

Efficient I/O Joining and Reliable Data Publication in Energy Harvested ISA100.11a Network

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Abstract—Energy harvesting technologies have brought a paradigm shift in the industrial automation sector by procreating self-powered wireless input/output (I/O) devices. Unfortunately, current wireless technologies for industrial applications, such as ISA100.11a and WirelessHART, are yet far from supporting harvester powered I/O devices. Although several works have been conducted to address the requirements of energy harvested I/O devices, most of those have focused on minimizing the I/O energy consumption during the steady-state phase of the network. However, a very important aspect, the energy consumption during network joining that consumes a significant amount of energy, is overlooked in these works. In this paper, we therefore analyze the I/O energy consumption in ISA100.11a network during the joining phase in addition to that in normal operation to better understand the challenges of energy harvesting communications. Then, we propose an energy efficient network joining scheme to support harvester powered I/O devices in ISA100.11a network. The proposed scheme significantly reduces the joining delay when compared with the traditional ISA100.11a joining scheme. We also propose a reliable data transmission scheme for energy harvested I/O devices by utilizing spatial diversity that can outperform ISA100.11a data publication through significant improvement in packet reception.

Index Terms—Industrial wireless communication, Energy harvesting, ISA100.11a, Fast I/O joining, Harvester powered I/O devices, Reliability.

I. INTRODUCTION

In recent years, wireless sensor networks (WSNs) have rapidly revolutionized the industrial automation sector [1], [2]. From wired monitoring and control systems, factories are moving towards complete wireless solutions. These innovations create many new opportunities, such as monitoring of the machine parts difficult to reach (e.g., moving parts), which wired counterparts have failed to address. Nevertheless, many new challenges arise with the inclusion of wireless technologies. For instance, mains powering the nodes or replacing the batteries are not always practical and economical in industrial environment. Thus, energy harvesters are becoming popular as an alternative power source for industrial wireless sensors/actuators (I/O devices). However, present day energy harvesters can generate only a small amount of energy, which allows the I/O devices to transmit/receive very limited number of packets per reporting cycle. The amount of harvested energy also varies over time depending on the ambience of the factory (e.g., amount of light/vibration). As a consequence, harvester

powered I/O devices face many practical challenges in the industrial network [3].

Several wireless standards, such as ISA100.11a [4] and WirelessHART [5], are recently developed to provide reliable and real-time communication for industrial automation. The success of these technologies highly relies on the precise clock synchronization between network devices as they utilize fully deterministic resource reservations. I/O devices in such networks have to follow complex network joining process and security mechanisms before being able to publish data. Harvester powered I/O devices can not afford these power hungry procedures due to their limited energy budget. Thus, this type of I/O devices may frequently lose their connectivity/synchronization when operating in the above mentioned industrial network. Alternatively, the harvester powered I/O devices may publish data by forming an ad hoc network whenever they gather sufficient energy. Such contention based communications do not require time synchronization between network devices. However, these systems are not suitable for industrial applications as they can not guarantee reliable communication.

A number of works are conducted in the academia to support harvester powered I/O devices in deterministic networks by reducing their energy consumption during steady-state phase [3], [6], [7]. However, the network joining phase is not discussed in any of these works, which usually consumes a significant amount of energy. This paper analyzes both of these phases to understand the real challenges of energy harvested communication. Although all the communications are scheduled in centralized systems as ISA100.11a, some communications can still be interrupted due to external interference or harsh industrial environment. To recover the lost messages, up-to *three* packet retransmissions are considered in these systems. However, such re-transmission scheme is not practical for the harvester powered I/O devices as these devices may have been already disconnected from the network before the retransmissions are scheduled. To combat this scenario, we introduce a new reliable data transmission strategy for the harvester powered I/O devices. The main contributions of this paper are as following.

- 1) The average I/O energy consumption during the network joining along with the steady-state phase are quantified under different conditions.
- 2) An energy efficient joining scheme is proposed to allow

harvester powered I/O devices in ISA100.11a networks.

- 3) A reliable data transmission strategy is proposed by utilizing spatial diversity that can reduce re-transmissions in the industrial environment..

