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SCHEDULING UAV FLEETS FOR THE PERSISTENT OPERATION OF UAV-ENABLED WIRELESS NETWORKS DURING NPP MONITORING

Motivation. *During nuclear power plant (NPP) monitoring, unmanned aerial vehicles (UAVs) can be used as an affordable and cost-efficient tool to deploy a UAV-enabled wireless network (UEWN) for providing the crisis centre (CrS) needed monitoring data from monitoring stations (MSs) of the automated radiation monitoring system in case of damage of wired networks. However, because of the high electrical power requirement, the normal operation time of a UAV of a multi-rotor type (MUAV) is just 20 to 30 min, limiting the operation time of a UEWN during NPP monitoring missions. The* ***subject matter*** *of the paper is the process of ensuring the persistent operation of a UEWN. The* ***aim*** *of this paper is to develop a queuing theory based approach to scheduling MUAVs for persistent operation of a UEWN during NPP monitoring. The* ***objectives*** *of the paper are: to propose a scheme of deployment of a UEWN to connect a MS with the CrS of Zaporizhzhia (ZNPP) in case of damage of the wired network between the MS and the CrS; to introduce the main parameters characterizing the automatic battery charging station (ABCS) as a multi-channel queuing system; to develop and describe in detail a queuing theory based approach to scheduling MUAVs of the UEWN for persistent NPP monitoring. The following* ***results*** *were obtained. A scheme of deployment of a UEWN, consisting of LoRaWAN and WiFi segments, to connect a MS with the CrS of ZNPP in case of damage of the wired network between the MS and the CrS was proposed and described. A shift schedule for 3 MUAV fleets to ensure the persistent operation of the UEWN during ZNPP post-accident monitoring missions was built. It was shown that the ABCS can be considered as a multi-channel queuing system, in which two or more channels (battery charge points at the ABCS) are available to handle arriving MUAVs. A queuing theory based approach to scheduling MUAV fleets of the UEWN for persistent NPP monitoring is developed and described in detail. It was evaluated and illustrated by means of plots how the number of occupied channels of the ABCS depends on: 1) the battery charging time for the MUAV at the ABCS, and 2) the flight distance for the MUAV between its location point in the WiFi segment and the ABCS. The* ***next research steps*** *can cover issues regarding to: 1) scheduling MUAV fleets for numerous UEWNs, 2) developing models of a UEWN operation using a LiFi segment for transmission of monitoring data, and 3) developing reliability/survivability models of a UEWN taking into account UAV failures or/and wireless signal interference.*

Keywords: *unmanned aerial vehicle; nuclear power plant; shift schedule; multi-channel queuing system; automatic battery charging station; wireless network.*

Introduction

As numerous abbreviations/notations are used in the paper, let us present them by means of Table 1 to make the paper more readable.

During NPP monitoring, UAVs can be used as an affordable and cost-efficient tool to deploy a UEWN for providing the CrS of the NPP needed monitoring data from MSs of ARMS in case of damage of wired networks [1-3]. However, because of the high electrical power requirement, the normal operation time of a MUAV is just 20 to 30 min, limiting the operation time of UEWN during NPP monitoring missions.

On the one hand, the NPP monitoring mission duration of typical MUAVs is limited to the capacity of their energy storage system. On the other hand, the amount of time UAVs can be autonomous during this mission should be as long as possible.

For prolonging the NPP monitoring time, ABCSs/ABRSs are used.

As the wired networks can be damaged during both pre- and post-accident NPP monitoring, it is vital to note that the post-accident period can be characterized by amazing factors causing numerous failures of UAVs and wireless signal interference. These factors can be taken into account when developing reliability/survivability models of NPP post-accident monitoring systems based on UEWNs. In this paper, the authors assume that there are no problems with both numerous failures of UAVs and wireless signal interference during the operation of the considered UEWN.

