined from the node network addresses and no routing tables are needed.

In this paper we propose a new link quality aware routing (LQAR) mechanism that improves the delay and packet loss experienced in WSAN by routing data based on established high quality link paths. Nodes establish the best quality routes to destinations by utilising data obtained from neighbour nodes packets during transmission. LQAR utilises the Zigbee node addressing scheme and distance calculation function and performs its routing based on the proposed route selection mechanism using link quality. The rest of this paper is organized as follows. Section II Provides an overview on WSAN for control applications. Section III Introduces the hierarchical tree routing (HTR) defined in Zigbee. In Section IV We present the LQAR mechanism and our routing link cost function and caching strategies. In Section V Performance studies are given. Finally, Section VI concludes this paper.

II. WSAN COMMUNICATION NETWORKS

A controls application WSAN architecture consists of sensor nodes (end node), actuator nodes (end node) and a controller (coordinator). The network can be extended using routers. Additional network components could include GPRS for location determination and time synchronization protocols. The nodes are small computing devices equipped with a wireless radio, a processor, and an autonomous power supply (battery) [9]. The sensor nodes are usually more resource constrained than the actuator nodes in terms of communication and computation power, and energy budget.

A controls application network architecture can consist of an explicit controller or each node functioning as a controller. The explicit controller architecture is described by [7] as semi-automated. Figure 1 shows the semi automated architecture and its control loops abstraction. In a semi automated architecture, the sensor nodes forward their data to the explicit controller, the controller then performs its control algorithms and sends the control data to the actuators. In most applications, sensor/actuator nodes are primarily static besides few setups that require mobility i.e. event tracking applications.

In WSAN for control applications, the sensor and actuator deployment is determined by the physical system to be monitored and controlled. Node deployment has a great impact on wireless networks as this determines certain goals i.e energy consumption, coverage, reliability and minimizing delay [8]. If the distance from the sensor node to the sink is short, direct routing would suffice, but where obstacles and large distance between the source and sink prevail, multi-hop routing is used. In multi hop routing, routers (cluster heads) can be introduced to manage the surrounding nodes at a local level and further routing the data directly to the coordinator or via other routers or to the actuator depending on the network architecture or packet destination.

In summary, the network architecture for systems monitoring and control application can be described as a deterministic multi-hop architecture.

A. Link Quality Analysis

Link quality is an important aspect in WSAN’s as it determines the reliability of data communication and control performance. A reliable link is quite basic and critical to the communication performance [10]. In WSAN, factors that affect link quality include the battery level, environment, radio frequency, bandwidth, noise, modulation scheme and hardware platforms (radio antenna). Packet loss rate (PLR) is a key indicator that determines the link quality of a WSAN. During WSAN setup, the optimal operating distance based on the packet loss rate should be considered when deploying sensors and actuators. However, it is important to note that link quality in terms of packet loss rate is not only affected by distance. Link quality indicator (LQI) is a practical and precise link estimator value that is reported with each received packet. Research in [10,11,12,13] has shown it is closely correlated with packet loss rate (PLR). LQI is calculated based on received packets energy detection only and does not require a reference. Most WSAN routing protocols do not consider link quality in determining route paths.

B. Delay and Real time Coordination in WSANs

One of the goals of a wireless control applications network would be to provide delay guarantees during packet transmission in the network. Delay is the time it takes to send
a packet from a source to its destination. Several factors contribute to the delay performance of a WSAN. These factors include interference, distance and the underlying protocols used in the network. Control systems are real time systems because their actions on physical systems should be performed within their time limits. In WSANs, actuators perform their actions based on received data from the sensor, hence delay bounds are crucial for real time performance.

Real time routing techniques for WSANs have been proposed by [18,19,20]. Real-time co-ordination and routing (RCR) frame work [20] combines a dynamic weighted clustering algorithm (DAWC) and delay-constrained energy aware routing (DEAR) to achieve real-time communication in WSANs. DAWC adapts the dynamic topology of WSANs based on a weighting formula set according to the applications need. DEAR establishes a distributed single path, in which the cluster-head selects the outgoing link such that the packet deadline is met with efficient energy consumption. It presents two versions of DEAR, (D-DEAR) and (C-DEAR) which are centralized and distributed versions i.e. automated and semi-automated architectures as described previously. In [18] the authors present (AODV2) ad hoc on demand delay constrained distance vector routing which is an extension to the widely used routing protocol AODV for providing delay constrained data delivery in mobile sensor/actor networks using delay-EDD (Earliest Due Date) scheduling algorithm as the admission control. However, most of the work done has not considered the bi-directional data transmission nature of control application systems and have very high routing overheads as such cannot be applied for time stringent control systems.

