Optimizing Power Consumption in IoT based Wireless Sensor Networks using Bluetooth Low Energy

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***Abstract*—This paper proposes an architecture that uses the ultra-low power Bluetooth Low Energy (BLE) wireless standard and a hybrid topology to reduce power consumption in IOT based wireless sensor networks (IOTWSN). A lot of work has been done in the field of Wireless Sensor Networks (WSN) in recent years. Efforts to make efficient, low cost, scalable and easily deployable WSN have been on going. In order to reduce cost and improve life of a sensor node, it is necessary to optimize battery usage and power consumption. This paper looks at BLE as a potential candidate to reduce power in IOTWSN. BLE based activity detection is also incorporated into the system to avoid power wastage in real-time monitoring. The power consideration of the proposed architecture is compared to existing wireless technologies used in WSN.**

Keywords—Bluetooth Low Energy; Bluetooth Smart; Wireless Sensor Network; low power WSN; NRF24L01P; Zigbee

I. Introduction

Wireless Sensor Network (WSN) (or Wireless Sensor and Actor Network (WSAN)) is a network of sensor nodes spatially distributed in a region to monitor real-world physical parameters and report the sensed values to a central controller. WSAN adds the capability to take actions based on the sensed values. WSNs are rapidly becoming ubiquitous in the world of Environmental Monitoring, Healthcare monitoring, Smart Cities and Home Automation.

Building Smart Cities and Smart Homes requires large scale data collection. A smart home is effectively an autonomous home automation system [1]. Actions like setting the thermostat based on factors like weather and user preference, turning lights and fans on/off without human intervention, tracking consumption of consumable products like soap and gas cylinders and a number of other tasks. Making daily life easier, more convenient and minimizing human intervention in mundane tasks are some of the main objectives behind home automation. However automating these processes requires acquiring data from a distributed array of sensors. WSN provides a possible solution to this problem. Making the sensor nodes autonomous makes collecting data easier. However this implementation requires efficient WSN systems to provide low-cost, scalable and deployable solutions.

Smart cities take the concept of a smart home to the next level. It involves large scale collection of data from throughout a city to optimize utilization of public resources, facilitate informed policy making by governing bodies, improve efficacy of urban services and improve overall quality of life of the citizens. Once again such large scale data collection can be achieved by WSN.

WSN provides an innovative and robust solution to problems in multiple spheres of life. With WSN's playing such a pivotal role in improving day-to-day life, development of low-cost, low-power wireless sensor networks is a matter of great research interest.

II. Related work (Existing Architectures)

Most WSNs are made up of a number of individual, autonomous sensor nodes. These nodes consist of sensor arrays, System-on-Chip (SoC), wireless communication interfaces and power supply and distribution units. The wireless communication aspect of a WSN allows each node to operate autonomously.

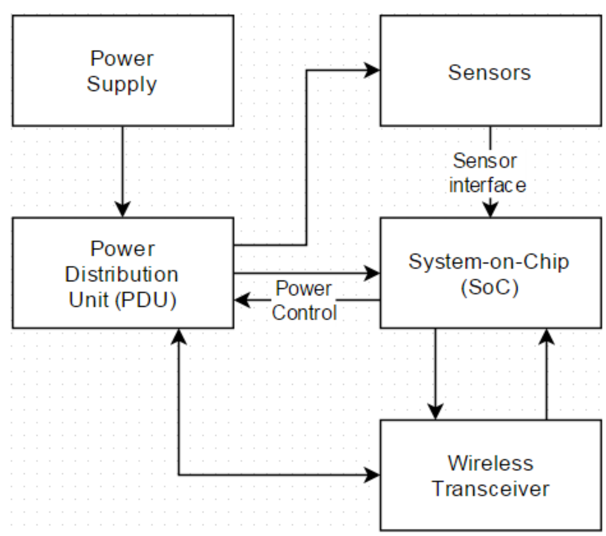

Fig. 1. Architecture of a wireless sensor node

A. Topology

The nodes are usually configured in a typical star topology (with each node connected directly to a central hub called a sink node), or more typically a multi-hop mesh network. In the star topology, each node is connected directly to the central hub. The main advantage of this topology is that the network is not affected by node failure as long as the hub is active. Star topology centralizes control, as only the sink node is aware of the status of all the nodes. For a single node to transmit data, other nodes do not need to be active. The disadvantage is apparent as size of network increases. The hub needs connect to larger number of devices which increases power consumption. The distance between the hub and other nodes also increases, which necessitates higher radio power.