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Table 1
Abbreviations/notations used

Abbreviation/ notation	Abbreviation/notation meaning
ABCS	automatic battery charging station
ABRS	automatic battery replacement station
ARMS	automated radiation monitoring system
AUAV	unmanned aerial vehicle of an airplane type
CrS	crisis centre
h	hour
km	kilometer
LiFi	light fidelity
LoRaWAN	low-power wide-area network
min	minute
MS	monitoring station
MUAV	unmanned aerial vehicle of a multi-rotor type
NPP	nuclear power plant
RP	rendezvous point
UAV	unmanned aerial vehicle
UEWN	unmanned aerial vehicle-enabled wireless network
WPT	wireless power transmission
ZNPP	Zaporizhzhia nuclear power plant

The paper is organized as follows. Section 1 discusses the existing studies on ensuring the persistent operation of UAVs via ABCSs using WPT and formulates the aim and objectives of the paper. Section 2 proposes and describes a scheme of deployment of a UEWN to connect a MS with the CrS of ZNPP in case of damage of the wired network between the MS and CrS. Section 3 considers a queuing theory based approach to scheduling MUAVs of the UEWN for persistent NPP monitoring. Section 4 presents the main results. Section 'Conclusions' concisely summarizes the results obtained and highlights the next research steps.

1. State of the art

In the previous work [3], authors of this paper primarily analyzed ABRSs/ABCSs using wired power transmission which requires some physical connection for drone battery charging. Even though wired power transmission is more efficient than wireless power transmission, the WPT technique is currently utilized for drone batteries charging. In this analysis, we focus on ABCSs using this technique.

Fetisov et al. [4] proposed to use a group of multicopters changing each other on duty over the object and a special charging station for their maintenance. The charging station includes a few charging terminals (2-contact terminals, 1-contact terminals, and non-contact terminals) laying on the horizontal flat site and powered from the common source.

A solution to utilize a drone as the round-the-clock surveillance system is suggested in [5]. The solution deals with the active landing-field which can support automatic charging and landing, the IoT-based command system, and the drone-user interaction application of the mobile device.

Reference [6] proposes a fully automatic charging station which operates wirelessly. The proposed system allows the drone to land on the platform freely, then, the station detects the position of the UAV on the platform and moves the charging coil under the UAV.

In [7], a cost effective automatic recharging solution for UAVs in outdoor environments is proposed using WPT. This research proposes a global positioning system and vision-based closed-loop target detection and a tracking system for precise landing of quadcopters in outdoor environment.

Campi et al. [8] propose the design and the optimization of a WPT charging system based on magnetic resonant coupling. In this study, a procedure for primary and secondary coil design is proposed. Key aspects for the design of the secondary coil onboard the UAV are the lightness and compactness of the WPT system components.

The ABCSs analyzed above can be used for the persistent operation UEWN during the NPP monitoring.

The aim of this paper is to develop a queuing theory based approach to scheduling MUAVs for persistent operation of a UEWN during NPP monitoring.

The objectives of the paper are:

– to propose a scheme of deployment of a UEWN to connect a MS with the CrS of ZNPP in case of damage of the wired network between the MS and the CrS;

– to introduce the main parameters characterizing the ABCS as a multi-channel queuing system;

– to develop and describe in detail a queuing theory based approach to scheduling MUAV fleets of the UEWN for persistent NPP monitoring.

2. A scheme of deployment of a UEWN for Zaporizhzhia NPP monitoring

Let us consider a UEWN deployed for ZNPP monitoring to connect MS14 with the CrS in case of damage of the wired network between MS14 and the CrS located on the south outskirt of Enerhodar (Fig. 1).

MS14, $MUAV1_R$, …, $MUAV8_R$, $MUAV9_{RG1}$, and UAV of an airplane-type ($AUAV_{RG2}$) form the WiFi segment of the UEWN.

The Low-Power Wide-Area Network (LoRaWAN) segment is used for $AUAV_{RG2}$-CrS communication.

$MUAVn_{RG1}$ acts both as a gateway for acquiring and storing data from $MUAV8_R$ and, being a RP, as a repeater for forwarding the data to $AUAV_{RG2}$. $AUAV_{RG2}$ gathers the data from $MUAVn_{RG1}$ during the assigned period and transmits them to the CrS.