We consider ISA100.11a standard as a baseline for this study due to its versatile applications. However, the proposed solutions can be applied to any other centralized systems, such as WirelessHART, ISA100.11a* [7], and distributed systems, such as D-MHR [8] for faster node joining and better supporting energy constrained devices in the network. The rest of the paper is organized as following. In Section II, brief overviews on ISA100.11a and energy harvesting are presented, then in Section III, we formulate the I/O energy consumption in ISA100.11a network, Section IV outlines our proposed approaches of fast I/O joining and reliable data publication, in Section V the simulation setup and model are described. The results are presented in Section VI, and finally, Section VII concludes the work and mentions our future research goals.

II. BACKGROUND

A. Overview of ISA100.11a

ISA100.11a is developed on top of IEEE 802.15.4-2006 Physical layer by specifying new Data-link, Network, Transport and Application layers to provide robust communications for industrial automation on 2.4 GHz ISM band. An ISA100.11a network has two parts: the plant network and the wireless network as shown in Figure 1. The wireless network consists of two types of nodes namely *routers* and *I/O devices*. Routers collect data from the I/O devices and forward this towards destination through other routers by forming mesh networks. On the other hand, I/O devices only transmit and receive data to and from the routers, and do not participate in the routing task. The routers periodically broadcast some reference messages known as *advertisements*, containing system information to facilitate I/O joining.

A central system manager (SM) handles all the communications in ISA100.11a by utilizing time division multiple access (TDMA) on top of channel hopping mechanism. Based on the requirements of I/O devices, SM decides which paths in the mesh network would be used and reserves communication resources along the paths by making schedules. For this, SM considers collections of time slots (e.g., 25 slots) known as *superframes*. Several links are established to forward the I/O devices' data towards the destination, where *link* is a connection between a pair of nodes (e.g., I/O device-router, router-router). A link is scheduled in a particular timeslot and repeated based on the publication period of the node; however, it switches the physical channel in every instance to achieve higher reliability. The sequence of physical channels followed by the links is known as *hopping pattern*. Multiple links can be scheduled in the same timeslot by using different *channel offsets*, where channel offset is a virtual number which can be considered as a delay on top of hopping pattern. The relationship between hopping pattern and physical channels can be expressed with following formulas,

$$\text{index} = (\text{ASN} + \text{Ch}_{\text{off}}) \% N_{\text{Ch}}, \quad (1)$$

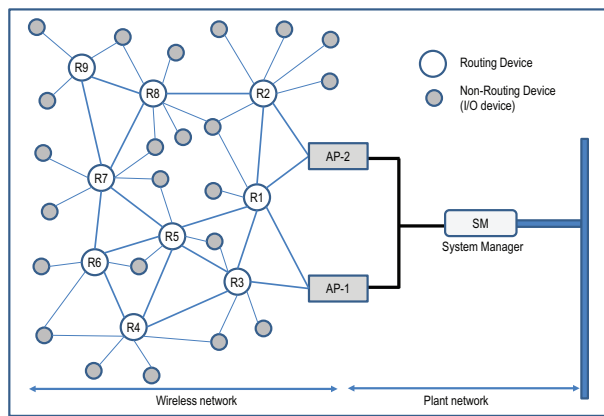


Figure 1. ISA100.11a sample network.

$$\text{Ch}\# = \text{Channel Hopping Sequence}(\text{index}), \quad (2)$$

where, ASN is the start slot number, Ch_{off} is the channel offset, N_{Ch} is the number of available channels and $\text{Ch}\#$ is the physical channel number.

a) *Advertisement broadcast*: The routers in ISA100.11a can broadcast their advertisements either on any of the physical channels in IEEE802.15.4 or limit those on subset of channels. The SM schedules broadcasting cells (channel offset and slot combination) for the routers to facilitate advertisement broadcasts. To make it easier, let us consider that the SM assigns a particular channel offset for all of the communications of a router including advertisement broadcasts. That means if channel offset 5 is assigned to a router, all the I/O devices want to communicate with that router have to follow the hopping pattern with offset 5.

b) *I/O joining*: When an I/O device wants to join the network, it has to discover at least one router by scanning all the available physical channels to receive advertisements from the routers. An I/O device scans each channel for a limited duration and then moves to the next channel. After detecting advertisements during the scanning phase, the I/O device sends a join request to the proxy router, which is then forwarded to the SM through the mesh network. The I/O device has to keep listening on the *joining links* that is mentioned in the advertisement, for *join response*. This listening duration depends on the hop distance between the I/O device and the SM. The SM then writes the management keys, adds links and frames for the data communication. Upon acknowledging these management messages, the I/O device becomes ready to publish actual data.