The multi-hop mesh network links each sensor node to its nearest neighbors [2]. Data is communicated to a server through the mesh by flooding and routing algorithms [3]. Mesh networks are more robust as compared to star topologies as it is more resistant to node failure. Data is pushed to a central hub by routing the packet through multiple nodes. Transmission power of each node can thus be lower, even if size of network is large. However there is a drawback. For a node located at the edges of the mesh, to transmit a packet to an opposite edge of the mesh, the routing path will pass through multiple intermediate hops. Each hop consumes power in each of the nodes it passes through. Hence as size of the network (number of nodes as well as spatial region covered) increases, the average power consumption of the entire network goes up. Control is partially centralized as the hub is the only node which is certain to know the state of every other node.

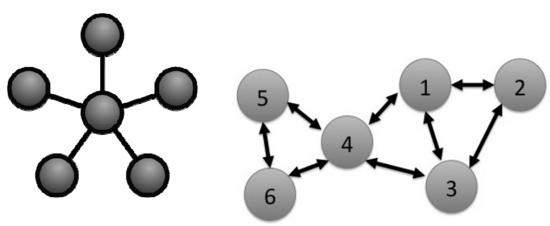

Fig. 2. Star and mesh topologies

B. Wireless Technology

Wireless communication is a high power-consumption block of any WSN. Since each node is autonomous and distributed in spatially diverse regions, minimizing power consumption of each node is an important aspect of any sensor node. Continuous power supply may not be available, which necessitates that a node must draw power from a battery pack or similar temporary power supply. Energy is one of the scarcest resources for any sensor node. If the energy consumption is too high, it will require frequent replacement of power cells [4].

Typical WSN implementations use some form of WPAN like Zigbee or more traditional RF modules like NRF24L01P and CC2500.

1) NRF24L01P

Basic wireless communication can be achieved using any readily available RF transmitters. The small, low cost NRF24L01P is a popular choice amongst hobbyists and students when designing systems which require wireless communication. While the NRF24L01P can be used in WSN, it wasn't designed to be power efficient. It also lacks any hardware based routing or networking algorithms. This means any routing and network formation has to done on a software level. [5]

NRF24L01P is capable of operating in 5 distinct modes.

a) Power Down Mode: Radio is disabled. Only registers and SPI interface are kept active to accept new configurations. This offers minimum power consumption.

b) Standby-I mode: Part of the oscillator circuit is activated. This mode is to ensure shorter start-up time than Power down mode at the cost of slightly higher power consumption.

c) Standby-II mode: This mode is primarily when data is to be transmitted at short notice. Additional clock buffers are activated. If data arrives in the Tx buffer, it gets transmitted after a minimal settling delay.

d) Rx mode: In this mode the NRF24L01P is actively listening for packets. The receiver continuously demodulates signals on the RF channel and checks if a valid data packet is received. The power consumption depends on the Air data rate being used. It increases with increase in air data rate.

e) Tx mode: This mode is when the NRF24L01P is actively transmitting data. Depending on the state of the TX buffer, the module switches between standby-II mode and TX mode. It has the highest power consumption of any mode. The power consumption depends heavily on the transmit power being used.

2) Zigbee

One of the most popular choices for wireless communication in WSNs is the implementation of the IEEE 802.15.4 standard popularly known as Zigbee. Zigbee is a high-level communication protocol which operates on a mesh topology. It is a self-organizing network, where each Zigbee device only needs to be assigned a role. The most convenient mesh network is then automatically created using Ad Hoc On-Demand Distance Vector (AODV) Routing [6]. Zigbee is a low cost system which is very well suited for WSN. Zigbee also supports low power sleep modes alongside active power consuming modes.

