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Employing Game Theory and TDMA Protocol to Enhance Security and Manage Power Consumption in WSNs-Based Cognitive Radio

MOHAMED S. ABDALZAHER^{1,2}, (Member, IEEE), AND OSAMU MUTA², (Member, IEEE)

¹Seismology Department, National Research Institute of Astronomy and Geophysics, Cairo 11421, Egypt

²Center for Japan–Egypt Cooperation in Science and Technology, Kyushu University, Fukuoka 819-0395, Japan

Corresponding author: Mohamed S. Abdalzaher (mohamed.abdelzaher@ejust.edu.eg)

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ABSTRACT The rapid development of wireless sensor networks (WSNs) is a significant incentive to contribute to vulnerable applications such as cognitive radio (CR). This paper proposes a Stackelberg game approach to enhance the WSN-based CR security against the spectrum sensing data falsification (SSDF) attack and conserve the consequently lost power consumption. The attack aims to corrupt the spectrum decision by imposing interference power to the delivered reports from the sensor nodes (SNs) to the fusion center (FC) to make a protection level below a specific threshold. The proposed model utilizes the intelligent Stackelberg game features along with the matched filter (MF) to maximize the number of protected reports sent by the SNs to the FC leading to an accurate decision of the spectrum status. Furthermore, the TDMA protocol is utilized to resolve the complexity of employing MF for the spectrum detection to avoid the collision between the delivered reports. The proposed model aims to enhance the number of correctly received reports at the FC, and hence manage the lost energy of reports retransmission due to the malicious attack effect. Moreover, the model can conserve the lost power of the failed communication attempts due to the SSDF attack impact. Simulation results indicate the improved performance of the proposed protection model along with the MF over six different environments against the SSDF attack as compared to two defense schemes, namely, random and equal weight defense strategies.

INDEX TERMS Wireless sensor networks, cognitive radio, game theory, threats mitigation, power conservation.

I. INTRODUCTION

With the dramatic lack of spectrum resources, the intelligent communication methodologies have flourished such as cognitive radio (CR) to resolve this issue. In the literature context, the spectrum quality-of-service (QoS) management, energy conservation for which the packet size optimization was one of the key roles, and security mitigation rise among most of the exerted efforts. Various CR paradigms were studied focusing on the spectrum utilization depending on the statistical QoS to support the real-time applications at the secondary users (SUs) [1]–[6]. Moreover,

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the SUs are used to support the primary feedback information to set up a primary user (PU)-aware routing technique exploiting the compressive sensing to gain the sparse nature of the PUs occupation [7], [8]. The packet size optimization has also introduced a valuable solution for prolonging network lifetime [9]. Different CR spectrum detectors have been evolved, most known of which: Energy, cyclostationary, and matched filter (MF) detectors [10]–[12]. MF was not only limited for CR applications, but its use has been extended to blood vessel detection [13]–[16]. Indeed, CR opens a wide technological gate for many competitive networks to cooperate with for enhancing the day-to-day challenges such as security front and power consumption management.

In this regard, secured WSNs can dramatically contribute to CR networks (CRNs) as the fusion center (FC) needs to rely on distributed sensor nodes (SNs) to sense the spectrum status. In other words, WSNs suffer from security and power management problems, especially in harsh environments. The uncontrolled WSNs security is a double defect: one is data deterioration, and second is losing power consumption in the transmission of designated infected data. Consequently, security in WSNs-based CR is a prominent issue that has been considered in [8], [17]–[22].

One of the eminent techniques utilized in the literature to handle the security problem in WSNs is game theory [23]–[27]. Game theory is a special optimization branch which tackles the interaction among a set of rational intelligent users that aim to enhance their individual gains in an intelligent and adaptive way [28]. To this end, three main dependent challenges affecting a smooth operation for CR are spectrum sensing, mitigating security threats, and the consequently lost energy. One of the security threats in CRNs is spectrum sensing data falsification (SSDF) attack [29], which is among the main CRN attacks.¹ Here, the defender represents the FC. Therefore, the whole communication system in such CRN can be strictly disrupted, and the network performance can be steeply degraded. In addition, this attack can disrupt the delivered reports at the FC, and hence, a wrong decision can be taken by the FC about the spectrum status. Moreover, it does reduce not only the number of correctly received reports (packets) at the FC but also enlarge the energy lost. Since the amount of energy to protect the allotted SNs is limited, an intelligent SNs protection mechanism is needed to minimize the amount of invested power.

In this paper, we propose a game-theoretic approach using a Stackelberg game along with MF detector to enhance WSNs-based CR security against the SSDF attack. To the best of our knowledge, no similar work has been presented in the literature which uses game theory along with MF to improve the detection performance of PU, handling the security threat, manage the consequent lost energy, and enhance the correctly delivered reports to be processed at the FC by which the decision is taken.²

The main contributions of the paper are three folds:

- The Stackelberg game model is designed along with MF detector to optimally detect the infected spectrum status reports, due to the rational external SSDF attack, transmitted from the deployed SNs. To decrease the complexity of employing the MF for spectrum detection, we utilize TDMA protocol to avoid collision between

¹The paper assumes a single CRN attack, and we focus on designing the game model for that as a challenging issue. To confront several CRN attack types, a comprehensive trust model using game theory is desired, which is out-of-scope of this paper.

²In the literature, various game-theoretic approaches such as Zero-sum game, Non-zero sum game, repeated game, bayesian game, etc. have been used for CRNs and cyber-physical systems [30]–[32]. However, to the best of our knowledge, the Stackelberg game model has not been investigated for solving the issues mentioned above due to the malicious SSDF attack effect at the presence of HW failure.

TABLE 1. Frequently used acronyms.

Abbreviation	Description
WSNs	Wireless Sensor Networks
CR	Cognitive Radio
SSDF	Spectrum Sensing Data Falsification
SN	Sensor Node
FC	Fusion Center
MF	Matched Filter
PU	Primary User
SU	Secondary User
HW	Hardware
OL	Outdoor Line-of-sight
ON	Outdoor Non-line-of-sight
UL	Underground Line-of-sight
UN	Underground Non-line-of-sight
IL	Indoor Line-of-sight
IN	Indoor Non-line-of-sight

the delivered SNs reports to the FC. Moreover, TDMA is used to support a robust synchronization between the FC and the deployed SNs, which facilitates the detection and protection process.

- For adopting a realistic paradigm, the proposed model considers the potential hardware (HW) failure occurred in the deployed SNs and can distinguish these nodes among the ones influenced by the attack while attaining improved performance with the presence of the SNs malfunction.
- The proposed model effectiveness is clarified by the achieved probability detection performance in the presence of SSDF attack and HW failure. The percentage of protected SNs reports denotes this achievement. In other words, the more protected SNs reports are, the more accurate decision is taken by the FC. Hence, the model can conserve the lost power of reports (packets) retransmission as a result of failed communication attempts due to the SSDF attack impact. The effectiveness of the above-proposed approach is verified through simulation evaluation over six different environments, outdoor line-of-sight (OL), outdoor non-line-of-sight (ON), underground line-of-sight (UL), underground non-line-of-sight (UN), indoor line-of-sight (IL), and indoor non-line-of-sight (IN).

The rest of the paper is organized as follows. Section II presents the related work. In Section III, the system model is discussed. The proposed game formulation is then presented in Section IV, while the SNs reports delivery is addressed in Section V. Section VI shows the obtained results. Finally, the paper conclusion is revealed in Section VII. Table 1 lists the frequently used acronyms.

II. RELATED WORK

This section discusses the related works to enhance the CRNs performance, including the security aspect. In the literature context, the security in CR can be the essential metric to guarantee the data privacy and to achieve robust communication system, specifically against the intelligent attacks

manipulations such as eavesdropper, primary user emulation (PUE), jamming, byzantine, and SSDF attacks [33]. As an eminent adaptive and intelligent tool to address the above security aspects, game theory can be utilized in CRN [34]–[39].

The eavesdropper and jamming attacks effect on CRNs, which recognizes the CRN data privacy, were adequately studied using Stackelberg game, zero-sum game, repeated game [34]–[36]. The problem of a full-duplex active eavesdropper, which represents a full-duplex mode of a jammer and a classical eavesdropper, has been mitigated by three-stage Stackelberg game [34]. Similarly, the potential eavesdropper in CRN has been confronted by a zero-sum game [35]. A repeated game was also utilized to build a multiple-channels communications security mechanism for SUs against the random eavesdroppers. The efforts of game theory were also extended to confront the PUE attack in CRN to minimize the miss detection using a nonzero-sum game model [37]. Game theory was exploited to formulate the anti-jamming channel selection problem as an anti-jamming dynamic game in CRN [38]. In [39], a zero-sum game was developed to model the corrupted nodes due to the Byzantine attack, which negatively influences the CRN routing reputation. The harmful impact is caused by the SSDF attack on the FC decision. Nevertheless, only a few works were presented to resolve this devastating issue in the CRNs.