3 ABCSs are deployed and each of them is available to charge batteries of 3 MUAVs simultaneously.

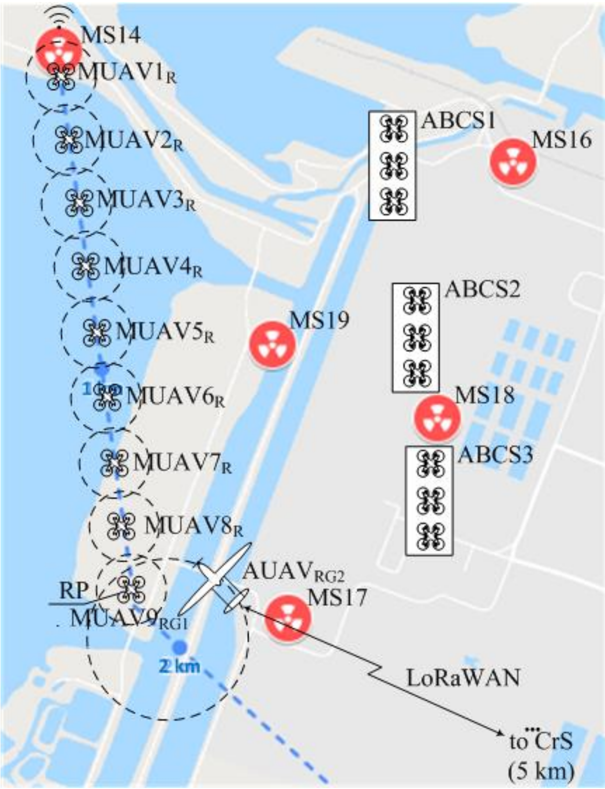

Fig. 1. Scheme of deployment of a UEWN used for Zaporizhzhia NPP monitoring (ZNPP) to connect MS14 with the CrS in case of damage of the wired network between MS14 and the CrS

The main parameters characterizing the UEWN are presented in Table 2.

Table 2

Main parameters characterizing the UEWN

Parameter	Value
The flight time of each MUAV	0.5 hours
The range of the onboard WiFi equipment of the MUAV	0.12 km
The length of the WiFi segment	1.8 km
The range of the onboard LoRaWAN equipment of the AUAV	5 km
The flight distance for each MUAV between its position in the WiFi segment and its position at ABCS	1 km

3. A queuing theory based approach to scheduling MUAV fleets of a UEWN for persistent NPP monitoring

To ensure the persistent operation of the UEWN, shown in Fig. 1, Kliushnikov et al. [3] propose to use 2 MUAV fleets (each fleet comprises 9 MUAVs), operating in accordance with the shift schedule and using ABRSs for battery replacement. According to [3], the shift schedule comprises 6 stages shown in Table 3.

Table 3

Stages of the shift schedule

Stage notation	Stage meaning
Fly_on	flight of each MUAV of the fleet from the ABRS to the point of its location in the WiFi segment
WiFi_conf	setting up the WiFi network configuration
On_duty	receiving and transmitting data
Fly_out	flight of each MUAV of the fleet from the point of its location in the WiFi segment to the ABRS (Fly_out)
Repl_bat	battery replacement (Repl_bat)
Waiting	each MUAV is waiting for the flight to the point of its location in the WiFi segment

Let us assume that we use battery charging via ABCSs instead of battery replacement via ABRSs. In this case, we have stage Charge_bat instead of Repl_bat.

The duration of the operation (duty time) for the MUAV fleet for the case when all the MUAVs have the same flight distance (S_{MUAV}) between their location point in the WiFi segment and the ABRS can be determined by the following expression:

$$t_{on\_duty} = E_{MUAV} - \frac{2S_{MUAV}}{v_{MUAV}} - t_{WiFi\_conf} \text{ (h)}, \quad (1)$$

where E_{MUAV} is the endurance of the MUAV (h); v_{MUAV} is the speed of the MUAV (km/h); t_{WiFi_conf} is the time to set up the WiFi network configuration (h).

The number of the MUAV fleets (shifts) for ensuring the persistent operation of the UEWN can be determined as

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

where t_{charge_bat} is the time to charge the battery at the ABCS.

The waiting time for the MUAV to flight to the point of its location in the WiFi segment can be calculated in the following way:

$$t_{wait} = t_{on\_duty} - \frac{2S_{MUAV}}{V_{MUAV}} - t_{WiFi\_conf} - t_{charge\_bat}. \quad (3)$$

As, traditionally, $t_{charge\_bat} \gg t_{repl\_bat}$, we can face the situation when Charge_bat stage has not finished yet but On_duty stage has already ended (Fig. 2).

To cope with the problem, the number of the MUAV fleets (shifts) for ensuring the persistent operation of the UEWN needs increasing (Fig. 3).

