Energy Savvy Network Joining Strategies for Energy Harvesting Powered TSCH Nodes

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***Abstract*—This paper presents methods that enable batteryless energy harvesting powered Time Synchronized Channel Hopping (TSCH) wireless sensor nodes to join a network with less energy wastage. Network joining of TSCH nodes is a very power hungry yet inevitable process to form a working wireless sensor network (WSN). Since the energy level from energy harvesting is scarce, energy passive methods are essential. A duty-cycled network joining process in combination with an appropriate capacitor size is proposed here as they are among the factors that can be easily controlled without extra energy. When a node joins the network in a duty-cycled manner, other nodes may join the network during the gap time, which reduces energy wastage of the nodes in waiting. With an appropriate capacitor size, the capacitor can be charged up within a reasonable time and power up the node for a sufficiently long time, which increases the probability to complete the network joining process of the node. With the combination of a join duty cycle of 50% with a 100 mF capacitor, a WSN was successfully formed by two energy harvesting powered wireless sensor nodes in one network joining attempt.**

***Index Terms*—batteryless, duty cycle, energy harvesting, network join, TSCH, wireless sensor network.**

I. Introduction

Sensors are indispensable in industrial applications for monitoring the conditions of assets or parameters such as temperature, vibration, pressure, and many more to ensure the integrity of the areas of interest [1]. Cable installation for both the power and communication requirements of wired sensors can incur up to 90% of the total cost of the wired systems [2]. Therefore, wireless sensors have gained increasing attention since the cost and effort to install them can be significantly reduced if compared with their wired counterparts. However, one of the potential stumbling blocks for wide adoption of wireless sensors is their power supply. The use of batteries is the most direct way of powering wireless devices but regular battery replacement is required to ensure the wireless devices can continue to operate once the batteries are depleted. Such a requirement is unappealing due to the high costs of battery replacement especially in remote areas and environmental issues related to batteries disposal are of concern [3]. It has been proposed that to fully benefit from the offering of WSNs, perpetual power sources have to be available to them [3].

Energy harvesting, which converts energy sources such as light [4], fluid flow [5], vibration [6], and heat [7] from the ambient environment into electrical energy has been seen as a potential way to power the nodes perpetually [2], [3], [8]. The availability and amount of energy sources differ with time and locations [8], [9]. The energy is usually stored in capacitors as they have a wider operating temperature range, higher peak power delivery, and higher charging cycle than rechargeable batteries [10]. Depending on the capacitor charge up time, each node might be powered up at a different time. Therefore, most energy harvesting powered wireless sensor nodes simply form an ad hoc network that is unidirectional where only the nodes send data to the network manager once they are powered on [11], [12]. However, a network with a more predictable behavior and better control over the nodes to achieve more sophisticated tasks is preferred in industrial applications [1]. Thus, it is crucial for the nodes to form a network that is bi-directional, consumes low power and has high reliability in its wireless communication.

To meet the demands of industrial applications, TSCH was developed [13], [14], and introduced in the IEEE 802.15.4e amendment to replace only the medium access control (MAC) of the IEEE 802.15.4 standard [15]-[18]. A network manager synchronizes all the TSCH nodes to the same time base and controls the schedule of the wireless communication among the nodes by continuously sending schedule to the nodes based on their needs to satisfy their requirements [18]. With the scheduled time slotted communication and channel hopping mechanism, TSCH has a reliability of over 99.999% and consumes about 80% less power than conventional IEEE 802.15.4 networks for its communication [19], which is favorable to energy harvesting as the usually low harvested power would still be able to sustain the operation of the WSN.

Many researches on energy harvesting powered WSNs have been focused on efficient energy usage during the operational state using methods such as MAC protocol designs [20]-[22] and transmission power control [23]. However, the nodes need to join a network first to become operational. This begins with the network manager advertises its presence on random channels. The nodes have to scan through all the available channels with only a limited duration spent on each channel [15], [16]. The nodes will be able to join the network when the manager and the nodes are sending and listening on the same

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channel, respectively [15], [17]. Thus, the join process may take up to several minutes [14]-[16], [24], [25]. So far, many proposed and recent solutions only focus on the advertisement to reduce the join time. With Random-based advertisement [26], nodes that are already connected to the network may advertise in a slot that is randomly selected from a given set with a probability equals the inverse of their advertising neighbors to reduce collision of the advertisement, which will make the network joining longer. To have a collision-free advertisement [24], a schedule for advertisement is built and mapped to cells with indices. An appropriate channel for transmission can then be determined. With the Deterministic Beacon Advertising, advertising nodes may repeat the advertisement in different slots and channels over all the available frequencies [16]. Another method utilizes a different timer from the routing and network layers to change the advertisement rate dynamically based on the statuses of the nodes that are already connected and intended to connect to the network [17]. However, these methods were only applied on nodes with steady power supplies such as batteries [17], [24], [26]. This is because it is quite demanding for an energy harvesting powered node to be an advertiser as extra energy is needed while the harvested energy is limited [15], [24]. Also, with the energy uncertainty in energy harvesting, it was suggested to use star network so that other nodes are unaffected when one node temporarily lose its power [27].

