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Impact of Delay in ZigBee WSNs for Smart Home Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A smart home is a comprehensive integration system that employs technologies such as computers, structured wiring and network communication to interconnect indoor subsystems, home appliances and electrical devices. WSNs play a crucial role in the functionality of smart homes. In this study, the IEEE 802.15.4/ ZigBee wireless communication standard was applied. Compared to other wireless communication standards, it offers a number of benefits, such as low battery and power consumption. Delays in ZigBee-based WSNs used in smart homes can be attributed to various factors, including network configuration, routing efficiency, device availability, sensor

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reporting intervals and power management. By optimizing the network parameters of ZigBee-based WSNs with concomitant reduction in inherent delays, it is possible to enhance the performance and user experience of smart home systems. Furthermore, the influence of coordinators and routers on ZigBee-based WSN delays is thoroughly examined and discussed. The results indicate that while adding more sensors to the WSN produces an extra delay, by contrast, the addition of an extra coordinator reduces the delay. Finally, the presence of a router in the WSN does not have a large impact on the delay.

Keywords: Wireless sensor networks; zigbee; delay; riverbed modeler.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are pivotal in the era of smart homes, providing real-time data for intelligent services. These networks consist of spatially distributed sensors that collect and process limited information through environmental interactions. In recent times, WSNs have gained immense importance due to their capacity to gather and manage vast datasets for a multitude of intelligent services. These networks utilize various communication technologies, including ZigBee, IrDA, Bluetooth, and GPRS.

Today, WSNs find applications in smart homes where multiple sensors are connected to a central gateway to facilitate energy management services [1]. Although these networks have great potential, several challenges persist in the design and operation of WSN applications. These challenges are primarily power resource constraints, which impact the overall network's longevity, and limitations in hardware resources. To address these issues, it is imperative that each sensor is not burdened with all software and middleware components, avoiding the provision of overly complex services. Moreover, bandwidth constraints present a significant hurdle, demanding precise management. Cost-effectiveness is also a key concern, which can be addressed by enhancing node capabilities.

This paper presents a solution using ZigBee technology to establish a routing path for home energy management services while considering the inherent limitations of sensors. The WSN performance is investigated using the Riverbed Modeler. The ZigBee network comprises device types such as coordinators, routers, and sensors, allowing for the deployment of nodes in various topological structures like star, mesh, ring, and tree. The utilization of efficient components in a WSN implementation for smart home services aims to reduce design costs while enhancing sensor capabilities. Additionally, this approach provides home energy management services, catering to different standards and meeting the requirements of diverse applications.

2. LITERATURE REVIEW

For the most part, existing literature has focused on the delay present in WSNs. For instance, in [2], it was found that a tree network with one coordinator and five sensors reduced end-to-end delay when using the ZigBee protocol. Using an OPNET modeler, the delay was examined in [3] in the context of a ZigBee WSN for various network scenarios based on the number of sensors, coordinators, and routers for smart home applications. Using an OPNET modeler [4,5,6], investigated delay for single and multiple coordinators in tree, star, and mesh ZigBee-based WSNs. Using the Riverbed simulation programme, the effects of adding more sensors to a ZigBee-based WSN on delay were examined, evaluated, and tested in [7]. Using a Riverbed modeler as in [8], Poisson conveyance exhibits higher performance in terms of throughput, delay, and quit-to-forestall put off.

