Received: 10 June 2019 | Revised: 14 August 2019 | Accepted: 26 September 2019

DOI: 10.4218/etrij.2019-0296

ORIGINAL ARTICLE

ETRI Journal WILEY

Exploiting cognitive wireless nodes for priority-based data communication in terrestrial sensor networks

Muhammed Enes Bayrakdar

Computer Engineering Department, Düzce University, Düzce, Turkey

Correspondence
Muhammed Enes Bayrakdar, Computer Engineering Department, Düzce University, Düzce, Turkey.
Email: muhammedbayrakdar@duzce.edu.tr

A priority-based data communication approach, developed by employing cognitive radio capacity for sensor nodes in a wireless terrestrial sensor network (TSN), has been proposed. Data sensed by a sensor node—an unlicensed user—were prioritized, taking sensed data importance into account. For data of equal priority, a first come first serve algorithm was used. Non-preemptive priority scheduling was adopted, in order not to interrupt any ongoing transmissions. Licensed users used a nonpersistent, slotted, carrier sense multiple access (CSMA) technique, while unlicensed sensor nodes used a nonpersistent CSMA technique for lossless data transmission, in an energy-restricted, TSN environment. Depending on the analytical model, the proposed wireless TSN environment was simulated using Riverbed software, and to analyze sensor network performance, delay, energy, and throughput parameters were examined. Evaluating the proposed approach showed that the average delay for sensed, high priority data was significantly reduced, indicating that maximum throughput had been achieved using wireless sensor nodes with cognitive radio capacity.

KEYWORDS

cognitive radio, CSMA, priority, sensor network, terrestrial

1 | INTRODUCTION

Due to technological advances in wireless sensors since 1978, wireless systems have been widely used for data transmission purposes—particularly in terrestrial sensors that monitor environmental conditions. There are many reasons for using terrestrial wireless systems, with the most important being low cost, low power consumption, good data processing and wireless communication capacities, a limited number of equipment usage requirements, and the small size of the sensors [1]. These features give terrestrial sensors an important role in the fields of wireless communication, observation, and data transfer. Because wired systems have to contend with problems such as cable breaks, high cable costs, and high-power consumption, wireless sensors are generally preferred for academic and commercial purposes.

The cognitive radio network is widely utilized in the field of wireless communication, due to its dynamic access capability. With the help of this characteristic, idle spectrum can be fully exploited, using cognitive radio technology, and the throughput performance of any network can be maximized.

In a cognitive radio network, there are licensed users, unlicensed users, and base stations. Licensed users have a license for their spectrum, while unlicensed users do not have any license for spectrum, and exploit unused portions of the licensed spectrum opportunistically, during idle time slots.

Licensed base stations organize communication between licensed users, while cognitive radio base stations achieve coordination between unlicensed users, by assigning idle licensed spectrum time slots.

In terrestrial or rural areas, wireless spectrum is not highly exploited by licensed users [2], and for efficient spectrum usage, unlicensed users may fully exploit unused spectrum portions. An unlicensed user may be any cognitive radio capacity-based user, such as a wireless sensor node, smartphone, laptop, or computer. Exploitation of unused spectrum by cognitive radio, capacity-based wireless sensor nodes is a very important aspect of maximizing the throughput performance of any wireless cognitive radio sensor network.

In this work, a priority-based data communication approach for wireless terrestrial sensor networks has been proposed. In this approach, cognitive radio technology is utilized for sensor nodes, and licensed users employ a nonpersistent, slotted carrier sense multiple access (CSMA) technique, while unlicensed sensor nodes use a nonpersistent CSMA technique. A simulation model of the proposed network has been presented in this study. To analyze the performance of the proposed network, delay, energy, and throughput parameters are investigated.

In Section 2, the literature has been reviewed and the main contributions of this study have been presented. In Section 3, the analytical model of the proposed approach has been introduced, while in Section 4, the simulation model of the proposed approach has been presented, including simulation parameters and a process flow diagram. In Section 5, performance of the proposed approach has been evaluated, using graphical demonstrations of the results, and conclusions drawn from this study have been listed in Section 6.

2 | RELATED WORK

Many wireless terrestrial sensor network studies have been described in the literature, with more recent work focusing on dynamic spectrum sharing and cognitive radio technology.

Bekhti and others investigated the path planning of autonomous unmanned aerial vehicles with tracking capabilities provided by terrestrial wireless networks [3]. Shaat and Perez-Neira studied the problem of the cross-layer design of the link scheduling and flow control in a hybrid terrestrial-satellite wireless backhauling network [4]. Baranda and others presented the ns-3 framework for modeling hybrid terrestrial-satellite mesh backhaul networks that carry LTE traffic, and a comparison of the different backpressure-based approaches against generic shortest-path routing, in a low-density suburban scenario for LTE networks [5]. Lin and others proposed a beamforming scheme to enhance wireless information and power transfer in terrestrial cellular networks coexisting with satellite networks [6], while Ahmad and others presented an advanced first-order energy consumption model for terrestrial wireless sensor networks [7].

Ghaleb and others proposed and developed a discrete event simulation, designed specifically for mobile data gathering in wireless sensor networks [8]. Garcia-Lesta and others introduced a wireless sensor network to detect the presence of snails in fields [9]: they also designed their own wireless sensor network simulator, to account for real-life conditions—of uneven spacing of motes in the field, or of different currents generated by solar cells at the motes. Shah and Akan formulated the approximate bandwidth available to secondary users for a given set of traffic channels operated under an exclusively available common control channel, taking dynamic spectrum access into account [10]. Mesodiakaki and others proposed a novel contention-aware, channel selection algorithm that focused on throughput and energy efficiency improvement, in cognitive radio ad hoc networks [11]. Hu and others considered medium access control protocols as radio parameters in the cognitive cycle, and proposed a new approach—called medium access control protocol identification—to implement smart cognitive medium access control [12].

Zhao and others tackled the problem of interference estimation in a channel, in a scenario with one primary user and multiple secondary users [13]. Mesodiakaki and others evaluated a novel, contention-aware channel selection algorithm that focused on energy efficiency improvement in a secondary network, in a scenario where other, non-cooperating secondary networks were also using the primary resources [14]. Mesodiakaki and others evaluated the performance of a secondary network coexistence scheme, in terms of fairness, and showed that, in comparison to other state-of-the-art approaches, it could achieve throughput and energy efficiency gains, while maintaining fairness among the coexisting secondary networks [15]. Bhattacharjee and others analyzed the delay performance of distributed and centralized cooperative sensing approaches, to identify which was suitable for sensing inter-packet white space [16]. Saad and others proposed a centralized cognitive medium access method that used prediction of white spaces to avoid collisions, as well as to improve use of transmission opportunities [17].

