INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 2 (2025) 43-53
https://publisher.uthm.edu.my/ojs/index.php/ijie

UAV Based Efficient Cooperative Spectrum Sensing in CRN: Time-Slot Optimization

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DOI: https://doi.org/10.30880/ijie.2025.17.02.004

Article Info

Received: 10 November 2024
Accepted: 24 June 2025
Available online: 18 July 2025

Keywords

Unmanned aerial vehicles, cooperative spectrum sensing, throughput, optimization, spectrum sensing

Abstract

Cooperative spectrum sensing in cognitive radio networks provides a strong way to increase the throughput, spectral efficiency, and energy efficiency. However, the increased number of secondary users increases the energy consumption, thereby reducing the energy efficiency. To overcome this, a novel technique called unmanned aerial vehicles based on cooperative spectrum sensing has been proposed to reduce energy consumption and enhance the throughput and energy efficiency in a cognitive radio network. In this paper, a UAV-based cognitive radio network is considered to improve the throughput. The performance of unmanned aerial vehicles is closely verified with parameters such as sensing time, path radius, and UAV velocity. Optimization of the number of time slots is considered to further enhance the throughput. Simulation results indicate that the maximum optimal N is 18 when the detection probability is 0.9, with a sensing time of 2 ms. However, as the sensing time increases to 10 ms, the optimal N decreases to 3. Thus, maximum throughput is achieved by either selecting a higher optimal N with a high detection probability and lower sensing time or a lower optimal N with a lower detection probability and higher sensing time. This optimization strategy improves the throughput of virtual cooperative spectrum sensing compared to conventional approaches.

1. Introduction

Nowadays, the wireless communication devices are increasing rapidly and the spectrum resources are becoming scarce. Therefore, cognitive radio networks (CRN) have been proposed to enhance resource utilization with the use of spectrum sharing [1,2]. In CRN, initially, the un-utilized spectrum resources called spectrum holes should be identified using various spectrum sensing techniques such as energy detection [3], matched filter detection [4], cyclostationary detection [5]. But these techniques are affected by noise uncertainty due to multipath fading and shadowing effects [6]. These effects are due to non-line of sight (NLOS) path between the antennas and its location [7-12]. Hence, cooperative spectrum sensing (CSS) has been proposed to mitigate the issues occurred in traditional spectrum sensing [13-15]. It will enhance the sensing efficiency and throughput but the energy consumption also rises with the number of sensing users and reduces the energy efficiency (EE). Therefore, unmanned aerial vehicles (UAVs) based CSS have been proposed to improve the throughput and EE in a wireless communication system i.e., fifth generation (5G), beyond 5G and sixth generation (6G) [16-20].

In a UAV based CRN, the sensing users are replaced with UAVs and the UAV will identify the un-utilized spectrum bands. It will provide better sensing results as the UAVs are placed at high altitude from the ground surface and it creates a LOS environment between the communication nodes. Hence, it will reduce the multipath fading and shadowing effects and also enhance the spectrum efficiency, throughput, energy efficiency and reduce the energy consumption [21]. Due to this, the UAVs are considered as an efficient communication device in various applications such as telecommunications, military, medical and rescue operations [22].

The spectral and energy efficiency was enhanced by optimizing the various parameters like transmission power, sensing time, number of nodes, etc. The CRN with UAVs was considered to improve the EE by optimizing the transmission power and sensing time [23]. In this paper, alternating dichotomy optimization, single optimization and particle swarm optimization algorithms were suggested as a solution of non-convex problem of EE. Multi-objective optimization algorithm was proposed to optimize the transmission power of a UAV in CRN and also to optimize the EE and spectral efficiency (SE) [24]. The SE and EE are improved by using a hybrid mode where the UAVs transmit power and spectrum performance are adjusted to satisfy the PU constraints. A multi-frame spectrum sensing scheme was proposed to further enhance the EE and SE. The proposed hybrid mode and multi-frame structure improved the system performance. A virtual CSS was considered to enhance the sensing performance and throughput by optimizing the number of sensing slots and sensing radian [25]. The sensing performance of a fading channel was improved with virtual CSS compared to the traditional CSS. In [26], two optimization algorithms are used to maximize the SE by optimizing the number of radians in a UAV based CRN. An alternative dichotomy algorithm was suggested to optimize the sensing performance under single radian and multi-radian schemes and observed that the multi-radian scheme provides better sensing performance.