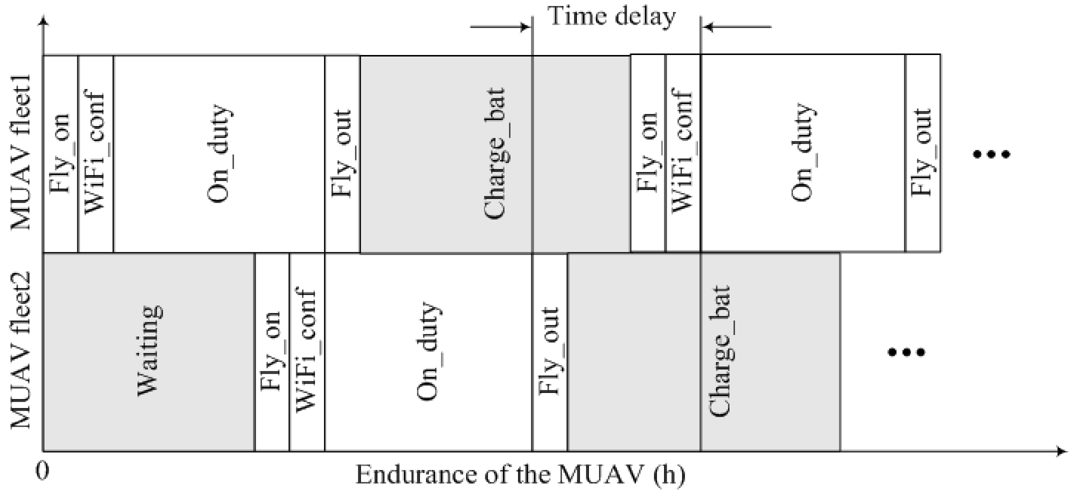

Fig. 2. Shift schedule for 2 MUAV fleets with time delay

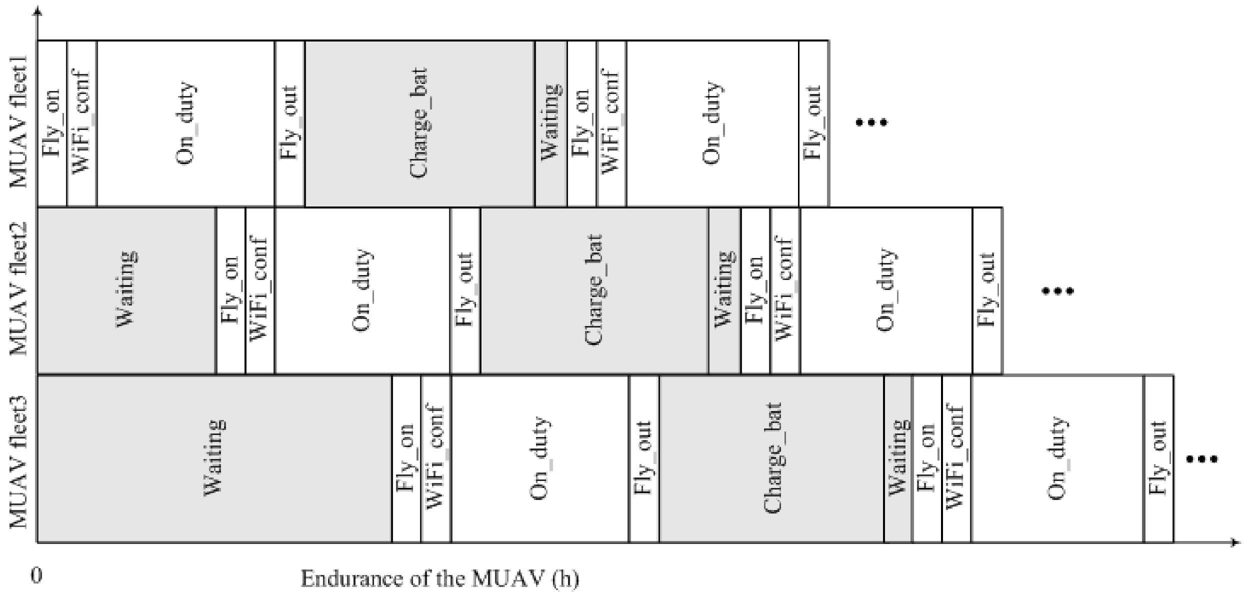

Fig. 3. Shift schedule for 3 MUAV fleets ensuring the persistent operation of the UEWN for ZNPP monitoring missions

Consider the ABCS as a multi-channel queuing system, in which two or more channels (battery charge points at the ABCS) are available to handle arriving MUAVs.