Zhuo and others proposed a distributed protocol of light complexity for congestion regulation in cognitive industrial wireless sensor networks—to improve channel utilization while achieving predetermined performance levels for specific devices, called primary devices [18]. Morcel and others proposed a new algorithm that added proactive behavior for channel allocation at the medium access control layer [19]. Rastegardoost and Jabbari proposed an asymptotically optimal, fast-converging channel selection algorithm—referred to as a modified-myopic strategy—for a single-user scenario, based on the results of multiarmed bandits [20]. Saad and others presented a single channel, cognitive, medium access control protocol, for wireless industrial communication in highly dynamic, shared environments [21]. Chen and others considered medium access control protocol design for random access cognitive radio networks [22].

Liu and others considered channel statistics-based secondary transmission strategy design problems in CSMA-based primary networks [23]. Mesodiakaki and others proposed a novel, contention-aware channel selection algorithm, where the secondary network under study firstly detected the licensed channels with no primary user activity—by exploiting cooperative spectrum sensing, secondly estimated the probability of collision in each one, and then, thirdly, selected the less contended channel for access [24]. Cammarano and others presented a distributed, integrated medium access control, scheduling, routing and congestion/rate control protocol stack, for cognitive radio, ad hoc networks that dynamically exploited available spectrum resources left unused by primary licensed users, maximizing the throughput of a set of multi-hop flows between peer nodes [25]. Kawamoto and others focused on data collection for location-based authentication systems, as an application of the industrial Internet of things (IoT) [26]. Chiti and others dealt with a cognitive overlay, IEEE 802.15.4e wireless sensor network, relying on a low-complexity, spectrum-sensing technique [27].

Majumdar and others proposed a multiple input-, multiple output-based, cognitive radio sensor network architecture for futuristic technologies, such as the IoT and machine-to-machine communications [28]. Raza and others presented a detailed discussion on design objectives, challenges, and solutions, for industrial wireless sensor networks [29].

Main contributions of this work are as follows:

1. Priority classes, that is, priority-1, priority-2, and priority-3, have been taken into account;
2. Energy consumption and average delay have been reduced, with the help of a nonpersistent CSMA technique;
3. Throughput has been increased, with the help of the cognitive radio capability of wireless sensor nodes;
4. Nonpersistent CSMA protocol, which is also a sensing-based technique, has been used in sleep-awake mode, to decrease energy consumption;
5. Simulation results obtained from Riverbed software have been validated, using analytical results acquired from MATLAB software;
6. The cognitive approach has been designed and simulated in Riverbed software, for priority-based purposes in terrestrial wireless sensor (TWS) networks, for the first time in the literature.

3 | ANALYTICAL MODEL OF THE PROPOSED APPROACH

In this study, the wireless sensor network environment for terrestrial sensor nodes which are not able to be re-energized due to their subtle locations was investigated. The TWS nodes transmitted their data to the collector station that was nearest to them, and if they could not transfer data directly to the collector station, they transmitted their data via other sensor nodes to the collector station, in an ad hoc manner. Licensed users in the network utilized a nonpersistent, slotted CSMA, medium access technique, while unlicensed sensor nodes used a nonpersistent CSMA technique, to avoid packet collisions. Unlicensed sensor nodes always sensed the spectrum to find licensed user slots that were idle. Non-preemptive priority classes—that is, prio-1, prio-2, and prio-3—were taken into consideration, to accelerate the transmission duration of a sensed data packet, based on its urgency. By providing continuous data transmission without any collisions in the network environment, energy consumption was minimized, and network throughput performance was maximized, by constantly using full spectrum capacity. By using all licensed user idle time slots, and maintaining unlicensed users in sleep-awake mode, the average network delay was optimized, to 0.25 ms, which is acceptable for the terrestrial sensor network [30].

In cognitive radio networks, idle spectrum is discovered with the help of spectrum-sensing techniques, of which the energy detection technique is one of the most used, due to its simple structure—and the fact that it does not need any prior spectrum information [31]. In the energy detection technique, energy in the definite spectrum is observed, and is compared with a predefined threshold: if the energy level is above the predefined threshold, it is concluded that the spectrum is used by a licensed user, and otherwise, it is not. For energy detection-based spectrum-sensing processes, A_0 and A_1 represent absence and presence of a licensed user in the spectrum, respectively:

$$\mathrm{RS}[x]=\begin{cases} N[x], & A_0, \\ \mathrm{TS}[x]+N[x], & A_1,\ x=1,2,\ldots,X. \end{cases} \tag{1}$$

In (1), RS[x] is a signal received by an unlicensed base station, N[x] is environmental noise, TS[x] is the transmitted signal, x is the sample index, and X is the total number of samples. In (2), the decision statistic, DS, is obtained, using the predefined threshold, PT:

$$\mathrm{DS} = \sum_{x=0}^{X} |\mathrm{RS}\,[x]|^2 \overset{A_1}{\underset{A_0}{\gtrless}} \mathrm{PT}. \tag{2}$$

In terms of finding spectrum holes, there are two important parameters in cognitive radio networks—the probability of false alarm, PFA, and the probability of detection, PD [32]. PD is defined as detecting a licensed user communication on the spectrum correctly, while PFA is described as detecting a licensed user communication on the spectrum incorrectly, when there is no licensed user communication on the spectrum. PD and PFA are defined in (3), where $P()$ is the probability function:

$$\mathrm{PD} = P\left(\mathrm{DS} \geq \mathrm{PT}|A_1\right)$$

and

$$\mathrm{PFA} = P\left(\mathrm{DS} \geq \mathrm{PT}|A_0\right). \tag{3}$$

The probability of detecting licensed user communication in the spectrum correctly and incorrectly has been defined in (4):

$$\begin{aligned} P\left(A_0|A_0\right) &\rightarrow \text{detecting absence of licensed user as absent,} \\ P\left(A_1|A_0\right) &\rightarrow \text{misdetecting absence of licensed user as existent.} \end{aligned} \tag{4}$$

1-persistent CSMA was mainly proposed for improving the CSMA performance, by decreasing the extent of idle time periods [19], although for high network loads, nonpersistent CSMA outperforms 1-persistent CSMA [23]. As different sensed data packets mean a very high load for the network environment, the nonpersistent CSMA technique was employed in this study. Licensed sensor nodes use nonpersistent, slotted CSMA, as unlicensed sensor nodes detect and exploit idle time slots—and do so at the beginning of each time slot. In contrast, owing to periodical time slot sensing of unlicensed nodes, licensed nodes use nonpersistent, slotted CSMA. Unlicensed nodes utilize the nonpersistent CSMA technique because they do not need any slotted structure.