A UAV based CRN was considered to enhance the throughput by optimizing the interference between the primary and secondary networks. In this model, the UAV communicates with the secondary ground terminals [27]. The power, time and hovering locations are optimized jointly to enhance the secondary network throughput by reducing the primary user interference. This proposed joint optimization model performance is better than the K-mean based approach and provides efficient spectrum usage. Combination of CR with UAV will enhance the communication performance, where the conventional secondary users are facing multipath issues. Therefore, UAVs with CRN were proposed to overcome the conventional path losses and to enhance the spectral efficiency. In [28], authors explored the advantages, applications and future challenges of a UAV based CRN. A centralized CRN with UAV was considered for an urban environment to reduce the path loss due to multipath fading. In this method, the ground control station identifies the available WiMAX frequencies with the use of CRN and SDR. If WiMAX frequencies are not available then the WiFi is used for communication to enhance the throughput and spectral efficiency [29].

In traditional CSS, initially N number of secondary users (SUs) sense the primary user (PU) channel, next the sensing decisions of SUs are combined using the various fusion rules and make a decision about the spectrum availability. In this method, as the SUs raises the energy consumption and diminishes the energy efficiency. Therefore, we considered UAVs based CSS to enhance the sensing performance, throughput, and EE. In this paper, we assumed a single UAV works as a multiple secondary user and the sensing time slot is divided into mini slots, which works as a virtual CSS. The spectrum availability can be identified using the majority fusion rule. Throughput and energy efficiency of virtual CSS are estimated based on various path radius, UAV velocity and sensing time. The paper is organized as follows in the remaining sections: section 2 provides a proposed model; section 3 gives the throughput estimation of an UAV based CSS, section 4 provides the optimization of sensing slots, section 5 explores the simulation results and section 6 provides the conclusion.

2. UAV Based Virtual Cooperative Spectrum Sensing

In this paper, an UAV based virtual CSS is analyzed, as depicted in Fig. 1(a). A frame of length T is comprised of N mini-time slots and data transmission, which is depicted in Fig. 1(b). From a standard CSS perspective, these mini-slots will be assumed as N-SUs. The UAV travels in a circular path of radius “R_s” and with a velocity of “V”. The UAV is placed at an altitude of “H” from the ground surface. The UAV and PU are separated by a distance “S”, which is given as

$$S = \sqrt{H^2 + {R_s}^2} \tag{1}$$

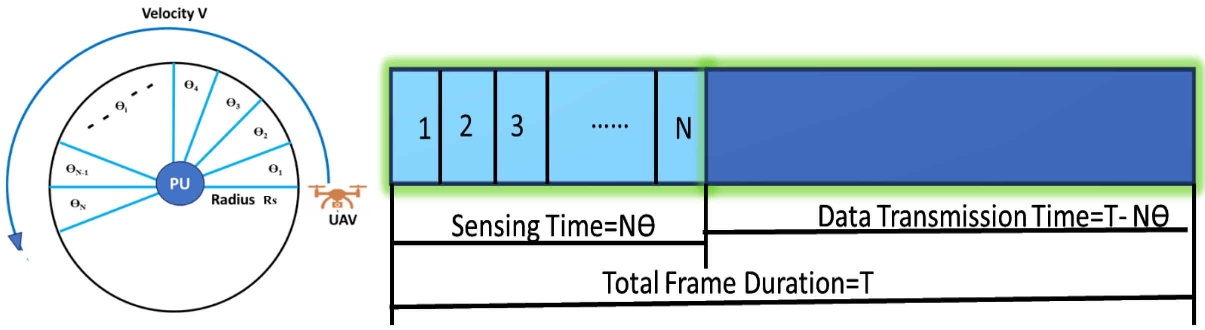

Fig. 1 An UAV *(a) Flight path; (b) Frame structure*

In CSS, the UAV senses the PU channel in N time slots with flight angles $\Theta_1=\Theta_2=$-----Θ_i----$=\Theta_{N-1}=\Theta_N=\Theta$ and the detected signal strength at ith time slot is given as

