A Markov Decision Process-based Collision Avoidance in IoT Applications

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***Abstract*—IoT covers various scales and types of wireless networks. The first constraint to be respected, for an efficient application, is to reduce as much as possible the amount of energy consumption. The idle listening process in existing Medium Access Control (MAC) protocols is a very energy consuming task. Recently, a new emerging technology based on a low power wake-up radio has shown real benefits by completely eliminating the problem of idle listening. Thanks to the use of this technology, an IoT device keeps its main radio in deep sleep until a wake-up message is received by the wake-up radio that consumes less energy. However, collision can occur among wake-up messages (i.e., wake-up plane). Collision in the wake-up plane, if not handled efficiently, leads to collision at the data plane which is more complicated. In this paper, we address this issue by modeling the wake-up decision using a Markov Decision Process (MDP). The goal is to formulate a decision policy that determines whether to send a wake-up message in the actual time slot or to report it, taking into account the time factor. Experiments have been conducted to determine the decision policies. Results of the proposed approach have been compared against those of RFIDImpulse, a CSMA\CA-based wake-up MAC protocol. The obtained results show the efficiency of the proposed approach.**

I. Introduction

Unmanned Aerial Vehicles (UAVs) have emerged recently and attracted both academic and industry attention as an interesting research area. It retrieves its power from its combination with IoT technology, that is gaining ground with its potential on making our daily life as smart as possible. UAVs, also known as drones, have been rapidly evolved and are now deployed in diverse sectors of our daily life. This is due to their small size and capability to fly without an on-board pilot, allowing to perform a wide range of activities from delivering a package, crowd surveillance, to diving into water for a specific underwater operations [1]. The applications of UAVs can be broadly divided into civilian and military models. The former can be utilized for governmental or non-governmental purposes [2]–[6].

One interesting application is the employment of UAVs in the field of agriculture for the role of crop management [7]–[9]. Regular aerial monitoring of agricultural lands allows deep analysis of crop performance. With the help of the different IoT devices (sensors and actuators) deployed either on the drone or on the ground, the health of these crops could be studied and immediate automatic actions could be taken accordingly. In this kind of applications, the ground sensors which are forming a wireless sensor network, regularly collect relevant data related to the studied phenomenon and report them to the UAV when it is flying in the neighborhood, in order to take strategic decisions. If a given ground sensor needs to announce some urgent data such as fire detection and flood monitoring, and that no drone has been captured in the neighborhood for a precise period of time, it sends this data to some alternative nodes which are assumed to have higher probability of being regularly in contact with flying UAVs. This not only leads to healthy crop growth, but also increases their yield.

Guaranteeing a long lifetime, and thus a solid and a reliable application is strongly dependent on ensuring long operation periods of the deployed IoT devices, without any human intervention after the initial deployment. This could only be guaranteed by assuring an energy efficient communication scheme. Avoiding Idle listening is thus considered mandatory to achieve this gaol [10], [11]. The integration of an additional low power wake-up radio [12] behind the IoT device's main radio is considered as a promising solution that completely eliminates the problem of idle listening [13], [14]. This is thanks to the fact that the main radio of the device could enter into the deep sleep mode whenever there is no transmission destined to it, while the low power wake-up radio is kept listening to the channel in order to detect possible incoming transmissions. The wake-up radio is either a passive circuit powered by the energy of the wake-up signal [15] or a semi-active one consuming few μ watts of power [16].

Adopting the wake-up radio technology in the aforementioned application may have a great impact on the energy efficiency, the fact that ground sensor nodes will never need to perform duty cycling to sense whether there is some drone flying in the vicinity. Instead they could stay in sleep mode as no drone is present in the neighborhood. Once the drone is within the transmission range of the intended node, it wakes it up using a wake-up signal which will be received by the low power wake-up radio. At this time, the sensor node switches on its main radio and starts transmitting the collected data toward the drone. Once data transmission has finished, the main radio goes back to sleep mode, saving thus energy.