In [25], a Stackelberg game model in some sense was utilized to mitigate the SSDF attack to detect the corrupted nodes reports in WSNs-based CR. Meanwhile, in [40], the problem of fake inspections sent by malicious SUs in CRNs due to the SSDF was studied using static game approach to establish a statistical trust model. In [25], [40], the energy detection method has been employed with game theory to detect malicious nodes behavior due to the SSDF attack. The energy detection is the simplest method of detection in CR but has crucial weaknesses, e.g., it can be deceived by the intellectual attack manipulations and cannot reach the optimal detection. For solving this issue, a more intelligent game model needs to be designed along with a robust detection scheme against the SSDF attack.

Unlike the previous related works, this paper presents an effective game model designed with the MF detector and TDMA based protocol to achieve an optimal solution against the security issue due to the SSDF attack under the existence of a possibility of HW failure. Besides, the model is utilized to manage the consequently lost energy over the six different environments, where Tmote Sky based SN model [41] is used to assume a realistic CRN system.

III. SYSTEM MODEL

The proposed model is considered in Fig. 1. Notations and variables related to the proposed model and its mathematical representation are summarized in Table 2. The FC relies on $|\mathcal{N}|$ SNs that are utilized to identify the spectrum holes. The SNs send the sensed spectrum as reports to the FC, as shown in Fig. 1. Using this sequence, we aim to provide a

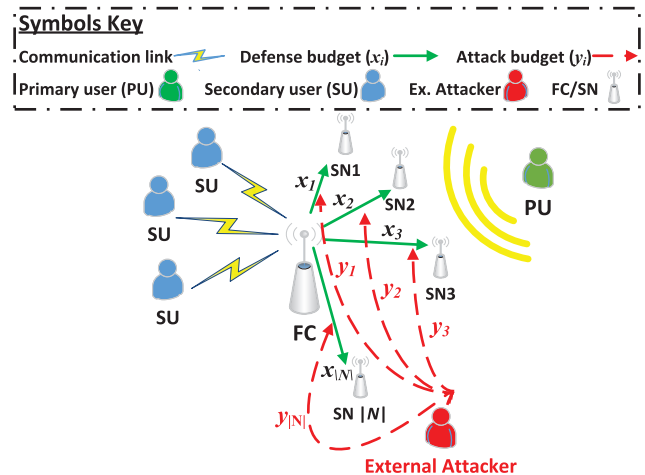


FIGURE 1. WSNs-based CR basic structure.

collision-free of spectrum access to the secondary users (SUs) based on the delivered protected SNs reports to the FC against the SSDF attack. We assume that the SSDF attack aims to devastate the communications between the SNs and the FC in WSNs-based CR over statics AWGN channel, i.e., all SNs are symmetrically distributed around the FC, where the distances between FC and all SNs are the same.

Figure 1 indicates the system structure of the proposed model for protecting the i -th SN report ($i \in \{1, 2, \dots, |\mathcal{N}|\}$) from the impact of SSDF attack. The distributed defense budgets (x_i s) on the SNs reports by the FC are used to countermeasure the attack budgets (y_i s). Indeed, the defense and attack budgets can represent the amount of power invested in the defense and attack actions, respectively. More particularly, the attack budget (y_i) is exploited as interference signal power, noise added to the original signal (report), to corrupt the transmitted reports from each SN to the FC. On the contrary, the defense budget (x_i) is effectively utilized to countervail the malicious effect of (y_i) on the original report. Therefore, we consider that the SSDF deteriorates the signal-to-noise ratio (SNR) by injecting noise power. Accordingly, after measuring the SNR of the delivered reports, the FC is guiding the SNs to change the transmission power by the adequate power that neglects the attack effect based on the proposed model strategy. The reports transmission from SNs to FC is organized based on TDMA to prevent the collision problem.

In other words, the FC defense budgets represent the desired transmission power of each SN to neglect the SSDF attack impact, and hence the performance is examined at the equilibrium point. The allotted defense budgets are represented by the green arrows to countermeasure the SSDF attack effect. The red icon is the external attacker that applies the attack budgets represented by the green arrows to disrupt the communication between the SNs and FC. To this point, in the next section, we propose a Stackelberg game to model this interaction between the FC and the external attacker, which represents the leader/follower nature of the problem;

TABLE 2. Notations of parameters and variables.

Symbol	Description
\mathcal{N}	The set of sensor nodes
\mathcal{Z}	The set of all nodes excluding the FC
X	The total defense budget
x_i	Applied defense budget for i -th report
Y	The total attack budget
y_i	Applied attack budget for i -th report
T_s	Time slot duration
T_g	Guard time between two consecutive time slots
T_t	Transmission time duration
T_p	Propagation time duration
T_b	Total busy time duration
pkt	Data packet length
ACK	Acknowledgment packet length
D	Payload length contained in a data packet
H	Header length contained in a data packet
PL_{iFC}	The path loss of the link between the every i -th SN and FC
PL_0	The free space path loss at the reference distance of the antenna far field
d_{iFC}	The distance between the communicating nodes i and FC
d_0	The reference distance of the antenna far field
n	The path loss exponent
σ	The standard deviation of the shadow fading
$P_{r,iFC}^A$	The received signal power at the antenna of FC from transmitting node i
P_t^A	The transmission signal power at the transmit antenna
P_{ct}	The transmission power consumption
γ	The signal-to-noise ratio
BER	The bit error rate
P_n	The receiver noise power
L	The number of bytes per packet
Pr_G	The process gain
P^S	The probability of successful packet reception
P^F	The probability of failure packet reception
P^{SHS}	The probability of successful handshake
P^{FHS}	The probability of failure handshake
R_e	The probability of re-transmission to achieve successful handshake
E_{dt}	The energy dissipation for transmitting a packet
E_{dpp}	The energy dissipation for processing a packet
E_t^{HS}	The total energy dissipation
T_A	The data acquisition time duration
m	A transmit energy level of the data packet
u	A transmit energy level of the ACK packet
P_{off}	The power consumption during sleep mode
B	The total energy of the sensor node battery
E_{DA}	The energy dissipation due to data acquisition per round
P_{DA}	The power dissipation due to data acquisition
T_{DA}	The data acquisition time
P_{cr}	The power consumption due to data reception

the FC acts as the leader, and the attacker acts as a follower. It should be noted that the attacker actions will be affected by the actions taken by the FC. Then, the defense budget can be utilized as an internal self-defense mechanism to protect the delivered reports from the potential corruption due to the rational SSDF attack manipulations.

Figure 2 shows the system structure of the proposed game model role along with the MF that aim to maximize the number of protected reports delivered from the distributed SNs to the FC leading to spectrum collision-free. In other words, the licensed user (PU) signals are protected from the collision caused by the SUs signals due to the wrong decision

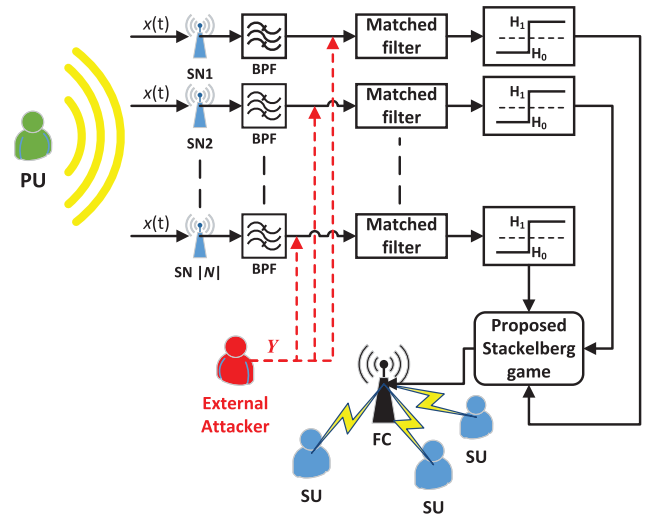


FIGURE 2. Game process along with MF detector with the presence of the attack.

taken by the FC. It is noted that the process starts by the deployed SNs to sense the spectrum status (busy, idle) from the PU. Then, the role of BPF comes to filter the observed signals by the SNs. To this end, it is considered a fragile signal stage that can be drastically influenced by the intelligent external attacker (SSDF) that aims to disrupt the designated delivered report to FC. After that, the MF and the thresholding level operations are executed, respectively. Therefore, one of two hypotheses is produced about the spectrum status. More particularly, the FC is in charge of making the final decision about being the PU is present or absent after taking into consideration the defense strategy presented by the proposed game model. This decision is based on the combined SNs reports passed the thresholding level.