3. BASICS OF WSN

WSNs are wireless networks that are self-configured and operate without any infrastructure, for the purpose of monitoring physical or environmental parameters such as vibration, motion, temperature, pressure, sound, and cooperate pass data within network to a prime location or sink data that analyzed and observed [9]. The WSN acts as an interference between the network and users. The important data can be restored from the network by injecting queries and gathering results from the sink. In reality, there are hundreds of thousands of sensor nodes in the WSN [10]. These nodes use radio signals to communicate with one another. Radio transceivers, power components, and computer and sensing devices are all present in a sensor node. The storage capacity, communication bandwidth, and processing speed of individual nodes within a WSN are naturally limited. With multiple hop communication, the sensor nodes play a crucial role in self-organization of an appropriate network infrastructure. Later, the onboard sensors collect data of interest. The sensor devices behaved to queries sent from a control site to do precise procedure or produce samples [11]. The nodes might be event or continuous driven in the working mode. To obtain position and locational data, one might reuse the Global Positioning System (GPS) and local positioning algorithms [12]. Actuators are built into these devices to perform certain functions. Cellular Sensor and Actuator Technologies are the name given to these networks, as stated in [13]. Finally, there is a lot of interest in WSN chip design, as seen in [14]. There are three basic elements of our design strategy in the WSN, which are:

3.1 Wireless Sensor Node

It is composed of four main units which are processing, sensing, power and transceiver units. It contains additional components as well, like locational feedback system and mobiliser. Each of these four basic units has two subunits which are physical sensors and ADCs [15]. The sensor produces analogue signals that transferred to digital signals through the ADC, after that this digital signal is supplied to the process unit that has a small RAM. The function of the transceiver unit is to connect the node to the network. Usually, the power unit is supported by solar cells to extend the battery life of the sensor.

3.2 Wireless Coordinator

Information gathering is the main purpose of sensor networks [16]. This indicates that every network has three nodes: one or more coordinator nodes that handle sending all of the information gathered throughout the network, router nodes that handle transmitting information, and terminal nodes for collecting information. High performance computing systems, independent distribution networks, and constant power supplies are the primary features of the nodes related to information processing and storage. This indicates that the flow of the data in the sensor infrastructure is known for sure. The network's current routers are used to transfer data from data gathering devices (terminals) to the information processing and storage nodes. When compared to remote sites, the rate of data transmission near the coordinating node is significantly higher [17].

3.3 Wireless Router Node

Computer-controlled transceivers known as router nodes (or routers) are used to reroute both inbound and outgoing WSN radio traffic. They don't gather information on their own. Rather, they take in data from adjacent nodes and send it over to a portal.

Additionally, inbound traffic from gateways and other routers can be rerouted by routers. The WSN's working range is increased, node power is preserved, traffic is accelerated, bandwidth is freed up, and the subnet of routers is used in place of high-power radio waves.

4. TYPES OF WSNs

WSN types are selected based on the environment in order to enable deployment in subterranean, on land, underwater, and other scenarios. Among the several kinds of WSNs are [18]:

1. Mobile WSNs
2. Terrestrial WSNs
3. Multimedia WSNs
4. Underground WSNs
5. Underwater WSNs

5. CLASSIFICATION OF WSNs

WSNs can be categorized according to their applications, however their main properties vary depending on the kind. WSNs are typically divided into several groups, such as the following:

It can be both static and adaptable, deterministic and unpredictable, single and multiple base stations, mobile and static base stations, single-hop and multi-hop wireless sensor networks, self-reconfigurable and non-self-configurable, homogeneous and heterogeneous.

5.1 Challenges of WSNs

The following are some of the several difficulties faced by wireless sensor networks:- Data aggregation, data compression, data latency, fault reliability, scalability, production cost, and operation environment

6. WSN APPLICATIONS

There are wide range of applications in WSN such as [19]:

- Environmental tracking like fire detection in forests, animal chase, flood detection, forest detection, forecasting, and weather monitoring. Commercial applications are considered such as seismic activity prediction and oberving.
- These networks are used by military applications including tracking and environment monitoring surveillance applications.
- Health applications, such as doctors' and nurses' patient monitoring [20].
- The most popular applications for wireless sensor networks in the transportation systems domain, like dynamic routing management, parking lot monitoring, and traffic monitoring, leverage these.
- The utilization of these networks is necessary for quick emergency response, industrial process monitoring, automated building climate control, ecosystem and habitat monitoring, civil structure health monitoring, etc.