When drones are flying, gathering data from ground sensors, it may happen, due to several control conflicts, that more than one drone is trying to wake up the same sensor node. Receiving several wake-up signals at the same time leads to the well known problem of collision. This could also happen when some ground sensor nodes are exchanging some urgent data, due to lateness of some drones. Collision is considered

978-1-5090-5019-2/17/$31.00 ©2017 IEEE

as another source of energy waste, since the energy depleted in transmission and reception of collided messages is just lost. Several retransmissions should take place, which results in supplementary energy consumption. This has been considered very costly, mainly for energy-constrained networks. However, non of the previous works have considered this problem, when implementing wake-up radio-based schemes. In this paper, we address the problem of collision at the wake-up plane, i.e between wake-up messages, by proposing an infinite horizon time Markov Decision Process (MDP). The aim is to derive a decision policy that determines whether a drone, when it is in the vicinity of the destined ground sensor node, should transmit a wake-up signal to initiate data gathering or postpone it for the next time slot. The same decision should be taken by the ground node before waking up its neighbor in case of exchanging urgent data. In addition to collision handling and energy efficiency guaranteeing, the driven policy should take the time factor into high consideration, avoiding thus large delays that may result from unnecessary postponing of decisions.

The reminder of the paper is structured as follow. Section II summarizes briefly how the relevant research work, proposed in the recent literature have handled the problem of collision in wake-up radio-based schemes. In Section III, we present the problem of collision in wireless networks and formulate the model based on MDP framework. The conducted experiments and the results analysis are presented in Section IV. Finally, the paper concludes in Section V.

II. Related work

A lot of research work has been conducted on wake-up radioin the literature [17]. However, just some of them discuss the problem of collision at the wake-up plane. In a few research work investigating the collision issue, only basic and traditional mechanisms, which are based on CSMA\CA protocol, have been adopted, such as carrier sensing [12] and random binary back-off. The work introduced in [18] was based on the IEEE 802.15.4 standard [19]. For each device in the network, an RFID reader and a tag are integrated behind the main radio. The RFID reader is used to wake up the RFID tag that represents a wake-up radio. When there is a packet to transmit, the sender, using its RFID reader starts by performing a clear channel assessment in a random chosen slot within the contention window. If the channel is found free, the wake-up message will be sent; otherwise a random back-off mechanism will be followed until the channel becomes idle, or the maximum listening duration will be reached. Authors in [20] proposed, for the wake-up radio, a scheme following the IEEE 802.11 protocol. The introduced work includes both physical and virtual carrier sensing as well as the RTS\CTS control packet exchange, before transmitting a wake-up message. Physical carrier sensing is achieved by sensing the channel to check whether it is idle or busy. Virtual carrier sensing is performed at each packet reception, in which the transmission duration is included. From this information, the receiver, that is not the intended one, could be aware of the duration for which the channel will be busy, and thus it prohibits itself from accessing the channel during that period.

In order to avoid collision at the wake-up plane, some other research work have proposed the use of multi channel techniques for the wake-up radio [21], [22]. In [21], different frequency channels have been assigned to 2-hops neighboring devices. When the transmitter has a packet to transmit to a receiver, it tunes its wake-up radio channel to the receiver's frequency channel and monitors it for a predefined period of time. If the channel is found free, the wake-up radio starts transmitting the wake-up message; otherwise, it should wait until the channel becomes free. Adopting multi-channel schemes could not alleviate the problem of collision at the wake-up plane. This could always happen when more than one nodes try to wake up the same receiver. A different research work [23] proposed the use of TDMA-like scheduling. For each device a schedule table is managed and maintained by a central point. The latter calculates the wake-up time of each device according to the packet generation rate. Another work, following also a TDMA scheme, has been proposed for bats tracking and monitoring in [24]. Scheduling communications based on TDMA protocol may avoid collision in small networks. However, it could not be applied in large scale networks, where the scheduling task becomes more complicated due to synchronization problems which result in high energy consumption.