c) *I/O data publication*: Upon joining the network successfully, an I/O device receives resources (links) from the SM according to its requirement. For reliability, every node in ISA100.11a network keeps a list of *two best neighbors* suggested by the SM in both up-link and down-link directions. However, one of these links is selected *randomly* in every instance for actual data publication. In case of packet loss

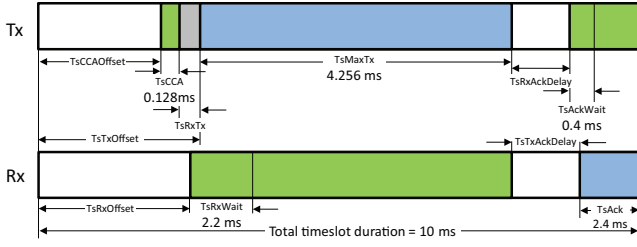


Figure 2. Timeslot structure in ISA100.11a/IEEE802.15.4e (TSCH mode).

(can be identified through unacknowledged transmissions), the I/O device re-transmits the packet by using either a dedicated slot scheduled in later superframe or a shared slot (which allows communications from multiple nodes, thus collision may occur).

B. Overview of energy harvesting

Energy harvesting refers to the conversion of any kind of ambient energy into electric energy, typically to feed low-power electronics. An approximate estimation of the potential of energy harvesting from some ambient sources, such as solar energy outdoor (15,000 $\mu\text{W}/\text{cm}^3$) and indoor (10 - 20 $\mu\text{W}/\text{cm}^3$), mechanical vibrations (300 $\mu\text{W}/\text{cm}^3$), air flow (360 $\mu\text{W}/\text{cm}^3$), is discussed in [9]. However, industrial applications are more likely to use mechanical vibrations given its availability for this type of environment. Machinery in factory are designed to have minimal vibrations. Thus, it is very hard to harvest energy from such systems during normal operations. On the other hand, increase in vibration often indicates faults in the industry. The nice thing about vibration energy harvesting is that it becomes effective whenever it is important to detect failures by producing significant energy from the increased vibrations, which allows frequent data transfer from the respective sensor nodes and helps to locate the fault soon.

Yet, the potential for vibration based energy harvesting depends on the specific transduction mechanism in place. The main challenge about industrial vibration as source for energy harvesting lies on the impedance matching between the source and the adjacent circuits. This implies that the most efficient extraction is given at a particular frequency for which the circuit can be optimized. However the frequency content of mechanical vibrations cannot always be predetermined or the energy is spread over a broadband frequency that limits the actual energy availability at particular frequencies. Fortunately, wireless, battery-less industrial condition monitoring systems are already being commercialized where ambient vibrations are used to generate output levels in the range of μW to mW . Perpetuum vibration energy harvester (VEH) [10] is such an example, which claims to produce up to 27 mW of usable energy harvested from industrial environment.

III. I/O ENERGY CONSUMPTION IN ISA100.11A NETWORK

The timeslot structure of ISA100.11a shown in Figure 2, is used to derive the energy consumption of different

Table I
ENERGY CONSUMPTIONS OF DIFFERENT TYPES OF TRANSMISSIONS AND RECEPTIONS IN ISA100.11A.

Parameter	Energy consumption
Acknowledged Tx	$E_{Tx} = TsCCA \times P_{Rx} + TsMaxTx \times P_{Tx} + TsAck \times P_{Rx}$
Failed Tx	$E_{FailTx} = TsCCA \times P_{Rx} + TsMaxTx \times P_{Tx} + TsAckWait \times P_{Rx}$
Acknowledged Rx	$E_{Rx} = TsMaxTx \times P_{Rx} + TsAck \times P_{Tx}$
Idle Rx	$E_{Idle} = TsRxWait \times P_{Rx}$
Advertisement Rx	$E_{Adv} = TsMaxTx \times P_{Rx}$
Failed adv Rx	$E_{FailAdv} = TsRxWait \times P_{Rx}$

types of transmissions and receptions in ISA100.11a through the method proposed in [11]. Table I lists these message types and the corresponding energy consumption. The total energy consumption of an I/O device comprises of the energy consumption in the joining phase and the steady state phase, which are further discussed below.