Attempts to power batteryless TSCH nodes using energy harvesting were reported, but the power required to join the network was higher than the power harvested using solar cells, which made the network join unsuccessful [28]. Another work that used vibration energy harvesting took 12 hours to charge up a 0.33 F capacitor, which can last for 12 s of network join process [29]. The harvested energy is wasted if the node could not join the network before the capacitor is depleted. The process has to restart again once sufficient energy has been accumulated. A successful attempt was to use the energy harvesting powered nodes in an asynchronous manner without joining the network. The nodes transmit data when they have enough energy, but this contradicts the motivation of using TSCH for a synchronized operation [14]. Thus, the network join process of energy harvesting powered TSCH nodes is little known as there is a lack of work on the nodes that are trying to join the network. There is a need to understand and address the network join issues of energy harvesting powered TSCH nodes to benefit from the virtually infinite energy from energy harvesting to realize perpetual operation of WSNs.

The energy constraint in energy harvesting powered nodes means methods that need extra energy are less viable. This paper herein presents an energy passive approach to enable batteryless energy harvesting powered TSCH nodes that are trying to join a network to get connected with higher success rates in one attempt before their energy storage depleted. The proposed method combines a proper capacitor size and duty-cycled network join process, which considered the trade-off among the randomness of energy consumption caused by the uncertain network join time, the upper limit of the energy capacity of the capacitor, and the time needed to recharge the capacitor. Network joining performances of two energy harvesting powered TSCH nodes that form a WSN were studied to verify the proposed methods.

II. Proposed Methods

Prior research has shown that the network joining process of TSCH nodes could be more than a few minutes [14]-[16], [24], [25]. When limited beacon channels were used, the network join time may be reduced [14], [15], [24], [28]. Thus, this approach is adopted here. An energy-aware interface that allows energy harvesting powered nodes to accumulate energy efficiently for their startup and further operations is also used [30]. Other methods that will be incorporated are as follows.

A. Duty Cycling of Network Joining Process

Once the advertisement is heard, the nodes send a join request and wait for a reply from the network manager, which is known as negotiating. Usually, with only one antenna, the network manager can only reply to one node at a time to allow that node to join the network. Therefore, some nodes may keep listening or negotiating until their energy storage is depleted, especially when there is contention from other nodes to join the network. This scenario usually happens when two or more nodes try to join the network with 100% duty cycle at about the same time but the network manager can only communicate with one node until that node has finished its process before replying to the other nodes. By that time, those nodes might have already ran out of energy and have to wait until they have accumulated enough energy to restart the network joining process again.

With a duty-cycled network joining process, the radio of a node is turned on or off based on the duty cycle set. When the radio is off, some energy can be replenished if there is energy available to be harvested. This means more energy is available to keep the nodes powered on longer for a better chance of successful network join in one attempt. Also, when the node that was initially attempting to join the network turned off its radio, the network manager can respond to other nodes that have been powered up during that time. This saves energy as other nodes may now connect to the network instead of using the energy to wait for the first node to end its process, either due to a successful connection or depleted energy.

B. Capacitor Sizing

Capacitors are often used as the energy storage devices in batteryless systems. The usable amount of energy ΔE in a capacitor is determined by two factors, namely the capacitance C of the capacitor and the operating voltage range of the system that the capacitor is going to power as given by (1).

$$\Delta E = \frac{1}{2}CV_{\text{TH-H}}^2 - \frac{1}{2}CV_{\text{TH-L}}^2 \tag{1}$$

where $V_{\text{TH-H}}$ and $V_{\text{TH-L}}$ are the higher and lower thresholds of the system operating voltage range, respectively. From (1), ΔE can be increased by increasing C as well as using a system that has a wide operating voltage range. However, there is usually a practical limit on the operating voltage range due to factors such as circuit topologies [31] and fabrication technologies

[32], depending on the system architecture used. On the other hand, capacitors with the appropriate C can be easily obtained from the commercial market based on the design specification. Differentiating the capacitance equation $Q = CV$ with respect to time t leads to an expression for current dQ/dt or I as in (2):

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = C\frac{\mathrm{d}V}{\mathrm{d}t}$$
$$I = C\frac{V_{\text{TH-H}} - V_{\text{TH-L}}}{\mathrm{d}t} \quad (2)$$

From (2), an appropriate C can be selected once the time dt for the capacitor to keep the nodes powered on has been set, and the operating voltage range of the system as well as the average current I consumed by the nodes during the network joining process are known. If the current that flows into the capacitor is known, (2) can also be used to determine the time to charge up a given C from a lower voltage $V_{\text{TH-L}}$ to a higher level at $V_{\text{TH-H}}$. This is useful in the capacitor selection as well since it is desirable for the nodes to boot after a reasonable amount of idle time when the capacitor is being charged up. A balance is required between the discharge and charge up time based on the outward and inward current of the capacitor, respectively. For example, smaller capacitances can be used if the energy harvester has high output power as the current after power conditioning could be high enough to sustain the network join process of the nodes directly or quickly recharge the capacitor if the first network join attempt failed.

III. System Design

LTC5800 from the SmartMesh IP family was chosen for the implementation of the WSN [18]. The WSN in this work is composed of two DC9003A-B nodes and a DC9001B network manager that all have the LTC5800 chip. Since the network manager has a very important role in managing the network, it will be connected to a computer to get a steady power supply to ensure that it is always on, and to allow more control and processing from the computer. Only the nodes were powered by energy harvesting using airflow [5], which can come from ventilation system or occur naturally and vibration, which can come from structures and machineries [6], where both sources are usually abundant in industrial environments.

