ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 629.7.014-519.064.5-022.332:621.311.25-047.36 **doi: 10.32620/reks.2019.4.03**

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USING AUTOMATED BATTERY REPLACEMENT STATIONS FOR THE PERSISTENT OPERATION OF UAV-ENABLED WIRELESS NETWORKS DURING NPP POST-ACCIDENT MONITORING

Motivation. *After the Fukushima, nuclear power plant (NPP) accident, an unmanned aerial vehicle (UAV)-enabled wireless network (UEWN) is considered to be used for transmitting the data from monitoring stations (MSs) to the crisis center (CrS) during NPP post-accident monitoring missions. Nevertheless, the popular lightweight UAVs have an endurance of about 20–40 minutes only. The last fact presents a significant barrier to use a UEWN in complex, long-term NPP post-accident monitoring missions. The* ***subject matter*** *of the paper is the process of ensuring the persistent operation of UEWN. This paper aims to propose an approach to ensuring the persistent operation of UEWN during NPP post-accident monitoring missions via automatic battery replacement stations (ABRSs). The* ***objectives*** *of the paper are: to propose a scheme of deployment of a UEWN with ABRSs for the given scenario; to give an example of the proposed scheme application for persistent transmitting the data from a MS to the CrS during Zaporizhzhia NPP (ZNPP) post-accident monitoring missions; to discuss an example of the proposed scheme application. The following* ***results*** *were obtained. A simplified scheme of deployment of a UEWN with ABRSs for transmitting the data from the MS to the CrS during NPP post-accident monitoring missions was developed and described. Two segments within the UEWN were considered: 1) Wi-Fi segment, comprising the WiFi equipment of the MS, the onboard WiFi equipment of the UAVs of a multi-rotor type (MUAVs), and onboard WiFi equipment of the UAV of an airplane-type (AUAV); 2) LoRaWAN segment, comprising the LoRaWAN equipment of the AUAV and the LoRaWAN equipment of the CrS. An example of deployment of a UEWN with ABRSs for transmitting the data from an MS of ZNPP to the CrS was given and described. A shift schedule for 2 MUAV fleets ensuring the persistent operation of the UEWN during post-accident ZNPP monitoring missions was built and analyzed. It was evaluated how the flight distance for the MUAV between its location point in the WiFi segment and the ABRS effects: the duty time for the MUAV fleet; the waiting time for the MUAV to flight to the point of its location in the WiFi segment; the number of the MUAV fleets for ensuring the persistent operation of the UEWN. The* ***new research*** *will aim at developing a scheme of deployment of the UEWN with ABRSs for several WiFi segments.*

Keywords: *unmanned aerial vehicle; nuclear power plant; a wireless network; WiFi; LoRaWAN; post-accident monitoring; monitoring station; a crisis center.*

Introduction

The Fukushima nuclear power plant (NPP) accident showed that wired networks, connecting monitoring stations (MS) of the automated radiation monitoring system (ARMS) to the crisis centre (CrS), are vulnerable to both natural and man-made disasters. To cope with the problem, a drone-based wireless subsystem (unmanned aerial vehicle (UAV)-enabled wireless network (UEWN)), which is a part of an Internet-of-Drone-based multi-version post-severe NPP accident monitoring system, can be deployed [1-3].

Nevertheless, the popular lightweight UAVs are equipped with several (generally four or six) electric motors (rotors) powered by a lithium battery that permits a flight time of about 20–40 minutes only.

This short battery life presents a significant barrier to use a UEWN in complex, long-term NPP post-accident monitoring missions. To increase the NPP monitoring mission time via drones, it is possible to equip the drones with a higher capacity battery, but this inevitably leads to its greater weight. Alternatively, this time can be prolonged by using one of the following stations: automatic battery replacement station (ABRS), automatic battery charging station (ABCS) or replacement and charging battery station (ABRCS).

The paper is organized as follows. Section 1 discusses the existing woks on ensuring the persistent operation of UAVs during their various missions via ABRS/ABCS/ABRCS stations and formulates the aim and objectives of the paper. Section 2 proposes and describes a scheme of deployment of a UEWN with ABRSs for the given scenario. Section 3 considers an example of the proposed scheme application for persistent transmitting the data from a MS to the CrS during ZNPP post-accident monitoring missions. Section 4 presents the main results. Section 'Conclusions' concisely summarizes the results obtained and highlights the next research steps.