Adopting basic mechanisms, which are based on random operations such as the random binary back-off techniques, for collision avoidance could be considered helpful. However, it is not the most efficient way to handle collision. In fact, in contention based schemes, when a device has a packet to transmit, it initializes a contention window with a minimal value and then chooses randomly a given slot within this window to perform a back-off. After each failed transmission, the contention window will be doubled up to a maximum value. When the number of devices involved in collision is important, collision persists and its probability becomes higher. This is attributable to the fact all devices are trying to retransmit in the same fashion (i.e., increasing the contention window and choosing a back-off value randomly). The key behind this issue in contention based scheme is that initially, and regardless the size and density of the network, all devices have the same probability to access the channel (i.e., the same contention window value), which is static during the network lifetime. This raises the need to develop other solid models, which must take into account the network dynamics and should be based on deep studies related to several factors (e.g., network density and packet arrival probability) to efficiently handle the problem of collision at the wake-up plane and ensure better fairness. In contrast to all previous works, in this paper, the wake-up decision is based on robust mathematical studies. Since in real wireless networks, wireless devices take actions and then transit from one state to another in a stochastic environment, this could be exactly imitated by modeling the network using the mathematical MDP framework that allows optimizing the network's objectives in an efficient way.

III. System Model

A. Problem Description

We consider the problem of collision at the wake-up plane. As has been mentioned earlier, each ground node is dotted with a wake-up radio, situated behind the main radio and responsible for waking it up when a wake-up message is received. To reduce potential collision between wake-up messages and data packets, two different frequency channels could be used, one for the main radio and the other for the wake-up radio. When a transmitter A, which could be either a drone or a ground sensor node, wants to transmit a data packet to a receiver B representing a ground sensor node, it starts by transmitting, using its main radio a wake-up message at the wake-up radio frequency channel asking the receiver to wake up and be ready to transmit or receive data. The wake-up message is a signal including the address of the sender and the receiver and could be used by the receiver's wake-up radio to power on itself and trigger the micro-controller which in turn wakes up the main radio [12] [25]. When the same ground sensor node receives more than one wake-up signals at the same time, collision happens and the receiver cannot send back an acknowledgment since it cannot detect the transmitter. Retransmissions should then take place until an acknowledgement is received. This results in a large amount of energy consumption, mainly that wake-up messages should be transmitted using the main radio of the sender. Collision at the wake-up plane, if not handled, may lead to collision at the data plane which is more energy consuming. However, if the wake-up message is successfully received, the receiver, using its main radio, broadcasts a message to its neighborhood indicating that it is receiving data from device A. This allows device A to start data transmission and prevents all others from transmitting during a predefined period of time.

B. Model Formulation

To solve the problem of collision at the wake-up plane, we model the system as a Markov Decision Process (MDP). The proposed model decides on whether a wake-up message should be transmitted in the actual time slot or reported to the next one. The MDP decision procedure is supposed to be implemented on UAVs as well as on ground sensor nodes. To derive the wake-up decision policy, we develop an infinite horizon MDP that associates actions, corresponding transition probabilities and rewards to each state. In order to improve the overall network performance, the proposed MDP models all the network, whereby each state represents not only the device condition but all the network behavior, taking in each state the action of the device that is ready to transmit a wake-up message.

We suppose the decision process starts when a UAV reaches the communication range of the intended node. In some cases, this process starts when an urgent data packet arrives at a given ground sensor node which will forward it to one of

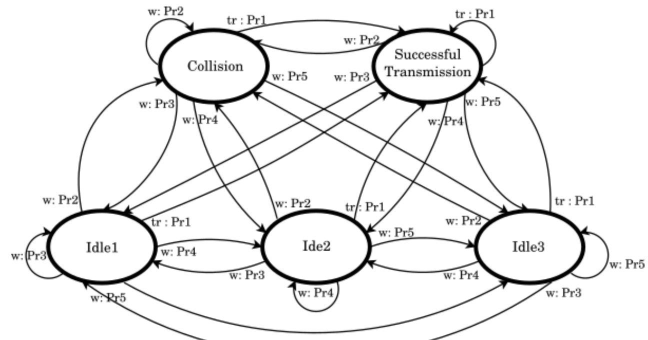


Fig. 1: MDP of collision handling at the wake-up plane
Pr1= pr(successful transmission$\backslash$s $\in \mathbb{S}$, a=tr), Pr2= pr(collision$\backslash$s $\in \mathbb{S}$, a=tr), Pr3= pr(idle1$\backslash$s $\in \mathbb{S}$, a=w), Pr4= pr(idle2$\backslash$s $\in \mathbb{S}$, a=w), Pr5= pr(idle3$\backslash$s $\in \mathbb{S}$, a=w)

