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A delay-aware spectrum handoff scheme for prioritized time-critical industrial applications with channel selection strategy

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ABSTRACT

Cognitive radio has emerged as an enabling technology in the realization of a spectrum-efficient and delay-sensitive industrial wireless communication where nodes are capable of responding in real-time. However, particularly for time-critical industrial applications, because of the link-varying channel capacity, the random arrival of a primary user (PU), and the significant delay caused by spectrum handoff (SH), it is challenging to realize a seamless real-time response which results in a quality of service (QoS) degradation. Therefore, the objectives of this paper is to increase spectrum utilization efficiency by allocating channel based on the priority of a user QoS requirements, to reduce SH delay, to minimize latency by preventing avoidable SHs, and to provide real-time response. To achieve an effective spectrum utilization, we proposed an integrated preemptive/non-preemptive priority scheme to allocate channels according to the priority of user QoS requirements. On the other hand, to avoid significant SH delays and substantial latency resulting from random PU arrival, a unified spectrum sensing technique was developed by integrating proactive sensing and the likelihood estimation technique to differentiate between a hidden and a co-existence PU, and to estimate the mean value of the busy and the idle periods of a channel respectively. Similarly, to prevent poor quality channel selection, a channel selection technique that jointly combines a reward system that uses metrics, e.g. interference range, and availability of a common channel to ranks a set of potential target channels, and a cost function that optimizes the probability of selecting the channel with the best characteristics as candidate channels for opportunistic transmission and for handoffs was developed. The simulation results show a significant performance gain of the delay-PritSHS in terms of number of SHs, Latency, as well as throughput for time-critical industrial applications in comparison to other schemes.

1. Introduction

Spectrum mobility is an important cognitive radio (CR) technology functionality, which allows CR users to make opportunistic-use of unoccupied portion of licensed frequency spectrum of the primary users (PU) for CR communication [1]. However, the opportunistic utilization of the licensed band by CR users is on the condition that CR transmission does not cause harmful interference to the activity of the high priority PU [2,3]. Therefore, CR users must pause on-going CR communication on the arrival of a PU on the channel that the CR users previously occupy and continue CR communication in a new target channel [4]. This process is known as spectrum handoff (SH) [5,6], and it is different from traditional handoffs (vertical or horizontal handover) as illustrated in Figs. 1 and 2 respectively. Therefore, existing SH algorithms in cognitive radio networks (CRNs) are developed to solve the problem of when a PU appears on a channel and CR users have to vacate the channel for a new target channel to complete unfinished CR communication. In addition, the typical SH strategy implemented in these existing algorithms is that CR communication is interrupted, while CR packets wait in a transmission buffer until CR transmission is switched to a new target channel to complete on-going CR communication.

However, unlike CRNs, in industrial wireless sensor networks (IWSNs), this approach introduces long waiting times and delays, which is contrary to, and negatively impact on delay-bound and time-critical QoS constraints of industrial applications [7,8]. For instance, in IWSNs e.g. control applications and robotics, typical delay constraints are less than 25 ms [3], whereas in CRNs, typical sensing duration for a new channel is about 20ms [9]. This results in channel switching time being longer than the delay constraints of IWSN applications. Furthermore, in CRNs, the arrival PU on the channel previously deployed by CR nodes for CR transmission, is the sole reason for implementing SH. However, in IWSNs, high level of signal attenuation in operating frequency due

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to massive multipath fading and shadowing effects from large metallic obstacles is the fundamental reason for large percentage of spectrum mobility. It is for this reason, for instance that WirelessHART adopts time synchronized mesh protocol for medium access control to provide interference-free and deterministic communication for measurements and control applications [10]. Similarly, some related efforts that have been implemented for enhanced medium access control in IWSN include industrial-WLAN developed to provide improved roaming and longer communication range.

Conversely, CR technology incorporated into IWSN (CR-IWSN) architecture, can improve spectrum utilization in IWSNs with well-designed SH strategies. Similarly, by incorporating dynamic spectrum access (DSA) techniques built for CR technologies into IWSNs, CR technology can ensure interference-free and deterministic industrial wireless communication (IWC) [11,12], while supporting delay-bound and time-critical constraints of industrial applications [13]. Consequently, some CR standards have been developed to exploit TV white spaces (TVWS) for improved spectrum mobility in IWSN e.g. IEEE802.15.4m, IEEE 802.15 WPAN, and IEEE 802.11WLAN, as well as IR-UWB, which is developed for time-critical IWSN applications [3,14,15]. However, similar to CRNs, in prospective CR-IWSN, to establish a new channel connection for seamless spectrum mobility is a non-trivial task [16]. This is due to several factors which are common to both CRNs and IWSNs, however, this challenge is aggravated by harsh industrial environment in IWSNs in particular [17]. Some of these factors include, availability of target channels, and probability of future availability of target channels during periods of SH, as well as common channel availability. To be efficient, as well as to mitigate these challenges, a SH scheme should take into account the random and nondeterministic nature of channel and time-varying pattern of PU activities, which leads to random appearance and departures of spectrum holes, which ultimately affects network performance [18]. Therefore, to deal with this challenges, we have proposed a novel delay-aware spectrum handoff scheme for prioritized time-critical industrial applications with channel selection strategy (delay-PritSHS) to increase spectrum utilization efficiency and to increase channel capacity for industrial wireless communication. The main contributions of this paper are summarized as follows:

- We propose an integrated preemptive/non-preemptive priority scheme to allocate channels to CR users according to the priority of the CR user QoS requirements, this is to enhance spectrum utilization efficiency and reduce handoff delay by preventing avoidable long waiting time for time-critical industrial application when connecting to a new channel. Similarly, this is to eliminate long waiting time and SH delays which are due to CR packets buffering as well as communication latency while waiting to resume transmission on the current channel.
- Spectrum sensing plays an important role in the delay-PritSHS scheme, therefore, for an effective spectrum sensing, we develop a unified spectrum sensing technique by integrating proactive sensing with the likelihood estimation technique to estimate the mean value of the busy and the idle periods of a channel and to differentiate between a hidden and a co-existence PU. This is to increase the probability of finding a channel that will remain idle while an opportunistic transmission is on-going without interfering with a PU activity. In addition to minimizing needless SHs and eliminating the time spent when scanning for a new channel at the instant an SH is triggered, as well as to reduce the overall channel switching time.
- To prevent avoidable SHs resulting from poor quality channel selection and for an improved throughput performance of the delay-PritSHS. We develop an enhanced channel selection technique, which uses a reward system, with metrics, e.g. interference range, and availability of a common channel, to rank a set of potential target channels, then, we introduce a cost function to optimize the probability of selecting the channel with the best characteristics as the candidate channel for opportunistic transmission and for handoffs.

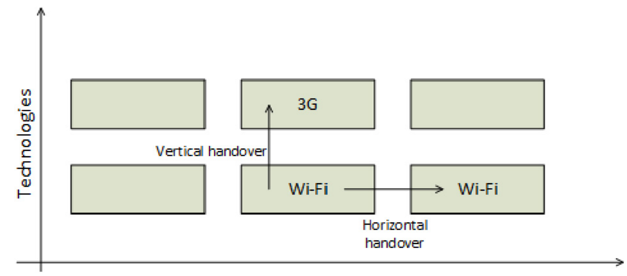

Fig. 1. Illustration of traditional handover.