7. WSNs IN A SMART HOME

Gathering both WSN and other Internet of Things (IoT) components go past remote access, as heterogeneous data frameworks can have the capacity to work together and give normal 2 administrations [21]. A WSN is an arrangement of disseminated self-sufficient sensors, which are called nodes, that screen the status of the space in which they are working [22]. WSN can be considered as an essential part of IoT including smart homes by gathering encompassing setting and condition data [23]. It is conceivable to interface the information created by the components of the WSN nodes (sensors) with web administrations in light of SOAP and REST [24], data components, (e.g. SMS) or informal organizations (e.g. Twitter) and websites (e.g. WordPress) (PRODROMOS). The WSNs are progressively being utilized as a part of the home for vitality controlling administrations. Now-adays individuals need to live in smart living spaces outfitted with home automation networks, these frameworks not just give them comfort, comport, security additionally lessen their day by day living expense by vitality sparing arrangements. The interest for home computerization items has been grown rapidly, that guarantee a potential market incline in close future [25]. A smart home is a space or a room which is given the capacity to get usual independent from anyone else to specific circumstances to make the tenants feel great [26]. Smart home appliances are the combination of innovation and administrations through home organizing for computerizing, enhancing, security, wellbeing, correspondence, solace and vitality sparing. In nowadays, smart home security has been turned into an imperative issue because of high rate of violations and everyone has proposed to get sensible measures to avoid interruption [27]. The WSN in the smart home empower monitoring and control applications for user comfort. A few associations and organizations have created WSN arrangements as indicated by various architectures and principles [28].

WSN in smart homes collects data from many sensors, including temperature, light, gas, and volume. The WSN transmits data to the controller, which subsequently sends it to security monitoring systems. The monitoring and management subsystem processes, analyses, and displays data in the form of graphs, reports, and curves. The WSN was built with ZigBee technology following the IEEE802.15.4 standard [29]. Integrating WSNs into smart home automation systems provides you with greater control and convenience, making your living area more pleasant, energy-efficient, and secure [30,31].

8. RIVERBED SIMULATION APPLICATIONS

A network simulator that mimics the functionality and behavior of any network is called RIVERBED software. The strength and versatility of the Riverbed modeler set it apart from other simulators. IT Guru provides pre-built models of protocols and devices. It enables the creation and simulation of several network topologies. There is no way to add new protocols or change the functionality of ones that already exist; the collection of devices and protocols is set.

8.1 Advantages of Riverbed Modeler

We can summarize the Riverbed advantages in the following

1. Riverbed Modeler is a free and open-source program.
2. Riverbed Modeler provides information on a large range of project scenarios.
3. Can be overlooked.

8.2 Uses of Riverbed Modeler

We can summarize the use of Riverbed in network planning and design, application debugging, hardware architectural validation, traffic modeling of telecommunication networks, protocol modeling, operational validation, and performance evaluation of complex software systems.

8.3 Process for Simulating Discrete Events

1. Establish/import configuration and topology
2. Generate movement.
3. Pick on statistics
4. Start the simulation.
5. Examine the outcomes.
6. Make a new or duplicate scenario.
7. Release the findings.

9. RESULTS

9.1 Design Strategy

Every sensor can be represented by a ZigBee end device while the master node would be represented by a ZigBee coordinator. The network delay will be calculated and sketched using the Riverbed Modeler V18.0 for every network design. This delay produces the total queuing and contention delays of the data frames that sent from 802.15.4 MAC. It is measured as a duration time whenever it is inserted into the transition queue for each frame. The calculated delay is considered as the arrival time for higher layer data packets and creation time for all the other types till the frame sent to the physical layer firstly. The main design is to allocate five sensors (used for glass break, motion detection, close-open a door or window, switching ON-OFF any electrical device, …etc.) for a single smart home, these five sensors are connected wirelessly to a single coordinator and then increase the number of sensors (as in Result1) or use more than one coordinator (as in Result2) or adding a router to the wireless network and check the network delay (as in Result3 and Result4).

