Energy-efficient wireless sensor network for nuclear radiation detection
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ABSTRACT
This work presents a design for nuclear radiation detection and monitoring system in a nuclear facility based on wireless sensor networks (WSNs). Energy efficiency is a critical factor in designing WSNs where a sensor node is small with limited power resources. A reliable WSN must be energy efficient to maximize its lifetime. Media access control (MAC) protocols are essential for the energy-efficiency objectives of WSNs as they directly control the most energy consuming part of a sensor node communications over the shared medium. Different MAC protocols for WSNs are presented. This search will explain the important role of MAC protocols for energy saving and why currently conventional protocols don’t fit for the actual requirements. A comparison between two MAC protocols, IEEE802.11 and sensor MAC (SMAC), is presented using network simulator—NS-2.35. Then their performance will be compared to each other. SMAC outperforms IEEE802.11 in total energy conservation by approximately 21%. Power saving is the main aim in the design of nuclear radiation WSN to guarantee more life time for the network.

KEYWORDS
Wireless sensor networks; energy efficiency; lifetime; media access control protocols

1. Introduction
Nuclear radiation is invisible, has no smell, makes no sound, and cannot be detected by any of human senses. It affects the atoms that it passes. The instruments that can identify the presence of radiation are known as radiation detection devices. These devices can measure radiation in the environment, on the surface of people, inside people, or what received by people as exposure. Detection of radiation starts with interaction of the radiation with matter (Morton, 1962).

Radiation detectors detect specific types of radiation such as alpha, beta, gamma, and neutron. Gamma rays are the most important, since almost all nuclear processes produce gamma rays. There are two major categories of nuclear radiation detectors: single-element detectors and imaging detectors (Murray & Holbert, 2009).

Generally, with respect to radiation detectors, the choice of the suitable detector is according to the application. Geiger-Muller tube is recommended for radiation measurements specially gamma rays in radiation monitoring networks. So, this detector is the first choice when a communication network is constructed for radiation detection.

Nowadays, wireless sensor networks (WSNs) are used in a wide range of applications such as in monitoring or tracking of a target in a specific field as active volcano, health care, precision agriculture, underground mining monitoring, and transportation tracking. WSN consists of low-cost sensor nodes that collect real-world data, process it, and transmit it by radio frequencies to their destination. Coverage and communication range of sensor nodes limited by their energy. The largest energy consumer in wireless sensor is the transceiver (Althobaiti & Abdullah, 2015; Odey & Daoliang, 2012). Efficient utilization of limited amount of energy is the first target in designing media access control (MAC) protocols for WSNs (Lakshmisudha & Arun, 2013). MAC protocols can manage the performance of transceivers as they provide the greatest effect over communication mechanisms. In addition, throughputs and delay are supported by MAC protocols. Designing an efficient MAC protocol is an important task as it provides following functions (Kabara & Calle, 2012; Narain, Sharma, Kumar, & Patle, 2011):

- Framing: It defines the format of frame and encapsulates data by adding protocol control information to protocol data unit for transmitting between devices.
- Medium access: It controls the access of node to the wireless medium.
- Reliability: MAC protocol carries out protection against errors through acknowledgement (ACK) messages and retransmissions when necessary.
- Flow control: it guarantee that there is no frame loss from beginning to end.
- Additionally, MAC protocols must be scalable and configurable to adapt to changes in the network size or topology.
In WSNs, to design a good MAC protocol the following aspects should be determined: energy efficiency, latency, throughput, and fairness (Anane, Bouallegue, & Raoof, 2015; Neha Trived & Raikwar, 2013).

However, among all of the above attributes the energy efficiency and throughput are the major attributes. MAC-layer protocols for WSNs must be energy efficient to maximize lifetime. Energy efficiency can be increased by minimizing the energy consumption and wastage (Verma, Singh, Singh, & Kumar, 2015).

Energy waste in WSN is basically due to collision caused by interference, overhearing as a node picks up packets that are destined to other nodes, control Packet overhead, and idle listening as a node listen to receive possible traffic that is not sent.