C. Power saving techniques

Since power consumption has to be minimized, many WSN architectures communicate with very low duty cycles. The sensor node is kept in a low power state, with the sensors and peripherals switched off and the controller and communication interfaces in a low-power, sleep-like state. The node becomes active for a short duration periodically, where it wakes up, senses the value, relays this value over the network and then returns back to the sleep state. While this approach does minimize power consumption, it suffers from a drawback. Applications requiring real-time data monitoring cannot use this approach. Real-time monitoring will require the duty cycle of the sensor node to be very high, which increases power consumption and decreases battery life.

Another measure to reduce power consumption, especially in larger sensor networks is to use a mesh topology. Mesh networks are generally preferred, since it makes the size and power of the wireless antenna smaller. This reduces cost of the node as well as the power consumption. However real-time data collection again introduces an issue. As network size and sensor node distribution density increases, average power consumption of all nodes rises. The chances of packet collision during transmission also increases, which introduces additional cost of retransmission. This is because as data is collected more frequently, amount of data that requires to be transmitted increases exponentially [4].

D. Accessing the Data

Once the data is communicated to the sink node, it needs to be processed and action needs to be taken on it. This requires that the data be accessible. Many WSN systems need to be remotely accessed to modify the configuration and read sensed values. A need for integrating the WSN with a system to provide easy access to the data is vital in order to maximize the usefulness of the data.

These problems make the following points clear –

- The wireless communication technology used in the sensor nodes need to consume as little power as possible
- The network topology chosen should minimize transmission power requirements while also providing robust network which is not sensitive to node failures
- Nodes should avoid real-time monitoring unless essential to reduce overall power consumption
- Node data should not be accessible only locally from a central sink node. A more reliable and robust method of accessing the network is needed.

III. Proposed Architecture

The efficiency of WSNs can be improved if we address each of these issues. Based on existing research and practical measurements, the following architecture is proposed-

A. Technology

One largely unexplored wireless technology in WSN is Bluetooth Low Energy (BLE) also known as Bluetooth Smart. BLE is a relatively new protocol (2011-12) which has very good specifications for low power wireless communication [2] [7]. The sensor nodes use BLE to communicate with each other. BLE provides lower power consumption as compared to traditional RF communication techniques [12] [13]. The design principle was oriented towards ultra-low power devices, making it suited for autonomous, battery operated sensor nodes.

Accessing the data of the sensor network is another important aspect. In most WSN systems, the data is sent to a central sink node. This node then transfers the data to some local storage. Instead, the data accessibility can be improved using the principles of IoT. By making some of the nodes internet enabled, we can push the data to the internet and make it accessible globally [8]. With modern SoCs boasting on chip internet interfaces, incorporating internet access in some of the nodes is inexpensive and practically feasible [9].

B. Topology

The network topology should be a hybrid of the star and mesh topologies. BLE can operate using traditional multi-hop mesh topologies as seen in [10]. However a better option is possible which combines the advantages of both mesh and star topologies. BLE primarily operates using an ad hoc topology. The BLE device initiating the connection acts as a master and the other device becomes a slave. The master slave roles decide who controls the connection and is dynamic i.e. can be changed. 1 master can connect to multiple slaves. However 1 slave can only be connected to 1 master at a time. Master devices can initiate communication at any point of time. Slave devices however have to be polled for getting a response. The basic network of 1 master and its connected slaves is called a piconet. A piconet consists of up to 8 devices, with one master and 7 slaves connected in a star topology.

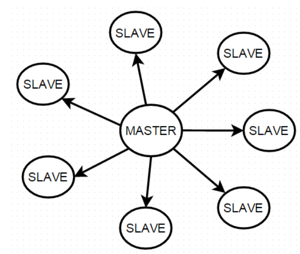

Fig. 3. Piconet with all slaves

Multiple piconets can then be connected to each other to form a scatternet. A scatternet consists of 2 or more piconets with a shared slave node. This slave does not simultaneously connect to both masters, but instead it switches between the two. Each piconet conducts intra-piconet communication autonomously, while inter-piconet communication is routed through the shared slave.