9.2 First Result

The end-to-end delay was taken for a network that have five sensors for every smart home connected wirelessly through a single coordinator. The delay was taken again when we increase the number of sensors to 10 and then to 20 (keeping the same ratio 5 sensors for every smart home) connected wirelessly to a single coordinator as shown in Fig. 1. In this figure, the time was taken from zero to 200 sec. At the transient state (from zero to 40 sec), the delay curves are identical for all the three networks. At the steady state, the delay increases when the number of sensors increases as seen from Fig. 1. When the number of sensors increases from 5 to 10, an extra 0.65 msec delay occurs while additional delay occurs (3 msec) when the number of sensors increases from 5 to 20. So, to overcome a large delay, use a single coordinator in every smart home.

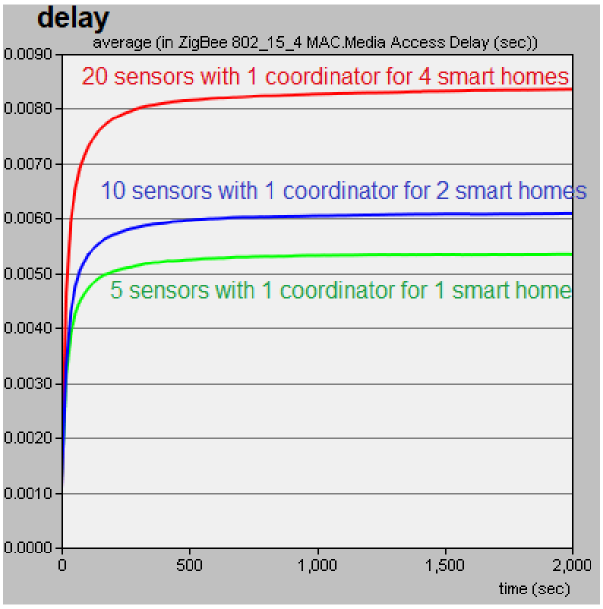

Fig. 1. Delay according to sensors

9.3 Second Result

The delay was taken using four network designs as in Fig. 2, the first design is to use 10 sensors connected wirelessly via a single coordinator. The second design uses 10 sensors connected via 2 coordinators. It can be seen from the figure that the delay decreases about 5 msec when the additional coordinator was added. A third design consists of 20 sensors with a single coordinator while the fourth design consists of 20 sensors with 4 coordinators that leads to a reduction in the delay about 7.5 msec as seen in Fig. 2. At the transient state (from zero to 200 sec), a little difference occurs in the delay while at the steady state (from 200 to 2000 sec), the delay curves had the same delay and reaches 2.05 msec at the end of simulation. So it is clear that any increase in the number of coordinators would decrease the delay time.

9.4 Third Result

Fig. 3 shows two end-to-end delay curves (this delay includes all the packets gotten by 802.15.4 MACs) for two networks both have 20 sensors with a single coordinator, one with a router and the other without a router. It is clear from the figure that the router existence increases the delay time about 0.3 msec. So we should overcome the router in the WSNs from delay point of view.