The main purpose in designing an efficient MAC protocol for WSN is to minimize the energy consumption. Reducing collision, increasing achievable throughput, and providing flexibility for various applications are the attributes of efficient MAC protocol.

There are many MAC protocols depending on their overhead, data delivery mechanism, energy efficiency, latency, band width utilization, fairness, and throughput. MAC protocols can be classified into specified categories according to classification parameter.

Previously, energy efficiency was the first priority in designing efficient MAC protocol. However, to support multi-task and efficient delivery of heavy traffic, new MAC protocols are provided which considered energy efficiency, throughput and delay. There are many studies and surveys of WSN MAC protocols where different classifications are presented. (Kumar & Jain, 2014; Gunn & Koo, 2009) classifies MAC protocols broadly into contention based and schedule based. Considering decreasing transmission latency (Teng & Kim, 2010) presented MAC protocols as a hard real time and a soft real time. (Patil, Modi, & Suma, 2013; Rajandekar & Sikdar, 2015) show MAC protocols as contention based, schedule based, and hybrid protocols. Chukwuka and Arshad, (2013) group different MAC protocols into controlled access (CA), random access (RA), slotted protocols (SP) and hybrid protocols (HP). According to Huang, Xiao, Soltani, Mutka, and Xi (2012), Lanjewar and Adane (2014), and Tamer and Korhan (2014), WSN MAC protocols are classified into four branches: asynchronous, synchronous, frame-slotted, and multichannel. The method of classification depends on the problem required to be solved by MAC protocol. Each branch intends to solve a major problem, this means that it is own challenge addressed by each branch. So, the basic obstacles must be determined before designing any MAC protocol. In this paper, the energy efficiency of the presented monitoring system is the dominant goal.

2. System model

Nuclear radiation has been spreading across countries as well as the Chernobyl disaster in 1986 and Fukushima nuclear crisis in 2011 (Steinhauser, Brandl, & Johnson, 2014). So there is a need to detect existing of ionizing radiation in atmosphere. In any country, radiation protection standards are set by government authorities, according to recommendations of the International Commission on Radiological Protection (ICRP) (Valentin, 2007). Ionizing radiation may be from nuclear power plants and all other nuclear facilities, the transportation of nuclear materials, and the use and storage of nuclear materials for medical, power, industry, and military uses. Detection of ionization radiation is carried out using communication networks which comprised of nuclear radiation sensors widespread in the monitoring area. Geiger tube is the recommended sensor for nuclear radiation detection in space. GQ GMC-320+ V5 Wireless Dosimeter Radiation Detector (GQ Electronics LLC, 2017) is the wireless sensor used in this search, it detects Beta, Gamma, and X-Ray not alpha particles. It can be used in real time testing in indoor, outdoor, water, and building material.

The development of the wireless sensing technology addressed many disadvantages that appeared in wired sensing. Wired sensor networks that used for nuclear radiation detection at boundaries of country have many problems in sensors, cables, repairing faults in network and reconfigurability. WSNs are more flexible and dependable. There is a need for a monitoring network that has reconfigurability and scalability benefits. These specifications can be achieved using a suitable MAC protocol. Therefore two MAC protocols are applied in this scenario to handle scalability while achieving the main goal of reduce power consumption in the network.

The wireless sensor nodes are deployed in several places to monitor nuclear radiation and any activities to be monitored. These sensor nodes may be static or mobile that can move in the monitoring area.