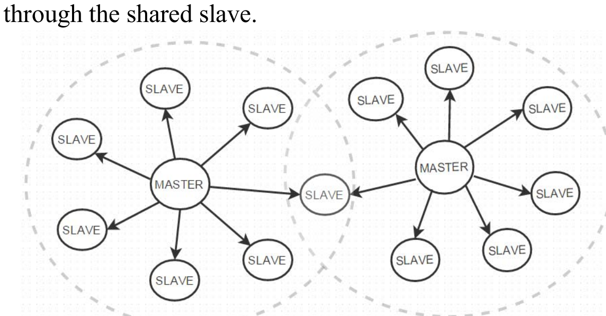

Fig. 4. Scatternet with 2 piconets

The benefits of such a technology are three-fold. For larger networks, individual node transmission power is as low as that of a traditional mesh topology. The distance between the communicating nodes doesn't change, just the routing. At the same time, control is decentralized. Rather than the single, central hub of star and mesh topologies, this hybrid topology can distribute network control and management amongst the master nodes of each piconet. This reduces number of packets that need to perform multiple hops. And finally, making the master devices 'things', we can incorporate IoT and push data to the internet. Spreading the internet access across multiple master devices in a large WSN network also improves resistance to node failure. If any 1 master loses access to internet, it is still possible to push the data from an adjacent piconet of the scatternet.

C. *Personnel Detection*

The final advantage of BLE is its widespread use in personal devices. Real-time monitoring is not required in most applications. If we take the example of Home Automation, most sensor values will not change much over time. Low duty cycle operation suffices. However when there are residents in the house, in particular regions of the house, it becomes necessary to scan values faster. Instead of adding additional sensors to monitor human presence, we can take advantage of the ubiquity of smartphones and other Bluetooth enabled personal devices. If BLE is used for sensor node intercommunication, it can also be used to detect presence of other Bluetooth devices like smartphones[3].

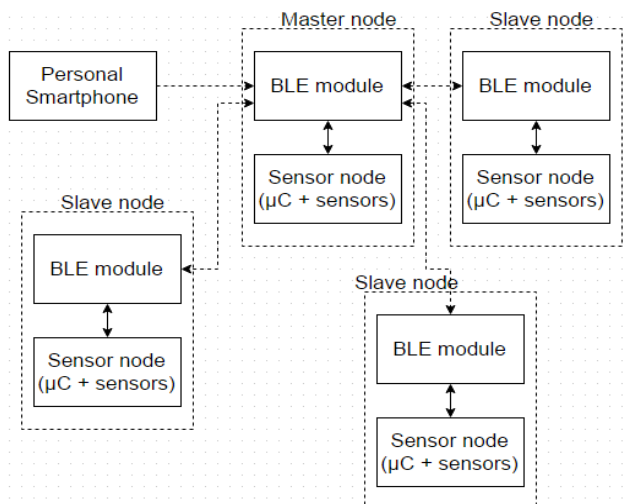

Fig. 5. Personnel Detection with BLE

If we only scan in real-time when needed and operate at lower duty cycles with long sleep times, we can save a significant amount of power and extend battery life significantly.

The proposed architecture makes an assumption about BLE that it consumes less power than other wireless technologies. It is necessary to compare BLE with other technologies in terms of power consumption.

IV. Results and Comparisons

For this system to be more power efficient, it must consume less power during transmission as well as lower average power consumption over time. To compare the performance, the NRF24L01P and Zigbee platforms have been chosen. The implementation done in our system is done with the following considerations -

- Data is transmitted in packets. Packets of size 1 byte, 2 bytes, 4 bytes and 8 bytes are chosen.
- Transmissions are performed intermittently with varying duration of sleep in between. The sleep time can vary from 0.1s between transmissions (real-time monitoring) to 5s.
- All comparisons are performed for 0 dBm transmit power and the highest supported air data rate.

A. *NRF24L01P*

Power consumption details of the NRF24L01P are based on data provided in [5] and [11].