Fig. 1 shows the architecture of the implemented system. The energy harvesting powered wireless sensor nodes consist of an energy harvester, a rectifier for ac energy sources such as vibration, a power management circuit, an energy storage device, an energy-aware interface (EAI), and a wireless sensor node. Power from the energy harvester is usually insufficient to instantly meet the demand of the wireless sensor node for network joining but enough to power up the power management circuit after a short time of energy accumulation in capacitor C_{i} [4], [5], [7], [12]. Once the energy is enough for the power management circuit to operate, it conditions the energy from the energy harvester and provides a usable output voltage to charge up the energy storage device and power up the wireless sensor node when sufficient energy has been accumulated in a larger capacitor C_{S} [12], [29], [30], [33].

To be able to assess fully the energy harvesting capability of the system designed, a supercapacitor C_{S} is used as the energy storage device instead of a battery, which can also be an energy source. The EAI controls the energy flow from the capacitor to the node. It disconnects the node from capacitor C_{S} to allow effective energy accumulation in the capacitor as it consumes only nanoamperes of current [12], [29], [30], [33]. The EAI connects the node to the capacitor to turn on the node once the capacitor voltage reaches 3.15 V [34]. When the voltage drops to 2.25 V, the EAI disconnects the node from the capacitor to prevent energy wastage because the node will still draw energy from the capacitor without performing any task when the voltage is lower than its minimum operating voltage of 2.1 V. Therefore, with the system architecture used here, the node is powered up when the capacitor discharges from 3.15 V to 2.25 V.

The vibration energy harvester (VEH) used is a M8528-P2 macro-fiber composite (MFC), which is able to harvest strain induced by vibrations on a structure [35]. The MFC generally outputs high ac voltage. Thus, the power management circuit used consists of a full-wave diode bridge (FB) rectifier to convert the ac voltage to dc voltage and a buck converter to step down the rectified voltage to charge up the supercapacitor [33], [36]. The buck converter outputs a maximum voltage of 3.3 V, which is within the voltage limits of the nodes at 3.76 V and the BestCap® supercapacitor used at 4.5 V. A maximum power point (MPP) controller is used to control the converter for energy transfer from the MFC at its MPP to the devices at the output of the converter [37]. The airflow energy harvester (AEH) is composed of a turbine and a dc generator [5]. Its output is dc with generally low voltage. Therefore, the FB rectifier is not required and a boost converter is used to step up the low voltage to a maximum of 3.3 V.

IV. Experimental Validation

A. Experimental Setup

Fig. 2 shows the experimental setup. The MFC was bonded onto a carbon fiber composite material and an Instron E-10000 machine was used to apply different vibration profiles onto the composite material to simulate vibrations that structures might experience. A wind generator with tunable airflow speed was used to generate airflow towards the AEH. Keithley 2612B sourcemeter units (SMUs) were used for current measurement or when both current and voltage measurements were required

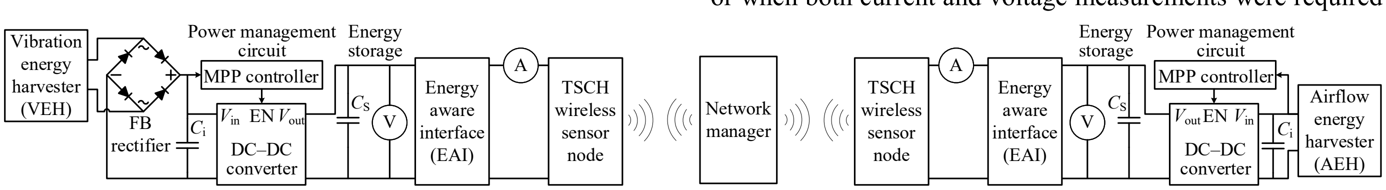

Fig. 1. Block diagram of the energy harvesting powered nodes with points for voltage and current measurements.

simultaneously and a Data acquisition (DAQ) system from National Instruments was used for voltage measurement with very long duration. All the instruments were controlled using a computer via an in-house built LabVIEW program.

By adopting the channel blacklisting method [28], only 7 channels, which is the minimum number of channels that has to be active out of the 15 channels of LTC5800 were used in all the tests [38]. Only two nodes were used to form a simple WSN without any external sensors since the focus here is on the network joining of the nodes. The nodes will be powered up to join the network using different test conditions, which will be explained later. Once the nodes are connected to the network, they will measure temperature using their onboard temperature sensor and send the reading every 2 s at 8 dBm.

B. Testing Methods

As described earlier by (2), it is important to understand the current requirement of the nodes to select an appropriate capacitance. The current profiles during the network joining of the nodes were measured to determine the average value.

Then, both nodes were set to join the network concurrently with the same duty cycle of 100%, and then 50% to determine the effect of a duty-cycled network join. The duty cycle can be configured by setting the ‘joindc’ parameter of LTC5800 with an integer from 0 and 255, representing 0.2 to 100% [25]. The ‘joindc’ was set to 128 and 255 for the duty cycle of 50% and 100%, respectively. The times required by the nodes to connect to the network successfully using different duty cycles was compared. Since the network joining time could be very long where energy harvesting might not be able to sustain, the nodes were powered by the SMUs. The measurement for each duty cycle was repeated for 50 times to determine the time distribution probability of joining the network successfully.

Based on the initial characterization of the nodes, different capacitances will be used in the experiment. The performance of a node that was powered by the VEH under different testing conditions will be assessed and compared using the different capacitors one by one. This test only used the VEH to power one node because it is easier to simulate low power conditions using piezoelectric transducers that usually have sufficiently high output voltage for the power management circuit to operate. Under low airflow conditions, the output voltage of AEHs could be too low for the power management circuit to work. Two extreme cases were chosen where peak-to-peak strain levels of 300 με at 2 Hz and 600 με at 10 Hz were applied onto the VEH to charge up the capacitors and power the node via the power management circuit in each test. The chosen strain and frequency range is typical for structures such as bridges [39], frame structures [40], and different types of aircrafts during flight mode [41]. The number of attempts and time required by the node to join the network were measured, with up to 4 attempts recorded in each scenario before ending the measurements as the network manager will declare that a node is lost after 5 retries. The retries can be doubled but it may affect the network performances [25].

