A Distributed Management Scheme for supporting energy-harvested I/O devices

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Abstract—Current wireless technologies for industrial application, such as WirelessHART and ISA100.11a, are not designed to support harvester-powered input/output (I/O) devices, where energy availability varies in a non-deterministic manner. The centralized management approach of these standards makes it difficult and costly for harvester-powered I/O devices (sensor/actuators) to re-join in the network in case of power failure. The communication overhead and delay to cope with the dynamic environment of a large-scale industrial network are also very high for an I/O device. In this paper, we therefore propose a Distributed Management scheme for Hybrid networks to provide Real-time communication (D-MHR) based on the IEEE 802.15.4e and Routing Protocol for Low power and Lossy Networks (RPL) standards, which can address the requirements of energy constrained I/O devices. In D-MHR, the routers can dynamically reserve communication resources and manage the I/O devices in the local star sub-networks. We demonstrate that D-MHR achieves higher network management efficiency compared to IS100.11a standard, without compromising the latency and reliability requirements of industrial wireless networks.

Keywords—ISA100.11a; IEEE 802.15.4e; Energy harvesting; Distributed management; Hybrid network topology; Resource reservation; Real-time; Process control.

I. INTRODUCTION

Day by day, wired industrial networks are being replaced by wireless solutions. While this creates new opportunities, challenges also arise. For example, the I/O devices in wireless monitoring and process control applications should last for a long time without maintenance. To enable such a working condition, harvester-powered I/O devices with or without additional power sources are increasingly applied. However, state-of-the-art energy harvesters designed for wireless sensor networks, can only generate sufficient power for a limited number of message transmissions/receptions per reporting cycle. Moreover, the availability of the harvested energy often varies in a non-deterministic manner over time. As a result, the harvester-powered I/O devices might frequently loose their connection with the network [1], [2].

In industrial scenarios, three types of network topologies are commonly considered, namely the star, mesh, and hybrid star-mesh topology [3]. In the mesh topology, all nodes (routers and I/O devices) are considered to have routing capabilities. However, harvester-powered I/O devices might not be able to perform routing tasks due to their limited energy budgets. On the other hand, I/O devices can be defined as nodes, with or without routing capabilities, in a hybrid star-mesh topology. This topology is therefore more appropriate for devices with constrained resources and we adopt it for our network.

The network management approach (e.g., centralized, distributed) also influences on the suitability of harvester powered devices in the network. Centrally managed networks have limitations in this perspective. First of all, when a harvester powered I/O device has to re-join such a network upon loosing its connectivity, the overhead is too high. The node needs to exchange many messages for this, which incurs high latency. Secondly, in a harsh and dynamic industrial environment, the link between an I/O device and a router may break due to the time varying nature of the channel. To fix such poor/broken links, a central network manager needs to send new instructions over several hops to the network devices, which takes a long time [4]. This problem is further exacerbated as the network scales up. In contrast, a distributed network management approach can address these challenges in a real-time manner with low overhead.

In this paper, we therefore present a Distributed Management scheme for Hybrid networks to provide Real-time communication (D-MHR) in industrial wireless automation. The preliminary concepts of D-MHR has been presented as a work-in-progress paper [5]. The key features of D-MHR are as follows:

1) It allocates the communication resources (a set of timeslots) to the routers in a distributed manner to facilitate real-time communication.
2) The routers in D-MHR are able to manage the I/O devices by forming local sub-networks.
3) The harvester powered I/O devices in D-MHR can choose the best neighbor routers based on their requirements.
4) It constructs the multi-path routes between the routers and reserves the communication resources along the path to provide end-to-end real-time communication.

The remainder of this paper is organized as follows. The related works and the motivation of this work are discussed in Section II. Section III describes D-MHR principles. Section IV outlines different management phases of the D-MHR scheme. Section V compares various performance evaluation matrices of D-MHR with ISA100.11a. Finally, Section VI concludes this work.

II. RELATED WORKS

Several wireless communication standards based on IEEE 802.15.4, such as ZigBee Pro [6], WirelessHART [7] and ISA100.11a [8], are developed to support industrial applications. ZigBee Pro is not designed to support industrial
process control applications, which have strict latency and reliability requirements. WirelessHART and ISA100.11a are the two standards most widely accepted by the industry. Both of these standards are managed by central network manager. WirelessHART supports full mesh topologies, while a hybrid star-mesh topology is considered in the ISA100.11a network.