The monitoring area is divided into several regions, and each region is monitored by one WSN. These WSNs communicate with a base station through tree or hierarchal topology to form the whole network that detects any nuclear radiation at boundaries of the country. A star topology is adopted which is a single-hop system that all wireless sensor nodes communicate bi-directionally with a sink node. The star topology conserve lowest power but the transmission distance is limited by radio in each node. The distance ranges from 10 to 100 m according to radio technology used by sensor node. In each network sensor nodes collects data from specified area transmitting it to sink node then data transmitted to a base station. In this paper, one star network from the whole network will be
analyzed through simulation which is sufficient for the monitored area. The designed network consists of three wireless sensor nodes collect data from the area under monitoring and transfer it to a sink node with a transmission radius of about 50 m which is the communication range for indoor networks. These nodes are distributed in a nuclear radiation facility that is of $100 \times 60$ rectangular meters as shown in Figure 1. Wireless sensor nodes are organized as follows; sink node (S3) at (50, 50, 0), sensor node 0(S0) at (100, 50, 0), sensor node 1(S1) at (50, 0, 0), and sensor node 2(S2) at (50, 100, 0). Sink node collect data and sends it to base station (BS). The performance of an experimental WSN is evaluated using different MAC layer protocols. Two contention MAC protocols used in this search which mean that there is no complexity of the design due to restricted time synchronization, also there is a flexibility to change topology and number of nodes occurring in WSN. The network layer protocol used with this scenario is dump agent (disable multi-hop routing) as there is routing is needed. (Sharma, Kumar, & Patle, 2012)

2.1. EEE802.11 (Wiethöler & Hoene, 2003)

IEEE802.11, the first wireless standard developed, is an asynchronous contention-based MAC protocol. It is defined in the physical and MAC layers in the OSI model. IEEE802.11 operates in two modes for wireless devices: an infrastructure mode where devices communicate through a central point called an access point (AP) using the point coordination function (PCF) and an ad-hoc mode where devices communicate with each other directly using the distributed coordination function (DCF). 802.11 controls medium access by using three inter-frame spaces: short inter frame space (SIFS), PCF inter frame space (PIFS), and DCF inter frame space (DIFS). Hidden terminal problem is serious problem inherent with 802.11 which results in a packet collision and retransmission is needed. Request to send (RTS) and clear to send (CTS) mechanism is used with DCF as shown in Figure 2 to overcome this problem. RTS contains a duration field assigns the time needed for CTS, DATA, and ACK. All receiving nodes in the network stores this value in network allocation vector (NAV) to determine the instant it can contend to the medium.

Fragmentation mode is added to 802.11 to divide long message into small fragments and each fragment is acknowledged independently. When a node has access to the medium, it transmits fragments and has acknowledgement for each fragment, this clarified in Figure 3. In the case of transmission failure in one fragment, the sender gives up the transmission and re- contends again for a medium access.

The main problem with IEEE802.11 is the large overhead in control and data packets also idle listening. These two issues cause higher power consumption with the sensor network.

2.2. Sensor MAC

Energy conservation and self-configuration are the important parameters needed to be achieved in WSNs due to the nature of sensors. Sensor MAC (SMAC) protocol is a synchronous contention-based MAC protocol. It aims to reduce energy consumption in WSNs due to all sources of energy waste. SMAC is developed with three basic techniques: periodic listen and sleep as shown in Figure 4, collision and overhearing avoidance, and message passing. These techniques reduce energy consumption in WSNs.

![Figure 1. Single hop WSN in nuclear facility area.](image1)

![Figure 2. RTS/CTS in 802.11 DCF (Malik, Chaudhary, Pathak, & Chakraborty, 2015; Wiethöler & Hoene, 2003).](image2)

DIFS, distributed coordination function-inter frame space; RTS, request to send; SIFS, short inter frame space; CTS, clear to send; NAV, network allocation vector; ACK, acknowledgement.
consumption while maintaining good scalability and collision avoidance (Wei, Heidemann, & Estrin, 2004; Ye, Heidemann, & Estrin, 2002).

The active period (listen) in SMAC protocol is divided into synchronous and contention intervals. The synchronous interval for broadcasting SYNC packet between nodes at the beginning and the contention interval is for data transmission where nodes that have data to send contend in this interval for medium access.

In the case of idle listening, sensors are idle for a long time without need. SMAC sets sensors in a periodic sleep mode; as nodes turn off radio and go to sleep for amount of time, they wake up according to timers that determine awake time.

