Powering 802.15.4/Zigbee Nodes on Harvested Energy

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Abstract. The future of electricity networks relies on the Smart Grid concept to implement reliable and sustainable services. Wireless Sensor Networks (WSNs) may be used to meet Smart Grid data delivery requirements. Powering WSN on environments with energy availability may nevertheless be expensive in both material and human resources. Replacing batteries is therefore an important topic of both academic and industrial work. This paper addresses software related implications of running a WSN node that uses a complex communication protocol and is running on harvested energy. A WSN node running 802.15.4/Zigbee protocol on harvested energy is proposed. The protocol compliant node uses a contact-less scavenger system able to power a WSN node from mains power lines thus provide an easily installable and inexpensive device for non-skilled workers.

Keywords: Energy Harvesting; Split-Core Current Transformer; Zigbee; Wireless Sensor Networks

1 Introduction

The energy source is the main constraint when operating Wireless Sensor Networks (WSN) [1]. The most obvious energy source for a WSN node is a battery, being these rechargeable devices or non-rechargeable ones (i.e. primary or secondary). Batteries have nevertheless a number of drawbacks that seriously limit the usage of WSN, and are in fact the main limitation to its widespread use. Low cost network implementation/operation will be addressed only if battery consumption is substantially reduced or altogether eliminated. In [2] financial costs associated with WSN deployment, commissioning and maintenance where presented. Eliminating batteries will be an advantage in all environments. An industrial environment provides a good illustration for the proposed considerations. Presently, due to the high competitiveness levels worldwide, in large modern industrial plants the overall reliability and the effective maintenance management are critical aspects. In that scope, when using a large number of three-phase squirrel-cage induction motors, the implementation of integrated motor diagnosis systems is highly desirable [3]. In this case, there is plenty of available energy supply, but installing a node always requires wire cutting and screw fastening. One should also consider that maintenance tasks are frequently executed under load as an alternative to stopping machines' labor. Connecting a WSN node to a power line in an industrial environment will therefore require a skilled technician to execute a hazardous operation. Moreover, physical power contacts may prevent free node placement within industrial facilities. Home automation provides a different scenario with similar considerations. Monitoring a large number of electrical charges in large office buildings requires the installation of a significantly large number of wireless devices. Again in this case, despite local power availability, the use of devices with no need for maintenance (e.g. battery replacement) provides the potential for decreasing maintenance costs. Power scavenger solutions may significantly contribute to reduce node placing and maintenance costs. Together with energy source WSN protocol operation is a fundamental concern. Data must be identified and related to its origin, network traffic must be routed and a network topology must be put into operation. Nodes must follow a protocol to be part of the network and are required to execute bidirectional communications. Moreover nodes must be able to listen before transmitting thus requiring more energy than if they were only sending a small number of bytes. Protocol operations such as registering with the network or joining to a group of nodes within the network are required. Protocol requires energy availability that strongly relates to protocol complexity.

In this paper, software implication of running a Zigbee node powered by an electromagnetic harvesting source using a Split-Core Toroidal Coil Current Transformer (SCCT) is presented. The Split-Core Transformer was successfully applied in [4] to power a battery-free wireless device running on harvested power that is capable of monitoring three-phase squirrel-cage induction motor parameters. This paper is organized as follows: Section 2 describes Zigbee characteristics that are the most relevant for the proposed objective. The implemented system architecture and hardware characteristics of proposed device are briefly described in Section 3. Original and proposed software adaptation of Texas Instruments Zigbee stack (Z-Stack) are described in Section 4. Conclusions are drawn in the subsequent section.

2 Wireless Sensor Networks Protocols

A number of protocols for wireless sensor networks may be found in both the literature and industrial applications. In [5], [6], [7] and [8] protocols that are usually compared with the ZigBee specification are presented. Also, Digimesh [9], developed by Digi International™and JenNet [10] from Jennic™are proprietary wireless protocols for network connectivity. In [11] the Zwave [6] protocol was used to implement an Advanced Meter Reading Infrastructure based on a wireless network. In [4] a simple protocol was proposed, its advantages and operational limitations identified. In [4] the SCCT based harvester was able to power a simple communications protocol. The protocol advantages where shown together with its operational limitations. Zigbee/IEEE802.15.4 [12], [13] and [14] is one example of a complex protocol that requires sending and receiving data in large amounts. The ZigBee protocol specifies a wireless technology based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs). Zigbee/IEEE802.15.4 is also a flexible and adaptable protocol allowing the implementation of low power systems with low data rate characteristics as well as high speed data transmissions with large current consumption devices. A number of protocol stack implementations are freely distributed ([15, 13, 16]), making it a very useful tool for test and verification of WSN with an added characteristic of small time to market implementation. To the purpose of this work the choice of this complex protocol is justified by the fact that if the system is able to operate using Zigbee, a less complex protocol will also be able to operate.