$$u_i(n) = g_i(n) \tag{2}$$

$$u_i(n) = h_p(n)p_i(n) + g_i(n) \tag{3}$$

where, $p_i(n)$ represents the PU signal, $h_p(n)$ is the PU channel gain, $g_i(n)$ represents the noise and $u_i(n)$ represents the UAV detected signal. The local decisions like the existence or non-existence of the PU is decided based on the total signal energy received by the UAV. The total sensing energy in L samples is estimated as

$$E_i(u) = \sum_{n=1}^{L} |u_i(n)|^2 \tag{4}$$

If the sensed data is less than the detection threshold (λ) then, it says the PU is absent and it is denoted by hypothesis H_0. Similarly, if the energy of the detected signal exceeds the detection threshold, then it says the PU is present and it is denoted by hypothesis H_1, which is given as

$$H_0\colon E_i(u) < \lambda \tag{5}$$

$$H_1\colon E_i(u) \geq \lambda \tag{6}$$

The UAV detection probabilities under H_0 and H_1 i.e., probability of false alarm (P_f) and detection (P_d) are given as [30]

$$P_f = P(E_i(u) > \lambda|H_0) = Q\left(\left(\frac{\lambda}{\sigma_0^2} - 1\right)\sqrt{\frac{\Theta R_s f_s}{v}}\right) \tag{7}$$

$$P_d = P(E_i(u) > \lambda|H_1) = Q\left(\left(\frac{\lambda}{\sigma_0^2} - \gamma - 1\right)\sqrt{\frac{\Theta R_s f_s}{v(2\gamma+1)}}\right) \tag{8}$$

where Q(.) represents the complementary distributed function, σ_0^2 represents the noise variance, γ denotes the signal to noise ratio, Θ denotes the sensing time and f_s is a sampling frequency. An UAV based CSS is considered to enhance the sensing performance and throughput.

Throughput and sensing performance can be further enhanced by improving the detection probabilities called the target P_f and P_d. Therefore, the P_f and P_d in terms of target probabilities are given as

$$P_f = Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right) \tag{9}$$

$$P_d = Q\left(\frac{1}{\sqrt{2\gamma + 1}}\left(Q^{-1}\left(P_f^{'}\right) - \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) \tag{10}$$

Where

$$\chi = \sqrt{2\gamma + 1Q^{-1}(P_d')} \tag{11}$$

In CSS, the local decisions at N time slots are combined to make a final decision using the fusion rules. The final probabilities P_f and P_d are denoted as Q_f and Q_d respectively using OR rule and are given as [14]

$$Q_f = 1 - (1 - P_f)^N \tag{12}$$

$$Q_d = 1 - (1 - P_d)^N \tag{13}$$

3. Throughput in a Virtual CSS

Throughput is defined as successful data transmission through the channel. In a virtual CSS, the total sensing time is divided into N time slots with sensing period of Θ'. This occurs, when the PU channel is ideal and it is detected as ideal by the UAV, then data is transmitted successfully (T_{r0}). Similarly, when the PU channel is busy and it is detected as ideal by the UAV, then the data is transmitted (T_{r1}), causes interference to the PU. These throughputs are estimated as

$$T_{r0} = \frac{T - N\Theta'}{T}\left(T_0\left(1 - Q_f\right)P(H_0)\right) = \frac{T - N\Theta'}{T}\left(T_0\left(1 - P_f\right)^N P(H_0)\right) \tag{14}$$

$$T_{r1} = \frac{T - N\Theta'}{T}\left(T_1(1 - Q_d)P(H_1)\right) = \frac{T - N\Theta'}{T}\left(T_1(1 - P_d)^N P(H_1)\right) \tag{15}$$

Where $P(H_0)$ and $P(H_1)$ denotes the ideal and occupied channel probabilities of PU and T_0 and T_1 are given as

$$T_0 = \log\left(1 + \frac{P_s|h_{SB}|^2}{\sigma_0^2}\right) \tag{16}$$

$$T_1 = \log\left(1 + \frac{P_s|h_{SB}|^2}{\sigma_0^2} + P_p|h_{PB}|^2\right) \tag{17}$$