1. State of the art

Researchers consider in [4-19] various types of ABRS/ABCS/ABRCS stations as it is shown in Table 1.

Michini et al. [4] introduce a hardware platform for automated battery changing and charging for multiple UAV agents. The automated station holds a buffer of 8 batteries in a novel dual-drum structure that enables a "hot" battery swap, thus allowing the UAV to remain powered on throughout the battery changing process.

Table 1
References and types of ABRS/ABCS/ABRCS stations presented in them

References	Replacement	Charging	On site	Mobile	Type
[4]	+	+	+	–	ABRCS
[5]	+	–	+	–	ABRS
[6]	–	+	+	–	ABCS
[7]	–	+	+	–	ABCS
[8]	–	+	–	+	ABCS
[9]	–	+	+	–	ABCS
[10]	–	+	+	–	ABCS
[11]	+	–	–	+	ABRS
[12]	+	–	+		ABRS
[13]	–	+	+	–	ABCS
[14]	–	+	+	–	ABCS
[15]	–	+	+	–	ABCS
[16]	–	+	+	–	ABCS
[17]	–	+	–	+	ABCS
[18]	+	–	–	+	ABRS
[19]	+	–	–	+	ABRS

An automatic battery replacement mechanism that allows UAVs to fly continuously without manual battery replacement along with the suggestion of the scalable and robust usage for the system is presented in [5]. Reference [6] is devoted to the development and hardware implementation of an autonomous battery maintenance mechatronic system that significantly extends the operational time of battery powered small-scaled UAVs. Reference [7] deals with the use of charging platforms as a part of automata-based techniques for generating collision-free motion plans for a UAV team to satisfy a temporal logic specification. Khonji et al. [8] for battery charging and Barrett et al. [11] for battery changing propose to use a mobile service station, mounted on a ground rover and equipped with a robotic arm. Reference [9] is related to path planning of electric UAVs considering recharging operations. Various types of wireless power transfer (WPT) systems to recharge the battery of electric UAVs are presented in [10, 14, 16]. The power relay platform which can guide the UAV to land, automatically replace the battery, store the replaced power-lack battery and get it fully charged, is developed in [12]. Shinkuma and Mandayam [13] study a range of network architectures that depend on the mechanized automation (access point separation and battery replacement) capabilities of UAVs and proposes heuristic UAV scheduling algorithms for each network architecture. A novel charge replenishment mechanism, that allows a swarm of drones to stay in the air perpetually, is proposed in [15]. This is achieved by employing a fleet of drones much larger than the flying swarm in order to continuously replace and charge energy-depleted drones. The required fleet size for various drone models is calculated analytically and through a simulation. Shin et al. [17] for battery charging and Erdelj et al. [18] for battery changing propose to use a special car. Reference [19] is devoted to the development of an approach to determine the optimal routing of a multi-rotor UAV, which uses an airborne automatic service station for its batteries replacement.

The aim of this paper is to propose an approach to ensuring the persistent operation of UAV-enabled wireless networks during NPP post-accident monitoring missions via ABRSs.

The objectives of the paper are:

– to propose a scheme of deployment of a UEWN with ABRSs for the given scenario;

– to give an example of the proposed scheme application for persistent transmitting the data from a MS to the CrS during ZNPP post-accident monitoring missions;

– to discuss an example of the proposed scheme application.

2. Developing a scheme of deployment of a UEWN with ABRSs for the given scenario

Let us have the following scenario. Wired network of the ARMS that connects a MS directly with the CrS has been damaged as a result of an NPP accident.

In order to continue providing the CrS the needed data from the MS, the UEWN (Fig. 1), consisting of n UAVs of a multi-rotor type ($MUAV1_R$, …, $MUAV(n\text{-}1)_R$, $MUAVn_{RG1}$) and one UAV of an airplane-type ($AUAV_{RG2}$), is deployed. $MUAV1_R$, …, $MUAV(n\text{-}1)_R$ act as repeaters. $MUAVn_{RG1}$ acts both as

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

a gateway for acquiring and storing data from MUAV(n-1)$_R$ and, being a rendezvous point (RP), as a repeater for forwarding the data to AUAV$_{RG2}$. The last UAV, communicating with MUAVn$_{RG1}$ during the assign time of its patrol mood, acts both as a gateway for acquiring and storing data from MUAVn$_{RG1}$ and as a repeater for forwarding the data to the CrS.