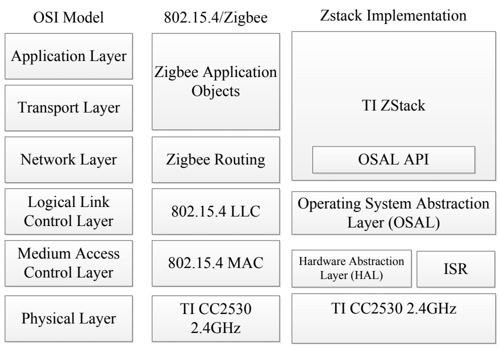


Fig. 1: OSI model applied to 802.15.4, Zigbee and Zstack.

The link between Zigbee and 802.15.4 can be described using the OSI (Open Systems Interconnection) model of abstraction layers as illustrated in Fig. 1. The 802.15.4 is a standard that defines the Physical and Medium Access Control (logical layer) for low power and low data rate wireless networks. Zigbee is built on top of 802.15.4 and provides a definition for two layers of the OSI model: the Application Layer (APL) and the Network Layer (NWL). Throughout this paper these two protocol definitions are referenced indistinctively. Zigbee defines two physical devices: full function devices (FFD) and reduced function devices (RFD). Full function devices, can work in any topology, are capable of being the Network Coordinator (NC) and can talk to any other device in the network. RFD cannot become a network coordinator can only talk to a network coordinator or router and may have a simple (e.g. hardware) implementation. Zigbee RFD can be low-power/battery-powered devices. A time division with multiple access (TDMA) scheme, with a carrier sense for multiple access with collision avoidance (CSMA/CA) mechanism is used by the radio for medium access. MAC data transactions are executed using four frame structures: Beacon frame, transmitted by a Zigbee Coordinator (ZC) for network information and synchronization. Data frame, used for data transfers. Acknowledgment frame, used at various levels to confirm successful frame reception. MAC command frame, used for handling all MAC peer entity control transfers. Even though non-periodic operation may be used, Zigbee protocol is well suited for periodic operation mode for all network participants. This is of particular importance to the proposed system. Wireless networks nodes are micro-controller based devices. If low power based operation is required, micro-controller devices must be able to enter a mode of low current consumption. In all systems identified in this section, micro-controllers make use of the same mechanisms to lower their current consumption. By entering sleep mode the processor shuts down its high frequency oscillator together with peripherals and processor core. Returning from low power modes is executed by some hardware interrupt mechanism. This interrupt driven wakeup may be based on internal timer or external hardware. In the first case a low frequency oscillator is used while in the later external actions are required. External circuitry frequently entails large current consumption or is based on human intervetion (e.g. pushbuttons). Nodes wakeup on internal timer interrupts periodically communicate with its router or coordinator.

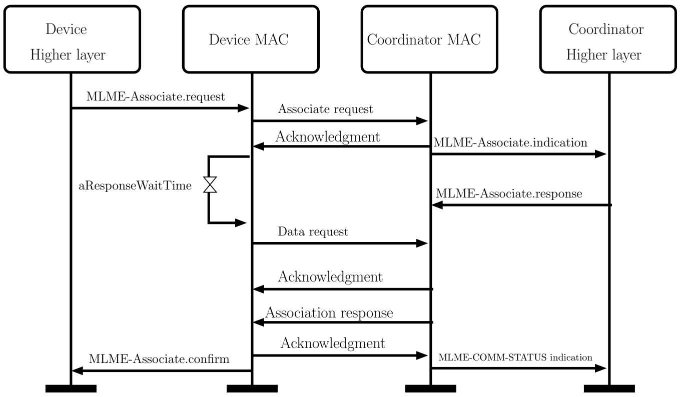


Fig. 2: 802.15.4 Join procedure sequence diagram.