Where P_s and P_p denoted the power required for data transmission by the UAV and PU, h_{SB} and h_{PB} represented the channel gain between UAV and Base station, PU and Base station respectively. Total Throughput is given as

$$T_r = T_{r0} + T_{r1} \tag{18}$$

The data transmission rate is higher when the PU is ideal and it is detected correctly without false alarm compared to the second condition i.e., when the PU is present and it is detected as ideal. Therefore, total throughput is approximated as T_{r0} because in eq (18) $T_{r0} >> T_{r1}$, which is given as

$$T_r = T_{r0} = \frac{T - N\Theta'}{T}\left(T_0\left(1 - Q_f\right)P(H_0)\right) \tag{19}$$

4. Optimization of Sensing Time-Slots (N)

Optimization technique is used to enhance the system performance. In this paper, sensing time slots optimization is proposed to maximize the throughput of a virtual CSS. In the maximization approach, eq (19) is differentiated with respective to number of time slots and equate to zero to find the optimized number of time slots. Therefore, the throughput in terms of N can be written using eq (9), eq (12) and eq (19) as

$$T_r(N) = \frac{T - N\Theta'}{T}\left(T_0\left(1 - P_f\right)^N P(H_0)\right) \tag{20}$$

$$T_r(N) = \frac{T - N\Theta'}{T}\left(T_0\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right)^N P(H_0)\right) \tag{21}$$

Differentiation of eq (21) with N is given as

$$\frac{d}{dN}T_r(N) = T_r(N+1) - T_r(N) \tag{22}$$

$$= \frac{T-(N+1)\Theta}{T}\left(T_0\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right)^{N+1} P(H_0)\right) - \frac{T-N\Theta}{T}\left(T_0\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right)^{N} P(H_0)\right) \tag{23}$$

$$= \left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right)^{N} \left(T_0 P(H_0)\right)\left[\frac{T-(N+1)\Theta}{T}\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) - \frac{T-N\Theta}{T}\right] \tag{24}$$

To find the optimal N value equate the eq (24) to zero, which is given as

$$\frac{d}{dN}T_r(N) = 0$$

$$\frac{T-(N+1)\Theta}{T}\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) - \frac{T-N\Theta}{T} = 0$$

$$(T-(N+1)\Theta)\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) - (T-N\Theta) = 0$$

$$T\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) - T = (N+1)\Theta\left(1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right) + N\Theta$$

$$N_{opt} = \frac{T\left[Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right] + \Theta\left[1 - Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right)\right]}{Q\left(\chi + \gamma\sqrt{\frac{\Theta R_s f_s}{v}}\right) - 2} \tag{25}$$

The optimized sensing slots are is derived, which is used to enhance the throughput of virtual CSS. This optimized value depends on the sensing time, sampling frequency, flight velocity, P_d and P_f and total frame duration. The increased number of sensing slots reduces the transmission time, which influences the throughput performance. Hence, we considered the optimization of sensing slots, and is derived using the differentiation approach. The step-by-step procedure to optimize the sensing time to balance spectrum detection accuracy and maximize throughput in UAV-based cooperative spectrum sensing networks is shown in Fig. 2.