The following communication technologies are used.

1) Wi-Fi (IEEE 802.11) for MS-UAV and UAV-UAV communication.

2) Low-Power Wide-Area Network (LoRaWAN) for UAV$_{RG2}$-CrS communication.

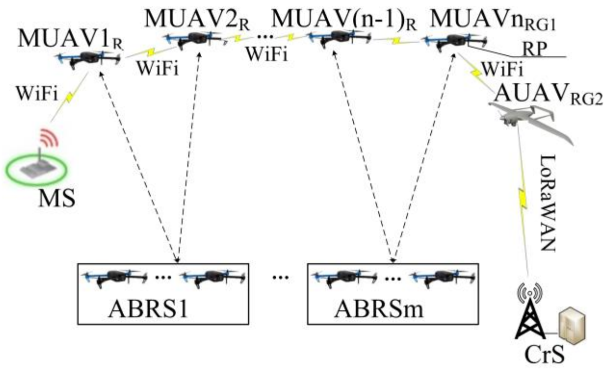

Fig. 1. Simplified scheme of deployment of the UEWN with the ABRSs for transmitting the data from the MS to the CrS during NPP post-accident monitoring missions

Thus, there are two segments within the UEWN:

1) Wi-Fi segment, comprising the WiFi equipment of the MS, the onboard WiFi equipment of the MUAVs, and onboard WiFi equipment of the AUAV;

2) LoRaWAN segment, comprising the LoRaWAN equipment of the AUAV and the LoRaWAN equipment of the CrS.

MUAV1$_R$, …, MUAV(n-1)$_R$, MUAVn$_{RG1}$ form the MUAV fleet.

It is required to ensure the persistent operation (without interrupting data acquiring and transmitting) of the UEWN during NPP post-accident monitoring missions via ABRSs. Assume that the capability of the ABRSs makes it possible to serve all the UAVs simultaneously. The duration of the operation (duty time) for the MUAV fleet can be determined by the following expression

$$t_{on\_duty} = E_{MUAV} - \frac{2\max[S_{MUAV1_R};\ \ldots;S_{MUAV(n-1)_R};\ S_{MUAVn_{RG1}}]}{v_{MUAV}} - t_{WiFi\_conf}, \quad (1)$$

where E_{MUAV} is the endurance of the MUAV; $S_{MUAV1_R}/\ \ldots/S_{MUAV(n-1)_R}/S_{MUAVn_{RG1}}$ is the flight distance for MUAV1$_R$/ …/MUAV(n-1)$_R$/MUAVn$_{RG1}$ between its location point in the WiFi segment and the ABRS; v_{MUAV} is the speed of the MUAV; t_{WiFi_conf} is the time to set up the WiFi network configuration.

To ensure the persistent operation of the UEWN, it is proposed to use the shift schedule for the MUAV fleets. The number of the MUAV fleets (shifts) for ensuring the persistent operation of the UEWN can be determined as

$$k = 1 + \frac{\frac{2S_{MUAV\_way}}{V_{MUAV}} + t_{repl\_bat} + t_{WiFi\_conf}}{t_{on\_duty}}, \quad (2)$$

where t_{repl_bat} is the time to replace the battery at the ABRS.

The total number of the MUAVs for the WiFi segment (MUAV fleet) is calculated as

$$n = \frac{D_{(MS-RP)}}{2R_{WiFi}}, \quad (3)$$

where $D_{(MS-RP)}$ is the distance between the MS and RP; R_{WiFi} is the range of the onboard WiFi equipment of the MUAV.

3. Example of the proposed scheme application

Let us consider an example of deployment of the UEWN with the ABRSs for transmitting the data from MS14, which is a part of the ARMS for Zaporizhzhia Nuclear Power Plant (ZNPP) (Ukraine), to the CrS located on the south outskirt of Enerhodar (Fig. 2).

Being equipped the WiFi equipment, MS14, 9 MUAVs (MUAV1$_R$, …, MUAV8$_R$, MUAV9$_{RG1}$) and 1 AUAV (AUAV$_{RG2}$) form the WiFi segment of the UEWN. The LoRaWAN segment of the UEWN is formed by means of the RaWAN equipment, placed on AUAV$_{RG2}$ and the CrS.