Indeed, the final decision is represented by a binary hypothesis testing problem. The two hypotheses in Eq. (1) are given in the presence of noise (H_0) or noise plus signal (H_1) taking into account the interference noise power added by the attack where we assume that all SNs have the same noise floor.

$$\begin{aligned}
 H_0 : y_i(n) &= CG_i \cdot s(n), \text{ PU absent} \\
 H_1 : y_i(n) &= CG_i \cdot s(n) + w_i(n), \text{ PU present}
 \end{aligned} \tag{1}$$

where $y_i(n)$ is the SN received signal, CG is the complex channel gain of the sensing channel, $s(n)$ is the PU signal, $w(n)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_i^2 , $n = 1, 2, \dots, N_{sm}$, N_{sm} is the sample number, $i = 1, 2, \dots, |\mathcal{N}|$.

The optimal filter that projects the received signal in the direction of the pilot x_p [42] can be written as follows:

$$c_i = \sum_{n=1}^{N_{sm}} y_i(n) x_p^*(n). \tag{2}$$

Using the Neyman-Pearson (NP) detector, it is well known that differentiating between the two hypothesis (H_1/H_0) is

based on the test statistics (c_i) [14] using a threshold λ_i as follows.

$$c_i \underset{H_0}{\overset{H_1}{>}} \lambda_i, \quad i = 1, 2, \dots, |\mathcal{N}|. \quad (3)$$

Accordingly, the probability of detection P_d^i , and the probability of false alarm P_f^i at i -th SN are already influenced by the attack interference power and can be given by

$$P_d^i = Pr(c_i > \lambda_i | H_1) = Q\left(\frac{\lambda_i - E}{\sqrt{E\sigma_i^2}}\right). \quad (4)$$

$$P_f^i = Pr(c_i > \lambda_i | H_0) = Q\left(\frac{\lambda_i}{\sqrt{E\sigma_i^2}}\right), \quad (5)$$

where $Q(\cdot)$ is a function that provides the tail probability of the standard normal distribution at i -th SN. The threshold level of every i -th report depends on the power level captured by each. E is the PU signal energy. Hereafter, we omit superscript i for simplicity of notation. The sensing threshold (λ) is a function of PU signal energy and noise variance giving by

$$\lambda = Q^{-1}(P_d)\sqrt{E\sigma_i^2}. \quad (6)$$

Indeed, the FC confesses the received report based on matching filter followed by a thresholding level to determine whether this report withstands the external attack interference power (y_i) or not. This interference power aim is to deviate the SNR (γ) from its interference-free value as

$$\gamma_i = \frac{G(S_i)}{P_n + y_i}, \quad i \in 1, 2, \dots, |\mathcal{N}|, \quad (7)$$

where G denotes channel gain. S_i and P_n represent transmission power of the i -th SN report and noise power, respectively.

Thus, the obtained P_d or P_f do not reflect the real spectrum observation. Consequently, we propose a Stackelberg game that aims at observing the attack interference power, detecting the infected reports, and hence enhancing the detection performance. Then, SNR is given by

$$\gamma_i = \frac{G(S_i + x_i)}{nP + y_i}, \quad i \in 1, 2, \dots, |\mathcal{N}|, \quad (8)$$

Therefore, the used (x_i) at the equilibrium point can neglect (y_i) in Eq. (7) as

$$\tilde{\gamma}_i = \frac{G(S_i + x_i^*)}{P_n + y_i^*} \implies \frac{G(S_i)}{n}, \quad (9)$$

where x_i^* and y_i^* are the optimal defense and attack budgets at the equilibrium point for the i -th report.

IV. GAME FORMULATION

In this paper, the MF detector is used in WSNs-based CR along with Stackelberg game features. To this end, in this section, we propose a Stackelberg game model, where the competition is between the FC and the external attacker. The attacker strategy depends on the defender (FC) strategy and

vice versa. The model is developed to confront the SSDF attack effect. More concretely, this approach concentrates on detecting the corrupted reports delivered to the FC in WSNs-based CR. Those corrupted reports aim to deceive the FC leading to a wrong decision taken by the FC.

In fact, the attacker selects to disrupt a group of SNs reports that have an energy protection budget below a specific thresholding level ξ . This mechanism follows the process shown in Fig. 2. It is worth mentioning that, the effect on the performance, the relationship of the probability of detection P_d and false alarm P_f , is evaluated at the equilibrium point.

The proposed model target is to protect the used SNs reports in the WSNs-based CR that are exploited to pinpoint whether the spectrum is idle or busy. The game model structure is based on a sequence of actions expressed by two players: a leader/defender (L), where (L) initiates the game, while the other player follower/attacker (F) replies with an action that yields to its optimal utility given the action L [28].

The utilities/payoffs functions of L and F are denoted by the $U_L(A_L, A_F)$ and $U_F(A_L, A_F)$, respectively, where $A_L = x_i$ and $A_F = y_i$ are the individual actions taken by L and F , respectively. The leader starts with a hypothetical action A_L^0 as the game assumes that L knows U_F , which is utilized to withstand the attacker deceptions. Consequently, L can determine the optimal action $A_F^*(A_L^0)$ of F Eq. (10) supposing that F is rational player, given that A_L^0 has been exerted. Therefore, the optimal action of L can be given by Eq. (11) [25].

$$A_F^*(A_L^0) = \arg \max_{A_F \in \bar{A}_F} U_F(A_L^0, A_F). \quad (10)$$

$$A_L^* = \arg \max_{A_L^0 \in \bar{A}_L} U_L(A_L^0, \arg \max_{A_F \in \bar{A}_F} U_F(A_L^0, A_F)). \quad (11)$$

Four definitions are now in order:

- **Definition 1:** The FC defense strategy is represented by $DS(X)$, where X is the total defense energy budget, which is indicated by the amount of electric power invested in the defense set of actions (\bar{A}_d). The action performed to protect i -th SN is $A_x = x_i, i \in \{1, 2, \dots, |\mathcal{N}|\}$, and the defender (FC) set of actions \bar{A}_d satisfy constraint $X \geq \sum_{i=1}^{|\mathcal{N}|} x_i$. More particularly, this defense budget is used to protect the SNs reports against the attack manipulations represented by injecting noise power to the observed signal to disrupt the delivered report to FC.
- **Definition 2:** The attack strategy is indicated as $AS(Y)$, where Y is the total attack energy budget which is represented by the amount of electric power invested in the attack set of actions (\bar{A}_a). The action performed to attack i -th SN is $A_a = y_i = [0, 1], i \in \{1, 2, \dots, |\mathcal{N}|\}$, and the attacker set of actions (\bar{A}_a) satisfy constraint $\sum_{i=1}^N y_i \leq Y$. More concretely, this defense budget is utilized to manipulate the attacker and mitigate its impact by countervailing the added noise power.
- **Definition 3:** The utilities (payoffs) functions of FC and attacker are represented by $U_d(A_d) = U_d(x_i)$ and $U_a(A_a) = U_a(y_i)$, respectively.

- *Definition 4:* We can achieve subgame Nash equilibrium (NE) at $(A_d^* = x_i^* \forall i)$ and $(A_a^* = y_i^* \forall i)$ as shown in (Appendix). NE can be defined as a set of strategies such that none of the participants in the game can improve their payoff, given the strategies of the other participants. In other words, NE can be explicitly defined as no player can improve its utility by changing its action/strategy, if the other players conserve their current actions/strategies [28].

The leader seeks to enhance its payoff using an appropriate A_L^* given that both L and F actions have been done in sequence. Consequently, L can accurately handle the only available action of rational F among (\bar{A}_F) as

$$A_F^* = \arg \max_{A_F \in \bar{A}_F} U_F(A_L^*, A_F). \tag{12}$$

Therefore, subgame NE can be attained using Eqs. (10, 11, 12). It is clear that in the examined WSNs-based CR, the game played by the defender (FC) representing the L and the attacker acting as F . The defender aims to protect the SNs delivered reports, while the attacker attempts to disrupt these reports. The interactions of L and F are executed over the network lifetime.