To ensure persistent operation of the UEWN, the number of the channels (battery charge points at the station) should be a multiple of two for each MUAV. The ABCS operating as a 6-channel queuing system is shown in Fig. 4. The main parameters characterizing the ABCS as a multi-channel queuing system are presented in Table 4. The parameters listed in Table 4, can be calculated by means of formulae (4) – (10).

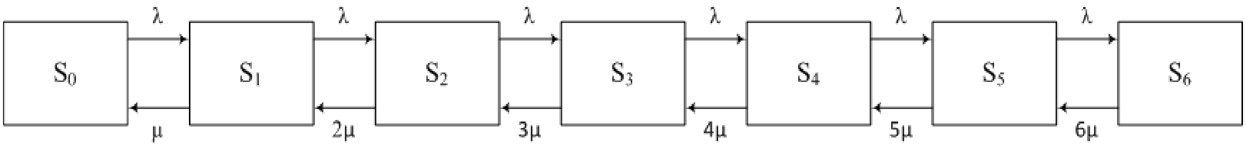

Fig. 4. ABCS operating as a 6-channel queuing system

Table 4

Main parameters characterizing the ABCS as a multi-channel queuing system

Parameter	Parameter meaning
n	number of the channels (battery charge points at the station)
z	number of MUAVs, which are charged at one ABCS
λ	arrival rate of MUAVs
μ	service rate of MUAVs
ρ	occupation rate
P_0	probability of all channels are idle
P_n	probability of all channels are occupied
n_b	number of occupied channels
k_b	occupation coefficient

$$\lambda = \frac{z}{t_{on\_duty} - \frac{2S_{MUAV\_way}}{v_{MUAV}} - t_{WiFi\_conf}}, \quad (4)$$

$$\mu = \frac{1}{t_{charge\_bat}}, \quad (5)$$

$$\rho = \frac{\lambda}{\mu}, \quad (6)$$

$$P_0 = \left(\sum_{n=0}^{n} \frac{\rho^n}{n!} \right)^{-1}, \quad (7)$$

$$P_n = \frac{\rho^n}{n!} P_0, \quad (8)$$

$$n_b = \rho(1 - P_n), \quad (9)$$

$$k_b = \frac{\rho}{n}(1 - P_n). \quad (10)$$

4. Main results

Let us evaluate how the number of occupied channels of the ABCS depends on: 1) the battery charging time for the MUAV at the ABCS, and 2) the flight distance for the MUAV between its location point in the WiFi segment and the ABCS. Results of this evaluating are presented in Figs. 5 and 6. (E_{MUAV} = 0.5 h, v_{MUAV} = 40 km/h, t_{WiFi_conf} = 0.017 h).

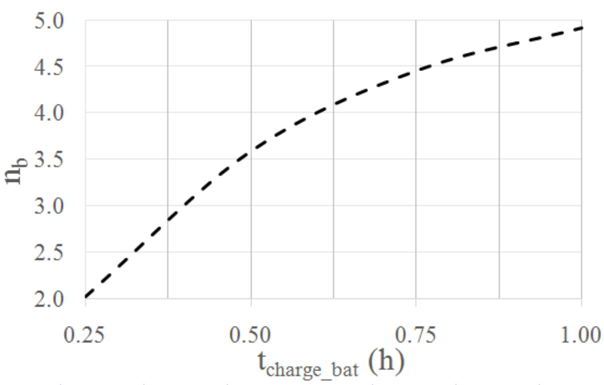

Fig. 5. Dependency of the number of occupied channels of the ABCS on the battery charging time for the MUAV at the ABCS

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 ABCS from 1 to 4 km leads to using more than 3 channels to serve the MUAVs (Fig. 5);

– growth in the battery charging time for the MUAV at the ABCS from 0.25 to 1 h leads to an increase in occupied channels of the ABCS by 2.5 times (5 channels are occupied instead of 2 ones) (Fig. 6).

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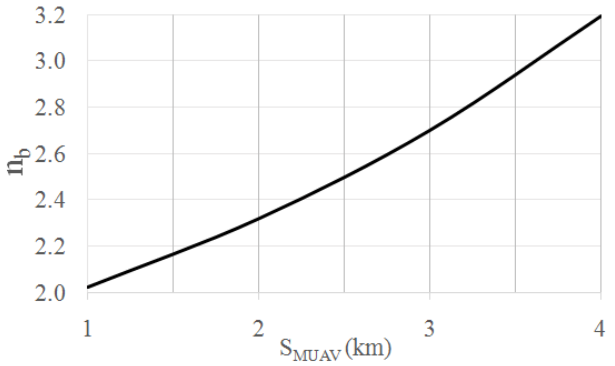

Fig. 6. Dependency of the number of occupied channels of the ABCS on the flight distance for the MUAV between its location point in the WiFi segment and the ABCS

Conclusions

A scheme of deployment of a UEWN, consisting of LoRaWAN and WiFi segments, to connect a MS with the CrS of ZNPP in case of damage of the wired network between the MS and the CrS was proposed and described.