A. Energy consumption during network joining phase

During the network joining, the radio of an I/O device has to be turned on continuously throughout the whole scanning period, which consumes a significant amount of energy. The energy consumption of an I/O device to scan N_{scn} slots on N_{ch} channels is

$$E_{scan} = N_{ch} \times N_{scn} \times T_{slot} \times P_{Rx}, \quad (3)$$

where the slot duration is T_{slot} . After receiving advertisements in the scanning phase, an I/O device sends a join request to the proxy router and receive links and frames from SM as described in Section II-A. Thus, the total energy required for an I/O device to join an ISA100.11a network is

$$E_{join} = E_{scan} + \underbrace{E_{Tx}}_{\text{join req}} + \underbrace{(N \times E_{FailAdv} + E_{Rx} + E_{Tx})}_{\text{mgt key}} + \underbrace{M(N \times E_{Rx} + E_{Tx})}_{\text{links \& neighbor}}, \quad (4)$$

where, the value of N depends on the number of hops between the I/O and the SM and M depends on the number of neighbors (routers) from which the I/O device can receive advertisements. Note that, the major portion of the joining energy is spent on the scanning phase.

B. Energy consumption during steady state phase

Energy consumption of an I/O device during normal operation depends on its publishing period and the advertisement rates of the neighboring routers. Thus, the average energy consumption of an I/O device over a fixed interval is

$$E_{IO} = E_{Mgt} + E_{Data}, \quad (5)$$

where, E_{Mgt} is the energy consumption to receive periodic advertisements and E_{Data} is the energy consumption for data transmission during this period. E_{Mgt} and E_{Data} can be calculated by using the equations 6 and 7 respectively, where $N_{...}$ represents the number of a particular type of messages

during the fixed interval (e.g., N_{RecAdv} is the average number of received advertisements).

$$E_{\text{Mgt}} = N_{\text{RecAdv}} \times E_{\text{Adv}} + N_{\text{FailAdv}} \times E_{\text{FailAdv}}. \quad (6)$$

$$E_{\text{Data}} = N_{\text{RecPkt}} \times E_{\text{Tx}} + N_{\text{FailPkt}} \times E_{\text{FailTx}}. \quad (7)$$

IV. PROPOSED APPROACH

A. Improved I/O joining

The I/O devices in ISA100.11a scan each available channels *sequentially* for a fixed period (N_{scn} slots) to receive advertisements. During the scanning phase, an I/O device might receive multiple advertisements from different routers, although discovering one router is enough for initial communications with the SM. Such scanning scheme consumes a significant amount of the energy during I/O joining as discussed in Section III. Thus, the following options are considered in this work to improve the traditional ISA100.11a scanning scheme.

- Option 1: Each I/O device scans the available channels *sequentially* similar to the traditional ISA100.11a scanning approach; i.e., the I/O devices always start scanning from Channel 11 and stay not more than N_{scn} slots on a particular channel. However, the scanning process is terminated as soon as N_{dis} routers are discovered or maximum scanning interval (T_{scn}) is passed. I/O devices with limited energy budgets use $N_{\text{dis}} = 1$ to discover a router for initial communications with the SM, while $N_{\text{dis}} > 1$ can be used when the I/O devices have adequate energy as discovering more routers gives more options to an I/O device for initial communications with the SM.
- Option 2: Each I/O device scans the available channels *randomly*, i.e., each I/O device chooses a random channel independently from the available set and scans N_{scn} slots before moving to the next channel. As soon as N_{dis} routers are discovered or maximum scanning interval (T_{scn}) is passed, the scanning process has been terminated.
- Option 3: Each I/O device scans a random channel on each slot and as soon as N_{dis} routers are discovered or maximum scanning interval (T_{scn}) is passed, the scanning process has been terminated.