The proposed Stackelberg game model is explicitly organized using **Algorithm 1** for detecting and protecting the WSNs-based CR from the delivered malicious SNs reports to the FC. Firstly, the FC distributes the defense budgets (x_i) 's to the deployed SNs for protecting them against the SSDF attack effect. On the other hand, the attacker allots the corresponding attack budgets (y_i) 's attempting to turning the maximum number of SNs reports into malicious. In fact, the attacker investigates every previous action done by the FC to protect the SNs reports. When the game starts, the utility function of the received reports (U_i) is investigated. This function denotes the difference between the defense and attack budgets on the i -th SN report as given by

$$U_i = x_i - y_i. \tag{13}$$

If U_i is less than zero, this i -th report is checked whether it is a result of an HW failure or by the SSDF effect. Otherwise, this i -th SN report is still benevolent. More particularly, to realize the proposed model, we assume a percentage of the SNs can suffer from an HW failure during the communication. Then, if the resulting U_i is noncontinuous negative, this is due to an HW failure for the corresponding SN. Conversely, if the value of this U_i is continuous negative, this i -th SN report is considered infected by the SSDF attack and can be excluded from the FC consideration.

The defense mechanism of the FC is to protect the maximum number of delivered reports leading to accurate spectrum status decision. Consequently, the defense scheme relies on the benevolent received reports about the spectrum. Indeed, the thresholding level (ξ) , which is application sensitivity dependent, is utilized to distinguish the strongly and weakly protected SNs reports that are sorted in a strong list (SL) and weak list (WL), respectively; given that the

Algorithm 1: Proposed Stackelberg Game Algorithm for SSDF Attack

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1 Distribute  $x_i$ ;
2 Input  $A_d = x_i, A_a = y_i$ ;
3 while NE does not exist (more SNs reports are still
   infected) do
4   Compute  $U_i$  by Eq. (13),  $\forall i \in |\mathcal{N}|$ ;
5   Determine the malicious nodes/HW failure;
6   if  $U_i < 0$  then
7     if This is 1st time  $U_i < 0$  then
8       | This  $i$ -th node  $\rightarrow$  HW failure list;
9     else
10      | This  $i$ -th node  $\rightarrow$  SA malicious list;
11    end
12  end
13  if  $U_i > 0$  then
14    | This  $i$ -th node is still benevolent;
15    if  $U_i > \xi$  then
16      | Add this  $i$ -th node to SL;
17    else
18      | Add this  $i$ -th node to WL;
19    end
20  end
21  Sort SL and WL in ascending order based on the
   resulting  $U_i$ ;
22  Top of heap of SS will be the strongest node (SSR);
23  if  $SL(2) > SL(1)$  then
24    | Resort SS in descending till finishing all WS;
25  end
26  Defender resorts  $(x_i)$ 's distribution based on
   Eqs. (17,18);
27  Attacker resorts  $(y_i)$ 's distribution based on
   Eqs. (15,16);
28  Check  $(A_d, A_a) \rightarrow (A_d^*, A_a^*) \forall i \in \mathcal{N}$ ;
29  Compute  $U_i$  using Eq. (13);
30 end
31 Output NE exist  $\leftarrow ((A_d^*, A_a^*), \forall i)$ 

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attacker budget is limited. The result of Eq. (13) determines the intelligent attack strategy in every new round. In this strategy, the attacker concentrates on the weak list (WL) of the SNs reports that have been protected with low defense budgets in the previous round. The attacker sorts the WL in a descending order based on Eq. (13) result. It means that the utility function of those reports satisfies the following constraint

$$U_i = (x_i - y_i) < \xi. \tag{14}$$

Based on the standard feature of the Stackelberg game, the leader knows the attack strategy, and thus, it will apply the same concept as the follower behaves to counter the attacker effect. Accordingly, F exerts a minimal extra attack budget α deducted from its attack budget applied on the strongest SN report (SSR) in the previous iteration to be added to the weak

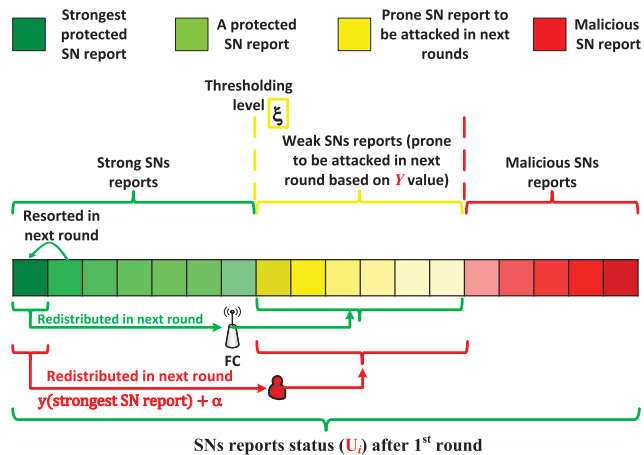


FIGURE 3. Graphical process of the mathematical induction.

SN report (WR) as

$$y_w(SSR)|_{new} = y_w(SSR)|_{old} - (U_r + \alpha), \quad (15)$$

$$y_r(WR)|_{new} = y_r(WR)|_{old} + (U_r + \alpha). \quad (16)$$

where w is an index of a strongly protected SN, and r is an index for a weakly protected SN. This redistribution strategy of attack budget is performed to make sure that U_r in the next iteration will be lower than zero; which compromising the weakly protected SN report r .

In contrary, the FC manipulates the attacker by adding ξ budget value to each weak SN report that has $(U_i < \xi)$ after subtracting enough (ξ) 's from the strongly protected SN report (SSR) to satisfy the requirements of weak SN report in the next iteration as given in the following equations:

$$x_w(SSR)|_{new} = x_w(SSR)|_{old} - (\xi), \quad (17)$$

$$x_r(WR)|_{new} = x_r(WR)|_{old} + (\xi). \quad (18)$$

Figure 3 graphically shows the mathematical induction used for the WL and SL of SNs reports leading to the NE at which no more negative effect added by the attacker. Obviously, the green cells indicate the SL of protected SNs reports in which SSR is the top of the heap (darkest green cell). After the first iteration, the FC deducts a ξ value from the previously applied defense budget of the SSR, i.e., $x(SSR) - \xi$, to be re-allotted on the WL (prone to be attacked in the next rounds). Consequently, the SL will be rearranged every subsequent iteration. The thresholding level (ξ) is the borderline between SL and WL. Then, it is followed by the yellow cells representing the list of weakly protected SNs reports. Conversely, the attacker will add a α attack budget to the previously applied attack budget of the SSR, i.e., $y(SSR) + \alpha$, to be redistributed on the WL. Finally, the red cells denote the malicious SNs reports.

Finally, this model makes sure that the system is reliable, given that the attacker has a limited budget. Consequently, when we deal with pure actions/strategies where the competitive players (FC and external attacker) choose deterministic

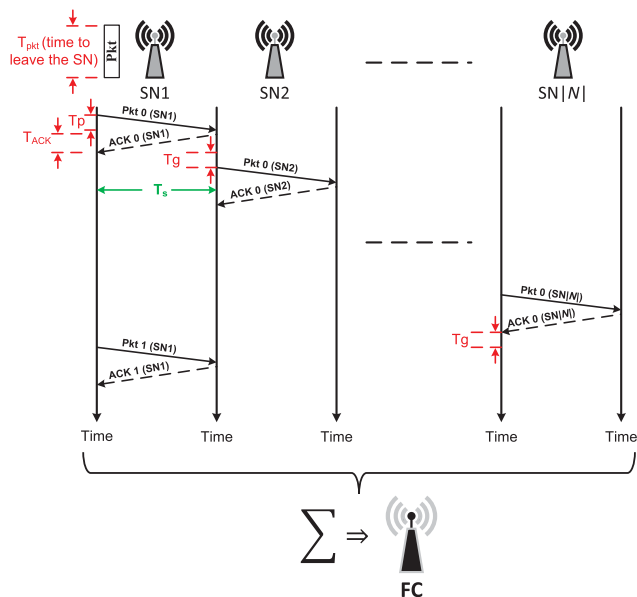


FIGURE 4. Time diagram based on TDMA technique.

actions, the NE is defined here as follows:

$$U_i(A_d^*, A_a^*) \geq U_i(A_d, A_a^*) \quad \forall A \in A, i \in \mathcal{N}. \quad (19)$$

V. REPORTS DELIVERY FORMULATION

This section explains the considered system model analysis and the reports (packets) delivery formulation. We assume that TDMA is used for data packet transmission to prevent the possibility of collision. TDMA time slots allocations are assigned by the FC as depicted in Fig. 4. We consider a star topology between the FC and the set of SNs observers, \mathcal{N} , where the number of SNs in the network is given by the cardinality of the set \mathcal{N} which is represented by $|\mathcal{N}|$.

In fact, the communication protocol between the SNs and the FC is based on transmitting a data packet from i -th SN to the FC and then the FC replies by an acknowledgment (ACK) packet to confirm receiving the data packet. This communication sequence is called a successful handshake.