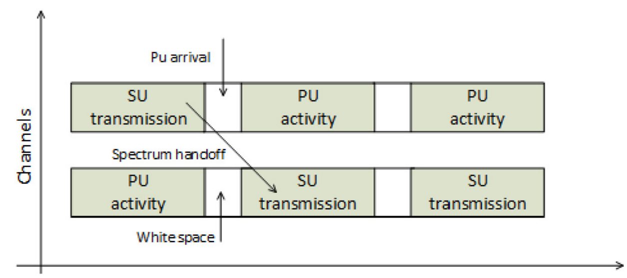

Fig. 2. Illustration of spectrum handoff.

We have organized the rest of the paper as follows. In Section 2, we discuss related work, then, our system model is explained in Section 3, furthermore, Section 4 gives details description of the proposed SH algorithm. In Section 5 simulation results are presented and discussed, then we conclude the paper in Section 6.

2. Related work

Only a few studies have considered application of CR technology for solving technical challenges in industrial wireless technology. Worse yet, most works applying CR concept to IWSNs, do so without considering the unique QoS requirements of IWSNs aggravated by the harsh industrial environments [19]. Here are some prominent works of the limited works in literature that have considered CR in IWSN and related environments. Authors in [20] considered several cognitive and non-cognitive solutions for IWC and evaluated both solutions for mission-critical and time-critical data transmission over several fading and interference channels. Their work showed that CR-based solutions sustained the performance of the network in harsh channels and under interference better than non-cognitive solutions. By taking into account collision among several SUs in a multiple-SU and an SH-scenarios like CR-IWSNs, in [21], an SH solution was developed by integrating proactive spectrum sensing and a recovery procedure. Their work allows a sensor node to opportunistically use a licensed channel if its transmission does not cause interference to the PU transmitter, and it ensures a continuous connectivity between CR sensor nodes in rapidly changing PU activity and implements an efficient control channel recovery. To address the challenge of spectrum scarcity in overlay CRNs the work in [22] proposed three approaches; a direct, a distributed, and an incremental selection techniques to identify and detect a PU signal so that CR users can share same spectrum with the PUs without interference. In the proposed method, the PU approaches the interference-free limit of the CR users over practical ranges of power level by exploiting the sparsity of the CR user's interference. Similarly, in [2], a smart unified communication strategy was developed for smart grid network (SGN) to improve communication efficiency in SGN.

In their work, a communication access technologies design with QoS constraints for SGN was implemented.

However, in the above cited literatures, and existing SH schemes, the QoS performance with respect to priority of CR user are not considered or supported. Conversely, in [23], authors investigated whether or not PUs should preempt the service time of the CR users. They observed that CRNs with single PU and multiple CR users are normally modeled as a queueing system where the PU has higher priority than CR users. Therefore, they compared the throughput and social welfare of CR users in the preemptive and non-preemptive cases. Their findings showed that the non-preemptive case outperforms the preemptive in certain scenarios, whereas, in some situations, it is optimal to allow preemptions. Similarly, most SH schemes usually assume that all CR users should have the same priorities. Nonetheless, some literatures have considered a CR user priority challenges. In [24–28], a CR user priority in CRNs have been discussed. However, most CR user priority-schemes usually permit higher priority CR users to always interrupt lower priority CR users, leading to frequent SHs and resulting in a degraded network performance, particularly in high traffic networks. Similarly, most CR user priority-schemes do not consider the effects of the industrial fading channels and interference, despite the fact that overlooking the effects of industrial fading channels may result in selecting poor quality channels leading to a degraded QoS performance. Particularly, for time-critical and mission-critical industrial applications if channels are selected arbitrarily without considering the quality of the selected channels, it may lead to poor QoS performance. Therefore, selecting channels with good quality should be considered as a key metric when designing channel selection strategies (CSS) integrated in SH procedure for IWSNs. Conversely, channel availability is the sole metric used in designing the CSS which are integrated into SH strategy in literature. Generally, no consideration is often given to channel quality as a key metric in designing CSS for SH strategies in existing literature.

However, in [29], authors showed that to design an efficient CSS, channel availability as well as channel quality are the two key metrics that should be considered. An L-CAQ channel selection scheme was design in their work, which selects channel that jointly maximizes channel availability probability as well as channel quality. In [30], authors designed a QoS-aware framework to select the best spectrum band by characterizing the fluctuations of available spectrum and classifying heterogeneous QoS requirements of CR users. They developed an admission control algorithm to stabilize the heterogeneous QoS requirements and a spectrum decision algorithm to select the best spectrum bands. The designed framework maximized throughput while maintaining fairness. Similarly, an adaptive channel selection method, was developed in [31] for hierarchical cluster-based CRNs. In this work, channels with the highest ranking position based on a predefined sensing policy are selected as potential backup channels, in case of decreasing channel quality for legacy systems. The work in [32] showed that adopting a selection strategy can reduce power consumption and financial cost of devices by facilitating the use of multiple access techniques. They use diverse metrics such as node and network capabilities, user preferences, and price to develop a context-aware selection scheme to select the best network. By taking into account behavior of PU on the channel and RSSI value, in [33], a channel selection method was developed for IEEE 802.22 based on fuzzy logic. The results presented in this work are helpful in ranking channels for selection as operating channel from backup channel list. The work in [34], proposed a link-aware channel selection technique, which considers the impact of unreliable wireless link, therefore in this work, a scheme which reroutes transmission on noisy links was developed for body networks.

To the best of our knowledge, a scheme that holistically considers the priority of a CR user for effective spectrum utilization, the delay-sensitive of time-critical industrial applications, and the selection of quality channels for an SH performance in IWSNs have not be considered in earlier literature.

3. System model

3.1. Network model and assumptions

Though the IWSN devices deploy the ISM unlicensed band for their communication, in this paper, we assumed that by incorporating CR abilities, the IWSN node can access more bandwidth by sharing the licensed band with the PUs in an overlay spectrum sharing mode for enhanced real-time capabilities. Moreover, an access to more spectrum bandwidth allows the IWSN node to match the strict requirements of industrial operations which requires time-critical and real-time responses. Similarly, an access to more bandwidth in the licensed band can alleviate the overcrowding and strict competition for scare spectrum in the ISM unlicensed band by heterogeneous networks. Therefore, we adopt a multiple-node model consisting of J PUs holders of N licensed channel bands and n IWSN nodes having CR capabilities (CR-IWSN nodes) existing side-by-side with partially overlapping coverage areas, where $n \geq 2$. We assume that CR-IWSN nodes start their communication in the ISM band. However, CR-IWSN nodes can share the licensed band with the PUs in an overlay transmission. In Table 1, we outline the key variables and notations used in the development and the performance analysis of the delay-PritSHS scheme.