III. OVERVIEW OF ZIGBEE ROUTING

Zigbee technology is a low cost, low power consumption and short distance wireless technology based on the IEEE802.15.4 standard for wireless personal area networks. The core of the ZigBee technology is in the networking protocols [14,21]. The Zigbee network topology types are star, cluster tree and mesh networks. A ZigBee network consists of a coordinator and multiple routers and end devices. The network backbone is formed by the coordinator and routers, which are IEEE 802.15.4 Full Function Devices (FFDs). End devices can only associate with the coordinator or routers and are Reduced Function Devices (RFDs). The Zigbee technology offers two routing protocols: a modified AODV protocol [15,16] and HTR. It uses the modified AODV as default and HTR as last resort [15]. In the AODV protocol, a sending node broadcasts a route request packet (RREQ) to neighbours who forward this message to theirs. As the RREQ travels between nodes, they set up a reverse path. When the RREQ arrives the destination node, the destination node unicasts a route reply packet (RREP) with the least hop count to the neighbour from which it received the RREQ. The nodes set forward pointers to the RREP source as the RREP travels back to the source of the RREQ. The source uses the RREP for transmission to the destination and saves the route in its table until a better route is learnt. The Zigbee cluster tree network consists of a network coordinator responsible for the network initiating and maintenance [14], end devices and the network is extended using routers. Communication follows an end-device to router, router to router/coordinator fashion. The routers which will be used as clusterheads in this research project is responsible for the control of the flow of data (routing protocol) between routers to the coordinator.

A. Zigbee Hierarchical Tree Routing

In the HTR, during network initialisation, network addresses are assigned to the nodes based on the network tree hierarchy and routing is performed based on the address hierarchy. The network coordinator/routers can connect Cm child nodes. These can consist of up to Rm routing nodes. Lm is the maximum depth of the network. To distribute addresses, the coordinator uses a calculation function Cskip(d) which is an offset that the coordinator distributes network addresses to child nodes based on the network defined parameters Cm, Rm and Lm. Cskip(d) is calculated as follows:

\[
C_{\text{skip}}(d) = \begin{cases} 
1 + C_m & (L_m - d - 1) \quad R_m = 1 \\
1 + C_m - R_m - C_n & R_m = i \\
1 - R_m & R_m = 1 
\end{cases}
\]

(1)

The coordinator assigns itself address =0 and depth = 0 then assigns address to other nodes as follows:

\[
A_{\text{coordinator}} + C_{\text{skip}}(d) \times (i - 1) + 1 \quad \text{to its i-th child router and}
\]

\[
A_{\text{coordinator}} + C_{\text{skip}}(d) \times R_m + i \quad \text{to its i-th child end device.}
\]

When a node A receives a packet addressed to one of its child end devices Adest, the packet can be processed directly. Otherwise, if the following formula is established A < Adest < A + Cskip(d − 1), the packet will be relayed to the child router of the destination node as follows:

\[
A_{\text{router}} = A + 1 + [A_{\text{dest}} - (A+1)/C_{\text{skip}}(d)] \times C_{\text{skip}}(d)
\]

(2)

Else, the packet will be forwarded to A’s parent. The distance P(Asrc,Adest) between a given source Asrc and a destination Adest can be computed from the following equation:

\[
P(A_{\text{src}},A_{\text{dest}}) = D(A_{\text{src}})+D(A_{\text{dest}})-2xD(LCA(A_{\text{src}},A_{\text{dest}}))
\]

(3)

where D(A) is the depth of node A, and LCA(Asrc,Adest) is the least common ancestor of Asrc and Adest.

Figure 2 shows an example of the ZigBee address assignment scheme. The controller is the ZigBee coordinator.
and the router nodes and end devices nodes (sensors and actuators) are represented in square, circle and triangle shapes respectively.

Figure 2 Zigbee address assignment scheme

IV. PROPOSED ROUTING MECHANISM

A. Link Quality Aware Routing

The LQAR mechanism routes packets based on node network address, link quality and overhearing neighbour nodes packet information. Each routing node node maintains two routing tables, neighbor and next hop to select the next hop. The attributes of the neighbor table are node_id, link_cost, direction and hop_rank. Each node has a unique node_id and a record is maintained for each neighbour node in the neighbour table. The link cost Q for a reliable transmission of a data packet over a single hop is calculated as follows:

$$Q = (1 - PRR) \quad \text{where} \quad PRR = LQI$$

(4)

PRR represents the packet reception rate and is determined by the LQI obtained from recieved packets. It has been shown in [10,11,12] that LQI has a high correlation with packet loss rate and hence a suitable candidate for link quality metric. Note Q is negative of quality, this is because the link cost selection is based on least cost.