The adopted path loss between every i -th SN and the FC (i, FC) is given by

$$PL_{iFC}[\text{dB}] = PL_0[\text{dB}] + 10n \log_{10} \frac{d_{iF}}{d_0} + \sigma[\text{dB}], \quad (20)$$

where PL_0 is the free space path loss at the reference distance d_0 of the antenna far-field, n denotes the path loss exponent, d_{iFC} is the distance between the transmitting i -th SN and the FC, and σ represents the standard deviation in dB of the shadow fading.

The received antenna signal power at the FC from the i -th transmitting SN with power level m can be given by

$$P_{r,iFC}^A(m)[\text{dBm}] = P_t^A(m)[\text{dBm}] - PL_{iFC}[\text{dB}], \quad (21)$$

where $P_t^A(m)$ is the transmission antenna signal power at power level m . Table 3 illustrates the transmission power

TABLE 3. Consumed transmission power P_{ct} and antenna output power P_t^A with every power level m [43].

P_{ct} (mW)	P_t^A (dBm)	m	P_{ct} (mW)	P_t^A (dBm)	m
25.5	-25	3	41.7	-5	19
29.7	-15	7	45.6	-3	23
33.6	-10	11	49.5	-1	27
37.5	-7	15	52.2	0	31

TABLE 4. Path loss parameters for the six environments [44].

Environment	n	σ (dB)	P_n (dBm)
Outdoor-LOS (OL)	2.42	3.12	-93
Outdoor-NLOS (ON)	3.51	2.95	-93
Underground-LOS (UL)	1.45	2.45	-92
Underground-NLOS (UN)	3.15	3.19	-92
Indoor-LOS (IL)	1.64	3.29	-88
Indoor-NLOS (IN)	2.38	2.25	-88

consumption with the eight available power levels ($P_{ct}(m)$) and the antenna transmission power P_t^A using Tmote Sky node [43].

The obtained SNR for the signal power transmitted from i -th node to the FC is given by

$$\gamma_{iFC}(m)[dB] = P_{r,iFC}^A(m)[dBm] - P_n[dBm], \quad (22)$$

where P_n is the receiver noise power. Table 4 depicts the path loss parameters for the available six environment measurements presented in [44]. In fact, the BER based on the used SN (Tmote Sky) is given by

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \quad (23)$$

where $\frac{E_b}{N_0} = \gamma_{iFC}(m)Pr_G$, Pr_G denotes the process gain which is the ratio between the chip rate and the bit rate of the spread spectrum system [43].

Thus, a successful packet reception probability of an uncoded L -Byte packet transmitted at power level- m among the communicating terminals (i , FC) is given by

$$p_{iFC}^S(m, L) = \left(1 - Q\left(\sqrt{16\gamma_{iFC}(m)}\right)\right)^{8L}. \quad (24)$$

On the other hand, the failure probability of receiving a packet is given by

$$p_{iFC}^F(m, L) = 1 - p_{iFC}^S(m, L). \quad (25)$$

The probability of a successful handshake denotes the probability that a data packet is successfully transmitted from the i -th node to the FC (p_{iFC}^S) with power level (m) and a successfully ACK packet is responded by the FC to the i -th SN (p_{FCi}^S) at power level (u), which is given by

$$p_{iFC}^{SHS}(m, u) = p_{iFC}^S(m, pkt) \times p_{FCi}^S(u, ACK). \quad (26)$$

Consequently, the probability of failure handshake is given by

$$p_{iFC}^{FHS}(m, u) = 1 - p_{iFC}^{SHS}(m, u). \quad (27)$$

Clearly, the data packets should be re-transmitted ($Re_{iFC}(m, u)$) times to ensure that the data packets are successfully transmitted. The number of re-transmissions is given by

$$Re_{iFC}(m, u) = \frac{1}{p_{iFC}^{SHS}(m, u)}. \quad (28)$$

Energy dissipation for transmitting a (pkt)-Byte packet from the i -th SN to the FC with power level (m) is given by

$$E_{dt}(m, pkt) = P_{ct}(m)T_{pkt}. \quad (29)$$

Indeed, when an SN accomplishes the packet transmission, it stays in the receive mode during the time slot. Therefore, this situation should be taken into consideration at calculating the total energy dissipation as

$$E_t^{HS}(m, pkt) = E_{dt}(m, pkt) + P_{cr}(T_s - T_{pkt}), \quad (30)$$

where P_{cr} represents the power consumption of the data received during the rest of the time slot, T_s is the slot time, and T_{pkt} represents the actual packet transmission time. Furthermore, the energy consumed for packet processing and re-transmission until attaining successful handshake is given by

$$E_{dt}(m, u) = E_{dpp} + Re_{ij}(m, u)E_t^{HS}(m, pkt), \quad (31)$$

where E_{dpp} is the energy dissipation for packet processing, which is computed once when successful handshake exists. On the other hand, the successful handshake energy dissipation at the receiver side, $E_r^{SHS}(u, ACK)$, consists of the energy consumed for receiving the data packet and the energy consumed for transmitting ACK to the transmitter. Thus, $E_r^{SHS}(u, ACK)$ is given by

$$E_r^{SHS}(u, ACK) = P_{cr}(T_s - T_{ACK}) + E_t^{ACK}(u, ACK). \quad (32)$$

Conversely, the energy dissipation of failed handshake due to the absence of data packet is given by

$$E_r^{FHS} = P_{cr}T_s. \quad (33)$$

Consequently, the total energy dissipation at the receiver taking into account all data packets re-transmissions and ACK packets re-transmissions is given by

$$E_{r,FCi}^{SHS}(m, u) = E_{dpp} + Re_{iFC}(m, u)[p_{iFC}^{SHS}(m, u) \times E_r^{SHS}(u, ACK) + p_{iFC}^S(m, pkt) \times p_{FCi}^F(u, ACK)E_r^{SHS}(u, ACK) + p_{iFC}^F(m, pkt)E_r^{FHS}]. \quad (34)$$

It should be noted that if a SN is not busy during a specific time slot it stays in the sleep mode, wherein the power consumption is P_{off} .

TABLE 5. Simulation parameters.

Parameter	Value	Parameter	Value
$|\mathcal{N}|$	50	$T_g = T_p$	100 μ s [46]
P_{cr}	69 mW	T_s	4.78 ms
P_{DA}	11.4 mW	Data rate	250 Kb/s
T_{DA}	5 ms	T_{pkt}	$\frac{pkt}{Data\ rate}$
E_{DA}	μ J	T_{ACK}	$\frac{ACK}{Data\ rate}$
D	120 bytes	Pr_G	$\frac{2M\ chip/s}{Data\ rate}$ [43], [47]
H	8 bytes	P_{off}	3 μ W
ACK	12 bytes	E_{dpp}	12.66 μ J
m	31	B	15 KJ

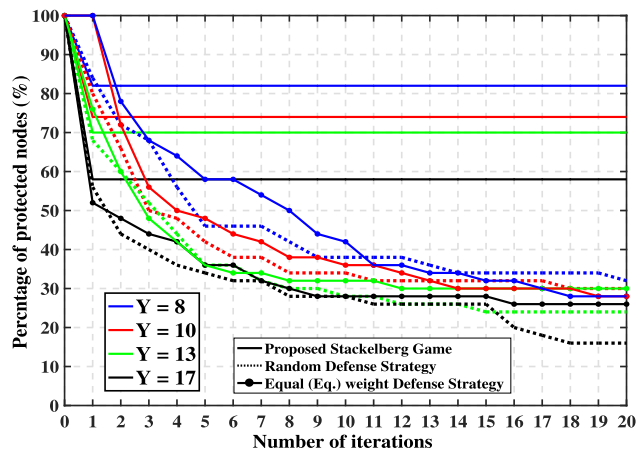


FIGURE 5. The ratio of delivered reports among the total number of delivered reports.

VI. SIMULATION RESULTS

This section presents the simulation results. The simulation parameters are presented in Table 5. We assume Tmode Sky [44], [45] as a realistic SN model and employ the parameters from the datasheet in [43]. We assumed that all SNs use power level $m = 31$. It is worth mentioning that the number of generated $pkts$ by every SN per round depends on the selected D . For instance, if D equals 120 bytes, only one data packet will be generated by every SN. If D equals 60, two data packets will be generated. We use four different total attack budgets $Y \in \{8, 10, 13, 17\}$ for model verification and $Y = \{8, 17\}$ for showing the WSNs-based CR performance using Eqs. (4,5) (P_d vs. P_f) and (P_d vs. SNR) with the same FC defense budget $X = 20$. In addition, the FC decision is affected by the observed signal level at the SNs over an AWGN channel, taking into consideration the shadowing fading. It is assumed that all SNs are located from the FC with the maximum coverage range of the Tmote Sky SN (125 m) to show the effectiveness of our model. Although the maximum distance is used, the model operates efficiently along with MF detector and TDMA over the six environments (OL, ON, UL, UN, IL, and IN).