The flight time of each MUAV is 0.5 hours. The onboard WiFi equipment of the MUAV has range of about 0.12 km. Hence, the WiFi segment of the UEWN has a length of about 1.8 km. The onboard LoRaWAN equipment of the AUAV has range of about 5 km. Thus, the LoRaWAN segment of the UEWN has a length of about 5 km as well.

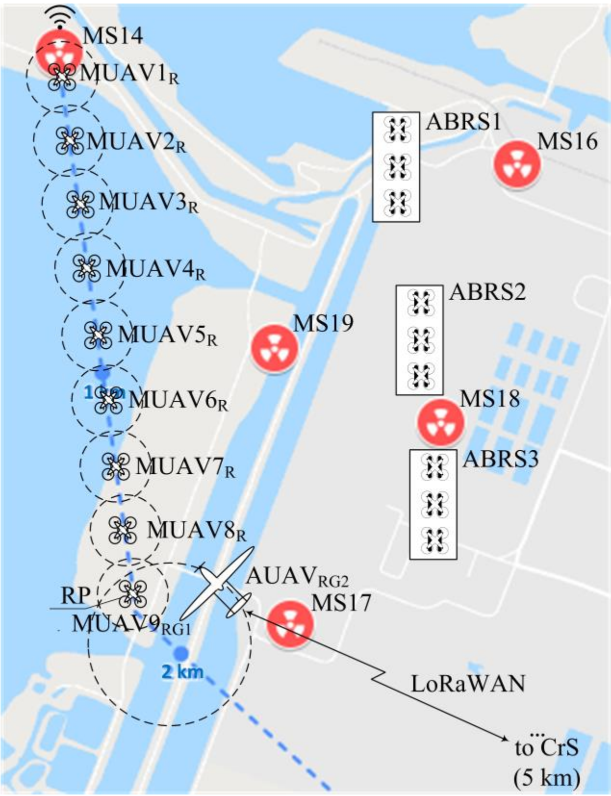

Fig. 2. Scheme of deployment of the UEWN with the ABRSs for transmitting the data from MS14 to the CrS during ZNPP post-accident monitoring missions

To ensure the persistent operation of the UEWN, 2 MUAV Fleets (each fleet comprises 9 MUAVs) operate in accordance with the shift schedule. 3 ABRSs are deployed and each of them is available to serve 3 MUAVs simultaneously. Assume that the flight distance for each MUAV between its location point in the WiFi segment and the ABRS is about 1 km ($S_{MUAV1_R} = S_{MUAV2_R} = \ldots = S_{MUAV8_R} = S_{MUAV9_{RG1}} = S_{MUAV} = 1$ km).

In this case, the shift schedule for the MUAV fleet comprises the following stages (Fig. 3):

– flight of each MUAV of the fleet from the ABRS to the point of its location in the WiFi segment (Fly_on);

– setting up the WiFi network configuration (WiFi_conf);

– receiving and transmitting data (On_duty);

– flight of each MUAV of the fleet from the point of its location in the WiFi segment to the ABRS (Fly_out);

– battery replacement (Repl_bat);

– each MUAV is waiting for the flight to the point of its location in the WiFi segment (Waiting).

The waiting time for the MUAV to flight to the point of its location in the WiFi segment is calculated by the formula:

$$t_{wait} = t_{on\_duty} - \frac{2S_{MUAV}}{V_{MUAV}} - t_{WiFi\_conf} - t_{repl\_bat}. \quad (4)$$