its neighbors. In order to formulate a state space, we assume each device (either a ground sensor node or a drone) willing to transmit a wake-up message, takes into consideration the other devices' actions. We denote by A=(tr, w) the vector representing the possible actions available for the decision maker at each state. Action tr designates that the agent decides to transmit a wake-up message, while w indicates that a decision of waiting has been taken. Taking into account the possible actions of the other devices, five different states could be driven (Fig. 1). The first one, referred to as $successful\ transmission$, reflects the network where only the decision maker decides to transmit a wake-up message. The agent tries always to increase his chances to enter this state. The second state, called $collision$, represents the network where the decision maker and some other devices decide to transmit simultaneously a wake-up message to the same destination. The three remaining states, represented by $idle1$, $idle2$ and $idle3$ could be reached when the action of wait has been chosen by the decision maker, while different actions have been taken by the other devices. In case only one device from the $(n-1)$ remaining devices has decided to transmit, so the others have chosen to wait, the agent is said to be in state $idle1$. When more than one of the remaining devices have decided to simultaneously transmit, collision between them happens. This leads the system to be in state $idle2$. State $idle3$ represents the network where both the decision maker and the remaining devices have decided to choose the action of wait. Hence the state space is defined as S=$\{$ $successful\ transmission$, $collision$, $idle1$, $idle2$, $idle3\}$.

In order to derive transition probabilities, we consider the network composed of a set of n devices including UAVs and ground sensor nodes. Let p be the probability of packet transmission rate which follows a Poisson distribution. We denote by Pr the transition probability matrix with $Pr(s'|s, a)$ indicating the transition rate between states s and s' in S taking a given action a, which in the proposed scenario, represents the network channels situation passing between

$$pr(s'|s,a) = \begin{cases} (1-p)^{n-1} & s' = \text{successful transmission, } s \in \mathbb{S},\ a = tr \\ 1-(1-p)^{n-1} & s' = \text{collision, } s \in \mathbb{S},\ a = tr \\ (n-1)p(1-p)^{n-2} & s' = \text{idle1, } s \in \mathbb{S},\ a = w \\ 1-((n-1)p(1-p)^{n-2}+(1-p)^{n-1}) & s' = \text{idle2, } s \in \mathbb{S},\ a = w \\ (1-p)^{n-1} & s' = \text{idle3, } s \in \mathbb{S},\ a = w \end{cases} \tag{1}$$

$successful\ transmission$, $collision$ or $idle$ states, when n devices take their actions. Thus, transition probabilities can be given as presented in (1).

For $t \in \mathbb{T}$, let s_t, a_t, and r_t denote state, action and reward at time t of the proposed MDP, respectively. Let $PR^a_{(s,s')}$= $pr[s_{(t+1)}$=$s'|s_t$=$s, s_{(t+1)}$=s', a_t=$a]$ indicates the transition probabilities, and $R^a_{(s,s')}$= $E[r_{(t+1)}|s_t$=$s, s_{(t+1)}$=s', a_t=$a]$ designates the expected reward associated to the transitions. A policy π, denoted as a_t=$\pi(s_t)$, is defined as a mapping that associates for each state s a given action a. Consequently, a policy π=$(\pi_1, \pi_2, \pi_3, ...\pi_T)$ represents the sequence of taken decision rules at all decision epochs. When the agent is in a given state, it has to decide to transmit a wake-up message in this time slot using action tr or waiting for the next time slot following action w. For each transition, given the state s where the agent actually is, the state s' where the agent will move on, and the chosen action a, a reward is achieved. This reward associates to each action at each state a precise value that is a function of the outcomes received from the actual and the next states, respectively.