In a disconnected operation the device only joins to the network when it needs to communicate. Connected operation mode requires that join procedure is executed once by the nodes. The Join procedure is therefore mandatory so that a node may be part of the network. By joining the network a device associates with other device that is already part of the network. A device that has other devices associated with it is a coordinator to those devices. Prior to joining the network each node must execute a network scan thus choosing a suitable parent using project design parameters. After potential parent identification, nodes issue an association request command frame. Parents must then determine if requesting nodes may join and sends a response frame in accordance. If join is successful, the response frame contains the short address that the device will use to be identified within the network. Fig 2 illustrates protocol behavior for a Join operation. As shown, join is a device initiated procedure that sends an Association Request to a ZC. This procedure entails a Data Request action from the ZED as well as an Acknowledgement (Ack) reception. After a *aResponseWaitTime* period of time a Data request is executed to determine if the join request was accepted. The answer is issued using an Association response. By using indirect mode ZED may sleep after sending the join request. In this case ZEDs must wake up to send a Data request for the join procedure and wait for ZC response and Acknowledgments. Fig 3 illustrates the Active Scan procedure sequence.

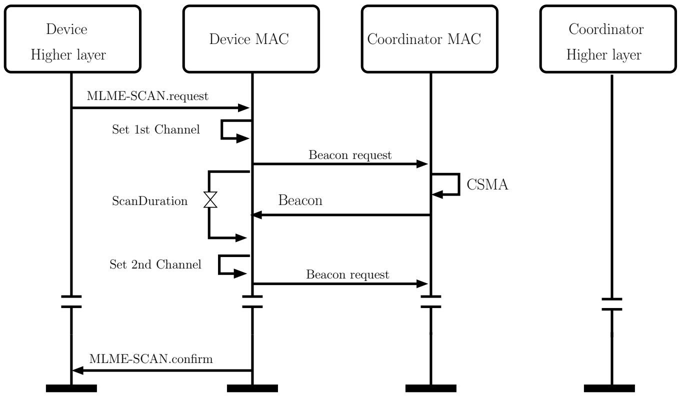


Fig. 3: 802.15.4 medium Active Scan procedure sequence diagram.

Active Scans consist on a sequence of beacon requests to determine the existence of network coordinators or routers using different radio channels. This operation is executed with radio frequency module turned on for each channel scan. Both Fig. 2 and Fig. 3 show that network joining may entail a prolonged turn on time for the radio frequency module being therefore energy consuming. Fig. 4 illustrates a data request sequence diagram that fulfills WSN purpose of data transfer between nodes. As illustrated by this sequence diagram, a data request entails less energy consumption than the join or the Active Scan procedures.

Join procedure is fundamental for protocol operation as nodes use it to acquire a valid network address. Only after acquiring a network address is protocol operation possible. Zigbee defines application objects to implement desired functionalities. Two nodes with linked functionalities share common application object structures and communications are possible by encapsulating these data structures into MAC data frames. The process that relates two nodes application objects is described as binding. Binding is therefore implemented with procedure illustrated by Fig. 4. Energy consumption of joining the network using an active scan procedure is the system main energy constraint. The system must therefore be built to comply with these procedures. System adaptation on hardware side