4. Proposed spectrum handoff scheme

This section introduces the delay-PritSHS scheme. As illustrated in Fig. 3, the design of the delay-PritSHS scheme consists of three main parts including: (1) *spectrum sensing and channel selection*: the CR nodes in the delay-PritSHS scheme employ two transceivers with software defined radio (SDR) capabilities. One of the transceivers is used for communication with other CR nodes, whereas, the other is used to scan for vacant channels and to detect the activity of a PU on channels being deployed for CR nodes opportunistic communication, (2) *spectrum utilization*: this delay-PritSHS scheme proposes an integrated preemptive/non-preemptive priority model to achieve an effective and efficient utilization of the spectrum between the PUs, the high priority and low priority CR nodes, and (3) *handoff decision*: in the delay-PritSHS scheme, two major criteria can trigger an SH process, and also determine whether the handoff procedure will continue or not. These include (1) the presence or absence of a PU signal on the channel selected by a CR node for opportunistic transmission, and (2) if channel condition in the current channel of CR nodes becomes attenuated, and does not meet specific QoS constraints/requirements of CR applications.

4.1. Spectrum sensing for PU presence and optimal channel selection

The CR-IWSN node in our scheme utilizes two transceivers with SDR capabilities. One of the transceivers is deployed for CR transmission while the other is used for spectrum sensing to perform the following functions: (1) to scan for idle channels to deploy for CR transmission and (2) to detect the activity of a PU on the channel being deployed for CR transmission [35]. Moreover, spectrum sensing is essential in observing channel usage and for gathering information to estimate future channel state. To effectively share the licensed bands with the PUs without interfering with their activities, a CR user should be able to detect the presence of a PU immediately it arrives on a channel. Therefore, in this paper, we assume that J PUs communicate with each other using N licensed channel bands through a synchronous time slot t which alternates between busy and idle periods, with each channel having a bandwidth of $B_0 = B/N$ [36]:

$$t = \left[S_1(t), \ldots \ldots S_N(t)\right] \qquad where\ S_i(t) \in \{0\,(idle), 1(busy)\} \tag{1}$$

At the beginning of each time slot, the CR-IWSN nodes use the clear channel assessment with energy detection and carrier sensing (CCA-ED-CS) technique to sense the channel in order to determine the status of

Table 1
Key parameters used in development and performance analysis of scheme.

Symbols	Meaning
$f(x)$	Probability density function of a variable.
D_0, D_1	Mean values of the idle and busy periods
P_n	Probability of channel being idle during an opportunistictransmission
$\theta_{m,n}$	Availability of m channels for CR node n transmission
$G_{n,k}$	Potential target channels for CR nodes n and k
$R_{m,n,k}$	Expected reward on channel m assuming it available for opportunistic Transmission between CR nodes n and k
$a_{n,k}$	Interference-free transmission range of CR nodes n and k
$c_{m,n,k}$	The metric that contemplates the availability of a common channel forrendezvous between CR node n and k
$b_{m,n,k}$	The actual reward computed by CR nodes n and k fortransmitting on channel m
$P_{m,n,k}$	The probability that a channel m will be selected byCR nodes n and k as the channel with the best characteristics
m_ρ	Channel with the best channel quality
P_d	Probability of false detection
P_f	Probability of miss-detection
ω	Spectrum sensing accuracy
R_j	The occupancy period of CR node j on channel m
S_{pj}	The effective transmission time of CR node j afterthe $(n-1)$th and before the nth interruption on channel m
S_{sj}	The time taken to complete one successfulpacket transmission on channel m.
χ_j	The arrival rate of CR node j.
B_j	The total transmission time of CR node j on channel m
D_i	Delay busy period of CR node i
D_j	Delay busy period of CR node j
W_j	Expected handoff delay of CR node j
$T^i{}_{un}$	The busy period initiated when the class α usersinterrupt the CR user j transmission to transmits its packet.
S_i	The service time of a packet i in the queue
$T^R{}_{un}$	The service time of the first class α user whichinterrupted the CR node j transmission at time t_m.
S_{Aj}	The period of time when the transmission of a CR node j can be interrupted by a CR-IWSN node i (preemptive periods)
S_{Bj}	The period when the transmission of a CR node j cannot be interrupted by CR-IWSN node i (non-preemptive periods)
C_A	Channel quality indicator
Δ	The total transmission time due to sensing error
$X(s)$	The Laplace transform of a variable

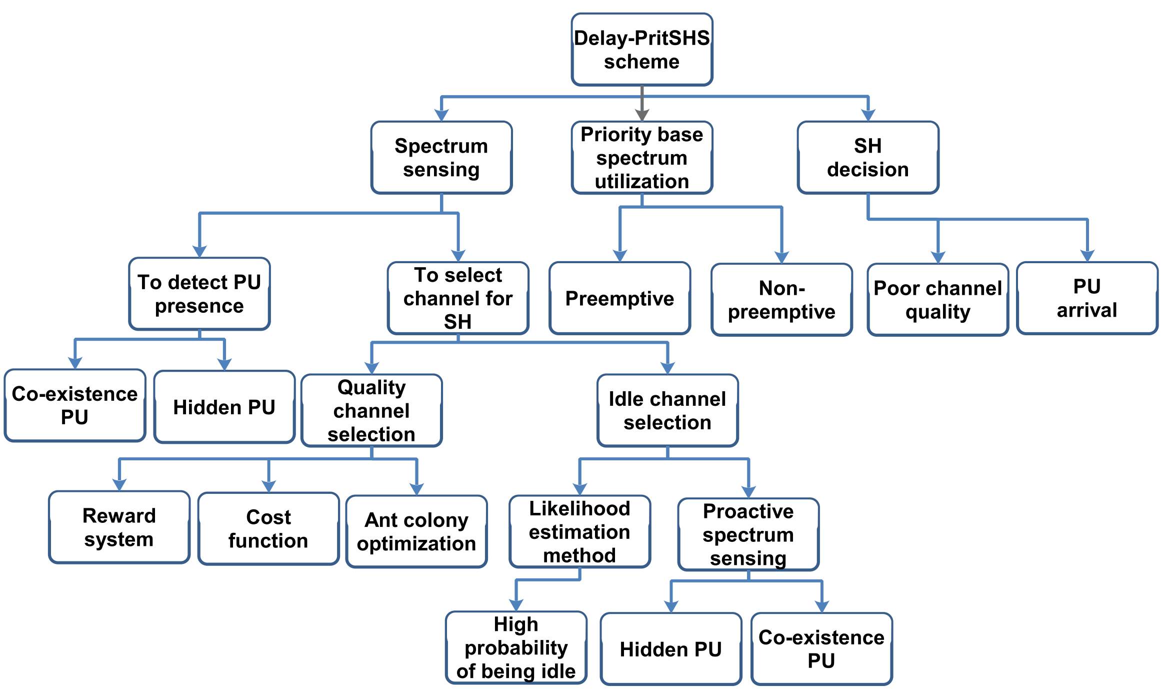

Fig. 3. Proposed SH scheme with sensing, channel utilization, and selection.