To the best of our knowledge, no industrial wireless standard has been developed by utilizing the distributed management approach thus far. This leads to the creation of the IETF Working Group 6TiSCH to address this issue; their proposed standards are still in a draft state. However, several academic works have focused on this area, which can be divided into two categories: node-based management and cluster-based management. Both node and cluster-based management schemes can also utilize multi-channel communication to improve the scalability and reliability in wireless sensor networks [9].

The node-based multi-channel MAC protocols, such as MMSN [10], MC-LMAC [11], Y-MAC [12], D-MSR [4] and MCMAC [13], try to assign different channels (communication resources) to nodes in a two-hop neighborhood to avoid potential interferences and to increase network throughput. These protocols, however, face practical issues in real WSNs, including: (a) scheduling overhead and (b) high protocol complexity that may not be suitable for constrained power I/O devices in practice [9]. The cluster-based multi-channel protocols such as TMCP [9] and [14], assign a different static channel to each cluster. These schemes are less complex and more suitable for the constrained power I/O devices. However, these solutions do not consider the advantage of dynamic channel hopping, which is utilized in our work.

III. D-MHR: NOVEL CONCEPTS AND THE STACK ARCHITECTURE

We propose a cluster-based multi-channel distributed network management scheme (D-MHR) to address the requirements of harvester powered I/O devices. This scheme is based on two standards: IEEE 802.15.4e (TSCH mode) [15] and Routing Protocol for Low power and Lossy Networks (RPL) [16]. We used standards in our work to promote acceptance in the industry. Simply combining these standards does not work. Instead, their proper integration into a single working scheme is very important, which therefore constitute a key focus area of this paper. In this work, routers act as cluster-heads.

A. Overview of D-MHR

D-MHR supports a hybrid network topology as shown in Figure 1 (a). The network topology has two levels, the routers form a mesh network, while the I/O devices are part of local star networks. In D-MHR, the RF space is modeled as a matrix of time and channel offset. Time is divided into discrete time slots and a collection of time slots creates a superframe. A sample superframe and two cycles of the sample superframe are shown in Figure 1 (b) and (c) respectively. A single element in the superframe is called a cell and a group of consecutive cells is called a segment. A segment may contain, 1, 2, 4 or any factor of the superframe length of cells. A sample of possible segment sizes is shown in Figure 2. A particular router (cluster head) can reserve multiple segments to manage its local sub-network and to enable future local communication in that sub-network. As the segmentation size decreases, the resource reservation becomes more dynamic and flexible and can support different traffic characteristics of the network. However, small segmentation size increases the management overhead to initiate and update the resource reservation in a distributed manner. Selecting the optimal segmentation size for resource reservation, i.e. choose between low complexity and high flexibility and vice versa, is beyond the scope of this paper. In this paper, we consider a complete row in the data communication period of the TSCH superframe (i.e., a channel offset) as a segment. A router (cluster head) use their chosen segment(s) to manage their local sub-network. All routers divide the communication resources among themselves by selecting different channel offsets in a distributed manner as shown in Figure 1 (b) and as further explained in Section IV-A2.

The I/O devices first get synchronized with the system after which they select the best two routers to provide reliable/redundant paths. The I/O devices use the local statistics of the neighboring routers (e.g. RSSI), as well as the advertised global rank (the qualifying numbers defining the router’s individual position relative to other routers with respect to the Gateway) of the routers to choose the best possible routers according to their requirements. To further communicate with the selected routers, the I/O devices use the communication resources (segments) reserved by the routers. In order to provide real-time communication and to reserve the communication resources toward the final destination, the I/O device informs the routers of its traffic characteristics. This includes specified bandwidth and latency information as
well as the communication type (periodic or non-periodic). In this paper, we assume the prevalence of periodic data traffic between sensors and actuators. The required resources along the multihop routes toward the final destination are reserved by following the D-SAR signaling protocol [17]. D-SAR is a distributed scheduling protocol that is based on concepts derived from ATM networks, which reserves communication resources based on the traffic characteristics requested by the source node.