A semi-automated control architecture follows a source to sink and sink to source communication pattern i.e data (sense) is sent to the controller from the sensor nodes via the routing nodes and the controller sends control (control) information to the actuators via the routing nodes. Direction specifies if the packet data is “sense” or “control” data. The hop_rank contains an integer value that represents the number of hops to the base station and is used to determine source to sink or sink to source data communication. At the outset of network setup, the controller (coordinator) broadcasts a hop rank message to nodes within one hop. The nodes with the rank 1 i.e one hop from base station broadcast their rank message to other nodes within one hop and this way all nodes get their ranks and updates their routing tables. The next hop table has (route_node,via,cost,hop_rank). Route_node is the neighbour nodes, via is the next node that can be reach from route_node with its associated cost (link_cost) and hop_rank is the distance from via to the controller. The next hop table updating strategy is discussed in the following section. When a node N wants to send a packet to a destination D, N computes the route node R. If the destination D is N’s neighbour, it sets R = D. Otherwise it computes R as follows.

1. It first checks the direction of the packet, if the packet is a sense packet it selects the neighbour nodes with a lower hop_rank. If it is a control packet it selects the neighbor nodes with a higher hop_rank.

   For each node X it further checks for the link_cost (LQI) nodes and marks the x nodes with link_cost values below a predefined threshold set point as ineligible. Then we compute R as link_cost\(_X\) + P(X,D), where P(X,D) is the minimum distance between the route node and destination and is calculated by Eq 3.

2. To determine the route_node, N checks its list of eligible nodes in the next hop table such that cost\(_X\) + P(via,d) +1 < link_cost\(_R\) + P(R,D). If so it updates R to route_node.

Figure 3: An example of LQAR topology
B. Next Hop Table Updating Strategy

The next hop table is vital to the path selection for the route_node R and hence requires regular updating. The next hop table is a temporary storage, we address the update strategy. Additional packet data information should include the previously traversed node id, the link quality during transmission, and the hop_count during the transmission (via,cost,hop_rank). where hop_rank is the hop count to the controller, and via is the node from which the data packet was received and the quality of the received signal. On receipt of a packet data, a node N can learn the hop_rank to the destination via the sender, the LQI and the senders neighbour nodes. From this, N will learn the entries (route_node, via, cost,hop_rank) to be added to its next hop table. To ensure the most relevant and high quality routes are maintained in the next hop table, the caching strategy works as follows: Let (route_node, via, cost,hop_count) be an entry learned by node N. The update strategy works as follows:

1) An entry route_node with the same via in the next hop table will be replaced if the new data link_cost’ + hop_count’ > link_cost + hop_count. The least used entry will be replaced.
2) Otherwise, if the next hop table is not full, the new data is added to the table.

There are two instances that may cause LQAR to fail.

1) The instability of the wireless links, which may cause the node via in the next hop table temporally unreachable. We call this a stale route. To overcome this problem, assuming there is an entry link_cost’, if link_cost’ = link_cost where link_cost is the original value in the next hop table it will assume that there exists a stale cache and use the next eligible R.
2) Varying wireless link network conditions can cause the link quality to fall below the predefined quality threshold hence no next hop can be selected. If this occurs, the next node with the highest link quality is selected for the next hop.

V. PERFORMANCE EVALUATIONS

A. Pre Simulation Results

The background link quality map used in figure 4 is obtained from [21] which is a test result of practical results of received signal energy levels in an office environment. We impose the LQAR topology on the link quality map for analysis. Assuming node x needs to send data to the controller (coordinator). Based on the Zigbee HTR routing protocol, the route to the base station will be X-I-D-A-BS. By taking the distance equation and LQI aware routing mechanism into account, the proposed LQAR route will be X-I-H-B-BS. This gives an improved path length reduction and any possible packet losses which might have been experienced using a less quality route and the delays experienced due to retransmissions.

B. Future Work

To prove the practicability of the proposed LQAR mechanism there is an intention to simulate and implement the LQAR mechanism using generally acceptable tools by researchers. Simulation and development tools include the Crossbow wireless sensor network development kit, NS2 network simulator, OPNET network modeler and Visual Sense network simulator. A comparison of LQAR against the traditional zigbee HTR and AODV protocols will justify the proposed LQAR mechanism in terms of packet loss, delay, throughput and overhead.

VI. CONCLUSION

Self organizing and adaptive networks is one of the desirable features of wireless networks for control applications to eliminate human intervention and guarantee desired QoS in undesirable network conditions. In this paper we have highlighted the importance and challenges of reliable data transmission and real time communications in WSAN’s for control applications. Achieving reliability and real time communication in WSAN’s is a challenging task due to severe limitations such as network bandwidth, energy and wireless link quality variations. Irrespective of the severe limitations, control applications require a high level of reliability. We have presented a communications framework to improve the reliability of communication and delay aware communication by providing a robust link quality and delay aware routing mechanism. This paper introduces a unique method of improving reliability and real time communication which is tied into the zigbee addressing scheme. The Zigbee routing
protocols do not consider link quality when routing. The strength of this communication framework is it improves communication reliability by routing the data through confirmed high quality paths thereby minimizing packet losses and possible delay due to retransmissions and the energy cost associated.

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