Neighboring nodes follow steps to compose virtual cluster to auto synchronize on sleep schedule. Firstly, each node listens for amount of time for any schedule from its region to follow it and exchanges this schedule with its neighbors. Each node has a table contains schedules of its neighboring nodes. In the case of the node does not hear any schedule then it chooses a time randomly to go to sleep and instantly broadcasts its schedule in a SYNC packets. Border nodes can follow more than one schedule which results in more power consumption. Synchronization between neighboring nodes is needed to prevent clock drift due to long listen time. Updating schedules of sensor nodes set according to an SYNC message which contains the address of sender and the instant when it goes to sleep. Immediately, receivers adjust their timers according to the SYNC packet.

Collision and overhearing avoidance are very important parameters to have an efficient MAC protocol. SMAC protocol follows the same procedures; physical carrier sense and virtual carrier sense and CTS/RTS procedure as contention MAC protocols for collision avoidance. When the medium is busy all neighboring nodes go to sleep until the end of transmission. The time the node kept silent is stored in NAV. SMAC resolves the problem of overhearing by allowing interfering (neighboring) nodes to go to sleep after hearing RTS or CTS packet.

A transmitting message contains related units of data and receiver must gain these units of data before in-network processing. SMAC adopts message passing technique in data transmission, it fragments long message into independent fragments as IEEE802.11 to overcome the problems results from sending long message. It sends these fragments as one burst and if one or more fragment does not sent correctly they retransmitted without a need for a long message to be retransmitted. After each fragment transmission there is ACK packet. Each data fragment and ACK has a duration field contains the time of transmission. Other neighboring nodes assign the instant to wake up according to duration field. Message passing guarantees a fewer contention and a small latency.

Periodic listen and sleep technique results in an efficient MAC protocol when traffic is light, periodic sleep of nodes causes excessive latency when traffic is heavy as the contention window (CW) is fixed. The solution of this problem is by using adaptive listening scheme, which improves latency and throughput but at the cost of energy consumption. Several researches were introduced to improve the medium access performance of SMAC protocol depending on adjusting CW size. An improvement of this technique achieved in AQ-SMAC (Gao, 2011) protocol. As a coordinating CW is used to dynamically adapt the flow of data. In Rao et al. (2018), a reduction of conflict between reducing the collision probability and idle listening duration is presented using self-adaptive implicit contention window adjustment (SICA) mechanism. Jieying, Shi, Yinglin, and Shaopeng (2018) proposed an adaptive energy saving mechanism (AES-SMAC) to improve the performance of SMAC protocol. This mechanism consists of adaptive synchronous period (ASP) and dual-element adaptive contention window (DEACW). Nearly all researches for improving SMAC protocol focus on latency and neglect the power consumption which is more urgent in many
applications. Only SMAC is the standard WSN MAC protocol and all improvements are application dependent and not standard.

3. Simulation setup

The simulation scenario consists of four nodes. The total simulation time is 300 s. The pause time is set to 30 s for phase initialization at the start of the simulation for IEEE802.11 (Wietzhöler & Hoene, 2003) and at 42 s for SMAC (Ye et al., 2002) as scheduling accomplished after 40 s. The simulation was accomplished using network simulator NS-2.35 (Issariyakul & Hossain, 2009). The simulation parameters are shown in Table 1.

The radiation WSN is simulated using NS-2.35 for two cases of MAC protocols: IEEE802.11 and SMAC. Table 1 shows the parameters of simulation; the simulation time is chosen to be 300 sec and there are four wireless Geiger detectors (GQ Electronics LLC, sep-2017) that are sufficient for the monitoring area. DumbAgent chosen for network layer as it simple protocol used for testing of WSNs that has one hop and there is no need for routing techniques because a direct connection between nodes and sink node. Figures 5 and 6 show NAM (network animator) output of four nodes radiation sensor network using the two MAC protocols.

Figure 5 shows snapshots of NAM output of IEEE802.11 WSN at six instances. In the case of IEEE802.11 MAC protocol, there is no any synchronization between neighboring nodes and nodes that have data to transmit contend for medium access.