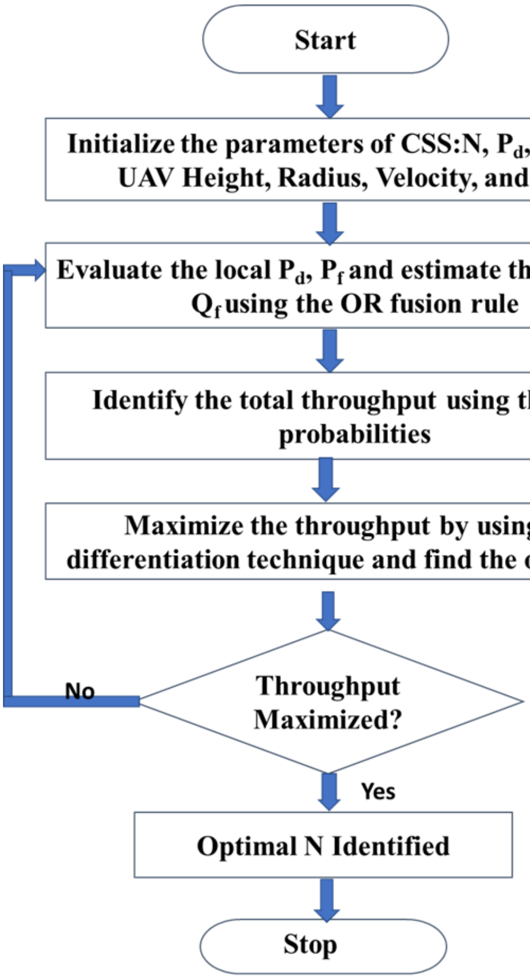

Fig. 2 *Flowchart to identify the optimal sensing time slot by maximizing the throughput*

5. Results

In this paper, we considered an UAV based virtual CSS with N time slots as N SUs and with a single PU. The UAV rotated around the PU in a circular path with constant velocity and sensed the PU channel. We considered the probability of ideal and occupied channel as 0.5, number of slots are N as 20, the total time duration of frame is T = 600 sec, the mini sensing time ϴ' of 0 msec to 0.01 msec, UAV height as 200 m, radius of the circular path as 200 m to 800 m, velocity as 5 m/s to 30 m/s, noise variance as 1 and SNR as −20 dB to−10 dB.

Figs. 3 to 6 shows the normalized throughput of a virtual CSS with detection threshold, path radius, UAV velocity, and sensing time. Fig. 3, shows the normalized throughput with detection threshold for various time slots, where the $\gamma = -18$ dB and velocity $v = 10$ m/s are fixed. From this figure, it is noticed that the normalized throughput is enhanced within the detection threshold and diminishes as the N rises. It is noticed that the rate of normalized throughput is greater than 80% for a variable number of time slots because in the virtual CSS, there exists a line-of-sight path between the transmitting antenna and the receiving antenna.

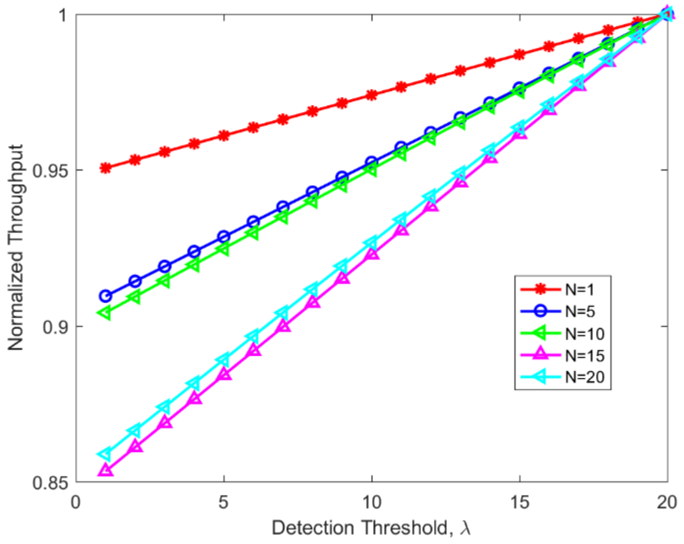

Fig. 3 *Normalized throughput with detection threshold and sensing time slots*

Fig. 4, shows the Throughput with detection threshold for various path radii. The normalized throughput is enhanced as the threshold rises. The throughput is high for a small path radius and it decreases as the radius increases because at a low path radius, the distance between two communicating nodes is less and it provides an LOS path. Hence the throughput increases. As the radius increases the path between communicating nodes increases, which leads to the NLOS path and it reduces the throughput. The higher the threshold, the higher the normalized throughput.