Figure 5 shows the percentage of benevolent SNs reports that withstand the attack manipulations among the total number of reports with the proposed defense mechanism, random defense scheme (the defense power budget is

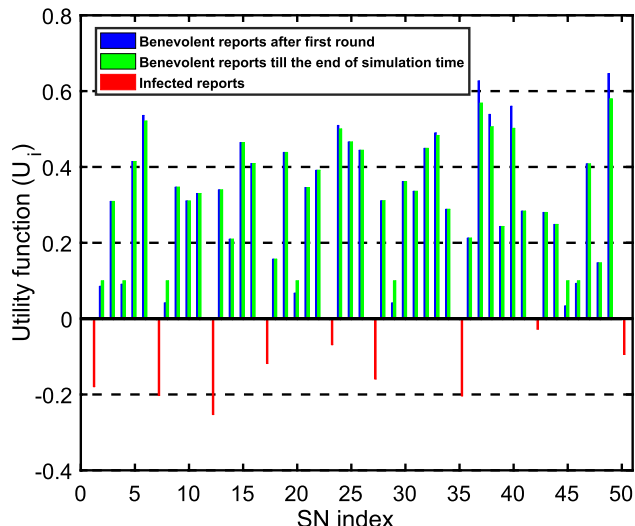


FIGURE 6. Utility function values based on the proposed Stackelberg game.

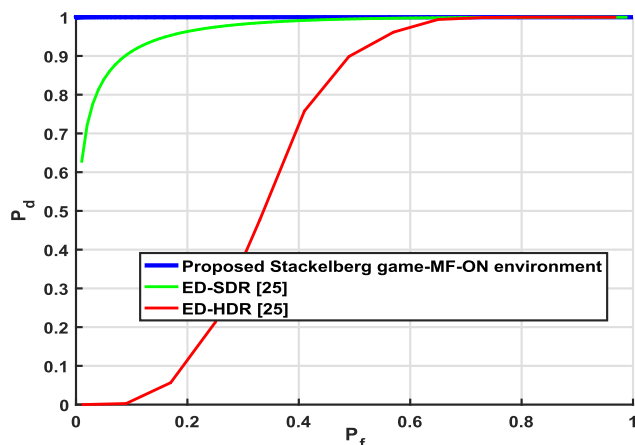


FIGURE 7. P_d vs. P_f comparison of the proposed model and the corresponding in the literature, $Y = 17$.

randomly allotted for the SNs) and equal (Eq.) weight defense schemes (the defense budgets are equally weighted distributed for the SNs) within 20 rounds. The percentages of protected SNs reports are about (83%, 74%, 70%, and 58%) due to the applied attack budgets (8, 10, 13, and 17), respectively. Meanwhile, the protected reports percentage steeply degraded while using random or equal protection mechanisms. Therefore, it can be estimated from the obtained results that the proposed model achieves efficient protection against the SSDF effect.

The resulting utility functions of the SNs reports due to the proposed attack-defense strategy are shown in Fig. 6. The results indicate the benevolent reports after the first round; the reports confronted the attack till the end of the simulation, and the ones that turned malicious due to the attack effect, which are colored by blue bars, green bars, and red bars, respectively. The results prove the success of the proposed model

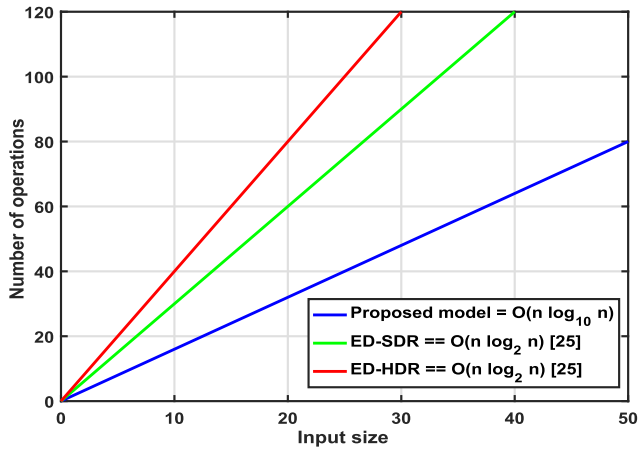


FIGURE 8. Algorithms complexity comparison between the proposed game and the corresponding in the literature.

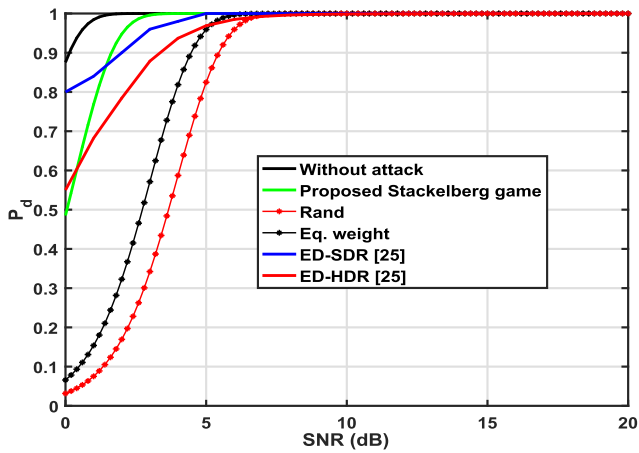


FIGURE 9. P_d vs. SNR comparison of the proposed model to random and equal weight defense strategies with nonfluctuating PU, $Y = 17$.

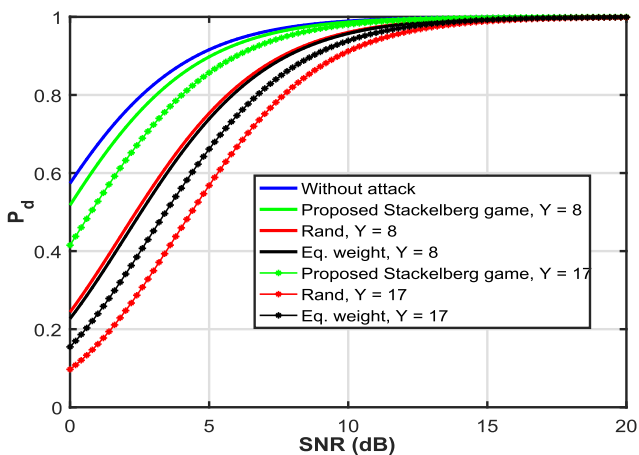


FIGURE 10. P_d vs. SNR comparison of the proposed model to random and equal weight defense strategies with fluctuating PU, $Y = \{8, 17\}$.

in protecting the majority of reports against the intellectual attack manipulations.

Figure 7 indicates that our model along with the MF outperforms the work in [25] in which energy detection (ED)

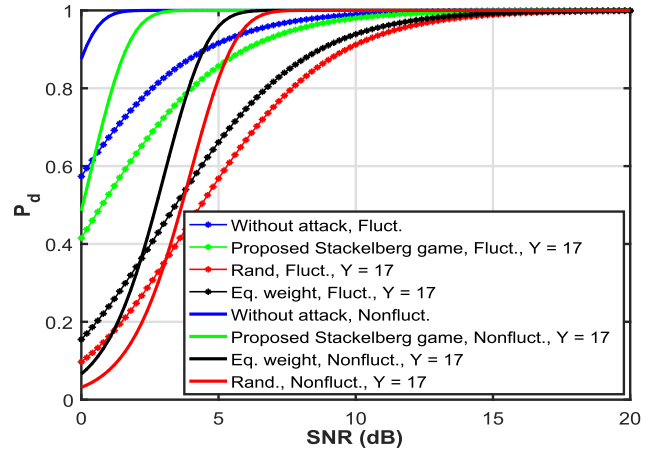


FIGURE 11. P_d vs. SNR (dB) comparison of the proposed model to random and equal weight defense strategies with NC receiver and fluctuating PU scenarios, $Y = 17$.

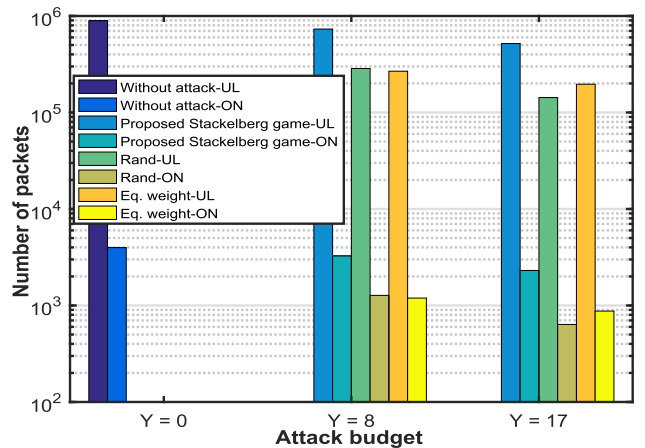


FIGURE 12. Number of correctly processed packets of the proposed model vs. rand and Eq. weight defense strategies based on (UL) and (ON) environments, $Y = \{8, 17\}$.