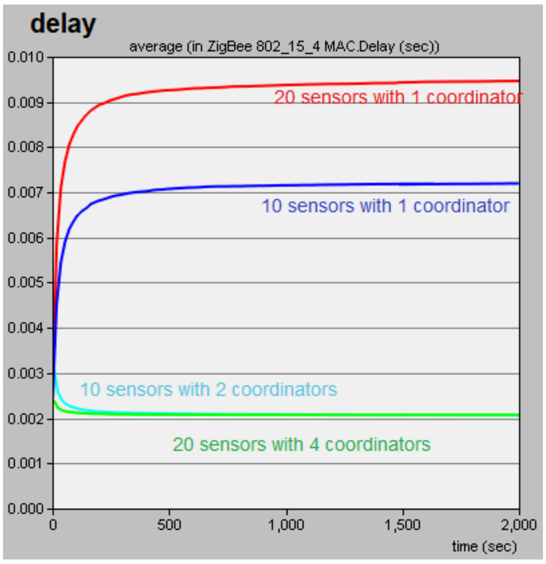

Fig. 2. Delay according to coordinators

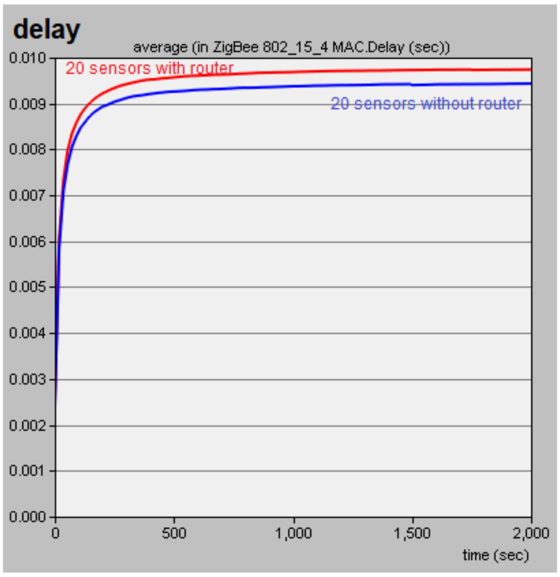

Fig. 3. Delay caused by a single router

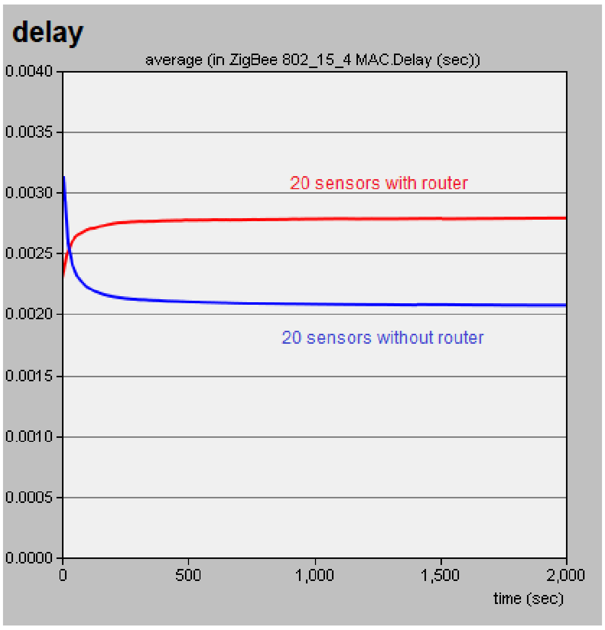

Fig. 4. Delay caused by a single router with 4 coordinators

9.5 Fourth Result

Another comparison was made to study the router effect in the delay of wireless sensor networks. In Fig. 3, the used networks have just one coordinator. Now we will use 4 coordinators with 20 sensors for 4 smart homes, one network with a router and the other one without a router as seen in Fig. 4. In the steady state, the router existence introduces about 0.7 msec extra delay. So it is obvious that from the figure that we don't recommend to use the router in the WSN from delay point of view.

10. CONCLUSION

For optimal results in every smart home system, it is recommended to use a single coordinator and five sensors, because even the addition of a single sensor above the optimal number of five sensors will produce an incremental delay, as shown in Fig. 1. To overcome this extra delay, an extra coordinator should be added as explained above in the second result (see Fig. 2). Moreover, the router itself introduces an extra incremental delay as demonstrated in Figs. 3 and 4.

To improve the delay in WSNs, this paper advises the network designer to reduce the number of sensors and increase the coordinators incorporated in the smart home and increase the coordinators.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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