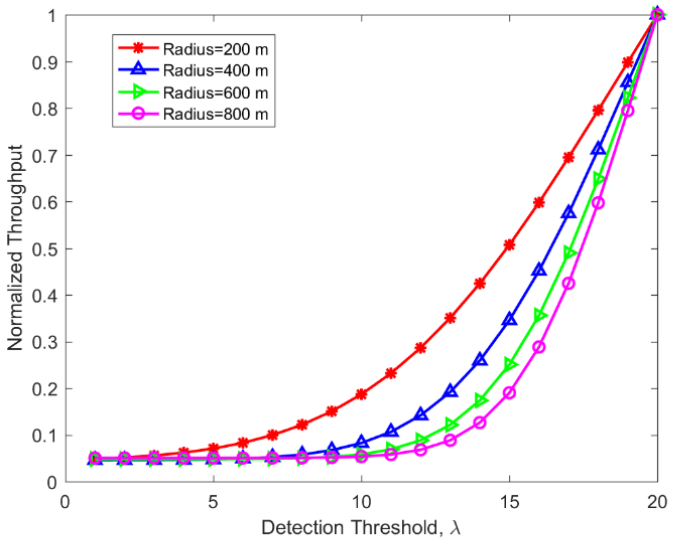

Fig. 4 *Normalized throughput with detection threshold and UAV path radius*

Fig. 5, shows the throughput variations with detection threshold and flight velocity. Throughput increases with the increase in detection threshold and UAV flight velocity. At high velocity the throughput is high compared to the low velocity due to reduction in sensing time. The reduced sensing time improves the data transmission time, which improves the throughput.

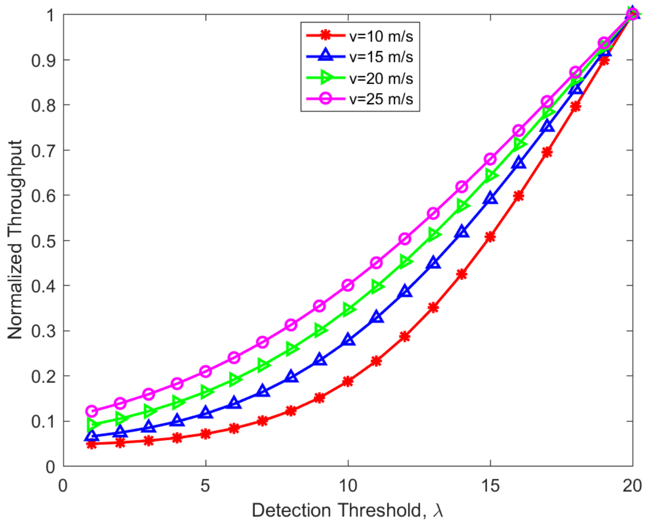

Fig. 5 *Normalized throughput with detection threshold and flight velocity*

Normalized throughput with sensing time and number of time slots is shown in Fig. 6. It increases with the sensing time and decreases with the number of time slots. As the sensing time rises the sensing accuracy improves, which leads to improved throughput.

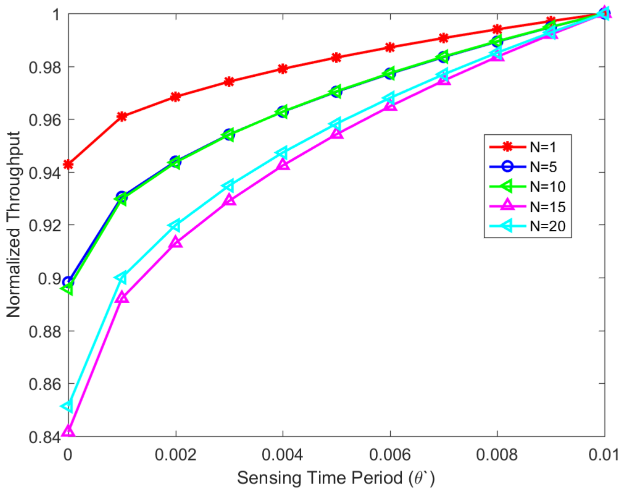

Fig. 6 *Normalized throughput with sensing time and time slots*

In this paper, we proposed optimization of sensing slots to improve data transmission rates. The higher data rates are achieved by increasing the probability of detection. Therefore, we considered the probability of detection (P_d) from 0.7 to 0.9 and these are considered as the target probability of detection. Because the UAV-based Virtual CSS is used in 6G and beyond to enhance the data rates. Therefore, the higher detection probabilities are considered and at these higher detection probabilities, we identified the optimized sensing time slots to maximize the throughput.