Let $C(s)$ be the function that associates for each state a cost. When a successful transmission occurs, i.e when a device enters this state, it will gain the difference between a certain constant g and the cost needed to transmit a wake-up message. At the other side, if a collision happens, this means that the transmitting device has only wasted its energy, and thus the cost at this state is the amount of energy consumed when transmitting a wake-up message. Since the energy is just wasted, so the cost will be a negative value indicating that the device has lost by entering this state. Since $idle1, idle2$ and $idle3$ represent states in which the device has preferred not to transmit, and in order to take into consideration the time factor and avoid extra delay, we consider the device executing this state is receiving a negative cost represented by the amount of time needed to transmit a wake-up packet. This is for the goal of limiting the waiting time, as choosing the action wait may lead to time loss. Taking into consideration the fact that state $idle1$ assumes that a successful transmission happens in the other side of the network (between the $(n-1)$ remaining devices) and so, the cost of this state is the sum of the time lost by choosing the action w (by the decision maker) and a certain percentage (represented by α) of the gain achieved when the $(n-1)$ devices perform a successful transmission. In the same way of reasoning, in state $idle2$, a collision happens between the $(n-1)$ devices. Since this has an impact on the whole network, so the cost when entering this state is always the time lost by the decision maker summed to a certain ratio (β) when collision happens between $(n-1)$ devices. In state $idle3$, and since all devices choose not to transmit, this may affect the delay. Therefore, the cost is the time lost by the actual agent added to a certain ratio (δ) of the time lost by the others. The possible costs are given as follows:

$$C(s)= \begin{cases} g-E & s=successful\ transmission \\ -E & s=collision \\ -I+\alpha(g-E) & s=idle1 \\ -I-\beta E & s=idle2 \\ -I-\delta I & s=idle3 \end{cases} \tag{2}$$

where E is the energy consumed when transmitting a wake-up packet. It is expressed as:

$$E=M_{length} * T_b * c_t * h \tag{3}$$

where M_{length} is the length of the wake-up message, T_b is the time needed to transmit one byte, c_t is the current drawn when the radio is in transmit mode, and h is the supply voltage. From (2), I is the time needed to transmit a wake-up message. It is defined as:

$$I=M_{length} * T_b \tag{4}$$

It is clear that $I < E$, and so there is always a gain when being in an idle state, in comparison to being in collision state. α, β and δ are thresholds used to improve the network performance. α, β and $\delta \in]0,1]$.

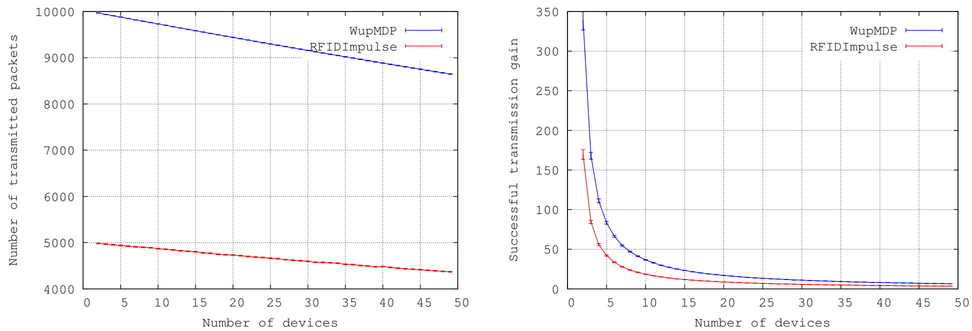
The reward function is thus a mapping that associates for each tuple (s, a, s') a value $v \in \mathbb{R}$. It is defined as the sum of the cost received when being in the actual state s and the cost obtained when moving to the next state s', taking action a. The reward is given as follows:

$$r(s,a,s')= \sum_{i \in \{s,s'\}} C(i) \tag{5}$$

Given an initial state s and a discount factor $\gamma \in]0,1]$, the expected total discounted reward for the policy π=$(\pi_1, \pi_2, \pi_3, ...\pi_T)$ is given as follows:

$$V^{\pi}_{\gamma}= \lim_{T\to\infty} E^{\pi}_{\gamma}\{\sum_{t=1}^{T} \gamma^{t-1} r_t\} \tag{6}$$

Let $V^*(s) = max_{\pi \in \Pi} V^{\pi}(s)$ denote the maximum discounted total reward, given the initial state s. From [26], the optimality equations are given by:



(a) Number of successfully transmitted packets in the network.