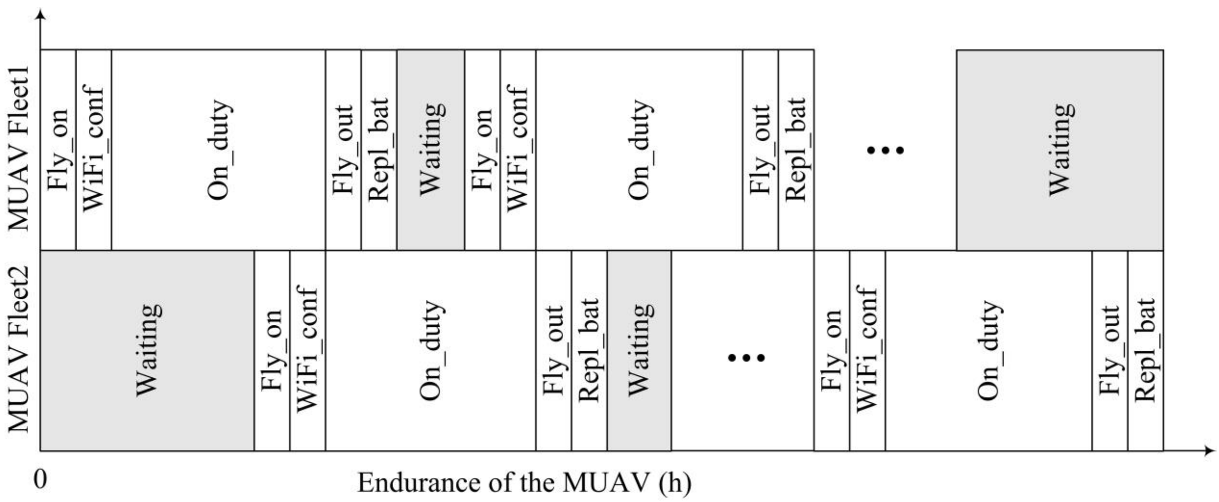

Fig. 3. Shift schedule for 2 MUAV fleets ensuring the persistent operation of the UEWN during ZNPP post-accident monitoring missions

 ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

4. Main results

Let us evaluate how the flight distance for the MUAV between its location point in the WiFi segment and the ABRS effects: 1) the duty time for the MUAV fleet, 2) the waiting time for the MUAV to flight to the point of its location in the WiFi segment, and 3) the number of the MUAV fleets for ensuring the persistent operation of the UEWN. Results of this evaluating are presented in Figs. 4-6 (E_{MUAV} = 0.5 h, v_{MUAV} = =40 km/h, t_{repl_bat} = 0.017 h, t_{WiFi_conf} = 0.017 h).

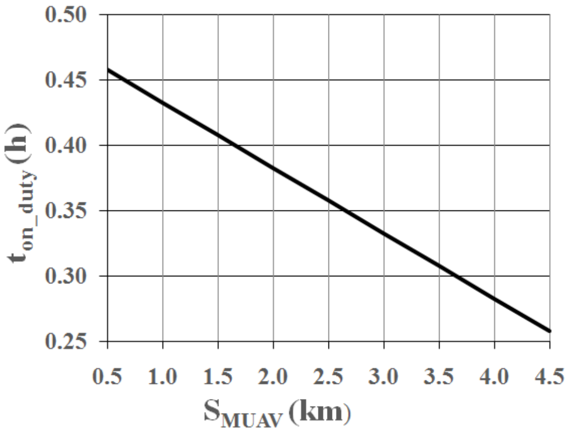

Fig. 4. Dependency of the duty time for the MUAV fleet on the flight distance for the MUAV between its location point in the WiFi segment and the ABRS

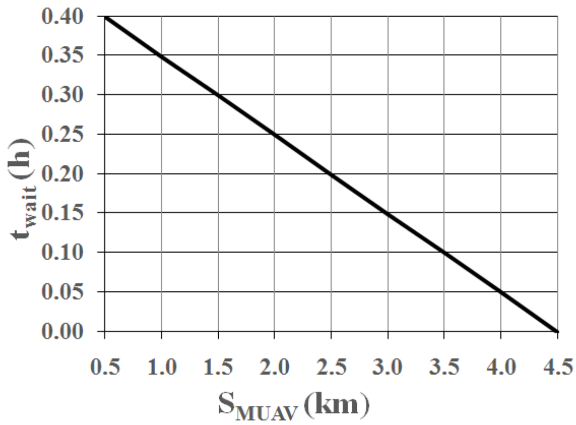

Fig. 5. Dependency of the waiting time for the MUAV to flight to the point of its location in the WiFi segment on the flight distance for the MUAV between its location point in the WiFi segment and the ABRS

Based on the obtained results, we can make the following conclusions:

– growth in the flight distance for the MUAV between its location point in the WiFi segment and the ABRS from 0.5 to 4.5 km leads to a per cent decrease in the duty time for the MUAV fleet by 43.5 per cent (0.26 h instead of 0.46 h) (Fig. 4);

– the waiting time for the MUAV to flight to the point of its location in the WiFi segment is zero when the flight distance for the MUAV between its location point in the WiFi segment and the ABRS is 4.5 km (Fig. 5);

– if the flight distance for the MUAV between its location point in the WiFi segment and the ABRS is more than 4.5 km, we have to use more than 2 MUAV fleets for ensuring the persistent operation of the UEWN (Fig. 6).