The normalized propagation time, a, of nonpersistent CSMA is calculated as shown in (5):

$$a = \tau / T, \tag{5}$$

where τ is an unsuccessful transmission period and T is a successful transmission period. The offered load is expressed as the total number of packets that the transmission process initiated at a specific time. For calculating the exact load, G, offered load, λ, was multiplied with a successful transmission period, as in (6):

$$G = \lambda * T. \tag{6}$$

The probability of successful packet transmission, P_{suc}, was defined as shown in (7):

$$P_{\mathrm{suc}} = e^{-(\lambda * \tau)}. \tag{7}$$

Expected useful time, U, has been calculated as shown in (8), by using (6) and (7):

$$U = T * P_{\mathrm{suc}}. \tag{8}$$

Derived from (8), the expected useful time is written as in (9):

$$U = T * e^{-(\lambda * \tau)}. \tag{9}$$

Throughput performance has been defined in this study as the total number of packets successfully transmitted over a given time. Throughput of nonpersistent CSMA, S, was calculated as shown in (10):

$$S = \frac{G * e^{-(a * G)}}{G * (1 + 2 * a) + \left(e^{-(a * G)}\right)}. \tag{10}$$

After editing variables, nonpersistent CSMA throughput was found as shown in (11) below:

$$S = \frac{\lambda * T * e^{-(\lambda * \tau)}}{\lambda * (T + 2 * \tau) + \left(e^{-(\lambda * \tau)}\right)}. \tag{11}$$

The throughput for unlicensed sensor nodes was calculated using the idle time slots of licensed users, as in (12). The probability of time slots being idle, P_{idle}, occurred only when the absence of a licensed user was correctly identified:

$$S = P_{\mathrm{idle}} * \frac{\lambda * T * e^{-(\lambda * \tau)}}{\lambda * (T + 2 * \tau) + \left(e^{-(\lambda * \tau)}\right)}. \tag{12}$$

By re-defining P_{idle} as $P(A_0|A_0)$, throughput was acquired, as shown in (13):

$$S = P\left(A_0|A_0\right) * \frac{\lambda * T * e^{-(\lambda * \tau)}}{\lambda * (T + 2 * \tau) + \left(e^{-(\lambda * \tau)}\right)}. \tag{13}$$

To calculate an effective throughput, time slot utilization, U_{ts}, was defined as the ratio of a successful transmission period over the total time period, as shown in (14) below:

$$U_{\mathrm{ts}} = T / (T + \tau). \tag{14}$$

Using time slot utilization, effective throughput—the S_{eff} of unlicensed sensor nodes—could be expressed as shown in (15):

$$S_{\text{eff}} = U_{\text{ts}} * P\left(A_0|A_0\right) * \frac{\lambda * T * e^{-(\lambda * \tau)}}{\lambda * (T + 2 * \tau) + \left(e^{-(\lambda * \tau)}\right)}. \tag{15}$$

Describing U_{ts} in (15), (16) was obtained—as the throughput of unlicensed sensor nodes:

$$S_{\text{eff}} = \left(\frac{T}{T+\tau}\right) * P\left(A_0|A_0\right) * \frac{\lambda * T * e^{-(\lambda * \tau)}}{\lambda * (T + 2 * \tau) + \left(e^{-(\lambda * \tau)}\right)}. \tag{16}$$

Throughput of nonpersistent, slotted CSMA, S_{slot}, was then calculated, using (17):

$$S_{\text{slot}} = \frac{\left(a * G * e^{-(a * G)}\right)}{(1+a) - \left(e^{-(a * G)}\right)}. \tag{17}$$

After editing variables, throughput for nonpersistent, slotted CSMA for licensed users was found by using (18):

$$S_{\text{slot}} = \frac{\lambda * T * \tau * e^{-(\lambda * \tau)}}{(T+\tau) - \left(T * e^{-(\lambda * \tau)}\right)}. \tag{18}$$

For unlicensed sensor nodes, an average delay, D_{u}, was expressed as in (19):

$$D_{\text{u}} = D_{\text{prio}} * \left\{T_{\text{s}} + \left[N_{\text{c}} * \left(T_{\text{bo}} + T_{\text{cw}} + T_{\text{cb}}\right)\right] + \left(T_{\text{bo}} + T\right)\right\}, \tag{19}$$

where D_{prio} is the delay coefficient according to priority class, T_{s} is spectrum-sensing time, N_{c} is the number of a collision, T_{bo} is an average back-off time period, T_{cw} is collision waiting time period, and T_{cb} is a collision-busy time period. The delay coefficient, D_{prio}, was 1, 2, and 3, for prio-1, prio-2, and prio-3 classes, respectively. Because there was no spectrum-sensing stage for licensed users, the equation for average delay, D_{l}, was as shown in (20) below:

$$D_{\text{l}} = N_{\text{c}} * \left(T_{\text{bo}} + T_{\text{cw}} + T_{\text{cb}}\right) + \left(T_{\text{bo}} + T\right). \tag{20}$$

Because energy is restricted for unlicensed sensor nodes in wireless sensor networks, minimizing energy consumption by removing negative factors in the environment—such as noise, reflection, and collision—was crucial. Average energy consumption for unlicensed sensor nodes, E_{cu}, was expressed as shown in (21):

$$E_{\text{cu}} = E_{\text{ss}}\left(E_{\text{cs}} + E_{\text{ct}}\right) + \left(E_{\text{cp}} + E_{\text{ack}}\right), \tag{21}$$

where E_{ss} is the energy consumption for spectrum sensing (sensing licensed spectrum), E_{cs} is the energy consumption for channel sensing, E_{ct} is the energy consumption for data transmission, E_{cp} is the energy consumption for propagation delay, and E_{ack} is the energy consumption for an acknowledgment packet. Because there was no spectrum-sensing stage for licensed users, the energy consumption equation could be expressed as in (22):

$$E_{\text{cl}} = E_{\text{cs}} + \left(E_{\text{ct}} + E_{\text{cp}} + E_{\text{ack}}\right), \tag{22}$$

where E_{cl} is the average energy consumption for licensed users.