The above mentioned approaches can reduce the scanning time a bit when compared to the traditional ISA100.11a scanning. However, still the I/O devices have to scan all of the 16 channels of IEEE802.15.4, which takes significant time and energy. Thus, to shorten the scanning time even further, we use only the *three* IEEE 802.15.4 channels that are non-overlapping with the frequently used WiFi channels for advertisement broadcasts. This makes the joining faster and affordable for the harvester powered I/O devices. A different hopping pattern containing the three respective channels is thus considered for advertisement broadcast, while the regular hopping pattern is used for data communication. To efficiently use these two different hopping patterns, we divide the superframe into two parts as shown in Figure 3. The first part is reserved only for advertisement broadcast and the second part is for actual

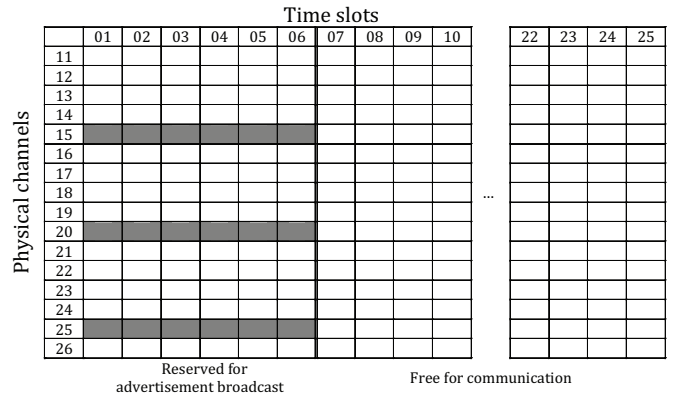


Figure 3. Modified superframe with dedicated advertisement broadcast period to facilitate fast I/O joining in ISA100.11a.

communication. Higher number of slots in the advertisement period provides higher scalability in the network. However, it reduces the effective throughput of the network as fewer slots are available for actual communication. This issue can be addressed by increasing the length of superframe.

B. Spatial diversity approach (SDA) for reliable data publication

ISA100.11a standard utilizes blind channel hopping to increase communication reliability, where packet transmissions between the same pair of devices (i.e., I/O device-router, router-router) take place over different physical channels in every instance. However, some packets may still be subjected to deep fading of industrial harsh environment and need to be retransmitted. This costs additional energy and increase communication latency. To reduce these packet retransmissions and latency, we utilize spatial diversity by using the built-in multiple paths of ISA100.11a. Instead of transmitting packets to a randomly selected neighboring router from a set of two best routers as suggested in a traditional ISA100.11a, the I/O devices in our approach send the copies of same packet to both routers. As these paths are independent from each other, the redundant copies of most packets overcome fading issues which increases the packet reception rate. Transmission of redundant packets in every transmission consumes almost double energy when compared with the ISA100.11a transmission policy. To reduce this overhead, the I/O devices only transmit redundant packets when it is necessary according to the following steps.

- Step 1: An I/O device always transmits the packets to the router which can be communicated earlier (scheduled in an earlier slot by the SM).
- Step 2: The second copy will only be transmitted (to another router) if the first transmission fails.

While improving reliability, this scheme can reduce the network traffic. Although additional energy is consumed for these extra transmissions, the overall increase in energy consumption is not significantly higher than that required for re-transmitting the failed packets in traditional ISA100.11a. Moreover, this approach can be employed locally by turning on only when an router reports significant packet losses from an I/O device

and turning off when both copies of the packet are successfully received for a while. No significant changes in the ISA100.11a stack is needed to apply this scheme.

V. SIMULATION PARAMETERS

A. Network setup

To evaluate the performance of the proposed approaches in this paper, we consider an industrial network of 40 uniformly distributed I/O devices and 16 systematically deployed routers in a 50 m × 50 m area. The routers broadcast advertisements with an interval varied between 0.25s to 4s. The I/O devices scan a particular channel for $N_{\text{scn}} = 40$ slots to discover one proxy router (i.e., $N_{\text{dis}} = 1$). The maximum scanning duration is fixed to $T_{\text{scn}} = N_{\text{Ch}} \times N_{\text{scn}}$ slots, where N_{Ch} can be either 16 or 3 depending on the number of channels used for advertisement broadcast. The transmission power is varied between 0 to 12 dBm. The I/O devices publish their data in an interval between 250ms to 1s. While implementing the channel hopping mechanism in the ISA100.11a simulation, the hopping pattern, $hp_1 = 19, 12, 20, 24, 16, 23, 18, 25, 14, 21, 11, 15, 22, 17, 13, 26$ is considered, where the numbers represent the corresponding channel of IEEE802.15.4. A different hopping pattern, $hp_2 = 15, 20, 25$, containing the IEEE802.15.4 channels which are non-overlapping with commonly used WiFi channels, is used for the advertisement broadcasts in our proposed fast joining scheme as discussed in Section IV-A.