The optimization of sensing slots to maximize the throughput for a target probability of detection over a given sensing period is derived mathematically using eq (25) and the simulation results are illustrated in Fig. 7. The figure demonstrates that the optimal number of sensing slots decreases as sensing time increases. Additionally, a lower target probability of detection also results in fewer optimal sensing slots. This suggests that more sensing slots are necessary for accurate system performance and enhanced throughput. Table 1 lists the optimal number of sensing slots required to maximize throughput for various detection probabilities. For a target P_d of 0.9, a larger number of sensing slots is required compared to probabilities of 0.8 or 0.7. At shorter sensing periods, more sensing slots are needed to enhance throughput due to lower sensing accuracy. As sensing time increases, accuracy improves, which reduces the number of slots are needed to maximize throughput.

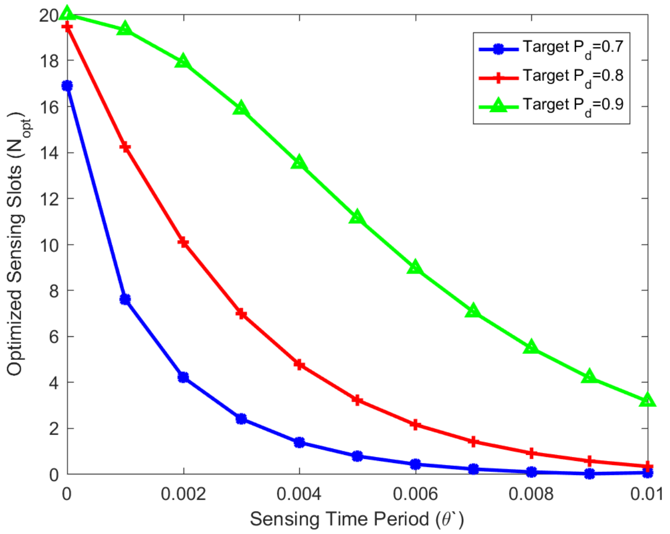

Fig. 7 *Optimized sensing time slots*

Table 1 *Optimal number of sensing slots*

Sensing Time (sec)	Nopt		
	Target P_d =0.7	Target P_d =0.8	Target P_d =0.9
0.002	4	10	18
0.004	2	5	14
0.006	1	3	9
0.008	1	1	6
0.01	1	1	3

The optimal number of sensing slots in a UAV-based virtual CSS is presented in Table 1. As sensing time increases, the optimal number of slots decreases. Longer sensing times reduce the probability of false alarms and increase the probability of detection, thereby maximizing throughput. Additionally, as the target probability of detection rises, more sensing slots are required to achieve maximum throughput. The increase in Nopt at a specific sensing time helps determine the number of sensing slots needed to enhance throughput for a particular application and target P_d.

6. Conclusion

A UAV-based virtual cooperative spectrum sensing approach has been proposed to enhance throughput. In this virtual CSS, a single UAV senses the primary user channel over multiple time slots, estimating spectrum availability in each slot, thereby improving communication system performance. This paper presents an estimation of normalized throughput for various path radii, flight velocities, sensing time slots, and sensing durations. Simulation results indicate that the normalized throughput of the virtual CSS improves with a smaller path radius, higher flight velocity, more sensing slots, and shorter sensing time. Additionally, we optimized the sensing slots for a target detection probability. The maximum optimal N of 18 is achieved when the detection probability is 0.9, with a sensing time of 2 ms. However, as the sensing time increases to 10 ms, the optimal N decreases to 3. Thus, maximum throughput is achieved by either selecting a higher optimal N with a high detection probability and lower sensing time or a lower optimal N with a lower detection probability and higher sensing time. Therefore, increased sensing time reduces the number of sensing slots while maximizing throughput.

Acknowledgement

This work is supported and funded by a Telekom Malaysia Research & development (TMR&D) grant, RDTC: 241126, MMUE/240081, Malaysia.

Conflict of Interest

Authors declare that there is no conflict of interests.

Author Contribution

The authors contribution to the paper are as follows: ***Study conception, manuscript drafting and results implementation:*** *Mardeni Roslee, Chilakala Sudhamani;* ***Manuscript review, analysis and funding:*** *Sufian Mousa Ibrahim Mitani, Anwar Faizd Osman, Fatimah Zaharah Ali, Athar Waseem. All authors reviewed the results and approved the final version of the manuscript.*

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