4 | SIMULATION MODEL OF THE PROPOSED APPROACH

The terrestrial wireless network environment has been depicted in Figure 1, showing that, in this environment, unlicensed sensor nodes, licensed users, a licensed based station, an unlicensed base station, and a collector station exist together. The licensed base station coordinates the licensed user spectrum, while an unlicensed base station finds idle spectrum, using a spectrum-sensing capability, and manages data transmission coordination among unlicensed sensor nodes. It is the duty of unlicensed sensor nodes to collect data from the surrounding environment.

Sensed data delivery time varies according to priority class, where prio-1 reaches the destination first and prio-3 reaches the destination last—that is, the priority of the sensed data changes according to its urgency. For example, prio-1 class consists of data related to a security event, disaster event, and so on, prio-2 class consists of data related to a monitoring event, surveillance event, and so on, while prio-3 class consists of data related to pollution control, weather conditions, and so on.

Using wireless communication technology in rural areas, cattle health may be observed using wireless sensors to monitor blood pressure, temperature, and so on. Cattle location may be controlled using wireless sensors for distance, position, and so on, while vegetation (cattle feed) and soil conditions may be monitored using wireless sensors for temperature, humidity, and other variables. In this instance, information from sensors monitoring cattle health is the first priority, information on cattle location is second priority, and information from sensors reporting vegetation soil conditions is the third priority.

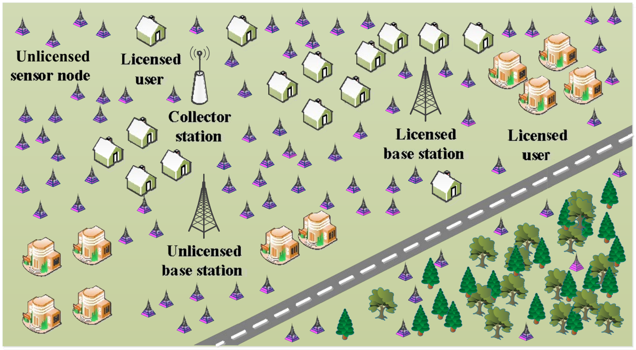

FIGURE 1 Terrestrial wireless sensor network environment

TABLE 1 Simulation parameters and values

Parameter	Value
Data rate	1000 kbps
Modulation scheme	BPSK
Number of unlicensed sensor nodes	81
Number of licensed users	23
Transmit power	20 mw
Data packet size	58 byte
Acknowledgement packet size	4 byte
Size of contention window	10
Back-off period	320 µs
Sensing time (Spectrum sensing)	100 µs
Sensing time (CSMA)	128 µs
Slot duration	100 ms
Frequency	3500 MHz

Unlicensed sensor nodes that are far from the collector station transmit their sensed data to the collector station via other nodes, in an ad hoc manner. The collector station collects all the sensed data coming from unlicensed sensor nodes, with the unlicensed sensor nodes consuming as little energy as possible by waiting in sleep mode when idle.

In Table 1, simulation parameters and values for the terrestrial wireless network environment are given. In the scenario tested here, the number of unlicensed sensor nodes was 81, the number of licensed users was 23, and the binary phase shift keying (BPSK) modulation scheme was chosen. Sensing time for the spectrum-sensing process was 100 µs, while sensing time for the nonpersistent CSMA technique was 128 µs. The slot duration of the nonpersistent, slotted CSMA technique was 100 ms and data packet size was 58 bytes, while the acknowledgment packet size was 4 bytes. The data rate was 1000 kbps, while frequency was 3500 MHz, for both licensed and unlicensed nodes [20]. Licensed nodes were given permission to use spectrum primarily without interruption, while unlicensed nodes sensed the spectrum and tried to find idle frequency bands, using cognitive radio capabilities [24]. Unlicensed nodes exploited the idle spectrum without causing any harmful interference to licensed nodes [27], and with the help of cognitive radio technology, use of license bands did not generate any conflict [24].

In Figure 2, the flow diagram for data transmission in the proposed, priority-based, unlicensed sensor node has been depicted. Initially, following determination of the sensed data priority class, the data packet is pushed into the queue, according to priority. Then, prio-1, prio-2, and prio-3 data packets start their sequential communication—that is, prio-2 data packets start their communication after all prio-1 data packets, and prio-3 data packets start their communication after all prio-2 data packets. The spectrum engaged by licensed users is sensed, and if there is idle licensed user spectrum, random Inter Frame Space (IFS) is identified.

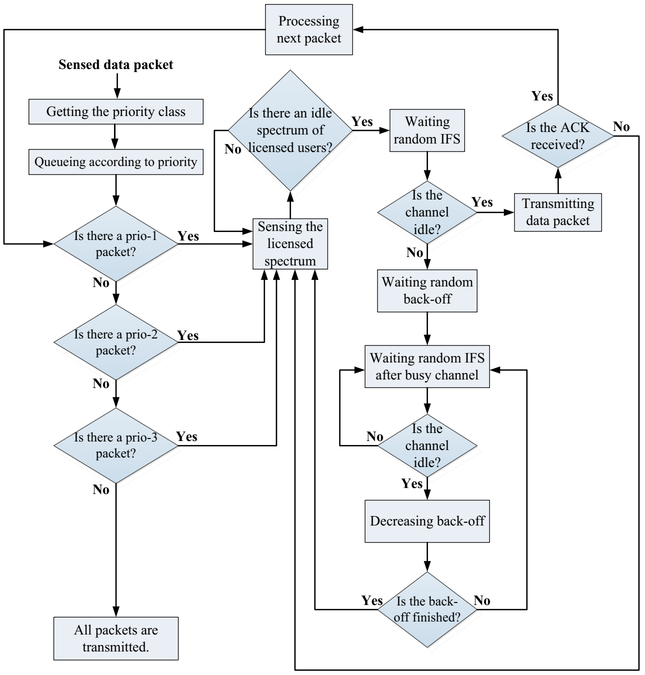

FIGURE 2 Data transmission flow diagram for proposed, priority-based unlicensed sensor nodes

If the status of the channel is idle, the data packet is transmitted, and if an acknowledgement (ACK) is received, the process of the next packet starts. If the ACK is not received after a defined time, the spectrum of licensed users is sensed, with the aim of re-transmitting the data packet. If the status of the channel is not idle, random back-off is applied, while for a busy channel, random IFS is applied. If the channel is idle, back-off is decreased, and if not, random IFS is applied to the busy channel. After decreasing back-off, a check is applied, to see if the back-off has finished, and if not, random IFS is applied to a busy channel. If the back-off is finished, the spectrum of licensed users is again surveyed, to make sure that the licensed user does not use this spectrum element. When all packets in the queue have been transmitted, the flow diagram shows that the process recycles, looking at the priority class of the next sensed data packet, in a continuing process.