the channel. If the channel is idle at the beginning of the slot, the CR-IWSN nodes commence its opportunistic transmission in the slot until the end of the slot. Otherwise, if the channel is busy at the beginning of the slot, the CR-IWSN node waits for the next idle slot to transmit. However, in the IWSN environment, spectral opportunities occur 60% of the time because of the bursty nature of the traffic. Therefore, in this paper, we consider a deterministic traffic model where the busy and idle periods in discrete time domain are exponentially distributed in a two-state process as represented in (2) and (3) respectively.

$$f(D_1) = \begin{cases} \lambda e^{-\lambda D_1}, & D_1 \geq 0 \\ 0, & D_1 < 0 \end{cases} \tag{2}$$

$$f(D_0) = \begin{cases} \beta e^{-\beta D_0}, & D_0 \geq 0 \\ 0, & D_0 < 0 \end{cases} \tag{3}$$

where λ and β are the rate parameter of the exponential distribution. $1/\lambda$ and $1/\beta$ are the mean values of the busy and idle periods, and D_1

and D_0 are the duration in the busy and idle periods respectively. By means of the traffic model in (2) and (3), we are able to replicate the 60% spectral opportunity in real IWSN-scenarios by controlling the rate parametersλ and β. To achieve this, we use small β values to increase the duration of the idle time, and large λ values to reduce the busy periods thus allowing time-critical industrial applications enough time to transmit. However, since the arrival of the PUs is unplanned, it is challenging to prevent interruptions to both licensed and unlicensed communications. Similarly, by means of the traffic model in (2) and (3), channel information, e.g., the mean of the busy and idle periods taken over a long period can be used to determine the channel availability. Based on this estimation, the CR-IWSN node can decide whether to continue on the current channel, or to handoff to a new target channel or to pause unfinished communication before the end of the current slot. In this paper, we use the maximum-likelihood estimation method to compute the values of the mean of the busy and idle periods to determine the likelihood that channel will remain idle while a CR-IWSN node is transmitting. Therefore, the probability p_n that channel $n$will be available for opportunistic usage given an N set of licensed channel is denoted in (4) as.

$$p_n = \frac{\psi_n}{\psi_n + \varpi_n} \tag{4}$$

where ψ_n and ϖ_n are vectors corresponding to values of the busy and idle periods respectively. Substituting $1/\lambda$ and $1/\beta$ into (4), the probability p_n of a channel being idle can then be given as (5).

$$p_n = \frac{1+\beta}{\lambda} \tag{5}$$

where $1 \leq n \leq N$. By periodic spectrum sensing, a CR-IWSN node continues to update the probability of each channel being idle in the next time slot. Assuming the N licensed channels are indexed as $1, 2, 3, \ldots, N$, the probability of each channel being idle in time slot S_{i+1} can be arranged as $p_1 \geq p_2 \geq p_3 \geq \cdots p_N \geq 0$.

However, even if a CR-IWSN node is in the middle of a transmission, it must vacate a licensed channel upon the arrival of an incumbent PU on the channel to continue its unfinished communication in a new channel. This approach is the typical technique implemented by conventional SH schemes to prevent harmful interference to a PU transmission. However, a CR-IWSN node can only cause harmful interference to a PU activity if the CR-IWSN node is within the PU transmission range. In this paper, we define a PU as either a coexistence node or a hidden node [21]. On the one hand, a PU is assumed to be a coexistence node if a CR-IWSN node is outside the PU coverage area. On the other hand, if a CR-IWSN node is within the PU coverage area then the PU is a hidden node. The moment a CR-IWSN node discovers that the PU occupying a channel is a hidden node it needs to perform an SH immediately to prevent harmful interference to the PU activity. Otherwise, if the PU is a coexistence node, the CR-IWSN node can still transmit on the channel without causing any interference. Here, a CR-IWSN node n keeps a hole information array (HIA)Θ, of m channels within any radius $r_{j,m}$ of a PU j to determine if the PU occupying the channel is a hidden PU node or coexistence PU node. In (6), Θ is described as an M by N matrix.

$$\Theta = \left\{\theta_{m,n} | \theta_{m,n} \in \{1(coexistence), 0(hidden)\}\right\} \tag{6}$$

such that;

$$\theta_{m,n} = \begin{cases} 1 & r_{n,m} \leq d_{n,j} - r_{j,m} \\ 0 & otherwise \end{cases} \tag{7}$$

where $\theta_{m,n}$ is channel availability, $d_{n,j}$ is the distance between CR-IWSN node n, and PU j, and $r_{n,m}$ and $r_{j,m}$ are the radius of the coverage area of the CR-IWSN node n and the PU j respectively. The other condition when a CR-IWSN node should sense and select a new channel is when the quality of the channel in the present channel no longer support the QoS requirement of the CR-IWSN node application. However, the idea is to select a channel with good quality, and this is because when a channel is selected arbitrarily, there is a likelihood of selecting a channel with poor quality, which ultimately affects the performance of the network. The sequence of the implementation of spectrum sensing for opportunistic and updating channel information are highlighted in the pseudo-code in Algorithm 1.

Algorithm 1

Spectrum Sensing for Opportunistic Transmission

```
Scan channel N
If channel is idle at the beginning of a slot, t ∈ {0(idle), 1(busy)}
   Transmit till the end of the slot
ElseIf channel is busy at the beginning of the slot
   Wait till next idle slot
EndIf
```

Updating Channel Information

```
Determine PU type, θ ∈ {1 (co − existence), 0 (hidden)}
Compute the mean value of the idle and busy periods, 1/λ, 1/β
Compute the probability of channel being idle during CR transmission using (5)
Keep hole information array of each channel N
Update information
```

4.2. Estimating channel quality to select the channels with best characteristics

Now, if we consider that CR-IWSN nodes n and k belong to a class N with time and mission critical QoS requirements. Assuming$G_{n,k}$ is a set of available channels being sensed by CR-IWSN node n intending to communicate with CR-IWSN node k through opportunistic transmission. If $\cap\, G_{n,k} \neq \emptyset$, then it holds that at least a channel exist that can support the QoS constraints of CR-IWSN nodes n and k applications. However, the best channel must be selected. In this paper, we use a reward system to rank the channels to select the channel with the best characteristics. Afterwarda, the channel with the best characteristics is selected as the most suitable channel for handoff. To achieve this, when a CR-IWSN node n communicates on channel m with CR-IWSN node k, a reward R is computed such that [37]:

$$R_{m,n,k} = a_{n,k} * c_{m,n,k} * b_{m,n,k} \tag{8}$$

where $a_{n,k}$ is a range vector that ensures that the transmission range$d_{n,k}$ of both communicating CR-IWSN nodes n and k is within an interference-free threshold d_{th}, such that:

$$a_{n,k} = \begin{cases} 1 & d_{n,k} \leq d_{th} \\ 0 & otherwise \end{cases} \tag{9}$$