To compare the RSSIs and packet losses, we consider the packet transmission and reception when all I/O devices are in the stable state. In total 50 different networks for each setup (combinations of different transmission power, advertisement rate, no of advertisement channels) are simulated in MATLAB to generate statistically significant results, where the location of the routers are kept fixed while the I/O devices have different positions in different networks.

B. Industrial channel propagation model

The radio signals suffer from free space path-loss, multipath fading and shadowing in indoor environment. In an industrial environment, this scenario become even worse due to the presence of heavy machinery made of metals which eventually makes the industrial channels unpredictable. In this work we used the IEEE802.15.4a channel model [12] to calculate the RSSI in the network which can be represented as,

$$PL(d) = PL_0 + 10n \log_{10}(d) + Sh + SSF + noise, \quad (8)$$

where, PL_0 is the free space unit path loss in dB (i.e., the loss after 1 m distance), n is the attenuation factor, d is the distance between a transmitter and receiver in m, Sh is the shadowing factor in dB and SSF is the small scale fading in dB. The noise is mainly added to achieve the time varying nature of the shadowing, which is a zero mean Gaussian random variable that varies over time. More specifically, $noise \sim \mathcal{N}(0, \sigma_n^2)$ dB.

Typically, for indoor home/ office environment the shadowing effect is modeled as an uniformly distributed random number and the value of shadowing effect is considered as

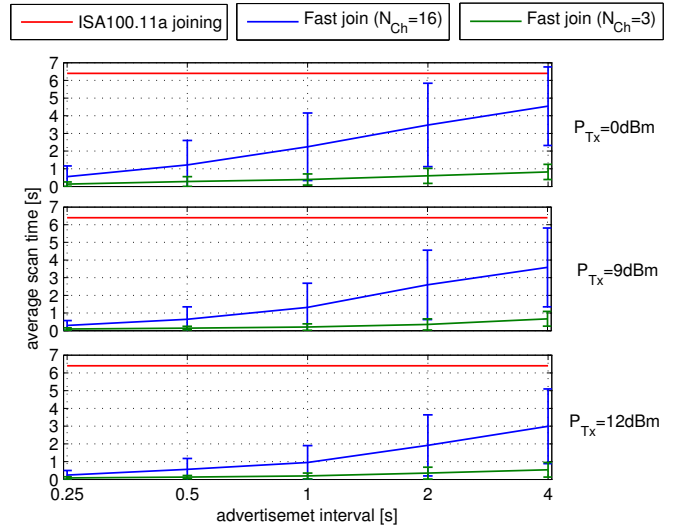


Figure 4. Average scan time with confidence interval required I/O joining in different scenarios.

a constant for a transmitter-receiver pair during the communication period. However, in factory environments, the movement of the machinery, highly reflective materials and electric impulses due to friction or other reasons can trigger time varying shadowing effect typically known as *temporal fading* [13]. To replicate a similar industrial environment, we model the shadowing as a multivariate Gauss distributed random number, where the shadowing varies over different IO device and router pairs and also with the channel used for communication. Mathematically,

$$Sh \sim \mathcal{N} \left(\begin{bmatrix} \mu_{io} \\ \mu_{rou} \\ \mu_{ch} \end{bmatrix}, \begin{bmatrix} \sigma_{io}^2 & \sigma_{io}\sigma_{rou} & \sigma_{io}\sigma_{ch} \\ \sigma_{rou}\sigma_{io} & \sigma_{rou}^2 & \sigma_{rou}\sigma_{ch} \\ \sigma_{ch}\sigma_{io} & \sigma_{ch}\sigma_{rou} & \sigma_{ch}^2 \end{bmatrix} \right),$$

where, μ represents the mean and σ represents the standard deviation of the distribution. The suffixes *io*, *rou* and *ch* represent I/O device, router and channel respectively. For the simulation, we set $PL_0 = 56.7$ dB, $n = 2.15$, $SSF = 12.99$, $\mu_{io} = \mu_{rou} = \mu_{ch} = 0$ dB, $\sigma_{io} = \sigma_{rou} = \sigma_{ch} = 6$ dB and $\sigma_n = 0.01$ dB according to the suggestions of [12]. The receiver sensitivity, $\gamma_{\text{th}} = -98$ dBm is selected based on the Nivis hardware specification [14].