In Figure 3, priority-based queue organization and the packet structure for unlicensed sensor nodes have been shown. In queue organization, prio-1, prio-2, and prio-3 packets are queued in sequence. New packet arrivals are queued in compliance with the first come first serve algorithm. In a packet structure, source information occupies 2 bytes, destination information takes up 2 bytes, priority information requires 2 bytes, data occupies 50 bytes, and error detection requires 2 bytes. For error detection, a cyclic redundancy check is utilized, owing to its simplicity, with the aim of re-transmitting packets that include an error.

Riverbed Modeler simulation software offers numerous tools, such as those required for simulation, design, and data

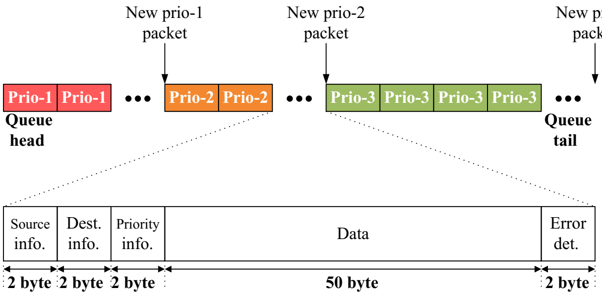

FIGURE 3 Unlicensed sensor node priority-based queue organization and packet structure

collection [33]; the software also provides an extensive development environment, covering wireless sensor network and distributed network system modeling. In this software, performance assessment of a simulation model is conducted using discrete event simulations. The software also presents a graphical user interface, with the aim of both configuring simulation models and developing wireless sensor network scenarios. Configuration of the wireless sensor network is performed in network, node, and process stages. In the network stage, the topology of the sensor network is organized, while the node stage defines the behavior of the node and monitors packet flow in the diverse parts of the node. The process stage is characterized by state machines, which are used for states, and for transitions between states. Riverbed Modeler simulation software source code is written in proto-C programming language.

Node and process models of an unlicensed sensor node, created with Riverbed Modeler, are shown in Figure 4. As the software is event-driven, after all variables have been defined, the first values are assigned to the initial state; the process then passes into the idle state, to wait for an interrupt, indicating the onset of a new event. In the priority state, the priority of the sensed data packet is determined before it is pushed into the queue according to priority, while in the sensing state, the cognitive radio sensing mechanism is employed to find idle time slots among licensed users. In the queue state, after an idle time slot has been identified, the source and destination information of the unlicensed sensor nodes are added to the sensed data packets coming from the upper stages. The data packets with complete information are then pushed into the queue, according to priority, after which the process passes into the transmit state, at the beginning of each time slot, to transmit the data packets existing in the queue.

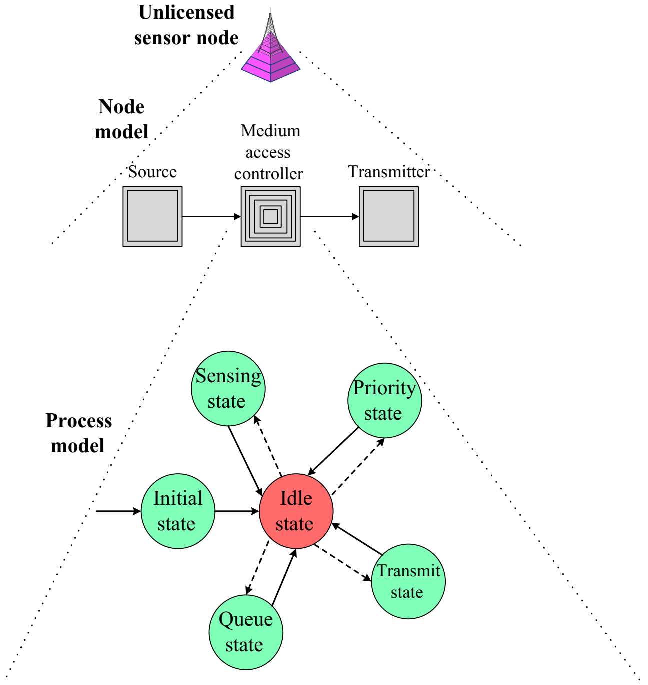

FIGURE 4 Riverbed Modeler unlicensed sensor node and process models

4.1 | Performance evaluation

The parameters' average throughputs, average delays, and average energy consumption were investigated to evaluate the performance of the TWS network. Simulation results were obtained from the Riverbed software [33], and analytical results were acquired from MATLAB software [34]. In the figures presented in this section, dotted lines represent analytical results, while the circles, triangles, and squares on the dotted lines represent simulation results.

In Figure 5, analytical and simulation results for average throughput performance attained by several medium access techniques are shown—and it can be seen that CSMA gave the best throughput performance.

Analytical and simulation results for average throughput by the proposed TWS network have been presented in Figure

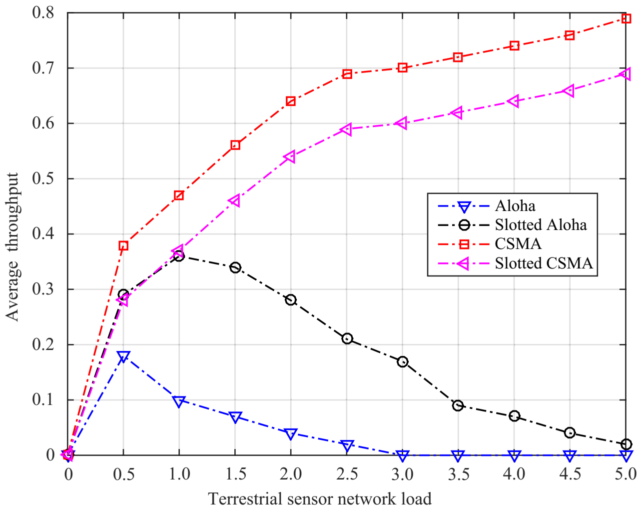

FIGURE 5 Average throughput using several medium access techniques

6, and it can be seen that, overall, the network achieved high throughput performance, helped by unlicensed sensor nodes fully utilizing the idle licensed user spectrum.