Due to channel hopping and multichannel communication, the process of joining and neighbor discovery are challenging issues. Another issue is the scheduling of broadcasting links in a distributed manner. To address these, we modified the TSCH matrix by dividing the superframe into two periods: (i) the broadcasting/advertisement period and (ii) the data communication period as shown in Figure 1 (b). The broadcasting period facilitates neighbor discovery. In the broadcasting period, nodes either broadcast their control messages (e.g. advertisements, routing layer messages) or listen to their neighbor's control messages. As no further unicast communications are scheduled in this period, effective data sharing between the nodes is guaranteed. To facilitate faster neighbor discovery and data sharing during a joining phase (especially for harvester powered I/O devices), we limit the number of channels used in that period to three channels namely, 15, 20, and 25. These three channels do not overlap with any of the three common IEEE 802.11 channels and hence less interference occurs in these channels. In the data communication period, the routers choose particular channel offsets to provide unicast communications. The network devices may in turn use the broadcasting and data communication periods to create a superframe of any length that is an even multiple of a basic superframe length (e.g. 250 ms), in which these periods are repeated. A sample superframe of D-MHR is illustrated in Figure 1 (c). For example, router R1 selects channel offset 1 by following the respective frequency-hopping pattern illustrated in Figure 1 (b). Router R1 uses physical channel 12 in the first slot of the data communication period based on the IEEE 802.15.4e physical channel calculation scheme (FH [1] =12). Any neighbor of router R1 (either an I/O device or a router) that wishes to transmit to router R1 in the first slot, will set their channel to the receiving channel of router R1 (i.e. 12).

B. D-MHR protocol stack architecture

The protocol stacks of ISA100.11a and D-MHR are shown in Figure 3. In ISA100.11a, a central system manager schedules all the communications and constructs all the routes through the data link layer management object (DLMO). It also establishes end-to-end connections in the network through the transport layer management object (TLMO). In contrast, the network setup is performed in a distributed manner in D-MHR.

The new sub-layers, modules and tables of our proposed D-MHR protocol stack are highlighted in Figure 3 (b). The data link layer consists of two sub-layers: the lower and the upper data link sub-layer. In the lower data link sub-layer, we modify the IEEE 802.15.4e (TSCH mode) standard to fit our requirements. A Two-hop Channel Offset table is added in this layer to enable the allocation of the communication resources to the routers and to enable the scheduling of interference-free communications in the network. In the upper data link sub-layer (the resource reservation layer), we implement D-SAR signaling protocol that is designed to reserve the resources in the multi-path routers. We also implement the neighbor connection manager modules, that is designed to define the initial communication link between the network devices [4]. This helps to configure the communication tables locally in the lower data link sub-layer. Additionally, the Neighbor table containing neighbor statistics, is implemented in this sub-layer. In the network layer, RPL is used with proper adjustments [16]. The End-to-end Connection Manager module is implemented in the transport layer. This module establishes the end-to-end connection through the D-SAR signaling protocol.

IV. D-MHR MANAGEMENT FUNCTIONALITY

This section describes how a wireless node (either a router or an I/O device) can join the network, discover its neighbors, select suitable routers (i.e. the parent in RPL) and ask for communication resources to enable its further communications. Then, we discuss how routers with management capabilities use their own local resources to address the I/O devices’ requirements by allocating the required bandwidth to them.
A. Router start-up, joining and maintenance

In D-MHR, it is assumed that routers have enough capabilities and resources to manage a star-network with I/O devices. The routers act as local system managers to their own sub-network. They handle the joining procedure and assign management communication resources by following the steps mentioned below.

1) Joining and neighbor discovery: In this phase, the new router scans the available physical channels and collects the advertisements (or beacons) from the neighboring routers. Then it selects the best advertisers and sends the association (or join) request to them. Upon acceptance, the advertiser transmits a join response/activation command to the new router. The new router follows both the same procedure as explained in [4] and the IEEE 802.15.4e standard to join a network and discover the neighboring routers.

2) Selection of an un-used advertisement cell and channel offset: Upon receiving the activation command from the selected parent router, the new router can start broadcasting its advertisement. To do so, the new router has to choose a free advertisement cell in the broadcasting period. The router also chooses a free channel offset to manage the scheduled communications with its local sub-network and to communicate with other routers in the network.

D-MHR includes some important information in the advertisement of each router, such as (i) advertisement cell numbers, (ii) channel offset numbers of the corresponding router and its immediate neighbors. This effectively allows a receiving router to gather advertisement cells and channel offsets information on its two-hop neighborhood. This enables the routers to choose a free advertisement cell as well as a channel offset in a distributed manner. We assume that the two-hop information guarantees that two routers which are in interference range, do not transmit at the same time, and hence do not cause collisions. As a result, two routers, which are two-hops away from each other, can choose the same advertisement cell or channel offset. If a node selects a timeslot to send the advertisement, the node will transmit an advertisement in the assigned channel most of the time. If it chooses not to transmit in that timeslot, it listens in a randomly selected channel (after having chosen from three advertisement channels) to receive advertisements from other neighbors. If a node is not scheduled to send the advertisement in a timeslot of the broadcasting period, the node will once again listen in a randomly selected channel.