(b) Gain between successfully transmitted and collided packets in the network.

Fig. 2: Performance evaluation of WupMDP for varying numbers of devices.

$$V^*(s) = max_{\pi \in \Pi}\{r'(s,a,s') + \sum_{s' \in \mathbb{S}} \gamma Pr(s'|s,a)V^*(s')\} \tag{7}$$

The solutions of the optimality equations correspond to the maximum expected discounted total reward $V^*(s)$ and the optimal policy $\pi^*(s)$. Note that $\pi^*(s) = argmax_{a \in A} \sum_{s' \in \mathbb{S}} Pr(s'|s,a)V^*(s')$. The latter indicates for the agent the optimal decision to take in each state. There are several algorithms that can be used to resolve the optimization problem given by the above optimality equations. Policy iteration is one example.

IV. Experimentation Results

In this section, the proposed scheme, WupMDP, is validated via computer-based simulations and compared to RFIDImpulse [18]; a CSMA\CA-based wake-up MAC protocol. The latter has been chosen as a representative scheme since all the research work, proposed for the wake-up radio in the literature, are based on CSMA\CA MAC protocol. The proposed model is evaluated in terms of the following metrics:

- Number of successfully transmitted packets in the network: defined as the total number of times devices enter the state $Successful\ transmission$.
- Gain between successfully transmitted and collided packets in the network: defined as the number of successful transmissions per collision. Formally, this metric represents the number of successful packets transmitted before one collision is occurred.

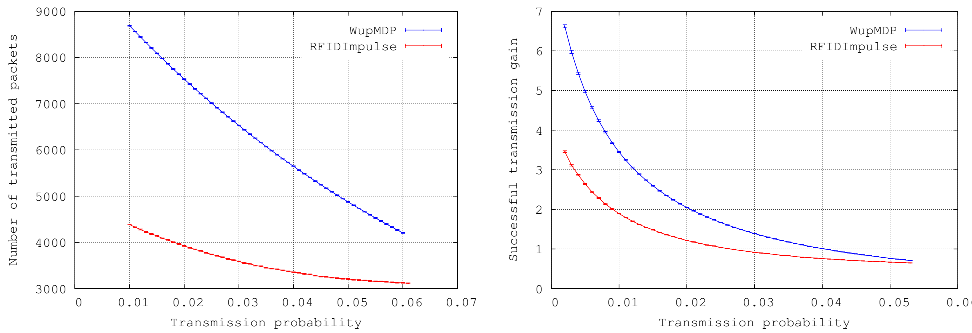
To derive the wake-up decision policy, we used a python implementation of the policy iteration algorithm presented in [27]. In the simulation results, each plotted point represents the average of 100 executions. The plots are presented with 96% confidence interval. The two schemes are evaluated by varying the number of devices n and transmission probability p. We conduct two sets of experiments. Firstly, we vary the number of devices n while fixing p to 0.03. Then, we vary p and fix n to 15.

Fig.2 shows the performance evaluation of the WupMDP as a function of the number of devices n. In Fig.2 (a), the number of successfully transmitted packets is calculated and compared to that of RFIDImpulse scheme. The observations we can draw from this figure are: $i)$ the number of successfully transmitted packets decreases by increasing the number of the devices in the network, $ii)$ the WupMDP, clearly outperforms the RFIDImpulse protocol. The effect of the number of devices n is highly expected. In fact, the increase of the global number of devices n in the network leads to a dense network, and thus an increased number of simultaneously competing devices. This basically results in an increased number of collisions. The results also show that WupMDP extremely improves the performance of the existing protocol RFIDImpulse. This is confirmed also from Fig.2 (b) wherein the gain between successfully transmitted and collided packets is depicted. As it is shown, WupMDP has always better gain comparatively to RFIDImpulse scheme.