Analytical and simulation results for overall spectrum utilization are shown in Figure 7, where utilization is described as a percentage.

Analytical and simulation results for spectrum utilization based on priority class have been presented in Figure 8. After some time in the simulation scenario, the average spectrum utilization by all of the priority classes converged—due to the number of higher priority class packets decreasing through simulation time.

In Figure 9, analytical and simulation results for average packet delay across the proposed TWS network have been presented. Here it can be seen that the unlicensed terrestrial sensor network was exposed to a higher average delay than the licensed network, due to sensing issues related to opportunistic spectrum access.

Analytical and simulation results for the average packet delay—based on priority classes—have been shown in Figure 10, and it can be seen that prio-3 was exposed to a greater packet delay than prio-1 and prio-2, as the higher priority packets waited in the queue for a shorter time than the lower priority packets.

Analytical and simulation results for average energy consumption by the proposed sensor network are shown in Figure 11. The unlicensed TWS network consumed more energy than the licensed network, due to sensing issues. However, overall energy consumption was at a level that was considered to be acceptable for any kind of wireless sensor network [35].

In Figure 12, analytical and simulation results for the average packet loss ratio in the proposed sensor network have been

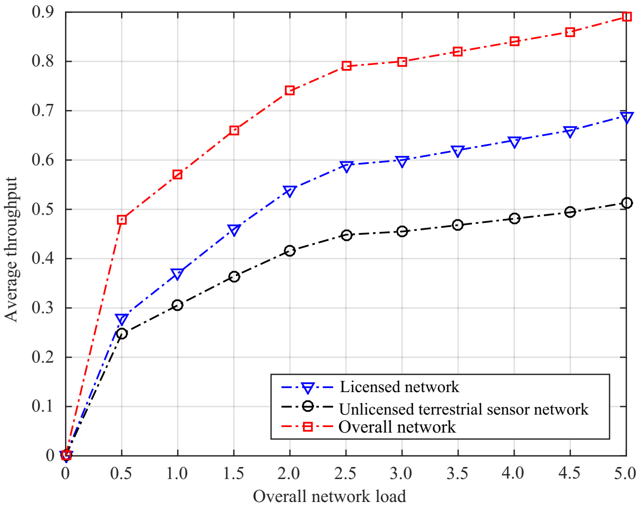

FIGURE 6 Average throughput for proposed terrestrial wireless sensor network

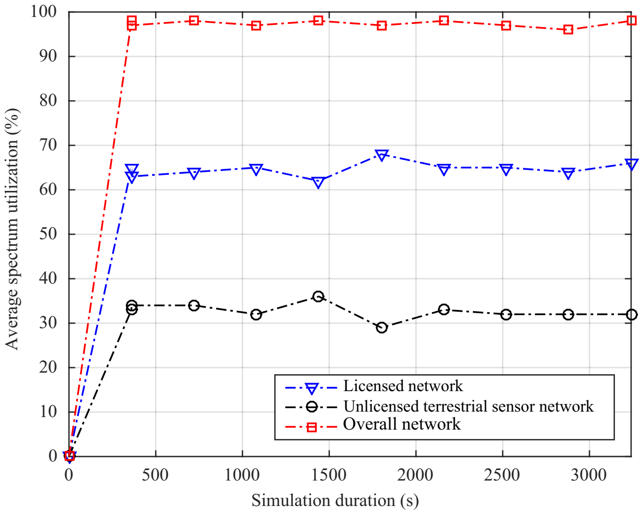

FIGURE 7 Overall spectrum use

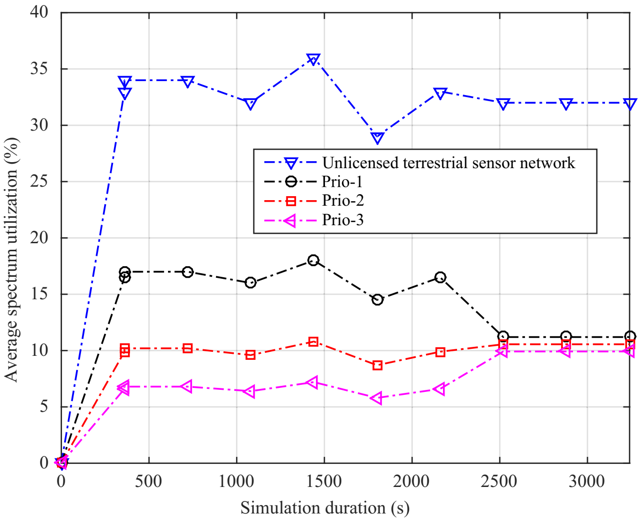

FIGURE 8 Spectrum utilization according to priority class

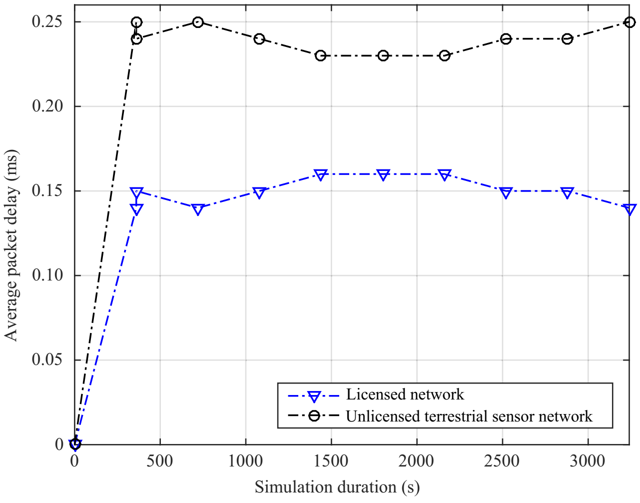

FIGURE 9 Proposed wireless terrestrial sensor network average packet delay

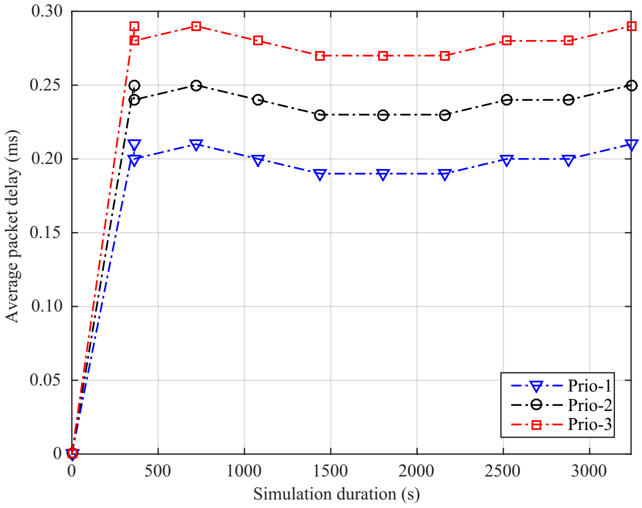

FIGURE 10 Average packet delay based on priority class

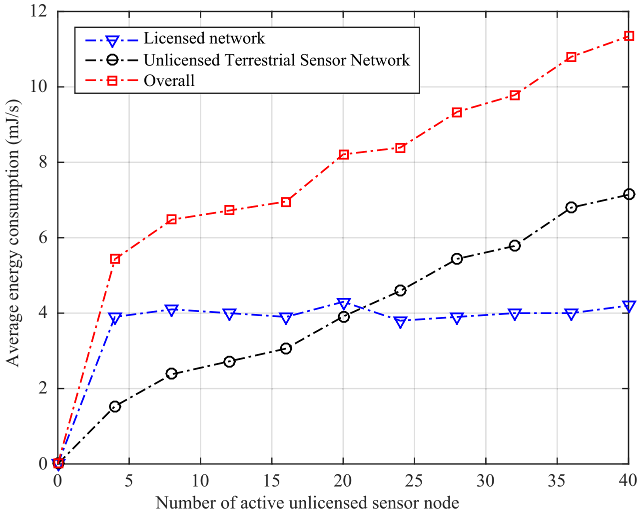

FIGURE 11 Average energy consumption for proposed sensor network

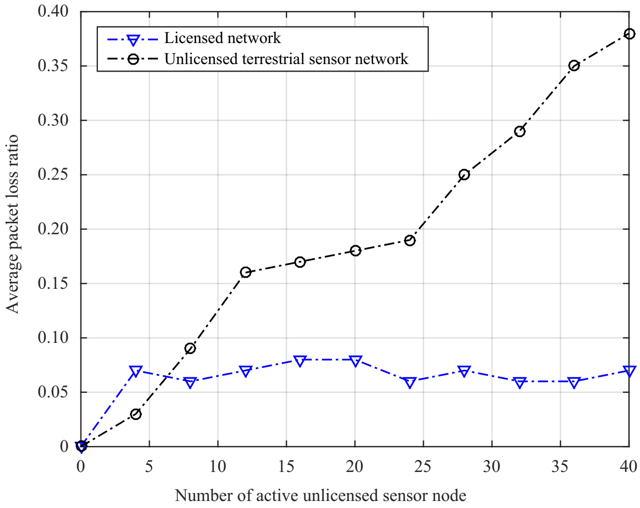

FIGURE 12 Proposed sensor network average packet loss ratio