A shift schedule for 3 MUAV fleets to ensure the persistent operation of the UEWN during ZNPP post-accident monitoring missions was built.

It was shown that the ABCS can be considered as a multi-channel queuing system, in which two or more channels (battery charge points at the ABCS) are available to handle arriving MUAVs.

A queuing theory based approach to scheduling MUAV fleets of a UEWN for persistent NPP monitoring is developed and described in detail.

It was evaluated and illustrated by means of plots how the number of occupied channels of the ABCS depends on: 1) the battery charging time for the MUAV at the ABCS, and 2) the flight distance for the MUAV between its location point in the WiFi segment and the ABCS.

The next research steps can cover issues regarding to: 1) scheduling MUAV fleets for numerous UEWNs, 2) developing models of the UEWN operation using a LiFi segment for transmission of monitoring data, and 3) developing reliability/survivability models of the UEWN operation taking into account UAV failures or/and wireless signal interference.

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СКЛАДАННЯ ГРАФІКА ВИКОРИСТАННЯ ФЛОТІВ БПЛА ДЛЯ ЗАБЕЗПЕЧЕННЯ БЕЗПЕРЕБІЙНОЇ РОБОТИ БЕЗДРОТОВИХ МЕРЕЖ НА ОСНОВІ БПЛА ПІД ЧАС МОНІТОРИНГУ АЕС

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Актуальність. Під час перед- та післяаварійного моніторингу на атомній електростанції (АЕС) безпілотні літальні апарати (БПЛА) можуть використовуватися у якості доступного і економічно ефективного інструменту для розгортання бездротової мережі на основі БПЛА (БПЛА-БМ) з метою забезпечення кризового центру (КЦ) необхідними даними моніторингу з постів контролю (ПК) автоматизованої системи контролю радіаційної обстановки у разі пошкодження дротових мереж. Однак через високі вимоги до електричної потужності, звичайний час роботи мультироторного БПЛА (МБПЛА) становить усього 20-30 хвилин, що обмежує час використання БПЛА-БМ під час моніторингу АЕС. Предметом статті є процес забезпечення безперебійної роботи БПЛА-БМ. Метою даної роботи є розробка заснованого на теорії масового обслуговування підходу до складання графіка використання флотів БПЛА для забезпечення безперебійної роботи БПЛА-БМ під час моніторингу АЕС. Завданнями статті є: запропонувати схему розгортання БПЛА-БМ для встановлення бездротового з'єднання між ПК і КЦ Запорізької АЕС (ЗАЕС) у разі пошкодження дротової мережі між ПК і КЦ; ввести основні параметри, що характеризують автоматичну зарядну станцію батарей (АЗСБ) як багатоканальну систему масового обслуговування; розробити і детально описати заснований на теорії системи масового обслуговування підхід до складання графіка використання флотів БПЛА для забезпечення безперебійної роботи БПЛА-БМ під час моніторингу АЕС. Були отримані наступні результати. Запропоновано і описана схема розгортання БПЛА-БМ, що складається із сегментів LoRaWAN і WiFi, для встановлення бездротового з'єднання між ПК і КЦ ЗАЕС у разі пошкодження дротової мережі між ПК і КЦ. Складено графік використання 3 флотів МБПЛА для забезпечення безперебійної роботи БПЛА-БМ під час моніторингу ЗАЕС. Показано, що АЗСБ можна розглядати як багатоканальну систему масового обслуговування, у якій існують два або більше каналів (точок зарядки акумулятора на АЗСБ) для обслуговування МБПЛА. Розроблено і докладно описано заснований на теорії масового обслуговування підхід до складання графіка використання флотів БПЛА для забезпечення безперебійної роботи БПЛА-БМ під час моніторингу АЕС. Оцінено і проілюстровано за допомогою графіків вплив на кількість зайнятих каналів АЗСБ наступних параметрів: 1) часу зарядки батареї МБПЛА на АЗСБ і 2) відстані між точкою знаходження МБПЛА в WiFi сегменті і точкою розміщення його на АЗСБ. Напрямки подальших досліджень можуть охоплювати питання, що стосуються: 1) складання графіків використання БПЛА в інтересах численних БПЛА-БМ; 2) розробки моделей функціонування БПЛА-БМ з використанням сегмента LiFi для передачі даних моніторингу; 3) розробки моделей надійності/живучості БПЛА-БМ з урахуванням відмов БПЛА і / або перешкод у бездротових мережах.