Table 1. Basic elements for the simulation of the designed WSN.

| Simulation system         | Network simulator (NS-2.35) |
|---------------------------|----------------------------|
| Simulation time           | 300 s                      |
| Number of sensor nodes    | 4 nodes                    |
| Sensor node               | GQ GMC-320+ VS Wireless Dosimeter Radiation Detector |
| Detectable range of GM    | 0.1–3.0 Mev                |
| Working voltage of GM     | 3.2–4.0 v                  |
| Antenna                   | OmniAntenna                |
| Routing protocol          | DumbAgent                  |
| MAC protocol              | IEEE802.11, SMAC           |
| Protocols family          | OSI                        |
| Idle power                | 0.1 w                      |
| Sleep power               | 0.5 w                      |

Figure 5. NAM output showing radiation network using IEEE802.11 protocol.
Hidden terminal problem appears with IEEE802 which results in more collisions.

Figure 6 shows six snapshots of NAM output of SMAC WSN. SMAC follows the same procedure of collision as IEEE802.11 but it has a local synchronization between nodes in the same virtual cluster. Collisions in the case of SMAC are due to contention between nodes that have data to send at the same time and there are no collisions from overhearing.

4. Results and discussion

IEEE802.11 is popular in wireless local area networks but does not suit WSNs because sensors should have mobility support, high throughput, fairness, and low latency. Also, energy conservation is the dominant target in designing WSNs. IEEE802.11 devices consumed high energy because nodes continue in listening mode without receiving messages. Table 2 presents the performance parameters from the simulation of the two networks.

Network lifetime is the time (in days) spends from the network’s initial deployment to the first loss of whole coverage; the time until the first network node runs out of energy. Energy consumption is the main parameter that affects the network lifetime. The performance of the WSN MAC protocols is determined according to energy consumption, throughput, and end-to-end delay.

End-to-end delay contention-based MAC protocols experience several delays: carrier sense delay, processing delay, queuing delay, transmission delay, propagation delay, and Bakeoff delay. SMAC has an extra delay inherent with periodic sleeping known as sleep delay.

The end-to-end delay in SMAC network is longer than that in the case of IEEE802.11 network, as shown in Table 2. This is due to periodic sleep of nodes and the scheduling in the case of SMAC that is determined in the start of network operation as slots are specified to all nodes in the network. Figure 7 shows the difference in the average end-to-end delay between the two protocols: series 1 describes average end-to-end delay of SMAC protocol and series two for IEEE802.11 protocol.
Energy consumption is the total energy exhausted to deliver the network data bits. Using the energy consumption rate values, it is possible to estimate sensor network lifetime for different protocols.

The main target in designing SMAC protocol is for power conservation where duty cycle of each node is decreased. From Table 2, the total energy consumed using SMAC protocol is lower than in the case of using IEEE802.11 protocol.

Throughput is the rate of successful message delivery over a communication channel. Throughput is usually measured in second. Throughput in the case of SMAC is approximately as that in the case of IEEE802.11 as shown in Figure 8. This is because in SMAC network only the active part is used for communication.

Table 2. Results of the simulation.

| Parameter               | IEEE802.11 | SMAC   |
|-------------------------|------------|--------|
| Average consumed energy | 337.25 J   | 278.62 J |
| Total consumed energy   | 1349 J     | 1114.48 J |
| Residual energy in node3 | 909.6259 J | 970.61 J |
| Average throughput (kbps) | 1.06 kbps  | 1.05 kbps |
| Average end-to-end delay | 0.011261 s | 2.24490 s |

Figure 7. Average end-to-end delay of the two wireless sensor networks.

Figure 8. Throughput of the two wireless sensor networks.
5. Conclusion

In this paper, two MAC protocols are applied in the design of a nuclear radiation WSN. The design with SMAC achieved more power conservation that results in more life time. Here the energy conservation is the main aim which assures high lifetime for network. The total energy consumed using SMAC protocol is lower than in the case of using IEEE802.11 protocol by approximately 21.04%. End-to-end delay in SMAC is longer than that in IEEE802.11 because of schedule sleeping technique. Also throughput is almost the same in the two networks although the SMAC network transmits data only in active period depending on duty-cycle value used. End-to-end delay and throughput are acceptable as the main objective in the design of radiation monitoring WSN is power saving. SMAC is preferred in this design.

Disclosure statement

No potential conflict of interest was reported by the authors.

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