Finally, the AEH and VEH were each used to power one node using different network join duty cycles and capacitors to study their effects on the network joining process. The VEH was excited by a peak-to-peak strain level of 600 με at 10 Hz. The wind generator was tuned to produce different airflow speeds to vary the output power of the AEH, which is generally much higher than the VEH [5], [11], so that the

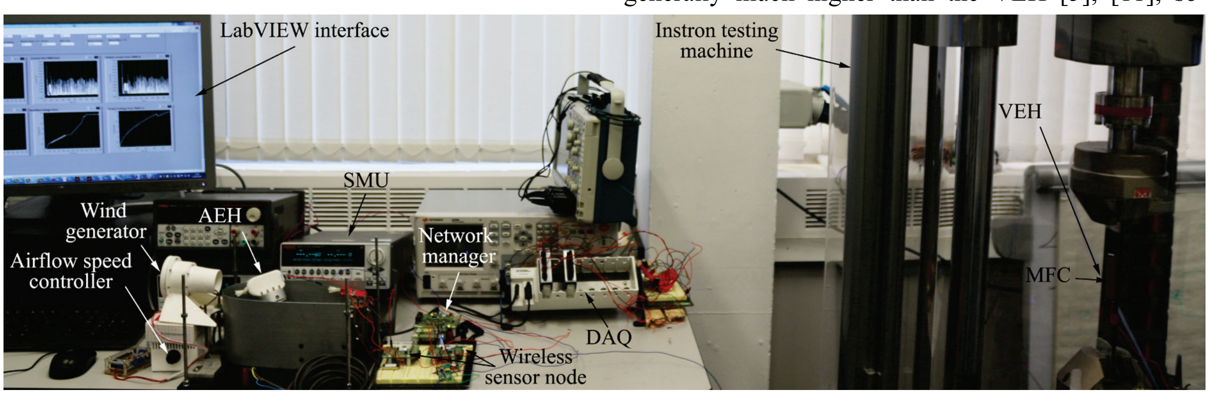

Fig. 2. Image of the experimental setup of the energy harvesting powered wireless sensor network.

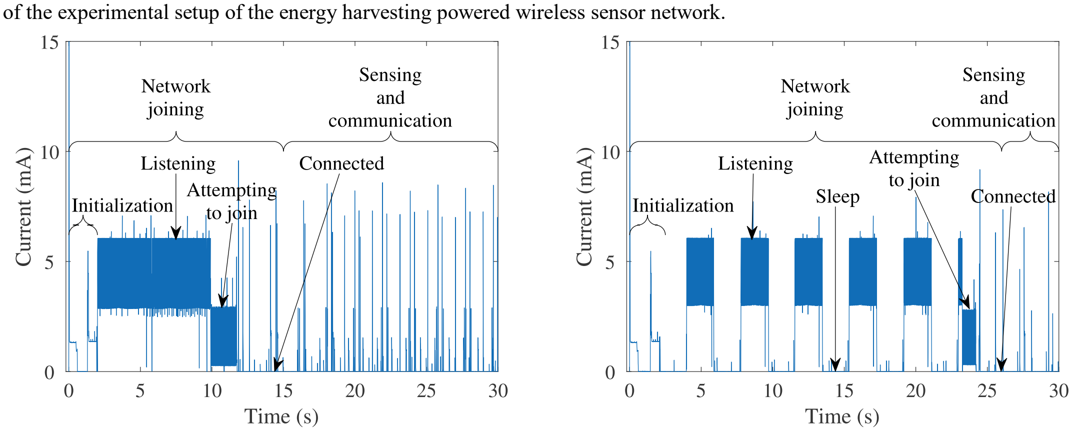

Fig. 3. Measured current profiles of the wireless sensor nodes at network join duty cycles of 100% (left) and 50% (right).

AEH can charge up the capacitor via its power management circuit at different rates according to the intended tests.

V. Results and Discussions

A. *Initial Characterization*

Fig. 3 compares the current profiles of the nodes during the network joining processes at join duty cycles of 100% and 50% to identify the processes that are power hungry. Once the nodes were powered up, a huge current surge appeared and eventually steadied at around 1.3 mA for about 600 ms before reduced to 0 for another 600 ms. The nodes then went through a similar cycle but with a lower surge during the initialization. The average current is around 1.3 mA and is the same in both the 100% and 50% network join duty cycles. The initialization phase is considered as part of the network joining here since it is the first process that all the nodes have to go through. Also, it consumes energy, which is a factor that needs to be considered in energy harvesting applications.

The network joining process and current profiles are similar in both cases. The only difference is that the node with the 100% join duty cycle will listen to the advertisement from the network manager straight after the initialization but the node with the 50% join duty cycle will go to sleep first before it starts listening, with the rest of its process duty-cycled until it has joined the network. The listening process has a current profile of high frequency pulses between 3 mA and 6 mA, which averages to 5.4 mA. When the node is negotiating with the network manager, the average current is 2.7 mA. Once the node has connected to the network and became operational, the average current consumption is 84 µA with the operation used as explained earlier in Section IV.A. The average sleep current with a duty-cycled network joining process is 4.5 µA. The overall average current consumption of the nodes with the network join duty cycle of 100% and 50% were found to be 4.8 mA and 2.5 mA, respectively.