We also assume that the network density allows the routers to find a free advertisement cell or free channel offset. In case of a dense network, in which there are insufficient communication resources to enable the routers to find a free advertisement cell, we can increase the superframe length. To solve the channels offset issue in the dense network, we can decrease the segmentation sizes as discussed in Section III. In such a case, D-MHR can consider a segment with 4, 8 or any factor of superframe length of cells, instead of using a complete row in the TSCH superframe as a segment. As the channel offset is assigned to each node upon joining, there are no longer any concerns over channel offset allocation to the links. This is because the senders set their channel offset to the receiver’s channel offset during the communication scheduling.

The remaining issue in reserving the communication resources is the allocation of common timeslots among the neighboring routers. Therefore, in the D-SAR signaling protocol, the neighboring nodes (in each hop) negotiate in order to find an unused common cell based on only the information on timeslots, while the channel-offset information is excluded.

3) Initial communication establishment with neighbors: After joining the network, the new router needs to find the route towards other nodes (including the gateway). The neighbor connection manager module of each network device, uses a handshaking mechanism in order to define one Tx and one Rx link with each of its neighboring routers [4]. Those links and a typical management superframe (i.e. 2s) will be added to the data link layer communication tables. These links enable a router to communicate with all its neighbors. After this, the routing protocol can be run to find the path between the endpoints.

4) Route construction: D-MHR uses RPL in the routing layer to find a path towards the gateway. By generating RPL control messages, the routing entries in the intermediate nodes as well as a complete path toward the new router will be constructed. Several control messages are periodically forwarded through the network to maintain and update the “up” (multipoint-to-point) and “down” (point-to-multipoint) routes. To select the best routers as parents, routers in D-MHR use the following information; (i) the Neighbor Router table statistics in the data link layer as local information and (ii) the advertised rank of the neighbor routers based on different objective functions (OFs), included in the RPL control messages, as global information.

Multipath routing in RPL: In order to increase redundancy/reliability and load balancing in the network, it is desirable to use a multipath route between a source and the final destination. In RPL, we assume that all the routers store the routing information. Upon receiving the sensor data or management messages from the previous child, each router chooses the next hop randomly from the two best parents in the “up” direction. This enables reliable multipath routing in RPL in the “up” direction. To enable multipath routing in the “down” direction, the prospective destination node (router or I/O device) sends/forwards Destination Advertisement Object (DAO) messages to its two best parents and finally to the gateway. As a result, the routing table in the intermediate routers, stores the potential multipath routes in the “down” direction.

5) Contract or end-to-end connection establishment: In D-MHR, the D-SAR signaling protocol [17] is used to reserve resources in a distributed manner toward the destination node along the multi-path route defined by the routing layer. The final destination can be either the gateway or the actuators.

Resource reservation scheme in multipath routing: In the D-SAR signaling protocol, the source node sends the setup message toward the destination node along the route defined by the routing layer. The setup message includes parameters such as a list of suggested common unused timeslots for further communication with the next hop, a final destination address, traffic ID, and a requested publishing period. The receiver of the setup message then performs a check of its available communication resources. If the required resources
are available, the receiver chooses one timeslot from the suggested free timeslots, based on the requested publishing period of the traffic. The selected time slot is then allocated by writing a new link and (if needed, new) superframe in the related tables of the data link layer. In the next step, the receiver (intermediate node) forwards the setup message toward the destination node. This process continues until the destination node receives the setup message. The destination node can either accept or decline the new connection request from the source node by sending the connect message or release complete message. This connect message traverses along the multi-hop network back to the source node. All the temporary communication resources, which are reserved during the setup message exchange, are switched to permanent reservation.

An alternative path from multipath routing can be used in case of node failure or a broken edge. We modified the D-SAR protocol to be able to reserve the communication resources in the potential reliable multipath routes. In the D-SAR extension protocol, each node sends the setup message to both potential next-hop neighbors as shown in Figure 4 (a). Node A, which has received the setup message, forwards it to both of its neighbors (node B and E) in the route. In this case, every node with two outgoing edges in each branch, should also receive two potential connect messages. For example, node A, B or C might receive two connect messages. Upon receiving both potential connect messages, the node forwards one connect message toward the source node, as shown in Figure 4 (b).

If a node (e.g. node D) in a branch with two incoming edges, receives two setup messages, it no longer forwards the second setup message. Upon receiving the connect messages, which is the reply of the first setup message, it sends two connect messages to both setup senders, toward the source node. Should a second setup message be received after the first connect message has been sent, the connect message will be sent immediately to the second setup message sender. In the D-SAR extension, the nodes in the branches with two outgoing edges induce the responsibility of the source node to wait and collect all the connect messages, as shown in Figure 4 (c).