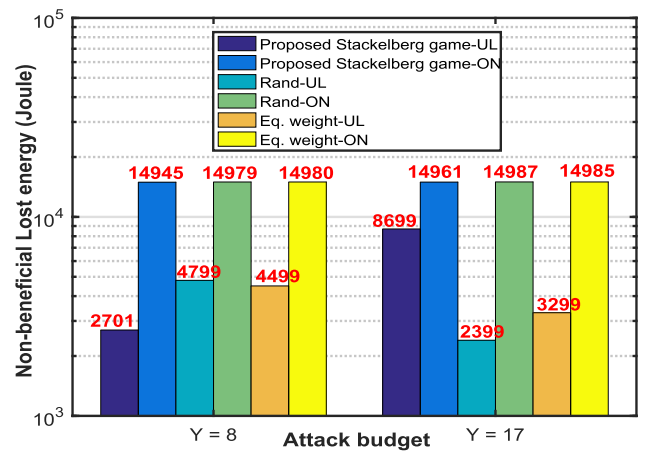


FIGURE 13. The non-beneficial consumed energy using the proposed model vs. rand and Eq. weight defense strategies based on (UL) and (ON) environment, $Y = \{8, 17\}$.

method was used, the hard decision rule (HDR) and soft decision rule (SDR). We have shown the results when using the maximum attack budget ($Y = 17$) wherein the obtained

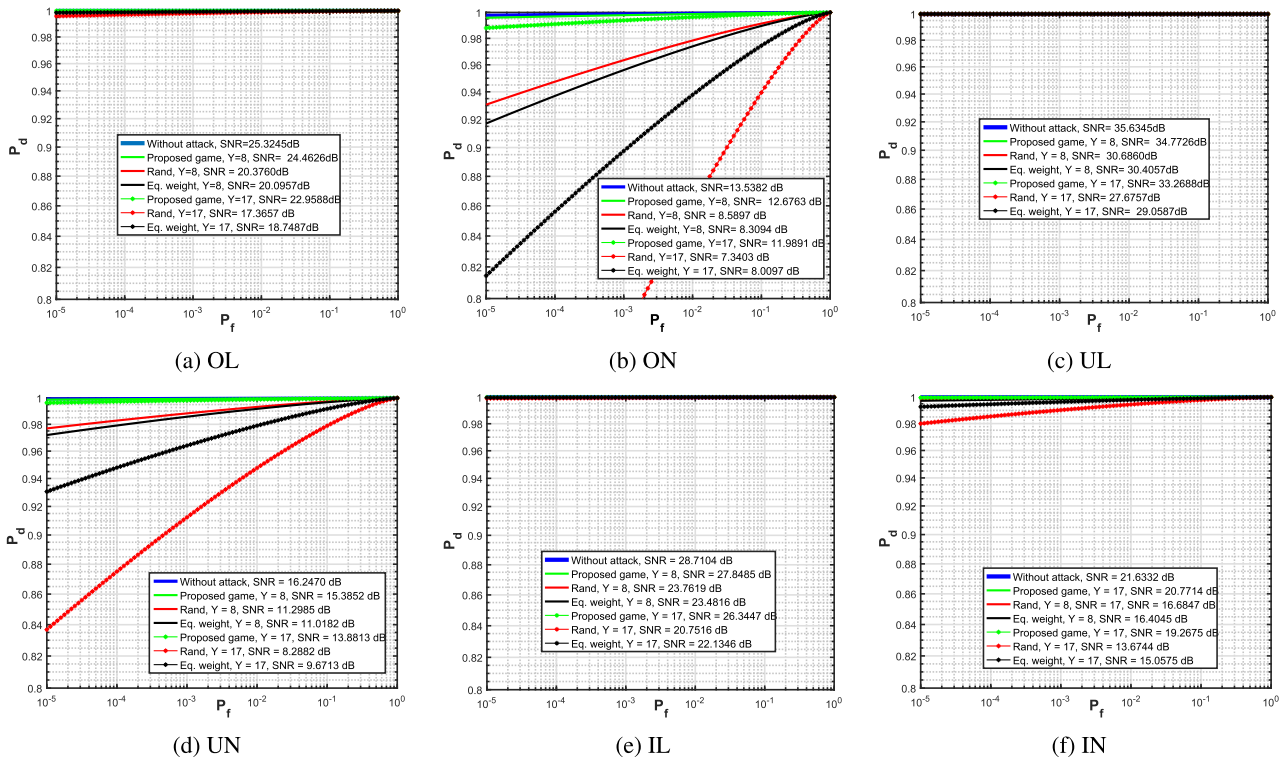


FIGURE 14. P_d vs. P_f of fluctuating PU with $Y = \{8, 17\}$ over the six environments.

simulations our model presents better performance even with the other values of attack budget $Y \in \{8, 10, 13\}$ over all the six environments. It is worth mentioning that, here, we only show the comparison when ON environment is utilized to indicate the effectiveness of the proposed model with MF among the work done in [25] even in the harsh environment.

Figure 8 illustrates the enhanced model complexity using the proposed game approach as compared to the corresponding one in [25]. The complexity is calculated by the number of operation versus the input size used to execute the model till. It is clear that the complexity of the proposed model is better than both ED-HDR and ED-SDR in [25], which reflects the effectiveness and applicability of the proposed model.

Then, the relationship between P_d and SNR has been extensively studied in two PU cases (nonfluctuating and fluctuating). The obtained results in both cases depict the improved performance, whether with fluctuating or non-fluctuating PU as shown in Fig. 9 and Fig. 10, respectively. Moreover, we found that changing the environment does not affect the relationship between P_d and SNR. In Fig. 9, we have compared the proposed model to random (rand), equal (Eq.) weight defense strategies, and the corresponding work in [25] showing the enhanced performance using the proposed approach. Note that, in all other simulations done, the proposed model presents better performance (P_d vs. SNR) as compared to rand and Eq. weight defense strategies, regardless of the attack budget value. Therefore, we only

show two samples when $Y = \{8, 17\}$, which represent the minimum and maximum used attack budgets, respectively.

After that, we have selected the maximum attack budget as an indicator of the effectiveness of our model to compare the nonfluctuating (Nonfluct.) and fluctuating (Fluct.) PU obtained curves showing the difference between the proposed model along with MF and without attack attempt applied, as shown in Fig. 11. It is clearly shown that the obtained results of the proposed model are very close to that scenario without attack. This means that the proposed model with MF can handle the SSDF attack manipulations.

Afterward, the indication of the proposed model on improving the number of correct packets (protected reports) to be processed by the FC and taking the decision based on is shown in Fig. 12. We have compared our model to the case of no attack exists and both rand and Eq. weight defense strategies over the best environment (UL) and worse environments (ON) when the attack budget is minimum and maximum ($Y = \{8, 17\}$). The results ensure the power of the proposed model with MF for confronting the SSDF attack as compared to without attack scenario and definitely with rand and Eq. weight defense strategies. It is clearly shown that the obtained results based on the proposed Stackelberg game model along with MF achieve a very close number of packets to be protected to that scenario of no attack whether the attack budget is minimum ($Y = 8$) or maximum ($Y = 17$).

Similarly, the lost non-beneficial battery energy of the FC due to continuous negative feedback (ACK) transmitted to the

SNs that its report is infected is shown in Fig. 13. We can figure out that the FC battery lifetime can be maliciously exhausted when the SNs are not effectively protected. It is clear that the harsh environment (ON) adds an extra negative impact plus the attack budget on losing the packets or interfering them which means negative ACK will be sent to those SNs that their packets are affected by the fading problem. Therefore, the results of ON environment get worse as compared to the ones of UL. Moreover, the scenario is worse when Y increases. Among the extensive obtained simulation results, we show the results when the attack budget equals ($Y = \{8, 17\}$) representing the minimum and maximum designated attack budgets, respectively.

Figure 14 shows the presented study on the fluctuating PU performance (P_d vs. P_f) over the six environments OL, ON, UL, UN, IL, and IN, respectively. Obviously, the results obtained are close to each other. Furthermore, both OL, UL, and IL environments represent very close perfect performance. The ON environment presents the worst performance as compared to the other environments results because of being a harsh environment. It is a result of being the ON possesses the highest path loss exponent, which owns much more impact on the path loss, among the other environments. However, it is still a feasible performance.