Similarly, for both CR-IWSN nodes n and k to be able to share information about the selected best channel, at least a common channel must exist for both nodes, $c_{m,n,k}$ defines a common channel metric where:

$$c_{m,n,k} = \begin{cases} 1 & \theta_{m,n} * \theta_{m,k} = 1 \\ 0 & otherwise \end{cases} \tag{10}$$

Finally, the CR-IWSN nodes needed to have transmitted on a channel to have a prior knowledge about the characteristics of the channel. Therefore, the reward for each channel is calculated after every transmission on the channel. Hence, assuming the condition in (9) and (10) are satisfied, the reward $R_{m,n,k}$ computed for a channel m is then given as:

$$b_{m,n,k} = B_0 * log_2\left(1 + \vartheta(A - 10n_p log_{10}(d_{n,k}) + \varphi_m)\right) \tag{11}$$

where ϑ is the signal-to-noise-interference ratio of the channel m, and n_p is the propagation-loss exponent, A is the received signal strength at 1m reference distance, and φ_m is a zero-mean Gaussian distribution. Then a cost function $\chi_{m,n,k}$ of selecting m channel as the best channel for handoff for class N CR-IWSN nodes is calculated based on the reward $b_{m,n,k}$ on each channel as:

$$\forall m \in G_{n,k} \Rightarrow \chi_{m,n,k} = \left[\frac{1}{\sum_{k=1}^{N} b_{m,n,k} * a_{n,k}}\right]^u \left[\frac{\theta_{m,n}}{M}\right]^v \left[\frac{\sum_{k=1}^{N} c_{m,n,k}}{N}\right]^{-w}$$

(12)

where u is the weight of the channel propagation characteristics, v is the weight of the channel availability, and w is the weight of commonality of the channel respectively. An Ant colony optimization is used to select the best channel based on the cost function computed for each channel. Pheromone trails which are inversely correlated to the cost function are deposited on the m channels to be selected for handoff by CR-IWSN node n. Based on the pheromone level on each channel, the probability $P_{m.n.k}$ of selecting a given channel m as the channel with best characteristics by CR-IWSN node n for communicating with node k is computed in (13) as.

$$P_{m.n.k} = \begin{cases} \dfrac{\rho^{s}_{m,n,k} * \eta^{t}_{m,n,k}}{\sum_{k=1}^{N} \rho^{s}_{m,n,k} * \eta^{t}_{m,n,k}} & m \in c_{m,n,k} \\ 0 & otherwise \end{cases} \tag{13}$$

where $\rho_{m,nk} = Q/\chi_{m,n,k}$ is the pheromone deposit on each channel, and Q is a scaling parameter. For dynamic models, the heuristic function $\eta_{m,n,k}$ is not always considered. Moreover, an ant colony system without heuristic function has been shown to perform better in [38]. Therefore, in this paper, by relying only on the pheromone concentration for our ant colony optimization, we simply set the value of $\eta_{m,n,k} = 1$, where s and t are weight of the pheromone deposit and heuristic information respectively. Therefore, based on the optimization, the channel with the best characteristics is selected as:

$$m_{\rho} = arg\ max\ P_{m.n.k} \tag{14}$$

to select the next channel with the best characteristics for handoff by CR-IWSN nodes the pheromone is updated by using (15):

$$\rho_{m,n,k}(t+1) = (1-\rho)\,\rho_{m,n,k}(t) + \mu\Delta\rho_{m,n,k} \tag{15}$$

where μ is the coefficient of pheromone evaporation which gives the relative weight of the previous solution to the next solution. After a pair of communicating CR-IWSN nodes have decided on the best channel to use for their transmission. The CR-IWSN nodes must continue to perform spectrum sensing, to detect any PU activity on the channel to avoid harmful interference to incumbent PU nodes. The pseudo-code detailing the execution sequence of the task of spectrum sensing to select the channel with the best characteristics are described in Algorithm 2.

Algorithm 2: Estimating Channel Quality

```
Sense G_{n,k} channels
If G_{n,k} ≠ 0
   Compute R_{m,n,k} using (8)
   If a_{n,k} = 1 and c_{m,n,k} = 1
      Compute b_{m,n,k} using (11)
      For each m ∈ G_{n,k}
            Compute χ_{m,n,k} using (12)
            Compute P_{m,n,k} using (13)
      EndFor
   EndIf
Select best channel using (14)
ElseIf G_{n,k} = 0
Goto 1
EndIf
```

4.3. Spectrum sensing accuracy

Spectrum sensing is an important CR functionality, which allows the CR user to detect new channels for handoff, as well as the presence of a PU on the channel to prevent interference. However, errors do occur during spectrum sensing. Usually, there are two types of sensing errors when sensing for a PU activity on a channel. These are the false-alarm error and the miss-detection error respectively. In the miss-detection error, the presence of PU activity/arrival of a PU is not detected resulting in harmful interference to the PUs. Whereas, in false-alarm error, the presence of a PU/arrival of a PU is falsely declared which results in unnecessary spectrum resources overhead. In this paper, we compute the probabilities of detection P_d and false-alarm P_f using the incomplete gamma and generalized Marcum Q-functions. To compute the probabilities, a CR-IWSN node compares a test statistics Y with a predefined threshold value γ using the CCA-ED-CS approach, respectively, by $P_r\left(Y > \gamma | H_1\right)$, and $P_r\left(Y < \gamma | H_0\right)$, where $\left\{H_1 | Y > \gamma\right\}$ means the PU signal is present, and $\left\{H_1 | Y < \gamma\right\}$ signifies the absence of the PU signal. Then, the probabilities are calculated as follows:

$$P_d = Q_{\psi}\left(\sqrt{2\delta}, \sqrt{\gamma}\right) \tag{16}$$

$$P_f = \frac{\Gamma\left(\psi, \frac{\gamma}{2}\right)}{\Gamma(\psi)} \tag{17}$$

where Q_{ψ} represents the generalized Marcum function, and the incomplete gamma function is denoted by Γ, which, in the integral form is defined as $\Gamma(a, x) = \int_x^{\infty} t^{a-1} e^{-t} dt$ and $\Gamma(a, 0)\,\Gamma(a)$, and δ is the end-to-end signal to noise ratio. Consequently, based on the detection and false-alarm probabilities, the accuracy of spectrum sensing is computed as follows:

$$\omega = P_d\left(1 - P_f\right) \tag{18}$$

where the value $081 \leq \omega \leq 0.99$. Note that a high accurate spectrum sensing allows the CR-IWSN nodes to be able to identify the PU traffic pattern correctly. As a result of which the CR-IWSN nodes can select the channel with the best characteristics for their communication. According to the IEEE standard, the probabilities of miss-detection and false alarm should be within the following ranges $0.01 \leq P_f \leq 0.1$ and $0.9 \leq P_d \leq 0.99$ respectively.