presented. Here it can be seen that licensed users were exposed to lower packet loss ratios, due to the miss detection probability of unlicensed sensor nodes. Average packet loss ratio increased as the number of unlicensed sensor nodes rose—due to spectrum and priority competition issues among them.

5 | CONCLUSIONS

In this paper, cognitive, radio-based data communication, using priority classes for sensor nodes in a TWS network, has been proposed. Licensed users utilized a nonpersistent, slotted CSMA technique, while unlicensed sensor nodes employed a nonpersistent CSMA technique for data transmission, in a TWS network environment. An analytical model of the proposed approach was developed, and a simulation model of the proposed wireless terrestrial sensor network was designed, using Riverbed Modeler. The performance of the terrestrial sensor network, in terms of delay, energy, and throughput parameters, was analyzed.

Overall network throughput has been maximized with the help of unlicensed sensor nodes that fully utilize idle licensed user spectrum, and overall spectrum use was similarly improved, by exploiting this idle spectrum. Data packets that were sensed as having high priority had less delay than other packets in the queue. Overall energy consumption was found to be at an acceptable level, with the value of 8 mJ/s.

In future work, wireless terrestrial sensor networks using optimization techniques may be tested, using different scenarios.

ACKNOWLEDGMENTS

I would like to thank my esteemed wife Sümeyye and my daughter Asel for their valuable support.

CONFLICT OF INTEREST

There is no conflict of interest regarding this study.

ORCID

Muhammed Enes Bayrakdar https://orcid.org/0000-0001-9446-0988

REFERENCES

1. M. Dahiya, *Need and advantages of 5G wireless communication systems*, Int. J. Adv. Res. Comp. Sci. Man. Studies **5** (2017), 48–51.
2. T. X. Brown and D. C. Sicker. Can cognitive radio support broadband wireless access? in Proc. 2007 2nd IEEE Int. Symp. New Front. Dynamic Spectrum Access Net., Dublin, NI, 2007, pp. 123–132.
3. M. Bekhti et al. Path planning of unmanned aerial vehicles with terrestrial wireless network tracking, in Proc. Wireless Days (WD), Toulouse, France, 2016, pp. 1–6.
4. M. Shaat and A. I. Pérez-Neira. Joint flow control and link scheduling in hybrid terrestrial-satellite wireless backhauling network, in Proc. Commun. Workshops (ICC Workshops), Paris, France, 2017, pp. 870–875.