Ключові слова: безпілотний літальний апарат; атомна електростанція; змінний графік; багатоканальна система масового обслуговування; автоматична зарядна станція батарей; бездротова мережа.

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СОСТАВЛЕНИЕ ГРАФИКА ИСПОЛЬЗОВАНИЯ ФЛОТОВ БПЛА ДЛЯ ОБЕСПЕЧЕНИЯ БЕСПЕРЕБОЙНОЙ РАБОТЫ БЕСПРОВОДНЫХ СЕТЕЙ НА ОСНОВЕ БПЛА В ХОДЕ МОНИТОРИНГА АЭС

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Актуальность. В ходе до- и послеаварийного мониторинга атомной электростанции (АЕС), беспилотные летательные аппараты (БПЛА) могут использоваться в качестве доступного и экономически эффективного инструмента для развертывания беспроводной сети на основе БПЛА (БПЛА-БС) с целью обеспечения кризисного центра (КЦ) необходимыми данными мониторинга с постов контроля (ПК) автоматизированной системы мониторинга радиационной обстановки систем в случае повреждения проводных сетей. Однако из-за высоких требований к электрической мощности обычное время работы мультироторного БПЛА (МБПЛА) составляет всего 20-30 минут, что ограничивает время работы БПЛА-БС в ходе мониторинга АЭС. Предметом статьи является процесс обеспечения бесперебойной работы БПЛА-БС. Целью данной работы является разработка основанного на теории массового обслуживания подхода к составлению графика использования флотов БПЛА для обеспечения бесперебойной работы БПЛА-БС в ходе мониторинга АЭС. Задачами статьи являются: предложить схему развертывания БПЛА-БС для установления беспроводного соединения между ПК и КЦ Запорожской АЕС (ЗАЭС) в случае повреждения проводной сети между ПК и КЦ; ввести основные параметры, характеризующие автоматическую зарядную станцию батарей (АЗСБ) как многоканальную систему массового обслуживания; разработать и подробно описать основанный на теории системы массового обслуживания подход к составлению графика использования флотов БПЛА для обеспечения бесперебойной работы БПЛА-БС в ходе мониторинга АЭС. Были получены следующие результаты. Предложена и описана схема развертывания БПЛА-БС, состоящей из сегментов LoRaWAN и WiFi, для установления беспроводного соединения между ПК и КЦ ЗАЭС в случае повреждения проводной сети между ПК и КЦ. Составлен график использования 3 флотов МБПЛА для обеспечения бесперебойной работы БПЛА-БС в ходе послеаварийного мониторинга ЗАЭС. Показано, что АЗСБ можно рассматривать как многоканальную систему массового обслуживания, в которой существуют два или более каналов (точек зарядки аккумулятора на АЗСБ) для обслуживания МБПЛА. Разработан и подробно описан основанный на теории массового обслуживания подход к составлению графика использования флотов БПЛА для обеспечения бесперебойной работы БПЛА-БС в ходе мониторинга АЭС. Оценено и проиллюстрировано с помощью графиков влияние на количество занятых каналов АЗСБ следующих параметров: 1) времени зарядки аккумулятора МБПЛА на АЗСБ и 2) расстояния между точкой нахождения МБПЛА в WiFi сегменте и точкой размещения его на АЗСБ. Направления последующих исследований могут охватывать вопросы, касающиеся: 1) составления графиков использования БПЛА в интересах многочисленных БПЛА-БС; 2) разработки моделей функционирования БПЛА-БС с использованием сегмента LiFi для передачи данных мониторинга; 3) разработки моделей надежности/живучести БПЛА-БС с учетом отказов БПЛА и / или помех в беспроводных сетях.

Ключевые слова: беспилотный летательный аппарат; атомная электростанция; сменный график; многоканальная система массового обслуживания; автоматическая зарядная станция батарей; беспроводная сеть.

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