4.4. Spectrum utilization based on preemptive and non-preemptive priority

In a typical CRN, the PU has preemptive right on the channel. Having a preemptive right implies that the PU can interrupt the transmission/reclaim the channel of a CR user any time the PU arrives on the channel. On the other hand, the activity of a PU cannot be interrupted (non-preemptive) by a CR user. This implies that a CR user has non-preemptive right on a channel occupied by a PU transmission. However, under the current licensing rules, types of licenses are not explicitly stated, for instance, while it states clearly that CR users should not interfere with PUs activity on the licensed band, no restrictions were imposed expressly on PUs, or other CR users regarding the activity of a CR user in the unlicensed bands. Therefore, it is assumed, albeit without stating it, that the unlicensed bands are freely available without restrictions. These assumptions have dire consequences from a technical perspective, since it means for example, that among CR users in the unlicensed bands, some CR users have no priority. Nevertheless, in specific scenarios, e.g. CR-IWSN scenarios, priorities which imposed challenges on the usage of unlicensed bands are defined among CR users [39]. Take for instance, control and monitoring systems which utilizes the unlicensed band, and requires uninterrupted connection with predefined delay tolerance and error margin. Certainly, the operation of this systems do not require interference and should definitely be given highest priority. Therefore, in this paper, we differentiate two types of CR users: (1) the high priority CR-IWSN node $i \in G$ which due to their time-critical constraints, requires real-time response, and (2) the low priority CR node $j \in N$ without the stringent time-critical requirement of industrial applications. Thus, we propose an integrated preemptive/non-preemptive priority scheme between the PUs, the CR-IWSN nodes i and CR node j to model the utilization of the spectrum. In this scheme, a CR-IWSN node i can choose any of two options whenever a PU reclaims the channel k which is previously occupied by the CR-IWSN node i. The CR-IWSN node i can decide to switch to a new channel m being occupied by CR node j to continue its unfinished transmission. Or, the CR-IWSN i node may choose to remain on the current channel k to resume its transmission again, once k becomes free. Based on a discretion rule, which we will define in subsequent section, if the condition for preemption is satisfied, the CR node j transmission is interrupted on channel m by the CR-IWSN node i. By the same token, the CR node j can choose to remain on channel m or switch to channel k. If the CR node j stays on m, it is assigned the head of the queue of its class N. Else, if the CR node j decides to switch to k it is pushed back to the tail of the queue of its class N. However, if the condition for preemption is not satisfied, the transmission of CR user j cannot be interrupted on channel m by the CR-IWSN node i. As a result, the CR user j continues with its transmission on channel m while the CR-IWSN node i waits until m becomes free to commence its transmission.

4.5. Computing the total transmission time and the occupancy period on a channel

In this section, we compute how long a CR node j stays on the channel m as well as how long it deploys channel m for its transmission. This is because both metrics are very vital information in the analysis of the expected handoff delay. Starting from the period a CR nodes j begins transmitting its first packet on channel m assuming it experiences N_j interruptions until the last packet is transmitted. Then, it implies that CR node j has transmitted $N_j + 1$ times on channel m until completing its last packet transmission. Therefore, the occupancy period R_j of CR node j on channel m can be computed as [40].

$$R_j = \sum_{j=1}^{N_j} \left(D_j + S_{pj} \right) + S_{sj} \tag{19}$$

where D_j is the time taken by CR-IWSN i to complete the transmission of its packet which are accumulated in the buffer during the non-preemptive periods of CR node j, and S_{pj} is the effective transmission time of CR node j after the $(n-1)$th and before the nth interruption on channel m and S_{sj} is the time taken to complete one successful packet transmission on channel m. Note that after the occupancy period R_j of a CR node $j \in N$ on channel m terminates, there may be a few high priority CR-IWSN nodes $i \in G$ waiting to transmit during the non-preemptive period of CR node $j \in N$ transmissions. Each of these CR-IWSN nodes i have to be allowed access to channel m to transmit their packets first before any CR node j is allowed to transmit again. Therefore, the total transmission time C_j of a CR node j consists of its occupancy period R_j on channel m plus a delayed busy period Y_i generated by high priority CR-IWSN nodes i. Where Y_i is a cumulative of each discrete D_j of each high priority CR-IWSN nodes i arriving during non-preemptive periods, which are allowed access to the channel before the CR node j. Now, if we consider B_j as the total time channel m was busy with the transmission of CR nodes j, and with the transmission of high priority CR-IWSN nodes i respectively. Then, B_j can be denoted as a busy period during which CR node i arrived with total transmission time C_j on channel m. Or the total time during which a CR node j occupied channel m until the moment channel m becomes available again for CR-IWSN node i transmission. Therefore, B_j can be designated as the total transmission time on channel m. The Laplace transform $B_j(s)$ associated with B_j can be written as [41]:

$$B_j(s) = C_j \left(s + \chi_j - \chi_j B_j(s) \right) \tag{20}$$

where χ_j is the arrival rate of CR node j. The delayed busy period generated by CR-IWSN node i is equivalent to the total time taken to transmit all of its packets which are accumulated during non-preemptive periods. In the same token, the delayed busy period of a PU can be considered as a delay cycle with the initial delay of D_i during which each CR-IWSN nodes i produces a sub-busy period of B_i. The delayed busy periods of a CR-IWSN node i and a PU follow the probability of χ_i/ϕ_i and $(\phi_i - \chi_i)/\phi_i$ respectively. Hence, we represent the Laplace transform $D_i(s)$ of D_i of a CR-IWSN nodes i in a recursive form as [40]:

$$D_i(s) = \frac{\chi_i}{\phi_i}(B_i) + \frac{\phi_i - \chi_i}{\phi_i} D_i \left(s + \chi_i - \chi_i B_i(s) \right) \tag{21}$$

where $i \geq 2$, $D_i(s) = 1$, and $\phi_i = \sum_{j=1}^{i} \chi_i$ respectively. Note that only a PU and a CR-IWSN node i with higher priority can preempt a CR node j and not any node in the class $j \in N$ with same priority as j.

4.6. Analysis of expected handoff delay

As much as our design protects the transmission of a PU from harmful interference from a CR user, nonetheless, we implement a delay-sensitive SH for the CR user. Therefore, in our SH design, a CR user has two options once its transmission is interrupted. On the one hand, a CR user might remain on its current channel until the channel becomes free again to continue its transmission. Otherwise, a CR user needs to switch to a new channel to continue its transmission. The decision to stay on its current channel or to switch to a new channel when it is interrupted is however determined by the *expected handoff delays* associated with each of the channels. A handoff delay is the waiting time between the instant a CR user transmission is interrupted, and the moment it starts to retransmit on the current channel again. Or, when it is successfully switched to a new channel to continue its unfinished transmission. For instance, if a CR user decides to switch channel, and the expected handoff delay in the new channel is longer than the expected handoff delay in its current channel, then it is sensible to remain on the current channel until it becomes free. To achieve this, the expected handoff delay associated with each channels is computed. To compute the expected handoff delay of an arriving packet k on each of the channels m (if CR user switches), and m'(if CR user stays) respectively. We assume the following class of users since the waiting time is directly related to the busy periods in the non-preemptive periods and the delay busy periods. The class includes the following (1) class α users, consisting of all PUs and CR-IWSN nodes i where $\alpha \in \{1, \ldots, j-1\}$, and has a higher priority $(j-1)$ than CR node j, (2) class β users, consisting of CR users with lower priority $(j+1)$ than CR node j such that class $\beta \in (j+1, \ldots, N)$, and (3) class j users, which include all CR nodes j with priority j. Based on this classification, we assume that the arrival of packets on channels m and m' follows a Poisson with a series of identically distributed alternating idle and busy periods. A busy period is a sequence of the following types of busy cycle: type α busy cycle: commences with the arrival of a PU or a CR-IWSN node i on the idle channel, type β busy cycle: initiated by the arrival of a class β user on an idle channel, and type j busy cycle: initiated by the CR node j in its protective non-preemptive periods. A busy period ends when the class of user that initiated the busy period departs from the channel. Or when a class α or j user leaves the channel.