VI. RESULTS AND DISCUSSION

To evaluate the performance of the proposed fast joining approach and the spatial diversity approach of data publication, we conduct several experiments by varying the transmission power, number of channels for advertisements, advertisement and I/O publication rate, etc. We compare several performance matrices to discuss the potentials of proposed schemes over traditional ISA100.11a schemes. We also identify the limitations of the proposed fast joining schemes.

A. Scanning time for I/O joining

Figure 4 provides a comparison on the average scanning time required in traditional ISA100.11a joining with that in our

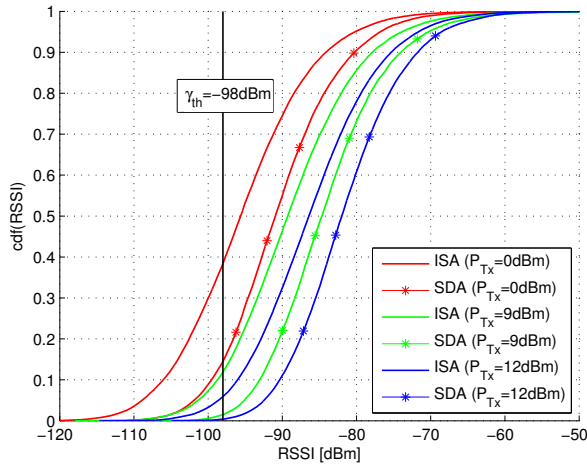


Figure 5. CDF of Packet RSSIs.

Table II
I/O JOINING OUTAGE PROBABILITY.

P_{Tx} [dBm]/ Adv.interval [s]	I/O joining outage (%)				
	0.25	0.5	1	2	4
0	0	2.7	5.1	24.1	48.1
9	0	0	0.2	6.3	26.5
12	0	0	0.1	4.9	18.5

proposed fast joining approach. ISA100.11a joining requires at least 6.4 seconds of scanning (400 ms on each of the 16 channels in IEEE802.15.4) [15] while the proposed fast joining approach reduces this significantly (between 87%-97%) by introducing several thresholds mentioned in Section IV-A. In the proposed fast joining approach, the scanning time goes up with the increase in advertisement interval as the I/O devices have to scan longer to detect an advertisement successfully. However, limiting the advertisement broadcasts on three channels can reduce the scanning time even when the advertisements are broadcasted less frequently because in that case the I/O devices have to scan fewer channels and the density of advertisements per channel is higher than the case where all the 16 channels are used. Note that all the three options in proposed fast joining approach result in almost similar scanning times.

B. I/O joining outage

As we terminate the scanning process after a fixed scanning window, a number of I/O devices are failed to join the network during the prescribed period. The scenario become worse when the advertisements are broadcasted less frequently. The situation can be addressed partially by increasing transmission power which also can reduce the required scanning time for I/O joining. In Table II, we presented the outage probability of I/O joining for different transmission power level and advertisement rate. Almost all of the I/O devices are able to discover a router during the scanning window with high advertisement rate (1 advertisement in every 0.25-0.5s) regardless of the

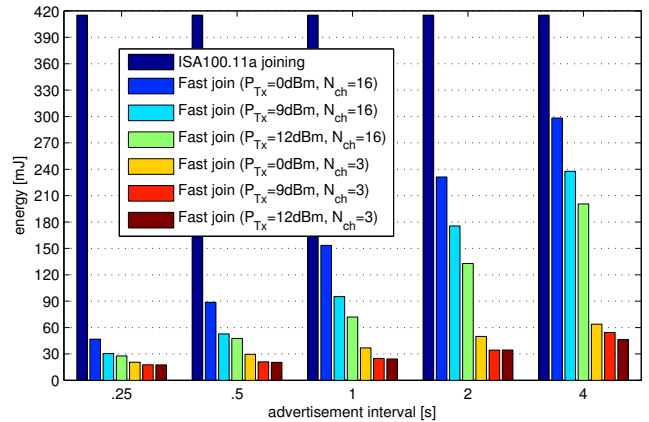


Figure 6. Comparison of I/O joining energy.

transmission power and number of advertisement channels while a significant outage is observed with lower advertisement rate. These results suggests that at least a moderate advertisement broadcast rate (1 advertisement/s) needs to be used for the success of our proposed energy efficient fast I/O joining scheme.