B. *Effect of Network Join Duty Cycle*

Fig. 4 shows the histograms of the time of the nodes joined the network successfully without considering the sleep time and their respective normal probability distributions. The sleep current is negligible if compared with other processes, which is not demanding for energy harvesting. Thus, the sleep time is disregarded here since the focus is on the time that the nodes consume high power. If the sleep time was taken into account, the time at 50% join duty cycle would almost double.

The occurrences of joining the network successfully after about 6 s of energy intensive process is relatively high in all the tests. When two nodes join the network simultaneously at 100% duty cycle, around 4–30 s is required. The network join at 50% duty cycle slightly reduced to about 27 s of energy intensive process. The test with the 50% join duty cycle was repeated by delaying the startup of one of the nodes by 2 s. A greater improvement was achieved with the energy intensive process reduced to between 2 s and 22 s.

The energy intensive process is inconsistent regardless of the duty cycle used. However, the probability of the nodes joined the network successfully after 15 s of energy intensive process is no less than 0.75. The lowest is with the 100% join duty cycle as the transmission channel is highly contentious and the highest is about 0.9 when one of the nodes with a join duty cycle of 50% had a delayed start. The results from the probability plots and histograms imply the network manager can communicate with other nodes when the radio of the node that initially occupied it is off. A network may form quicker as the nodes spend less energy and time on contending among each other for a response from the network manager, which increase their chance of become connected to the network earlier while they still have the energy.

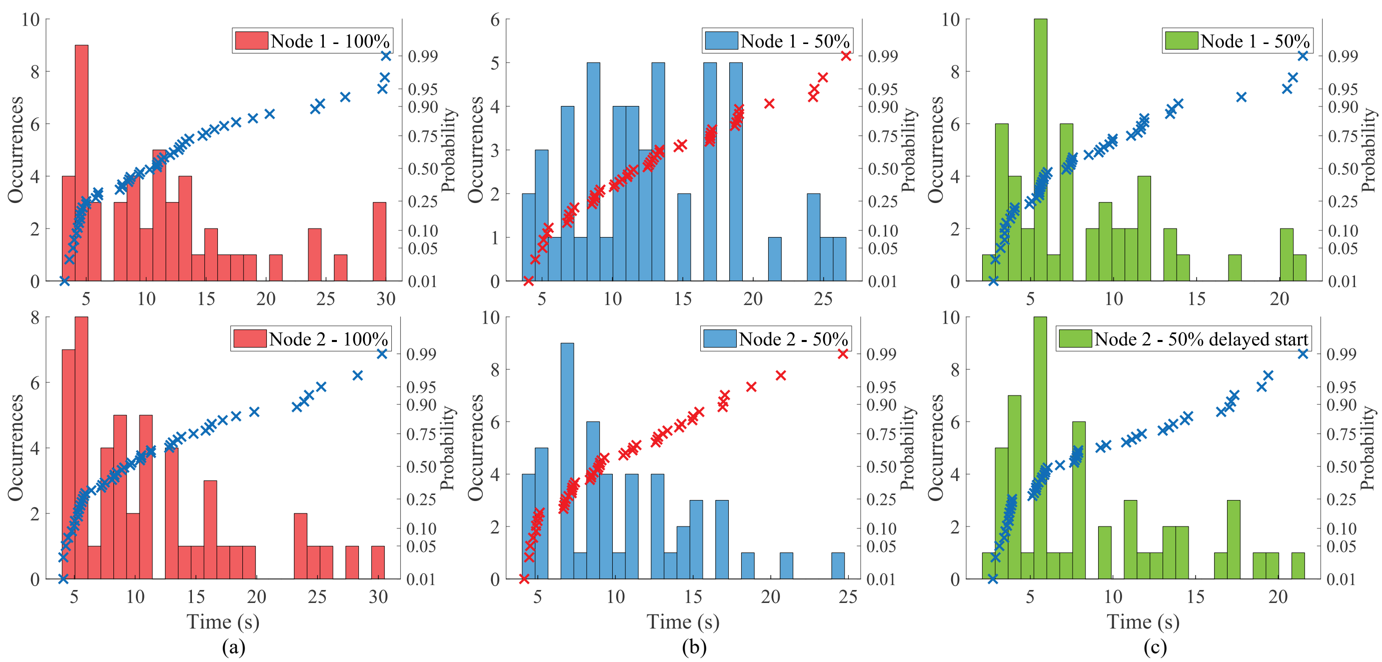

Fig. 4. Occurrences and normal probability of the time spent by the nodes in energy intensive process to join the network successfully at different conditions of: (a) 100% join duty cycle, (b) 50% join duty cycle, and (c) 50% join duty cycle but one of the nodes has a delayed start up.