Fig.3 shows the impact of the transmission probability value p on the performance of WupMDP. Fig.3 (a) represents the number of successfully transmitted packets compared to that of RFIDImpulse protocol. From the figure, we can observe that the number of successfully transmitted packets decreases by increasing the transmission probability p. Logically, higher packet arrival rates lead to higher probability of transmission which results in an increased number of collisions. However, the efficiency of WupMDP is clearly significant comparatively to the RFIDImpulse scheme. Fig.3 (b) shows the gain between successful transmissions and collisions. The difference between the two schemes is great when executing them for small probabilities. After $p = 0,05$ both schemes start approaching to the same gain.

V. Conclusion

In this paper, we introduced WupMDP, a MDP-based model for collision handling at the wake-up plane in wireless sensor networks. The proposed model permits the determination of efficient policies that allow to avoid collision between wake-up messages and thus conserve the energy wastage due to this issue. By implementing this model, a device can decide whether to transmit a wake-up message in the actual time slot



(a) Number of successfully transmitted packets in the network

(b) Gain between successfully transmitted and collided packets in the network

Fig. 3: Performance evaluation of WupMDP against transmissions probability.

or postpone it for the next one to prevent collision. Experimentation results show that the WupMDP scheme achieves high performance in terms of collision reduction, and that is in comparison to previous CSMA\CA-based wake-up MAC protocols.

References

[1] K. P. Valavanis and G. J. Vachtsevanos, *Handbook of unmanned aerial vehicles*. Springer Publishing Company, Incorporated, 2014.

[2] N. H. Motlagh, M. Bagaa, T. Taleb, and J. Song, "Connection steering mechanism between mobile networks for reliable uavs iot platform," in *International Conference on Communications*. IEEE, Paris, France, May 2017, pp. 1–6.

[3] N. H. Motlagh, M. Bagaa, and T. Taleb, "Uav selection for a uav-based integrative iot platform," in *Global Communications Conference*. IEEE, Washington, USA, Dec 2016, pp. 1–6.

[4] N. H. Motlagh, T. Taleb, and O. Arouk, "Low-altitude unmanned aerial vehicles-based internet of things services: Comprehensive survey and future perspectives," *IEEE Internet of Things Journal*, vol. 3, no. 6, 2016, pp. 899–922.

[5] S. Ouahouah, T. Taleb, J. Song, and C. Benzaid, "Efficient offloading mechanism for uavs-based value added services," in *International Conference on Communications*. IEEE, Paris, France, May 2017, pp. 1–6.

[6] S. Koulali, E. Sabir, T. Taleb, and M. Azizi, "A green strategic activity scheduling for uav networks: A sub-modular game perspective," *IEEE Communications Magazine*, vol. 54, no. 5, 2016, pp. 58–64.

[7] I. Simelli and A. Tsagaris, "The use of unmanned aerial systems (uas) in agriculture." in *the 7th HAICTA*, Kavala, Greece, Sep 2015, pp. 730–736.

[8] F. G. Costa, J. Ueyama, T. Braun, G. Pessin, F. S. Osório, and P. A. Vargas, "The use of unmanned aerial vehicles and wireless sensor network in agricultural applications," in *International Geoscience and Remote Sensing Symposium*. IEEE, Munich, Germany, Jul 2012, pp. 5045–5048.

[9] J. Primicerio, S. F. Di Gennaro, E. Fiorillo, L. Genesio, E. Lugato, A. Matese, and F. P. Vaccari, "A flexible unmanned aerial vehicle for precision agriculture," *Precision Agriculture*, vol. 13, no. 4, 2012, pp. 517–523.

[10] *CC2420 Single-Chip 2.4 GHz RF Transceiver Retrieved from Texas Instruments. Mar. 2010 http://focus.ti.com/lit/ds/symlink/cc2420.pdf.*

[11] J. Da Silva, J. Shamberger, M. J. Ammer, C. Guo, S. Li, R. Shah, T. Tuan, M. Sheets, J. M. Rabaey, B. Nikolic, *et al.*, "Design methodology for picoradio networks," in *Design, Automation and Test in Europe, Conference and Exhibition*. IEEE, Munich, Germany, Mar 2001, pp. 314–323.