TABLE I. NRF24L01P Power Consumption

Mode of operation	**Power Consumption (V_{DD} = 3V)**
Power down mode	2.7 µW
Standby-I mode	78 µW
Standby-II mode	960 µW
RX mode (@ 2 Mbps)	41.5 mW
RX mode (@ 1 Mbps)	39.3 mW
RX mode (@ 250 kbps)	37.8 mW
TX mode (@ 0 dBm)	33.9 mW
TX mode (@ -6 dBm)	27 mW

As we can see the operational power of NRF is a few tens of mW during active operation, and even at lowest power consumption in power down mode, the power consumption is in the order of 1 µW. This is significantly higher power consumption as compared to the other technologies mentioned below.

B. *Zigbee*

A number of studies have been conducted on the comparison of power consumption of Zigbee and BLE [7] [11]. The Zigbee shows a marginally elevated sleep power. However this is offset by the lower active transmission power.

The typical power consumption on Zigbee is shown below. Power consumption of Zigbee provided under test conditions and values provided in [7] [11] [14] [15]

TABLE II. ZIGBEE POWER CONSUMPTION

Mode of operation	Power Consumption (V_{DD} = 3V)
Power down mode	<3.3 µW
Sleep mode	14 µW
Wake-up (RX mode)	20 mW
TX mode	31 mW

While these values are marginally better than the NRF, it still compares poorly to BLE. The main disadvantages of both NRF and Zigbee are the long wake up times required to reinitialize connection after sleep.

C. Bluetooth Low Energy

BLE has lower overall power consumptions and connection establishment is much faster than NRF or Zigbee [4]. Since the BLE is faster at waking up, it can spend a greater amount of time sleeping, thus saving power. The average consumption of power by the BLE based platform is

TABLE III. BLE POWER CONSUMPTION

Mode of operation	Power Consumption (V_{DD} = 3V)
Sleep mode	2.6 µW
Wake-up (RX mode)	15 mW
TX mode	15 mW

As we can see, the overall power consumption and performance of BLE is an improvement over NRF and Zigbee.

D. Increasing sleep time

Effects of increasing sleep time between transmissions are shown below. The longer the sleep time allowed, the longer the sensor node can remain in a low power state and save power.

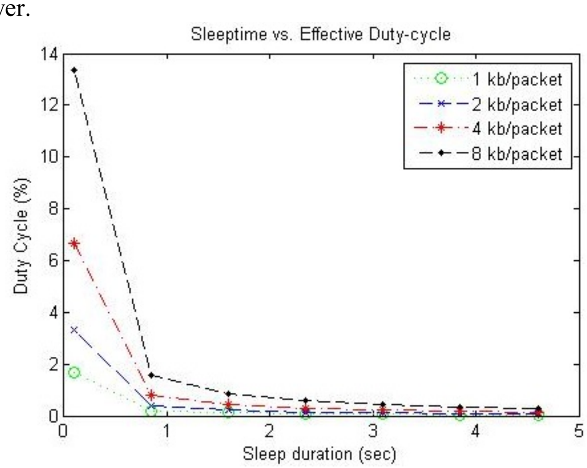

Fig. 6. Sleep time vs. Effective duty cycle for packets of varying sizes

As we can see, increasing the sleep duration reduces duty cycle of the wireless communication. The size of the data is less relevant when the sleep duration is sufficiently high. If real-time monitoring is not a requirement, then it makes sense to allow the transceiver to sleep for longer time and then transmit any data collected during that duration in a single burst.

V. CONCLUSION

Existing WSN technologies employ RF or Zigbee based wireless networks. However newer technologies like Bluetooth Low Energy which are designed for ultra-low power applications can lower energy costs and improve functionality of the network. Not only does BLE consume lesser power during operation, it also connects faster. This allows it to remain in low power sleep mode for longer durations and still achieve the same data throughput as traditional wireless techniques. using BLE in sensor networks can also help solve issues related to real time monitoring of data. Using BLE for personnel detection can help extend sleep time of the sensor node without addition of any additional hardware. This greatly reduces power consumption by ensuring real-time data monitoring is only performed when required.

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