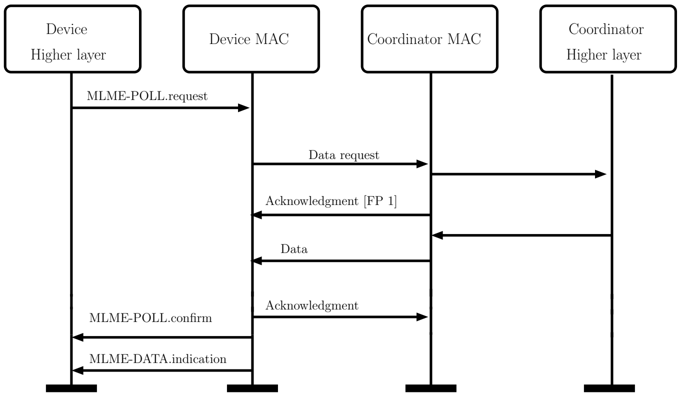


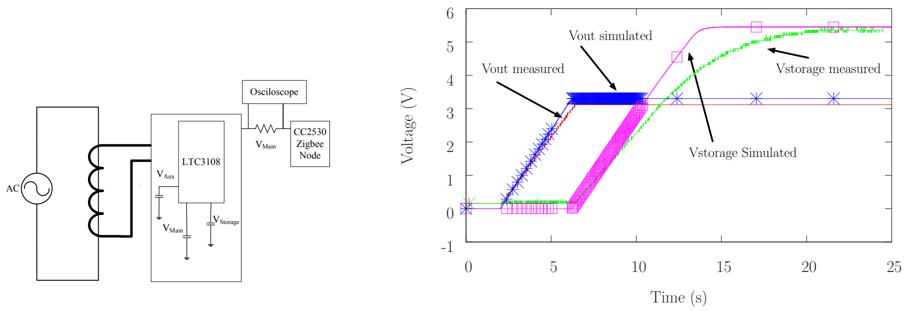
Fig. 4: 802.15.4 data request procedure sequence diagram.

was developed by dimensioning energy storage capacitors to be able to comply with join and active scan actions. On the software side system must guarantee that these two procedures are executed with minimum energy and that processor is returned to sleep mode immediately after.

3 Mains Current Contact-less ElectroMagnetic Power Generator

In this work a magnetic power generator is used to build a contact-less energy harvesting system for a Zigbee module. The harvesting device uses the magnetic field generated by current flowing through a power line. A Split-Core Current Transformer (SCCT) is used to generate a current from the induced electromotive force. The toroidal coil was used to scavenge energy from wires connecting electric charges (e.g. electrical grid last mile power lines). However, the output of the energy harvester can't be used to directly power the wireless module [17]. A conversion circuit has been built to accommodate voltage and power levels. The implemented AC/DC conversion circuit is based on the LTC3108 [18] from Linear Technology. A study of the proposed harvesting device was presented in [19] and its implementation presented in [20] For the harvesting system development, a SPICE model was implemented and its results confronted with device measurements thus demonstrating system viability. Fig. 5a illustrates the implemented system architecture. The system was developed so that the device is able to execute sensing and communication tasks. When used within the scenario discussed in Section 1 for induction motor monitoring, the device may be used to measure motor temperature or vibration. Temperature measurements may be done using CC2530 internal sensor while vibrations may be sensed using a low power piezoelectric sensor.

The LTC3108 implements a charge pump from the AC SCCT rectified voltage. The rectified voltage is used to operate a booster circuit that regulates



(a) (b)

Fig. 5: (a) Energy Harvester Architecture [18], (b) simulated and measured LTC3108 successful operation for a 800mA mains current

to the desired stable output value. LTC3108 operation voltage uses stabilizing capacitor connected to Vaux that as it reaches 2V allows output capacitor connected at Vmain to begin charging. Vmain in turn charges to maximum design defined voltage which for this system is optionally 2,5V or 3,3V. Once reached maximum Vmain voltage, Vstorage is allowed to start charging, that in turn charges up to 5,25 V. Fig 5b illustrates both simulated and measured device operation for 800mA mains power line current and 330 μF Vmain and Vstorage capacitors. Full charging is possible for mains currents as low as 500 mA. After Vstorage full charging, excess current is shunted to ground if no load exists at the device output or the input source is generating more power than is required by the load. Table 1 shows system behavior for a number of mains currents.

Vstorage can be used as an energy reservoir to power Vmain when source energy is missing. The behavior shown by the lines Vaux, Vmain and Vstorage can be used to characterize the harvesting system operation. System characterization can be related to mains current value. The SCCT source must first be able to power Vaux line and therefore start LTC3108 operation thus corresponding to the first mains current characteristic level. A mains current under this first characteristic value doesn't not allow system startup. Higher mains current level allows the Vmain capacitor charging. A second characteristic mains current level is determined by Vmain full charging to specified value. A third characteristic level for mains current can be identified as Vstorage charging ability.