C. RSSI and packet loss probability

The I/O devices start publishing data according to their publishing periods as soon as the SM assigns communication resources for them. Some of these data packets fall into deep fading in harsh industrial environment. We monitor the health of the received packets in the network by calculating their RSSI. Figure 5 shows the cumulative distribution functions of RSSIs with different transmission power levels and number of scanned channels for both schemes. Around 38% of the received packets fall below the threshold of error-less detection in the network utilizing ISA100.11a data publication approach when the transmission power is set to 0 dBm. On the other hand, the proposed SDA out performs ISA100.11a approach of data publication by achieving higher packet reception rate in every scenario. We are able to reduce down the packet loss probabilities from 38% to 14.5%, 12% to 1.5% and 6% to 0.4% by using SDA data publication with transmission power 0dBm, 9dBm and 12dBm respectively. Note that no re-transmission policy is implemented in our simulation for fair comparison.

D. Energy consumption

The energy consumption of any network depends on the hardware specifications as well as the communication protocol. In this paper we consider the specifications of Nivis VarsaNode 210, whose transmission power is 180 mW (when transmitting at 12 dBm) and reception power is 63 mW. To calculate the average energy consumption of the I/O devices in the steady-state phase (when the network is in stable condition), we have to consider packet transmissions and advertisement receptions for a fixed period. Results from 5 minutes of network simulation in the steady-state phase is presented in this paper. On the other hand, the joining energy consumption is independent of

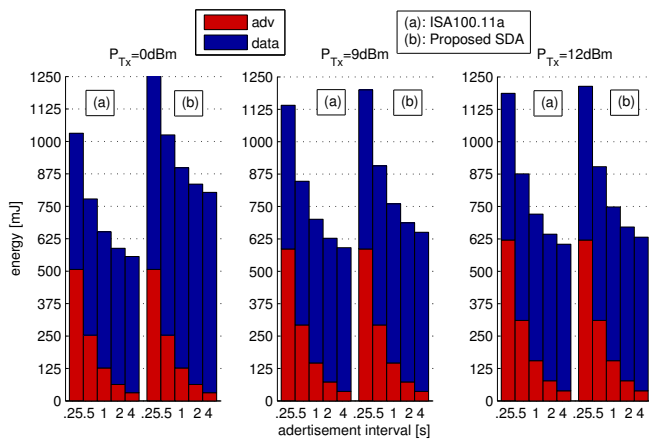


Figure 7. Comparison of I/O energy consumption during 5 minutes in the steady-state phase.

this period and only required during the network (re-)joining. This portion of the energy has to be harvested at first so that the nodes can (re-)join the network. The proposed fast joining scheme can reduce up-to 95% (when advertisements are broadcasted on 3 channels with 0.25s interval and 12 dBm transmission power is used) of energy consumption required in traditional ISA100.11a joining, as shown in Figure 6. The comparison of I/O energy consumption in the steady state phase between the networks utilizing ISA100.11a approach and proposed spatial diversity approach are shown in Figure 7. The energy spend during the steady-state phase comes from two different parts: energy to receive advertisement and the energy for actual data communication. The first part somehow depends on the advertisement broadcast interval, which is calculated assuming that I/O devices attempt to receive all the advertisements from two neighboring routers. However, an I/O device does not need to receive all the advertisements from all its neighboring routers to maintain synchronization, instead it can be selective when the available energy level is critically low. The energy consumption for data communication depends on the publishing periods of I/O devices. In our proposed scheme with spatial diversity, data communication energy is naturally higher than that in traditional ISA100.11a due to the redundant packet transmissions. However, with our scheme less re-transmissions are required whereas traditional ISA100.11a results in much higher re-transmissions, which will cost additional energy (ignored in this calculation).

VII. CONCLUSION

This paper analyzes the energy consumption of the I/O devices in different phases of communication to check the feasibility of energy harvesting industrial communication. It is clear that even though measures have been taken to reduce the average energy consumption of existing wireless protocols, still the node joining phase remains expensive for the harvester powered devices. In this paper, we propose a fast node joining procedure that is able to reduce the joining energy significantly without sacrificing quality in most of

the cases. In addition, our proposed spatial diversity scheme for data publication can achieve higher reliability and fewer retransmissions in the network when compared with traditional ISA100.11a approach. This scheme is particularly suitable for harsh industrial environment where higher packet loss is expected. Future works include testbed implementation of the proposed schemes to verify the results in real industrial environment.

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