5. J. Baranda et al. Evaluation of hybrid terrestrial-satellite suburban wireless mesh backhauls for LTE networks, in Proc. Eur. Conf. Netw. and Commun. (EuCNC), Oulu, Finland, 2017, pp. 1–6.
6. Z. Lin et al., *Beamforming for secure wireless information and power transfer in terrestrial networks coexisting with satellite networks*, IEEE Signal Proc. Lett. **25** (2018), no. 8, 1166–1170.
7. A. Ahmad et al., An Advanced Energy Consumption Model for terrestrial Wireless Sensor Networks, in Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC), Paphos, Cyprus, 2016, pp. 790–793.
8. M. Ghaleb et al., *A performance simulation tool for the analysis of data gathering in both terrestrial and underwater sensor networks*, IEEE Access **5** (2017), 4190–4208.
9. D. García-Lesta et al., *Wireless sensor network with perpetual motes for terrestrial snail activity monitoring*, IEEE Sens. J **15** (2017), no. 15, 5008–5015.
10. G. A. Shah and O. B. Akan, CSMA-based bandwidth estimation for cognitive radio sensor networks, in Proc. Int. Conf. New Technologies, Mobility Security (NTMS), Istanbul, Turkey, 2012, pp. 1–5.
11. A. Mesodiakaki et al., Energy-efficient contention-aware channel selection in Cognitive Radio Ad-Hoc Networks, in Proc. IEEE Int. Workshop Comp. Aided Modeling Des. Comm. Links Net. (CAMAD), Barcelona, Spain, 2012, pp. 46–50.
12. S. Hu, Y. Yao, and Z. Yang, MAC protocol identification approach for implement smart cognitive radio, in Proc. IEEE Int. Conf. Commun. (ICC), Ottawa, Canada, 2012, pp. 5608–5612.
13. Y. Zhao et al., Analytical interference model in CSMA-based cognitive radio networks, in Proc. IEEE Int. Conf. Electro-Information Tech. (EIT) 2013, Rapid City, SD, 2013, pp. 1–6.
14. A. Mesodiakaki et al., Energy efficiency analysis of secondary networks in cognitive radio systems, in Proc. IEEE Inter. Conf. Commun. (ICC), Budapest, Hungary, 2013, pp. 4115–4119.
15. A. Mesodiakaki et al., Fairness evaluation of a secondary network coexistence scheme, in Proc. IEEE Int. Workshop Comp. Aided Model. Des. Comm. Links and Nets (CAMAD), Berlin, Germany, 2013, pp. 180–184.
16. S. Bhattacharjee, S. Mandal, and B. Sardar, Performance analysis of CSMA/CA protocol during white space identification in cognitive radio networks, in Proc. Appl. Inn. Mob. Computing (AIMoC), Kolkata, India, 2014, pp. 91–96.
17. A. Saad, B. Staehle, and Y. Chen, On the effectiveness of medium access with predictive collision avoidance, in Proc. IEEE Emerg. Tech. Factory Automat. (ETFA), Barcelona, Spain, 2014, pp. 1–4.
18. S. Zhuo et al., Adaptive congestion control in cognitive industrial wireless sensor networks, in Proc. IEEE Int. Conf. Indust. Inform. (INDIN), Cambridge, UK, 2015, pp. 900–907.
19. R. Morcel et al., Proactive channel allocation for multimedia applications over CSMA/CA-based CRNs, in Proc. Int. Conf. Adv. Computational Tools Eng. Appl. (ACTEA), Beirut, Lebanon, 2016, 178–183.
20. N. Rastegardoost and B. Jabbari, Blind channel selection strategies for distributed cognitive MAC, in Proc. IEEE Ann. Int. Symp. Personal, Indoor, Mobile Radio Commun. (PIMRC), Valencia, Spain, 2016, pp. 1–6.
21. A. Saad, B. Staehle, and R. Knorr, Predictive medium access control for industrial cognitive radio, in Proc. IEEE Ann. Cons. Commun. Netw. Conf. (CCNC), Las Vegas, NV, 2018, pp. 1–8.
22. Q. Chen et al., *MAC protocol design and performance analysis for random access cognitive radio networks*, Proc. IEEE J. Selected Areas Commun. **31** (2013), no. 11, 2289–2300.
23. Y. Liu, N. Kundargi, and A. Tewfik, *Channel idle time statistics based spectrum accessing strategies with CSMA based primary networks*, Proc. IEEE Trans. Signal Proc. **62** (2014), no. 3, 572–582.
24. A. Mesodiakaki et al., *Performance analysis of a cognitive radio contention-aware channel selection algorithm*, IEEE Trans. Vehicular Tech. **64** (2015), no. 5, 1958–1972.
25. A. Cammarano et al., *Throughput-optimal cross-layer design for cognitive radio ad hoc networks*, IEEE Trans. Parallel Distributed Syst. **26** (2015), no. 9, 2599–2609.
26. Y. Kawamoto et al., *Effectively collecting data for the location-based authentication in internet of things*, IEEE Syst. J. **11** (2011), no. 3, 1403–1411.
27. F. Chiti, R. Fantacci, and A. Tani, *Performance evaluation of an adaptive channel allocation technique for cognitive wireless sensor networks*, IEEE Trans. Vehicular Tech. **66** (2017), no. 6, 5351–5363.
28. C. Majumdar et al., *Packet-size optimization for multiple-input multiple-output cognitive radio sensor networks-aided internet of things*, IEEE Access **5** (2017), 14419–14440.
29. M. Raza et al., *A critical analysis of research potential, challenges, and future directives in industrial wireless sensor networks*, IEEE Commun. Surveys Tut. **20** (2018), no. 1, 39–95.
30. D. Bein and B. B. Madan, Reducing the data communication delay in wireless sensor networks, in Proc. IEEE Int. Conf. Intell. Comput. Comm. Process. (ICCP), Cluj-Napoca, Romania, 2016, pp. 361–368.
31. R. Shrestha, V. Swargam, and M. S. Murty, Cognitive-rad io wireless-sensor based on energy detection with improved accuracy: Performance and hardware perspectives, in Proc. Int. Symp. VLSI Design and Test (VDAT), Guwahati, India, 2016, pp. 1–6.
32. A. A. Owayed, Z. A. Mohammed, and A. A. Mosa, Probabilities of detection and false alarm in multitaper based spectrum sensing for cognitive radio systems in AWGN, in Proc. IEEE Int. Conf. Commun. Syst., Singapore, 2010, pp. 579–584.
33. Riverbed Software, https://www.riverbed.com/gb/, 2019, [last accessed May 2019].
34. Matlab Software, https://www.mathworks.com/, 2019, [last accessed May 2019].
35. F. Luo et al., Node energy consumption analysis in wireless sensor networks, in Proc. IEEE Vehicular Tech. Conf. (VTC2014-Fall), Vancouver, Canada, 2014, pp. 1–5.

AUTHOR BIOGRAPHY

Muhammed Enes Bayrakdar received his BS and MS degrees in electronics and computer education from Kocaeli University, Kocaeli, Turkey, in 2010 and 2013, respectively. He received his PhD degree in electrical-electronics and computer engineering from Düzce University, Düzce, Turkey, in 2017. From 2010 to 2017, he was a research assistant with Kocaeli and Düzce universities and has been an assistant professor at Düzce University since 2017. His research interests include cognitive radio, sensor networks, and medium access control protocols. He won 2018 and 2019 Publons Peer Reviewer Awards, as a top 1% reviewer in the computer science category. He is an associate editor in IET Communications.