To reserve the resources in the “up” direction in the multipath RPL, each node (either source or intermediate node) sends the setup message to its two highest ranked potential parents. This process continues until the setup messages reach the DODAG root. As a response, the D-SAR signaling protocol extension is able to reserve the resources in the “up” direction in the multipath RPL. To reserve the resources in the “down” direction in the multipath RPL, each node sends the setup message to both potential next-hops in the routing table. These two potential next-hops are added to the routing table, when the two potential DAO messages from a final destination is received from these two next-hop children. The D-SAR extension signaling protocol waits in the branches with two outgoing edges to receive the two potential connect messages, and then sends one connect message to the parent.

The I/O device is typically a multi-hop away from the final destination (either actuator or gateway). Due to the earlier discussed mesh routing, there might be multipath routes toward the final destination. By allocating the required communication resources in each hop, based on the sensor traffic characteristic, most of the reserved resources might be wasted. This is because, during the normal operation of the network, only one path among several alternatives is selected to forward the traffic. As a response, when a device or router has two successors as a next hop, the transmission rate in the setup message will be reduced to half of the original sample rate. A similar approach is used in the centralized scheme in [18]. All the I/O devices or routers follow this policy to reduce the transmission rate in the signaling protocol in the intermediate branches. Eventually, by accumulating all the reserved resources on each edge in the multipath routes, the
requirement of the original transmission rate of the source I/O devices will be satisfied.

6) Coping with internal interference in the network: In D-MHR, routers that are two-hops away from each other can reuse a channel offset. In realistic scenarios, the interference range of a node may be much larger than its transmission range. When two pairs using the same selected channel offset, communicate concurrently, interference will be unavoidable. Thanks to the scheduled communication concepts, this internal interference can be detected by observing the constant packet loss in those cells after reservation. The router that detects the potential conflict can change its chosen channel offset and, subsequently, the I/O devices’ channel offsets.

B. I/O device start-up, joining and maintenance

The steps that an I/O device follows to join the network and start publishing/subscribing the periodic sensor data are explained below. The I/O devices might be powered by energy harvesters.

1) Joining and router discovery: When starting up, an I/O device scans the channels to receive potential advertisements from the neighbor routers. Upon receiving advertisements, the I/O device adds the desired information (e.g. received RSSI, RSQI, RPL rank and router channel offset) to the Candidate Router table. The Candidate Router table in D-MHR is similar to the Candidate Neighbor table of heardover routers in the ISA100.11a standard. In addition to the Candidate Router table, each I/O device stores the statistics on linked/associated routers in a related table. These local statistics and the information on the routers’ rank help the I/O device to choose the best possible router.

Using the statistics stored in the candidate router table, the I/O device selects two best ranked routers for further communication. Then, the I/O device sends join requests to this selected router(s) through the advertised Rx link and listens for advertisements on the Tx link to receive the activation command. The router, upon receiving the join request from the I/O device, will process the join request locally. Following this, the selected router should send an activation command to the I/O device. These tasks resemble the system manager’s responsibilities in the ISA100.11a standard.

2) Selection of an un-used advertisement cell: Upon receiving the activation command, the new I/O device starts to send advertisements. The selection procedure of a free advertisement cell is similar to that of a router, as explained in Section IV-A2. However, unlike the routers, the I/O devices do not need to select an un-used channel offset. Any I/O device that is scheduled to transmit to/receive from a router, sets its channel to the router’s channel at the scheduled timeslot.

3) Initial communication establishment with the selected routers: In this phase, the I/O devices follow the same procedure as the routers, as explained in Section IV-A3.

4) Router selection and route establishment: The new I/O device chooses the best router(s)/parent(s) based on the following information: (i) the candidate router table statistics as local information and (ii) the routers’ rank in RPL in terms of different OFs. To provide reliable routing, each I/O device chooses the two best routers as its RPL parents. During the normal network operation, the I/O device might need to change the routers to cope with possible changes in the network. In that case, the I/O will still use the earlier mentioned information to select the best two routers.

The I/O device, upon selecting the RPL parents and joining the RPL, starts to send the DAO message to its potential parents/routers to construct the “down” path in the network. The routers that have received the DAO, update the routing information in their table. Unlike the RPL routers, the I/O devices (i.e. the RPL leaf) do not advertise the RPL by broadcasting the DODAG information object (DIO) message.