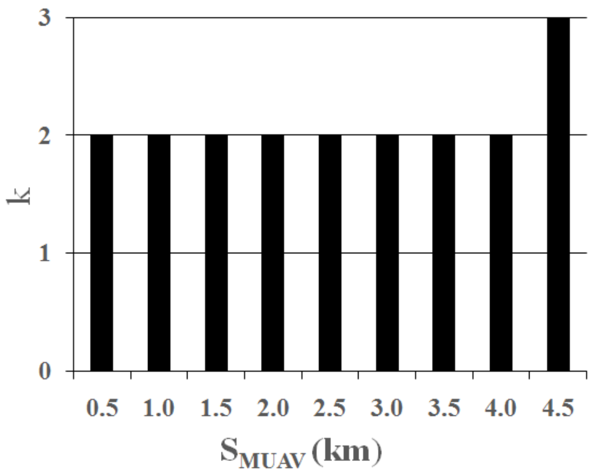

Fig. 6. Diagram showing how the flight distance for the MUAV between its location point in the WiFi segment and the ABRS effects the number of the MUAV fleets ensuring the persistent operation of the UEWN

Conclusions

A simplified scheme of deployment of a UEWN with ABRSs for transmitting the data from the MS to the CrS during NPP post-accident monitoring missions was developed and described.

An example of deployment of a UEWN with ABRSs for transmitting the data from a MS, which is a part of the ARMS for ZNPP, to the CrS located on the south outskirt of Enerhodar was given and discussed.

A shift schedule for 2 MUAV fleets ensuring the persistent operation of the UEWN during post-accident ZNPP monitoring missions was built and analyzed.

It was evaluated how the flight distance for the MUAV between its location point in the WiFi segment and the ABRS effects: 1) the duty time for the MUAV fleet, 2) the waiting time for the MUAV to flight to the point of its location in the WiFi segment, 3) the number of MUAV fleets for ensuring the persistent operation of the UEWN.

The new research will aim at developing a scheme of deployment of the UEWN with ABRSs for several WiFi segments.

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Надійшла до редакції 10.11.2019, розглянута на редколегії 10.12.2019

ВИКОРИСТАННЯ АВТОМАТИЗОВАНИХ СТАНЦІЙ ЗАМІНИ БАТАРЕЙ ДЛЯ ЗАБЕЗПЕЧЕННЯ БЕЗПЕРЕБІЙНОЇ РОБОТИ БЕЗДРОТОВИХ МЕРЕЖ НА ОСНОВІ БПЛА ПІД ЧАС ПІСЛЯАВАРІЙНОГО МОНІТОРИНГУ АЕС

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Актуальність. Після аварії на атомній електростанції (АЕС) в м. Фукусіма бездротова мережа на основі безпілотних літальних апаратів (БПЛА-БМ) використовується для передачі даних з постів контролю (ПК) в кризовий центр (КЦ) при здійсненні післяаварійного моніторингу АЕС. Однак, час польоту популярних легких БПЛА становить всього близько 20-40 хвилин. Останній факт являє собою серйозну перепону для використання БПЛА-БМ при складному і тривалому післяаварійному моніторингу АЕС. Предметом статті є процес забезпечення безперебійної роботи БПЛА-БМ. Мета статті – запропонувати підхід до забезпечення безперебійної роботи БПЛА-БМ в ході післяаварійного моніторингу АЕС за рахунок використання станції автоматичної заміни батарей (САЗБ). Завданнями статті є: запропонувати схему розгортання БПЛА-БМ з використанням САЗБ для заданого сценарію; надати приклад використання запропонованої схеми для забезпечення безперебійної передачі даних від ПК до КЦ під час післяаварійного моніторингу Запорізької АЕС (ЗАЕС); обговорити приклад використання запропонованої схеми. Були отримані наступні результати. Розроблена і описана спрощена схема розгортання БПЛА-БМ з використанням САЗБ для передачі даних від ПК до КЦ під час післяаварійного моніторингу АЕС. При цьому розглянуті два сегмента в складі БПЛА-БМ: 1) сегмент WiFi, що включає обладнання WiFi на ПК, обладнання WiFi на борту БПЛА мультироторного типу (МБПЛА) і бортове обладнання WiFi на борту БПЛА літакового типу (ЛБПЛА); 2) сегмент LoRaWAN, що складається з обладнання LoRaWAN на борту ЛБПЛА і обладнання LoRaWAN в КЦ. Наведено і описано приклад розгортання БПЛА-БМ з використанням САЗБ для передачі даних від ПК ЗАЕС в КЦ. Складено і проаналізовано графік змін для 2 флотів МБПЛА, що забезпечують постійну роботу БПЛА-БМ під час післяаварійного моніторингу ЗАЕС. Оцінено вплив польотної відстані МБПЛА від точки його розташування у сегменті WiFi до точки його розташування на САЗБ на такі параметри: час чергування флоту МБПЛА; час очікування початку польоту МБПЛА до точки його розташування у сегменті WiFi; кількість флотів МБПЛА для забезпечення безперебійної роботи БПЛА-БМ. Напрямок подальших досліджень включає розробку схеми розгортання БПЛА-БМ з використанням САЗБ для декількох сегментів WiFi.