C. Effect of Capacitor Size

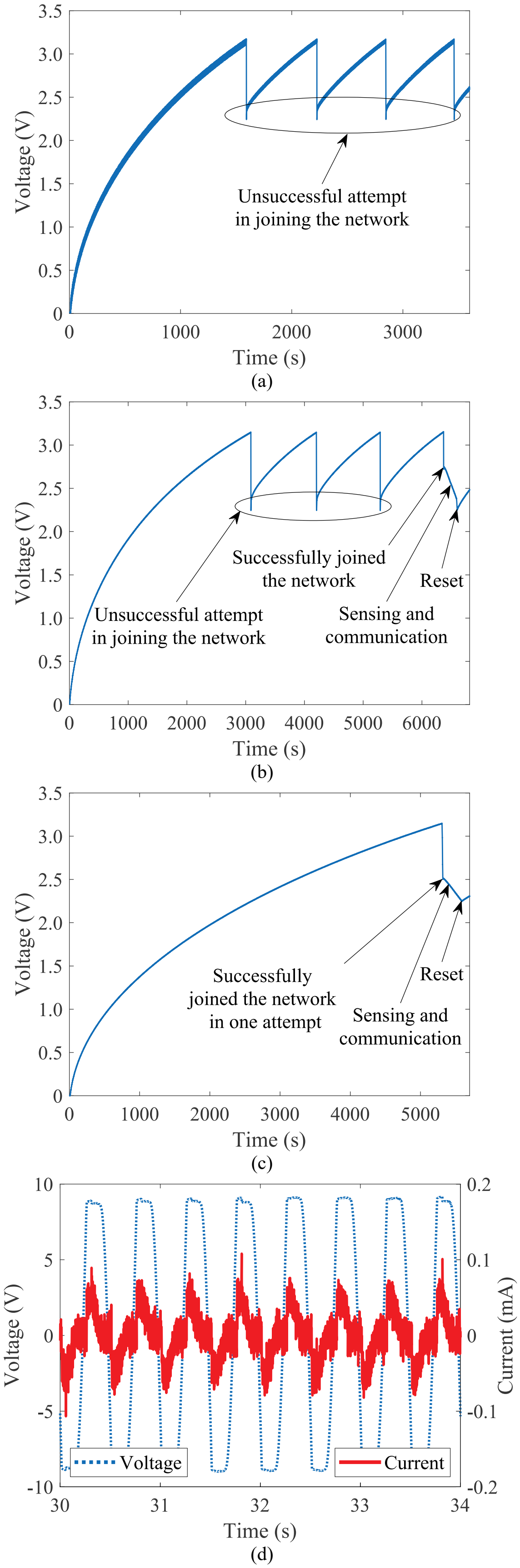

Fig. 5. Measured voltage across the energy storage capacitor of: (a) 33 mF, (b) 50 mF, and (c) 100 mF as well as (d) the voltage and current from the VEH that was under a peak-to-peak stain loading of 300 με at 2 Hz.

Based on the results from the preceding experiments, 15 s,

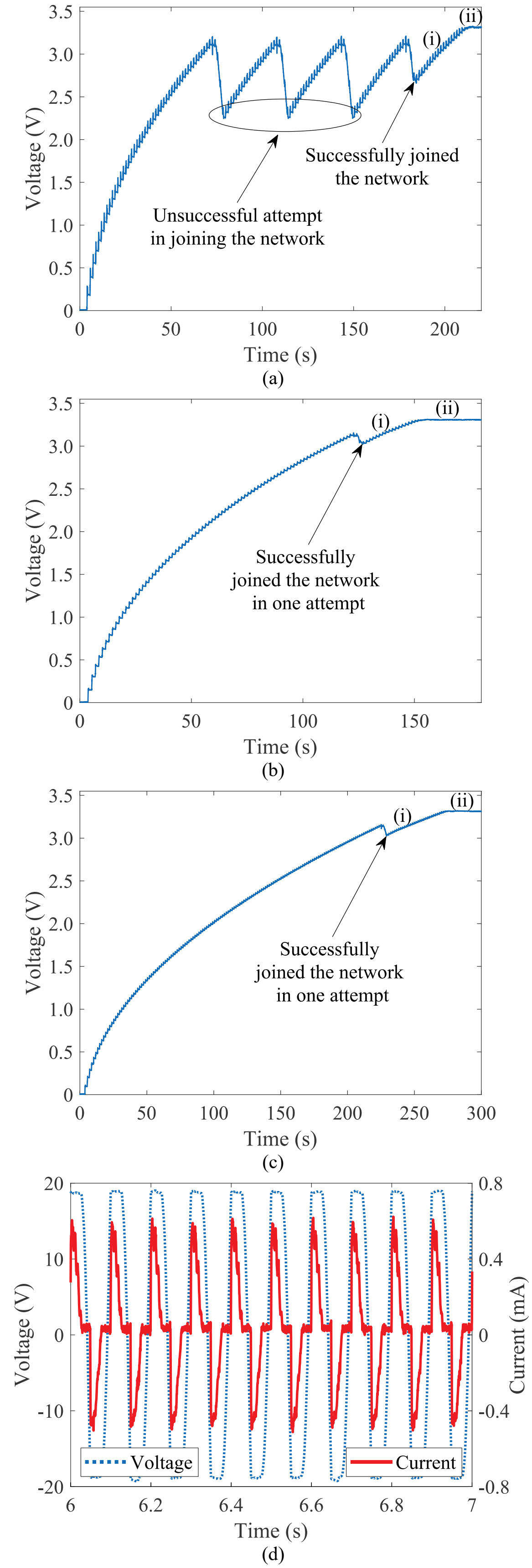

Fig. 6. Measured voltage across the energy storage capacitor of: (a) 33 mF, (b) 50 mF, and (c) 100 mF as well as (d) the voltage and current from the VEH that was under a peak-to-peak stain loading of 600 με at 10 Hz.

4.8 mA, 3.15 V, and 2.25 V were substituted into dt, I, and $V_{TH-H,L}$ in (2), respectively, which gives C a value of 80 mF. Considering some possible tolerances and energy is needed for subsequent operation of the node after joining the network, a 100 mF capacitor is used. The capacitors of 33 mF and 50 mF were also used for comparison purposes. Since only one node was used, its network join duty cycle was set to 100 %.