4.6.1. Estimating handoff delay when a CR user switches to a new channel

If a CR node j decides to switch to a new channel m, it may find the channel is the *idle state* (when it is in a state 0) or in a *busy period* (when it is in the busy cycle of types α user, or a type β user respectively). Assuming a CR node j arrives on channel m at time t_m and encounters a number of packets Q_α of class α users on the queue. Then, the CR node j must wait in the queue for the entire packet to be delivered out of the queue. Therefore, we express the Laplace transform of the expected handoff delay of a CR node j in the queue, assuming it finds channel m in a steady-state $l \in \{0, \alpha, \beta, j\}$, as [40,41]:

$$W_j(s) = \pi_0 + \pi_\alpha W_{j/\alpha}(s) + \pi_j W_{j/j}(s) + \pi_\beta W_{j/\beta}(s) \tag{22}$$

where the steady-state probability π_j that the channel will be in state l at time t_m is illustrated as follows:

$$\pi_0 = 1-\delta,\ \pi_\alpha = \delta_\alpha (1-\delta)/(1-\delta_j-\delta_\alpha), \pi_j = \delta_j (1-\delta)/\left(1-\delta_j-\delta_\alpha\right), \quad \pi_\beta = \delta_\beta/\left(1-\delta_j-\delta_\alpha\right) \tag{23}$$

where δ is a utilization factor that contemplates the arrival rate and the effective service time of a CR node j on channel m.

4.6.2. Estimating handoff delay when a CR user remains on its current channel

If a CR node j decides to remain on the current channel m', it must wait in the queue for the entire packets of each class α users to be delivered out of the queue. However, immediately after the interruption, it will commence its transmission ahead of any class β users or class α user. Therefore, its waiting time can be considered as a type α busy cycle. We present the Laplace transform of the waiting time in (24), as [42]:

$$W_J^*(s) = W_{j-1/\alpha}(s) = Q_\alpha E\left[S_i\right] + E\left[\sum_{i=1}^{n_\alpha} T^i{}_{un} + T^R{}_{un}\right] \tag{24}$$

where $T^i{}_{un}$ is the busy period initiated when the class α users interrupt the CR user j transmission to transmits its packet. S_i represents the service time of a packet i in the queue, n_α is the number of a class α type interruptions during the waiting time from the arrival of a CR node j until a CR node j starts to retransmit. $T^R{}_{un}$ is the service time of the first class α user which interrupted the CR node j transmission at time t_m. The idea is that, based on the expected handoff delay on a target channel in comparison to the current channel, a CR user can decide whether to stay on its current channel or switch channel to a new target channel. However, in our SH scheme, a CR user will only switch channel if the anticipated handoff delay in the target channel is less than the estimated handoff delay in the current channel as given in (25). This is to prevent redundant SHs and long communication delay which are not inevitable.

$$W_J{}^* < W_j \tag{25}$$

where $W_J{}^*$ is the expected handoff delay when a CR user switches channel to a new channel, W_j is the expected handoff delay if a CR user decides to stay on a channel until the channel becomes free.

4.7. Guaranteeing real-time response for time-critical applications under strict delay constraints

Industrial applications operate under strict delay constraints due to the time-bound requirements of time-critical industrial applications. Therefore, when packets arrive late, or packets are dropped, or an on-going connection is dropped in time-critical industrial applications, a critical failure is considered to have occurred. Therefore, the open question here is how does a CR-IWSN node i behave when a PU comes back and the CR-IWSN i is interfered or when a handoff is failed?. In this work, firstly, the CR-IWSN node i attempts to limit these possibilities by using the likelihood estimation method in (5) to select only channels with high probability of being free of any PU interruptions. However, in the event that an interruption by a PU occurs to an unfinished CR-IWSN node i transmission, CR packet transmission is paused temporally while the CR-IWSN node i implements a fast channel-switching with minimum delay by selecting a target channel from a list of potential target channels. To achieve this, CR-IWSN node i always keep a list of potential target channels N, indexed as $1, 2, 3, \ldots, N$, with probability $p_1 \geq p_2 \geq p_3 \geq \cdots \ldots \ldots p_N \geq 0$, where p_n is the probability of each channel being free of any interruptions in time slot S_{i+1}. The CR-IWSN node i is always scanning for idle channels with one of its transceivers. When an idle channel is discovered, the channel is merged into the pool of target channel. The channel on top of the list with the highest probability is the best channel and is always the one to deploy for opportunistic communication. Similarly, does a CR-IWSN i drop packets when it is interfered or handoffs fail?. Again, all potential target channel in the channel list have their associated expected handoff delay already estimated. Therefore, assuming that $i_j{}^{(1)}, i_j{}^{(2)}, \ldots ..i_j{}^{(H_i)}$ is the sequence of target channel selection based on the associated expected handoff delay $w_{i_j}{}^{(1)} \leq w_{i_j}{}^{(2)} \leq w_{i_j}{}^{(3)} \leq \ldots w_{i_j}{}^{(H_i)}$ of each channels during a CR-IWSN node i transmission. Therefore, in the event of an interruption or when handoff fails, the CR-IWSN node i selects the channel with the highest probability p_n and the least expected handoff delay $w_{i_j}{}^*$ for a fast channel-switching with minimum delay where $(1), (2), \ldots (H_i)$ represents the handoff number.

4.8. Condition for spectrum handoff

For an effective spectrum utilization, we have defined an SH scheme which utilizes spectrum resources on a preemptive and non-preemptive priority basis. However, some challenges, such as head-of-line blocking may occur in the scheme. To mitigate such possibility, we use a separate priority queue for the different class of users on each channel. Similarly, we assume that the activity of a PU on one channel is independent of the activity of other PUs in the other channels. Subsequently, we go on to define two variables S_{Aj} and S_{Bj} which are used to develop the discretion rule. The discretion rule determines the conditions for SH, and it is developed from the elapsed service time S_j, of the low priority CR node j. The variable S_{Aj} is used to delineate the period of time when the transmission of a CR node j can be interrupted by a CR-IWSN node i (preemptive periods). Whereas S_{Bj} specifies the period when the transmission of a CR node j cannot be interrupted by CR-IWSN node i (non-preemptive periods). Invariably, the service time S_t, of CR node j can be computed in (26) as the sum of the preemptive and non-preemptive periods.