Ключові слова: безпілотний літальний апарат; атомна електростанція; бездротова мережа; Wi-Fi; LoRaWAN; післяаварійний моніторинг; пост контролю; кризовий центр.

ИСПОЛЬЗОВАНИЕ АВТОМАТИЗИРОВАННЫХ СТАНЦИЙ ЗАМЕНЫ БАТАРЕЙ ДЛЯ ОБЕСПЕЧЕНИЯ БЕСПЕРЕБОЙНОЙ РАБОТЫ БЕСПРОВОДНЫХ СЕТЕЙ НА ОСНОВЕ БПЛА В ХОДЕ ПОСЛЕАВАРИЙНОГО МОНИТОРИНГА АЭС

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Актуальность. После аварии на атомной электростанции (АЭС) в г. Фукусима беспроводная сеть на основе беспилотных летательных аппаратов (БПЛА-БС) используется для передачи данных с постов контроля (ПК) в кризисный центр (КЦ) при осуществлении послеаварийного мониторинга АЕС. Однако время полета популярных легких БПЛА составляет всего около 20–40 минут. Последний факт представляет собой серьезную трудность для использования БПЛА-БС в ходе сложного и длительного послеаварийного мониторинга АЕС. Предметом статьи является процесс обеспечения бесперебойной работы БПЛА-БС. Цель статьи – предложить подход к обеспечению бесперебойной работы БПЛА-БС в ходе послеаварийного мониторинга АЕС за счет использования станций автоматической замены батарей (САЗБ). Задачами статьи являются: предложить схему развертывания БПЛА-БС с использованием САЗБ для заданного сценария; показать пример использования предложенной схемы для обеспечения бесперебойной передачи данных от ПК к КЦ в ходе послеаварийного мониторинга Запорожской АЭС (ЗАЭС); обсудить пример использования предло-

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

женной схемы. Были получены следующие результаты. Разработана и описана упрощенная схема развертывания БПЛА-БС с использованием САЗБ для передачи данных от ПК к КЦ в ходе послеаварийного мониторинга АЕС. При этом рассмотрены два сегмента в составе БПЛА-БС: 1) сегмент Wi-Fi, включающий оборудование WiFi на ПК, оборудование WiFi на борту БПЛА мультироторного типа (МБПЛА) и оборудование WiFi на борту БПЛА самолетного типа (СБПЛА); 2) сегмент LoRaWAN, состоящий из оборудования LoRaWAN на борту СБПЛА и оборудования LoRaWAN в КЦ. Приведен и описан пример развертывания БПЛА-БС с использованием САЗБ для передачи данных от ПК ЗАЭС в КЦ. Составлен и проанализирован график смен для 2 флотов МБПЛА, обеспечивающих постоянную работу БПЛА-БС в ходе послеаварийного мониторинга ЗАЕС. Оценено влияние полетного расстояния МБПЛА от точки его расположения в сегменте WiFi до точки его расположения на САЗБ на такие параметры: время дежурства флота МБПЛА; время ожидания начала полета МБПЛА до точки его расположения в сегменте WiFi; количество флотов МБПЛА для обеспечения бесперебойной работы БПЛА-БС. Направление дальнейших исследований включает разработку схемы развертывания БПЛА-БС с использованием САЗБ для нескольких сегментов WiFi.

Ключевые слова: беспилотный летательный аппарат; атомная электростанция; беспроводная сеть; Wi-Fi; LoRaWAN; послеаварийный мониторинг; пост контроля; кризисный центр.

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