Although Fig. 4 shows there is a high number of times that the nodes with a 100% join duty cycle successfully joined the network within 6 s, the process is random and the probability remains low. This was proven in Fig. 5(b) when the 33 mF capacitor was used. With a peak-to-peak strain level of 300 με at 2 Hz applied onto the VEH, the node could not join the network in all the four attempts. This is because the energy stored in that capacitor can only sustain the network joining process of the node for a short period of time, which has a low successful connection probability. However, the node joined the network successfully in the fourth attempt using the 50 mF capacitor, as shown in Fig. 5(c) and in one attempt using the 100 mF capacitor, as shown in Fig. 5(d). In both cases, once the nodes have joined the network, the capacitors discharged at a slower rate than during the network joining process until the voltage drops to 2.25 V. This is because the energy from the VEH is rather low as shown in Fig. 5(d) when the applied peak-to-peak strain level is 300 με at 2 Hz. The output from the power management circuit is 86.7 μW, which is less than the minimum power required for communication and sensing of the node. Then, the EAI disconnected the nodes from the capacitors to allow the capacitor to be recharged.

When a higher peak-to-peak strain level of 600 με at 10 Hz was used, the node joined the network successfully with all the different capacitors used as shown in Fig. 6(a)–(c). Several attempts were required using the 33 mF capacitor, but apart from the energy released by the capacitor, there is more energy from the VEH due to the higher applied strain as shown in Fig. 6(d), with the power management circuit output 2.53 mW. This prolongs the window of powering the node and increases the chance of joining the network successfully than the test that uses a low strain level and frequency. With the 50 mF and 100 mF capacitors, the node can join the network successfully in one attempt. This is because the larger capacitors can store more energy to give the node a longer network join window before the voltage level drops to the cutoff threshold of the EAI. Once the nodes have joined the network successfully, the harvested energy is enough for the sensing and communication tasks with surplus to charge the capacitors simultaneously as indicated by (i) in all the 3 cases. The capacitors were eventually charged up to 3.3 V as indicated by (ii) while the nodes continue to operate.

D. *Energy Harvesting Powered WSN*

The first test uses a network join duty cycle of 100% and a 100 mF capacitor to power up both nodes at approximately the

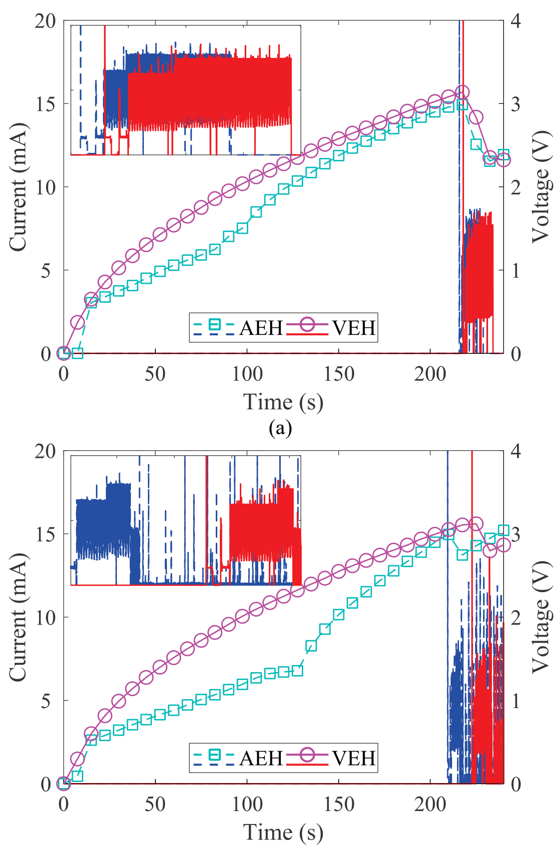

Fig. 7. Measured voltage (marker) across the capacitor and current profiles of the wireless sensor nodes using a capacitor size of 100 mF and a 100% join duty cycle, which were powered on (a) at approximately the same time (b) with a large time gap. Insets show the enlarged view of the current profiles.

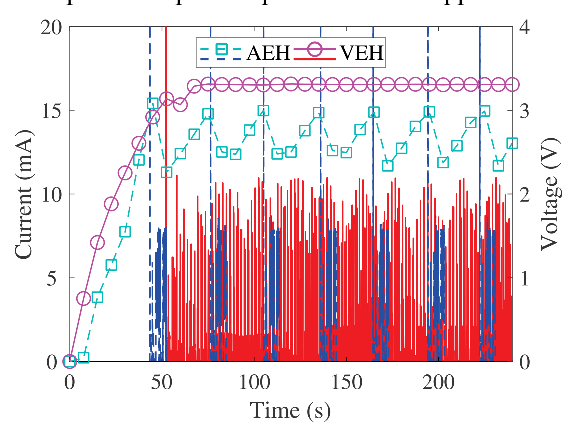

Fig. 8. Measured voltage (marker) across the capacitor and current profiles of the wireless sensor nodes powered by AEH and VEH using a capacitor size of 22 mF and a 50% join duty cycle.