5) Contract or end-to-end connection establishment: The I/O device sends setup messages to both selected routers to communicate with the potential destination (gateway or actuator). These messages also include its traffic characteristics information. To provide real-time communication, it is important to reserve communication resources before the I/O device starts to publish its sensor data. The router forwards the same setup message to the requested destination along the established multi-path routes by RPL, upon receiving a setup message from an I/O device. The router(s) receives the final connect message from the final destination upon allocating the required resource in the mesh network. The details of reserving the communication resources in multi-path mesh routers are described in Section IV-A5.

The I/O device might decide to leave the router (or might be forced to do so) and choose a new one for various reasons. For example, due to a power failure from an energy harvester. In that case, the router should determine whether it considers the device as being removed or not. The timeout mechanism can be used to decide. Based on the timeout, the I/O device may terminate its contract by sending a release message before leaving the router. The router forwards the release message along the multipath routes toward the final destination to free up the allocated resources in the network. The details of releasing the resources are specified in our previous work [17].

6) Sensor data publication/subscription: The I/O device, as a sensor node, publishes its sensor data toward an actuator or gateway. The I/O device uses the constructed routers in RPL and the selected parent(s) to deliver the data toward the final destination.

V. PERFORMANCE EVALUATION

To compare the performance of D-MHR with ISA100.11a, different matrices, such as channel re-use factors, end-to-end packet delivery latency, management efficiency, etc. are evaluated in this paper. After explaining the simulation setup, we explain the performance matrices below.

A. Simulation setup

Both the D-MHR and ISA100.11a protocol stacks are implemented in NS-2. We consider a network of 38 I/O devices, 22 routers, 2 access points and 1 gateway in a $80m \times 40m$ area. The routers are placed systematically in the network, while the I/O devices are randomly distributed. The transmission range of all the nodes are considered 15m. We use the two-ray ground radio model in the simulation. The constant bit rate (CBR) traffic model is employed to generate the sensor data.
in our simulation. The application data publishing period in ISA100.11a and D-MHR is 4 seconds while the advertisement period is 4 seconds.

**B. Communication schedules and network throughput**

In D-MHR, the communications are scheduled by the routers in a distributed manner, as explained in Section IV-A2. Routers far away from each other (more than two-hops) can choose the same channel offset. This means that a same cell can be reused in several neighborhoods. On the other hand, in ISA100.11a, the central system manager schedules all the communication and there is no scope of re-using the dedicated cells in the network. We compare the communication schedules of ISA100.11a (Figure 5 (a)) and D-MHR (Figure 5 (b) and (c)) for the same traffic scenarios, where the cell reuse numbers are displayed with different colors. As expected, the communication matrix of ISA100.11a uses a particular cell only once.

For D-MHR, we show two different scenarios. In the first case, a router chooses the first available channel offset among the free channel offsets, which are not used in the two-hop neighborhood (Figure 5 (b)). Here, some channel offsets are unused, while some cells are reused multiple times in different parts of the network. As shown in Figure 5 (b), certain cells, e.g. cells in channel offset 1, are reused by six pair of nodes in different neighborhoods. In the second case, a router randomly selects the channel offset from the free channel offsets (as shown in Figure 5 (c)). As a result, the communication schedules are more spread than in the previous case and almost similar to the ISA100.11a matrix, but with cell reuse possibility.

The spatial reuse of communication resources (i.e. channel offsets) in D-MHR leaves 81% and 77% of cells un-used in the first and second schemes, respectively, whereas in ISA it is 64%. The spatial reuse of communication resources in D-MHR helps to improves the network throughput in a large scale-network.

The first scheme of D-MHR can be used to mitigate external interference. This is because, it can easily blacklist the problematic channels, either locally or in the entire network. The hopping pattern sequence can also be adapted without interrupting the network or without having to re-schedule all the communications. In addition, by deploying more than one antenna or by increasing the number of access points, we can use the un-used channel offsets and increase the network throughput. However, the network might be more vulnerable to internal interference. Since in a realistic setting the interference and transmission ranges may not be equal, the following problem can be occurred. Different pairs of nodes, which are using the same cell to communicate, may cause transmission failure, even when they are two hops away from each other. In such scenarios, the second scheme of D-MHR can provide more robust communications.

To address this issue, we evaluate the relation between packet delivery ratio and increased internal interference in the network. For example, in case of internal interference, the data delivery ratio in D-MHR is 94% and 98% for the first and second schemes, when the interference range is 70% higher than the transmission range. However, the routers can detect the potential conflict and change their channel offset by applying the monitoring scheme (discussed in Section IV-A6). Then the data delivery ratio rises to 100%. On the other hand, in ISA100.11a, in which no spatial reuse of communication resources is assumed, the data delivery ratio is 100%.