For the proposed device a Texas Instruments CC2530 microntrontroller with a radio frequency module for 2.4-GHz IEEE 802.15.4 and ZigBee applications implements the processing and communication system capabilities. Also as illustrated in Fig 5a a small resistor was placed in series with the CC2530 power line thus allowing current consumption measuring. The system was programmed using Texas Instruments Zigbee protocol (Z-Stack [15]). Z-Stack is Texas Instruments IEEE 802.15.4/ZigBee compliant protocol stack. Fig 6 illustrates system current consumption behavior when powering Z-Stack. System low power operation may be characterized by voltage line variation in Fig. 6. The microcontroller

Table 1: Simulated and measured contact-less energy harvesting device charging times in seconds for different mains current

Mains Currrent		Vmain (3,3 V)	Vstore
400 mA	Measured	Nr	Nr
	Simulated	Nr	Nr
500 mA	Measured	15,2	42 (3,12 V)
	Simulated	17	52 (3,2 V)
600 mA	Measured	7,2	32 (3,76 V)
	Simulated	9,1	36 (3,8 V)
700 mA	Measured	9,0	23 (4,16 V)
	Simulated	8,9	29 (4,9 V)
800 mA	Measured	4,8	17 (5,2 V)
	Simulated	5,6	22,9 (5,27 V)
900 mA	Measured	3,8	19,2 (5,2 V)
	Simulated	4,9	20,8 (5,28 V)
1000 mA	Measured	3,0	13,6 (5,2 V)
	Simulated	4,2	14,4 (5,27 V)
1200 mA	Measured	2,8	10,1 (5,2 V)
	Simulated	3,23	11,78 (5,28 V)

is initially powered off. As power voltage is supplied Z-Stack initialization procedure is possible and a small current consumption is measured. After initialization, system enters power down mode waiting for enough energy to be harvested to Zigbee operation. Thereafter, when protocol operation is possible, the node is able to execute network Join and device Bind procedures. As shown in this figure the harvesting system was able to power regular Zigbee operation as a 5 second communication period was sustained.

4 Zigbee protocol running on harvested power

Texas Instruments Z-Stack implements a small operative system that is referred a board support package (BSP). This BSP consists of a hardware abstraction layer (HAL) and an operating system abstraction layer (OSAL). OSAL is a mechanism for task allocation of resources, implementing a cooperative, round-robin task servicing loop where each operation in Z-Stack runs as a task that is capable of communicating with other tasks through a message queue.

Fig. 7a illustrates OSAL operation. The software executes system initialization before entering stack main loop. System start-up executes initialization to memory allocation system, OSAL basic timer, message queue, power management and task system. Each sub-system of the Z-Stack runs as an OSAL Task.

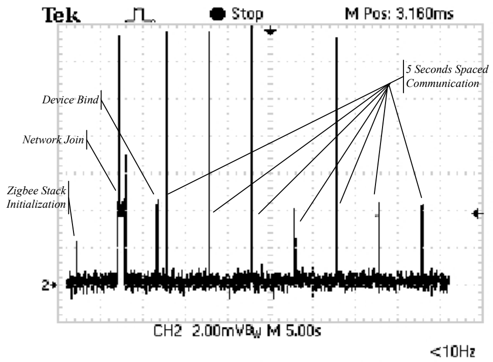
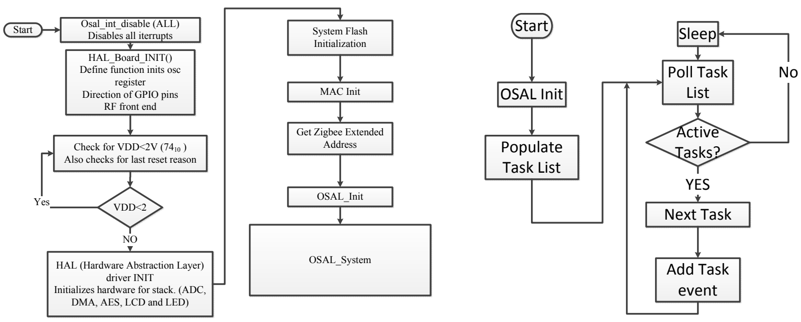


Fig. 6: CC2530 operating a Zigbee compliant stack current consumption.