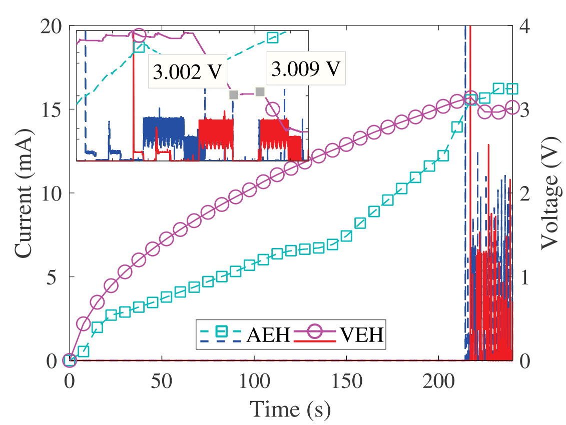

Fig. 9. Measured voltage (marker) across the capacitor and current profiles of the wireless sensor nodes powered by AEH and VEH using a capacitor size of 100 mF and a 50% join duty cycle. Inset shows the enlarged view of the measurements when both nodes were connected to the network.

same time. However, none of the nodes manages to join the network as shown in Fig. 7(a). Here, every failed attempt costs 0.25 J of energy, which can be used for over 900 s of sensing and communication. When the AEH was tuned to charge the capacitor faster, which powered up the node earlier to avoid competing with the VEH powered node on the communication with the network manager, both nodes joined the network successfully. This shows that contention among the nodes to join the network especially in the context of energy harvesting with limited energy is detrimental to the network formation where it adversely affects the success rate of the nodes joining the network in a shorter time or with fewer attempts.

The next test uses a 22 mF capacitor and a network join duty cycle of 50%. Fig. 8 shows that the VEH powered node joined the network fairly quick even with the small capacitor. However, the AEH powered node was not able to connect to the network at all after 7 attempts. This confirms the network join time is random and a node has limited number of attempts to join the network. Although the host can increase the number of retries or re-establish the session for fresh attempts, it is not always possible to do so in practice especially when the nodes are placed in remote areas. Thus, it is crucial for the nodes to be able to join the network successfully with minimal attempts to save energy and ensure a successful network formation.

The final test uses a 100 mF capacitor for a longer network join window that usually has a higher network join success rate and a network join duty cycle of 50% to reduce contention among the nodes to communicate with the network manager. Fig. 9 shows both nodes joined the network fairly quick in one attempt. The AEH was manually adjusted so that the capacitor was charged up to power the node slightly earlier than the VEH powered node, which better reflects the real world scenario since the nodes are likely to be powered up at different time if they were installed at different locations as the energy availability would not be the same. The inset shows that the capacitor is recharged when the nodes go to sleep, which confirms the benefits of a duty-cycled network join process that not only reduces the contention among the nodes but also allows energy replenishment for a longer operation.

All the prior results imply nodes with a capacitor that can supply energy lasting for at least 15 s of energy intensive process in a duty-cycled network join process are preferable. It is possible to use a join duty cycle of 100% but a larger capacitance is needed to have a higher network join success rate at a cost of a much longer charging time. For example, if a probability of 0.9 is desired at a 100% join duty cycle, a capacitance that is about twice the one used in the nodes with a 50% join duty is needed. The probability improved by 0.15 but the charging time almost doubled. Since the power from energy harvester is usually low to sustain the network joining of the node directly or quickly recharge a capacitor for another attempts, it is sensible to use a 100 mF capacitor. It can be charged up within a reasonable timeframe even when the input power is less than 100 μW and power the node for a time that is usually long enough to join the network in one attempt.

VI. Conclusion

The network joining process of the TSCH based wireless sensor nodes is the most power hungry process. However, once they have connected to the network, the average power required is generally low, which in this studied case, 50 times lower than the network joining. Thus, in the context of energy harvesting where energy is limited, it is important for all the nodes to join the network with the fewest possible attempts in the shortest possible time. The proposed approach is to use a duty-cycled network join with a properly-sized capacitor.

Experimental results show that duty-cycled network joining does not necessarily save the energy required by an individual node to join the network since the process is random. Yet, it is beneficial if there are many nodes that need to communicate with the network manager to form a network at approximately the same time. The success rate of joining the network within a shorter time is higher, which saves the overall energy used by all the nodes to form the network. This is because with the duty-cycled network joining process, there is less contention among the nodes. There will be some time slots available for each node to communicate with the network manager when one of the nodes goes to sleep instead of having to wait for the node that is establishing its connection with the network manager to finish the joining process.

Appropriate sizing of the capacitor is vital to keep the nodes powered on for a sufficiently long time to ensure that the node is able to join the network successfully in the first attempt. For every failed attempt, the energy storage requires extra time and energy for recharging where the process may repeat for many cycles. This is undesirable as the wireless sensor node could not begin its operation without successfully joining the network first. A 100 mF capacitor was found to be appropriate here. Although a lower capacitance can be used if the energy harvesters can provide high power, the nodes still risk having to try several times before successful, which overall may use more time and energy to join the network. In the worst case, the nodes might be declared lost by the network manager and can no longer join the network after too many failed attempts.

By selecting an appropriate network join duty cycle and capacitor size, the AEH and VEH powered wireless sensor nodes successfully formed a WSN in just one attempt by using a join duty cycle of 50% and a 100 mF capacitor. Under the tested conditions, the energy harvesters can provide sufficient energy for perpetual operation of the wireless sensor nodes once they have formed a network. The energy is sufficient to sustain the sensing and communication operation of the wireless sensor nodes with surplus to recharge the capacitor. Given that the proposed method is energy passive without modification to the communication protocol, star network structures such as low-power wide-area network are also able to benefit from the proposed method since the TSCH nodes in this paper also use this network structure.

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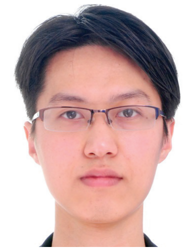

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