**C. Reliability and real-time guarantee**

To evaluate the reliability and real-time guarantee of D-MHR and ISA100.11a in the presence of external interference, we introduce failures between I/O devices and routers in the star sub-network. After this, the packet delivery ratio and the time interval of the consecutive packets are calculated at the
destination. Figure 6 (a) illustrates that the packet delivery ratio suddenly drops for both approaches when we apply the external interference. However, compared to D-MHR, it takes longer for the ISA100.11a to reach back to the stable state. Figure 6 (b) shows the jitter in the time interval of the consecutive packets received at the final destination. It varies slightly around the expected value of four seconds (data publishing interval) in normal operations. When the interference is applied, the jitter in ISA100.11a dramatically increases and requires considerably more time to reach back to the normal values than in D-MHR. In ISA100.11a, the system manager has to perform repairs on receiving the periodic neighbor diagnostic reports, which takes time. On the other hand, in D-MHR, the I/O devices can use their local statistics to fix the problem, which improves the reliability and real-time aspects of our approach.

D. Data delivery latency

To evaluate the end-to-end data delivery latency, several end-to-end connections are considered in the network. We also evaluate the potential delay jitter, and the average number of hops that the received packets need to travel to reach their destination through the defined end-to-end connections between I/O devices. We classified connections into four categories based on the shortest hop distance between a sensor and its final destination (e.g. the actuator) via the gateway. Beforehand, the required resources are reserved by applying the various mechanisms discussed in each protocol, based on the sensors’ traffic characteristics.

In Figure 7, we can see that the end-to-end delay in D-MHR is less than in ISA100.11a. The average number of hops that the sensor data travel in D-MHR is less than in ISA100.11a, as is shown in Figure 7 (b). This confirms (i) the lower end-to-end delay in Figure 7 (a) in the related classification and (ii) the fact that in D-MSHR the packets travel less distance to reach the destination. This difference can be explained by the fact that the data packets in D-MHR (thanks to the usage of RPL in the network layer) may be able to reach the final destination (i.e. actuator) without passing through the access-points and gateway. It is noticeable that in practice, the average number of hops that the packets travel is higher than the end-to-end shortest path shown in the horizontal axis of the figure.

E. Evaluating Management Efficiency

1) Performance during node joining: To evaluate the I/O joining delay and communication overhead in ISA100.11a and D-MHR, we group the I/O devices based on their distance from the gateway. In D-MHR, I/O devices send join requests to the selected routers and then reserve communication resources for management message exchange between the routers in the mesh network. In the evaluation, we neglect the scanning delay during the joining process for both schemes. The total joining delay and the communication overhead to reserve the management resources are considered. In ISA100.11a, the I/O join requests are forwarded toward the system manager, after which the system manager defines the graph and reserves the communication resources for the new I/O device.

Figure 8 (a) and (d) display the I/O’s joining delay and the communication overhead (number of messages sent) respectively, for different distances to the gateway in ISA100.11a and D-MHR. It is noticeable that both the joining delay and communication overhead increase significantly in the ISA network with the increase in hop distances. In contrast, in the D-MHR network, the joining delay and communication overhead seem to be independent from the corresponding I/O’s distance to gateway. Thus, the proposed D-MHR scheme can perform far better in a large-scale network. This also makes them suitable for scenarios in which the harvester-powered I/O devices have to join and leave the network frequently.

2) End-to-end connection establishment between I/O devices: As explained in the previous section, we grouped the I/O devices based on the hop distances. However, in this section, the distance is calculated from an input device (sensor) to an output device (actuator) via the gateway. This is because we calculate the delay in establishing end-to-end connections by reserving the communication resources between sensors and
final destination (i.e. gateway or actuators). Figure 8 (b) and (e) show the connection establishment (reserving communication resources) delay and the number of required communications to establish those connections. The connection establishment delay and communication overhead increase along with the hop distances in the ISA100.11a network. On the other hand, in the D-MHR network, the I/O devices can establish the connection much faster than in ISA100.11a and with low message exchange overhead. The delay and communication overhead do not increase if the network scales up. This difference can be explained by the fact that D-MHR and ISA100.11a use different management approaches. Whereas D-MHR relies on the distributed approach (D-SAR signaling protocol), ISA100.11a makes use of the centralized management approach, which is far more expensive in terms of time and resources.

3) Coping with changes and disturbances in the network: In case of network dynamicity, such as edge failure between I/O device and routers due to interference, the I/O devices might have to re-join the network or find a new router. In this evaluation, we intentionally introduce interference in the network, which causes edge failures in different regions of the network. Figure 8 (c) and (f) show different behaviors of D-MHR and ISA100.11a in the case of edge failures between the I/O devices and chosen routers.