(a) (b)

Fig. 7: (a) OSAL initialization procedure, (b) OSAL system operation

User applications run on tasks that must be created in software code. This is accomplished by adding task to the task array and at least one must be created. The OSAL searches for events created by the tasks and only allow the processor to sleep after all events have been served. System initialization workflow is shown in Fig. 7b. The procedure thus shown is responsible by the first current spike illustrated in Fig. 6. The initialization procedure executes the following functionality:

- All initialization procedure is executed without interrupts. Z-Stack first operation is interrupt disabling.
- Board configuration is executed. Z-Stack is distributed with software support for a number of Texas Instruments test boards. CC2530 IO ports are configured;
- Power line voltage value is verified. Original OSAL only checks voltage line value once. Z-Stack runs only when power availability exists;
- Peripheral functions are initialized for Z-Stack operation;

- Flash memory is initialized;
- Medium Access Control is initialized. CC2530 radio frequency module is configured;
- Zigbee extended address is obtained;
- OSAL tasks are initialized;
- OSAL starts running;

Unaltered Z-Stack running with the harvesting device was not possible. Unlike battery powered devices this system is unable to power the Zigbee protocol tasks for prolonged periods of time. To prevent uncontrolled device power down a return to sleep mode is mandatory within a time frame in the order of 100ms. Moreover the proposed system implements a ZED using a changed Z-Stack that must maintain compatibility with unaltered ZC software. Energy harvesting for WSN requires a meaningful change in node behaviour when compared with battery operated nodes. Nodes running on harvested energy may be programmed so that their energy constraints are short term while battery operated nodes have strong long term energy limitations. Current consumption reduction was achieved by imposing firm limits to full power operation times and whenever possible operating on low frequency oscillator. The CC2530 8051 core may be operated based on two high frequency oscillators (16MHz and 32MHz) while a 32KHz low frequency crystal may be used to operate a low power timer. Original OSAL always operates on the 32MHz oscillator while proposed alterations is done, whenever possible, with 16 MHz.

Original OSAL implementation is developed for battery operated nodes with no short term energy limitations. Original implementation executes Z-Stack initialization, 802.15.4 Join and Zigbee Bind procedures as fast as possible without entering low power mode and only then returning to processor sleep mode. This is a natural and desirable behaviour for battery operated nodes. For such power supply short term energy exhaustion is not a problem and is therefore indifferent to remain on full power mode for 1 second or 10 seconds. Operating on harvested energy poses different engineering challenges. For one such system, prolonged (100ms+ seconds) full power operation is impossible because only the energy storage in the capacitor banks is available. That is short time energy availability is small. On the other hand, in the long run, energy is harvested thus allowing long term device powering. This work proposes alteration to the Original Z-Stack implementation so that a full Zigbee compliant node is possible to run on harvested power. Changes are proposed to the initialization procedure as well as to the main round robin operation. Table 1 shows proposed and implemented changes. Implemented software changes allowed Zigbee nodes running on harvested power to maintain communication sequence as a battery powered ones.

5 Conclusion

Texas Instruments Zigbee protocol stack is a powerful implementation tool for WSN. It is nevertheless a complex implementation whose operation may be con-

Table 2: Original Z-Stack procedures vs implementated changes

Changed	Original	Proposed
Main Oscillator frequency	Always runs at 32 Mhz	Whenever possible runs on 16 Mhz
Initialization	Runs at 32 Mhz	Only MAC Init runs at max frequency. All other tasks run at 16 Mhz
Initialization	Node doesnt enter sleep mode after Init	After Init procedure systems enters deep power down mode
OSAL system operation	Tasks may schedule events at will	Tasks only schedule events if power line reads enough value
OSAL system operation	Join procedure executes three network discoveries attempts	Join procedure executes one discovery procedure
OSAL system operation	Node doesnt sleep after Join procedure	Node always sleeps after Join procedure
Zigbee operation	Bind procedure executes after network Join without entering sleep mode	After Bind node enters sleep mode (wakeup on timer)

trolled through a large number of compile and run time options. Moreover the Zigbee specifications provides a strong support for battery operated nodes but does not consider nodes that run on harvested energy. The work presented in this paper addresses this omitted characteristic of Zigbee/802.15.4 definition. Energy harvesting solution present a challenge to complex communication protocols. Within the context of battery-free nodes, Zigbee active scan and join activities where found to be critical for node operation. In this work an energy management strategy was implemented based on the available tools. The original Texas Instruments software stack was successfully adapted to operate on harvested energy. The proposed solution uses Texas Instruments Z-Stack Zigbee software bundle. Performed adaptation allowed 802.15.4/Zigbee protocol compliance to be maintained while system operation made possible for a micro power scavenger.

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