VII. CONCLUSION

In this paper, we have presented an effective attack-defense strategy based on the Stackelberg game along with MF to alleviate the problem of corrupted SNs reports delivered at FC in WSNs-based CR over different six communication environments in which the data transmission is organized by TDMA technique. Moreover, TDMA is adopted to handle the complexity of MF along with the proposed model and to avoid the delivered reports collision. We also considered a realistic scenario of the SNs HW failure. However, the proposed model can detect this malfunction. Based on the obtained simulation results, the proposed model achieves effective protection against the SSDF malicious attack effect. In addition, the proposed approach protects about 83% of the total number of SNs reports at the presence of the intelligent attack manipulations. Although the obtained percentage of protected reports is not rigorous, the optimal PU detection probability is achieved, leading to spectrum collision-free against the SSDF attack impact under the simulated scenarios. Moreover, equilibrium can be achieved with a minimal number of rounds. In addition, the model effectiveness appears in the relationship between the detection probability and SNR in which the model proves an enhanced performance very close to no attack presence, whether with fluctuating or nonfluctuating PU. Furthermore, the number of packets that are correctly received by FC from the deployed SNs using the proposed model is promoted to be very close to the ideal case of no attack exists and exceeds the other defense strategies by thousands of packets. This improved performance is achieved, whether with the best environment (UL) or worse one (ON). Accordingly, the lost non-beneficial

energy due to the attack impact has been strictly managed as about 50% of the lost energy is saved using the proposed model, whether with UL or ON environment. Consequently, the proposed Stackelberg game model, among the intelligent and adaptive game-theoretic approaches, along with MF and TDMA strictly prove beneficial for improving spectrum sensing, mitigating security threats, enhancing data privacy, and managing the power consumption in WSNs-based CR. In future work, we would like to extend the proposed model to a comprehensive game theory-based trust model for considering multiple intelligent attack types.

APPENDIX

∴ Attack strategy $AS =$

$$y_1, y_2, \dots, y_{|\mathcal{N}|} = \alpha x_1, \alpha x_2, \dots, \alpha x_{|\mathcal{N}|}$$

∴ the attacker benefit is maximized based on redistributing its budget from y_r to y_q to manipulate the defender, where ($r \neq q$).

$$y_1, y_2, \dots, y_r - \phi, y_q + \alpha, \dots, y_{|\mathcal{N}|},$$

where the attacker deducts an attack budget α from the strong protected CM and add that to the weak protected CM.

∴ The alternative attack by redistributing its budget and sorting those CMs in a descending order based on the previous status of the utility functions is denoted as

$$AS_A = y'_1, y'_2, \dots, y'_{|\mathcal{N}|} \tag{35}$$

∴ The redistribution of the AS is denoted as $D_{r,q}^\alpha$.

∴ any AS_A can be represented by a redistribution sequence budget $|\mathcal{N}| - 1$ from the optimal attack strategy (AS^*) as

$$D_{1,2}^{\alpha_1}, D_{2,3}^{\alpha_2}, \dots, D_{|\mathcal{N}|-1,|\mathcal{N}|}^{\alpha_{|\mathcal{N}|-1}}$$

Assume the budget redistribution from $AS_A \implies AS^*$ as

$$D(1), D(2), \dots, D(N - 1)$$

∴ The mathematical induction with respect to heuristic concept is utilized by α -th redistribution for the i -th CM (U_i) in the (WL) depending on the first node (SCM) as

$$U_1 = (y_1 - L \cdot \alpha) - x_1, \tag{36}$$

where $L_{>\mathbb{R}}$ is the subtracted number of (α)'s from the strongest report budget given that the strongest report is the top of heap of the (SL). More specifically, $U_1 > U_2$.

$$AS^* = \max U_a \quad \forall i = (1, 2, \dots, |\mathcal{N}|) \tag{37}$$

$$U_i \begin{matrix} > \\ > \\ < \end{matrix} \gamma, \quad i \in (1, 2, \dots, |\mathcal{N}|). \tag{38}$$

To check the availability of finding $AS_A > AS^*$

$$U_{a_i} > U_{d_i} | i \notin WL \text{ or } SL \tag{39}$$

∴ The attacker concentrates on WL.

TABLE 6. Action matrix of the proposed Stackelberg game.

Actions sequence		Attack actions						
		1	2	...	$x_{\gamma-1}, y_{\gamma-1}$	$x_{\gamma+1}, y_{\gamma+1}$	...	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
FC actions	1	x_1, y_1	x_2, y_2	...	$x_{\gamma-1}, y_{\gamma-1}$	$x_{\gamma+1}, y_{\gamma+1}$	...	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
	2	x_1, y_1	x_2, y_2	...	$x_{\gamma-1}, y_{\gamma-1}$	$x_{\gamma+1}, y_{\gamma+1}$	...	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
	⋮	x'_1, y'_1	$x'_2, y'_2 + \alpha$	...	$x_{\gamma-1}, y_{\gamma-1}$	$x_{\gamma+1}, y_{\gamma+1}$	...	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
	⋮	x'_1, y'_1	x'_2, y'_2	...	$x'_{\gamma-1}, y'_{\gamma-1} + \alpha$	$x_{\gamma+1}, y_{\gamma+1}$	...	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
	⋮	x_1, y_1	x_2, y_2	...	$x_{\gamma-1}, y_{\gamma-1}$	x_{γ}, y_{γ}	$x_{\gamma+1}, y_{\gamma+1} + \alpha$	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$
	$|\mathcal{N}|$	x_1, y_1	x_2, y_2	...	$x_{\gamma-1}, y_{\gamma-1}$	x_{γ}, y_{γ}	$x_{\gamma+1}, y_{\gamma+1} + \alpha$	$x_{|\mathcal{N}|}, y_{|\mathcal{N}|}$

∴ There is no AS_A satisfies $U_a > U_d \forall i$ as illustrated below using the chain budget redistribution.

$$\begin{aligned}
 AS^* &= y_1, y_2, \dots, y_{\gamma-1}, y_{\gamma+1}, \dots, y_{|\mathcal{N}|} \\
 &D_{1,2} \downarrow \\
 &y'_1, y_2 + \alpha, \dots, y_{\gamma-1}, y_{\gamma+1}, \dots, y_{|\mathcal{N}|} \\
 &D_{2,3} \downarrow \\
 &y'_1, y'_2, \dots, y_{\gamma-1}, y_{\gamma+1}, \dots, y_{|\mathcal{N}|} \\
 &\vdots \\
 &D_{\gamma-1+\alpha, \gamma} \downarrow \\
 &y'_1, y'_2, \dots, y_{\gamma-1+\alpha}, y_{\gamma}, y_{\gamma+1}, \dots, y_{|\mathcal{N}|}
 \end{aligned}$$

∴ the action matrix leading to the NE presented in Eq. 19 is given by Table 6.

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MOHAMED S. ABDALZAHER (S'015–M'16)

received the B.Sc. degree (Hons.) in electronics and communications engineering, in 2008, the M.Sc. degree from Ain Shams University in Electronics and Communications Engineering, Cairo, Egypt, in 2012, and the Ph.D. degree from the Electronics and Communications Engineering Department, Egypt–Japan University of Science and Technology (E–JUST), in 2016. He was a special Research Student with Kyushu University, from 2015 to 2016. In April 2019, he has joined the Center for Japan–Egypt Cooperation in Science and Technology, Kyushu University, Japan, where he is currently a Postdoctoral Researcher. He is also an Assistant Professor with the National Research Institute of Astronomy and Geophysics (NRIAG). His research interests include data communication networks, wireless communications, WSNs security, the IoT, and deep learning. He is a TPC with Vehicular Technology Conference and with International Japan–Africa Conference on Electronics, Communications and Computers (JAC-ECC) and a Reviewer of the IEEE INTERNET OF THINGS JOURNAL, IEEE ACCESS, and IET Journals.



OSAMU MUTA received the B.E. degree from

Ehime University, in 1996, the M.E. degree from the Kyushu Institute of Technology, Japan, in 1998, and the Ph.D. degree from Kyushu University, in 2001. In 2001, he joined the Graduate School of Information Science and Electrical Engineering, Kyushu University, as an Assistant Professor, where he has been an Associate Professor with the Center for Japan–Egypt Cooperation in Science and Technology, since 2010. His current research interests include signal processing techniques for wireless communications and power line communications, MIMO, and nonlinear distortion compensation techniques for high-power amplifiers. Dr. Muta is a Senior Member of IEICE. He received the 2005 Active Research Award from IEICE technical committee of radio communication systems, the 2014, 2015, and 2017 Chairman's Awards for excellent research from IEICE technical committee of communication systems, respectively.

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