[12] J. Ansari, D. Pankin, and P. Mähönen, "Radio-triggered wake-ups with addressing capabilities for extremely low power sensor network applications," *International Journal of Wireless Information Networks*, vol. 16, no. 3, 2009, p. 118.

[13] J. Oller, I. Demirkol, J. Casademont, J. Paradells, G. U. Gamm, and L. Reindl, "Wake-up radio as an energy-efficient alternative to conventional wireless sensor networks mac protocols," in *the 16th ACM international conference on Modeling, analysis & simulation of wireless and mobile systems*, Barcelona, Spain, Nov 2013, pp. 173–180.

[14] V. Jelicic, M. Magno, D. Brunelli, V. Bilas, and L. Benini, "Analytic comparison of wake-up receivers for wsns and benefits over the wake-on radio scheme," in *the 7th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*, Miami, USA, Oct 2012, pp. 99–106.

[15] L. Gu and J. A. Stankovic, "Radio-triggered wake-up capability for sensor networks." in *IEEE Real-Time and Embedded Technology and Applications Symposium*. Citeseer, Toronto, Canada, May 2004, pp. 27–37.

[16] G. U. Gamm, M. Sippel, M. Kostic, and L. M. Reindl, "Low power wake-up receiver for wireless sensor nodes," in *6th International Conference on ISSNIP*. IEEE, Brisbane, Australia, Dec 2010, pp. 121–126.

[17] F. Z. Djiroun and D. Djenouri, "Mac protocols with wake-up radio for wireless sensor networks: A review," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, 2017, pp. 587–618.

[18] R. Jurdak, A. G. Ruzzelli, and G. M. O'Hare, "Multi-hop rfid wake-up radio: design, evaluation and energy tradeoffs," in *17th International Conference on Computer Communications and Networks*. IEEE, Virgin, Islands, Aug 2008, pp. 1–8.

[19] *IEEE 802.15.4 MAC/Phy standard for low-rate wireless personal area networks*, (LR-WPANs) http://www.ieee802.org/15/pub/TG4.html.

[20] P. Sthapit and J.-Y. Pyun, "Effects of radio triggered sensor mac protocol over wireless sensor network," in *11th International Conference on Computer and Information Technology*. IEEE, Paphos, Cyprus, Aug-Sep 2011, pp. 546–551.

[21] K. R. Chowdhury, N. Nandiraju, P. Chanda, D. P. Agrawal, and Q.-A. Zeng, "Channel allocation and medium access control for wireless sensor networks," *Ad Hoc Networks*, vol. 7, no. 2, 2009, pp. 307–321.

[22] K. Ravichandran, K. Sivalingam, and P. Agrawal, "Design and analysis of a dual radio node architecture and medium access control protocols for ultra wide band based sensor networks," in *4th International Conference on Broadband Communications, Networks and Systems*. IEEE, USA, Sep 2007, pp. 889–897.

[23] M. Al Ameen, N. Ullah, M. S. Chowdhury, and K. Kwak, "A mac protocol for body area networks using out-of-band radio," in *11th European Wireless Conference Sustainable Wireless Technologies*. VDE, Vienna, Austria, Apr 2011, pp. 1–6.

[24] F. Dressler, B. Bloessl, M. Hierold, C.-Y. Hsieh, T. Nowak, R. Weigel, and A. Koelpin, "Protocol design for ultra-low power wake-up systems for tracking bats in the wild," in *International Conference on Communications*. IEEE, London, UK, June 2015, pp. 6345–6350.

[25] G. U. Gamm and L. M. Reindl, "Range extension for wireless wake-up receivers," in *the 9th International Multi-Conference on Systems, Signals and Devices*. IEEE, Germany, Mar, 2012, pp. 1–4.

[26] M. L. Puterman, *Markov decision processes: discrete stochastic dynamic programming*. John Wiley & Sons, 2014.

[27] *Python Markov Decision Process Toolbox Documentation*, https://media.readthedocs.org/pdf/pymdptoolbox/latest/py mdptoolbox.pdf.