In the ISA100.11a network, the system manager chooses two routers for each node (I/O device or router) to increase reliability. Should the I/O device loose one of those routers, the node might send the connectivity-alert to the system manager. The system manager may configure new routers instead of the older one. Then the new routes and potential resources might be reserved in the new path. In the event of a connection loss in the D-MHR network, a node may choose a new router based on its requirements. It sends a joining request to the newly selected router and use the D-SAR signaling protocol to reserve the communication resources on the multipath route towards the gateway. This enables reliable and real-time communication with the rest of the network. Due to the distributed manner of the procedure, relatively low delays and low message exchanges overhead are required to fix the edge problem. For example, when the edge failure takes place on an I/O device which is four hops away from the gateway, the communication overhead for the network maintenance is on average 90% less for D-MHR than for ISA100.11a. Furthermore, for a central manager it takes a long time to fix a problem in a mesh network. As a consequence, the network recovery delay is 42% higher in ISA100.11a than in D-MHR.

F. Power consumption

To evaluate the energy-consumption of network nodes in ISA100.11a and D-MHR, we consider two states of network operation, namely a static and a dynamic environment (e.g. link failures). In the static environment, we measure the energy needed to exchange network management messages (periodic updates), as well as application data messages (from sensors to actuators). In the dynamic environment, we measure the energy consumed for network maintenance. We run the simulation for 1,000 seconds while the calculations follow the equations and parameters given in [4].

<table>
<thead>
<tr>
<th>Environment</th>
<th>Item</th>
<th>ISA100.11a</th>
<th>D-MHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Average router energy</td>
<td>2.01 J</td>
<td>1.25 J</td>
</tr>
<tr>
<td></td>
<td>Average I/O device energy</td>
<td>0.35 J</td>
<td>0.29 J</td>
</tr>
<tr>
<td></td>
<td>Network management energy</td>
<td>31.32 J</td>
<td>17.18 J</td>
</tr>
<tr>
<td></td>
<td>Application data energy</td>
<td>28.37 J</td>
<td>22.72 J</td>
</tr>
<tr>
<td></td>
<td>Total energy (without idle)</td>
<td>59.69 J</td>
<td>39.90 J</td>
</tr>
<tr>
<td></td>
<td>Idle listening Energy</td>
<td>60.49 J</td>
<td>45.92 J</td>
</tr>
<tr>
<td>Dynamic</td>
<td>Network recovery energy</td>
<td>3 hop distance</td>
<td>0.03 J</td>
</tr>
<tr>
<td></td>
<td>Application data energy</td>
<td>5 hop distance</td>
<td>0.044 J</td>
</tr>
<tr>
<td></td>
<td>Total energy (with idle)</td>
<td>4 hop distance</td>
<td>0.105 J</td>
</tr>
</tbody>
</table>

The energy consumption of the ISA100.11a and D-MHR networks in different environments are presented in Table I. The routers consume on average five times more energy than the I/O devices in both approaches. The network management energy consumption in D-MHR is significantly lower than in ISA100.11a due to the D-MHR data sharing mechanism in the broadcasting period. Unlike ISA100.11a, in D-MHR the nodes are not scheduled in the specific broadcasting links to exchange their data. As a result, they save more energy during broadcasts to their neighbors. The application data energy consumption in D-MHR is also lower than in ISA100.11a, because the RPL forwards the traffic through shorter routes that do not necessarily pass via the gateway. As a result, the total energy in D-MHR is also less than in ISA100.11a. Table I also lists the consumed energy for network recovery in case of edge failures. D-MHR consumes considerably less energy in the whole network to cope with the edge / node failures than ISA100.11a, due to the distributed management scheme of D-MHR.

VI. CONCLUSIONS AND FUTURE WORKS

This paper presented a distributed network management scheme for hybrid networks named D-MHR, which can support industrial applications by providing reliable and real-time communication. D-MHR can achieve a lower latency in data delivery than ISA100.11a. The nodes can (re-)join the D-MHR network significantly faster than the ISA100.11a network with much lower communication overhead. The connection establishment phase is also faster and cheaper in our proposed scheme. Moreover, D-MHR can fix the network problem more quickly and with less message exchanges overhead in case of internal and external interference than the ISA100.11a standard. Thus, D-MSR can better support the monitoring and process control applications in industrial automation, including energy constrained I/O devices (e.g., harvester powered). To further evaluate the performance of D-MHR and ISA100.11a, future works will focus on test-bed implementation. In addition, the simulation model and scripts can be used for research purposes, and will become available as an open source implementation in the near future.

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