$$S_t = S_{Aj} + S_{Bj} \tag{26}$$

The conditions for a CR-IWSN node i to switch/handoff to a channel m currently being held by a CR node j, which in other words are the conditions for satisfying the discretion rule are given in (27) as:

$$\begin{cases} S_{AJ=}min\left\{S_j, \vartheta_j\right\} \\ S_{BJ=}max\left\{0, S_j - \vartheta_j\right\} \\ S_t < \vartheta_j \end{cases} \tag{27}$$

where ϑ_j is a predefined threshold, and since a PU has the highest priority and it is non-preemptive, for a PU, $S_{Aj=}0$ and $S_{Bj} = S_t$ respectively, and the PU needs not observed the discretion rule. As result a PU can interrupt the transmission of a CR user at any time it arrives at the channel. The other conditions when a CR-IWSN node can switch to a new channel is when its present channel no longer supports its QoS requirements. A pair of communicating CR-IWSN nodes acquire several values of received signal strength indicator (RSSI) of the IWSN environment from their transceivers to estimate C_A throughout periods with poor packet reception rate. By this information, CR users are able to judge if the quality of its current channel is no longer acceptable and therefore CR users can begin to initiate SH procedure.

$$C_A = 1 - \frac{\sum_{i=0}^{i<n} Q_i}{n} \tag{28}$$

where Q_i is equal to 0 or 1 depending on the value of τ, as indicated by (29), in which;

$$Q_I = \begin{cases} 0 & if\ R_i < \tau \\ 1 & if\ R_i \geq \tau, \end{cases} \tag{29}$$

where τ, is a QoS threshold, n is the number of signal samples used to calculate Q_i, and R_i is RSSI. Based on this information, the process of SH is activated or not, the hypothesis is presented in (30);

$$\begin{cases} H_3 & if C_A < 0 \\ H_4 & if\ C_A = 1, \end{cases} \tag{30}$$

Hypothesis H_3, means that quality of the link in channel state does not support CR node QoS requirements and CR nodes should perform SH. Conversely, hypothesis H_4 implies that quality of the link in channel state does support CR node QoS requirements and CR nodes should continue with on-going CR transmission.

4.9. Estimating overhead of the spectrum handoff model

Based on the assumption that CR-IWSN nodes will only switch channel if the anticipated handoff delay in the target channel is less than the estimated handoff delay in the current channel as given in (25), we proceed to calculate the overhead of delay-PritSHS scheme. As shown in Fig. 4, a pair of CR-IWSN nodes exchange a request-to-send (RTS) and clear-to-send (CTS) control messages in the connection time T_c to start CR packet transmission. Once the CR-IWSN node that initiates the RTS control message receives the CTS packets, it starts to transmit CR packets in application time T_{A1}. However, during T_{A1}, the CR-IWSN nodes continuously sense the current channel for any PU that may arrive on the channel. If a PU signal is detected, the CR packet transmission is paused temporally. At that moment, the CR-IWSN transmitter sends a channel-switching-request (CSR) with information concerning the newly selected channel in the handoff delay period T_d. Consistent with the assumption in (25), at least one channel will be in the *idle state* in the target channel list during the period T_{A1} according to the steady-state probability π_j in (23). After receiving the CSR packet, the CR-IWSN receiver responds with a channel-switching-acknowledgment (CSA). As soon as the CR-IWSN transmitter receives the CSA packet, and a channel switching agreement is established between both transmitting pair, both CR-IWSN nodes switch to the newly selected channel. Instantly, the CR-IWSN nodes resume CR packet transmission in application time T_{A2} on the newly selected channel.

The total time taken to handoff (delay) T_d is given in (31) as;

$$T_d = T_r + T_a \tag{31}$$

where T_r and T_a is the time taken to send and to receive the control packet CSR and CSA respectively, and T_{TA} is the total time taken to transmit CR packet as represented in (32);

$$T_{TA} = T_{A1} + T_{A2} \tag{32}$$

Then, the total time taken from the moment CR packet transmission is initiated and the time CR packet transmission is completed at the end of the slot is given as T_T in (33) as;

$$T_T = T_c + T_{TA} + T_d \tag{33}$$

Therefore, the overhead of the SH model is calculated in (34) as:

$$\text{overhead} = \frac{T_d}{T_T} \times 100\% \tag{34}$$

4.10. Effects of sensing error on expected transmission time

A CR user transmission is predisposed to several interruptions by the intermittent activities of a PU on the licensed band. These interruptions are further aggravated by the false alarm sensing error where an idle channel is falsely declared as busy with a PU activity. If a false alarm occurs, the performances of the PU and the CR users are degraded respectively. In Fig. 5, we illustrate how false alarm can affect the transmission time of CR user. In this example, suppose a CR user begins a transmission that requires 7 time slots at t_1 on ch_1. Assuming that $ch_2, ch_3, \ldots N$ is the sequence of the target channel selection. Then the expected effect of false alarm on the transmission time of CR user can be demonstrated in the following steps: (1) CR user starts transmission on ch_1 at t_2, however, at t_5 a PU presence is falsely declare on ch_1, (2) CR user estimates that the expected handoff delay will last 2 time slots, as a result, CR user paused its transmission until it is successfully switched to a new channel, (3) at time t_6, CR user effectively switches its operating channel from ch_1 to ch_2 to continue its unfinished transmission, (4) however, due to another sensing error, at t_8 a PU presence is falsely declared on ch_2, (5) as a result, CR user switches to ch_3 and finally completes its transmission at t_{11}. Obviously, from this example, due to false alarm sensing error, the CR user have had to perform two needless handoffs which resulted in a transmission time requiring 9 time slots instead of the estimated 7 time slots. Based on this illustration, we proceed to compute the total transmission time of a CR user as a result of sensing error. We assume that $i_j^{(1)}, i_j^{(2)}, \ldots .i_j^{(H_i)}$ is the sequence of target channel selection and $w_{i_j}^{(1)}, w_{i_j}^{(2)}, \ldots . w_{i_j}^{(H_i)}$ is the associated expected handoff delay with each channels during a CR user transmission, where $(1), (2), \ldots (H_i)$ represents the handoff number. However, if a false alarm occurs during the CR user transmission, the sequence of target channel selection will be altered to $i_j^{(1)}, \ldots .i_{j_1}^{(j_1)}, \ldots .i_{j_m}^{(j_m)}, \ldots .i_j^{(H_i)}, \ldots, i_j^{(H_{i1})}, \ldots i_j^{(H_{in})}$ where $j_1, j_2, \ldots .j_m$ are the indices indicating where the false alarm occurred. If $H_{i1}, H_{i2}, \ldots .H_{in}$ represents all the needless SHs due to the sensing error. Then, the total transmission time due to sensing error is given as [42,43]:

$$\begin{aligned} \Delta &= \sum_{l=1}^{m} E\left[\Delta_t^{(l)}\right] \\ &= \sum_{l=1}^{m} \left\{ P_{f,ij}{}^{(l)} max \left((w_{i_{j^*}}{}^{(l)} - w_{i_j}{}^{(l)}) + (j - j^*) \right) \tau, 0 \right\} \end{aligned} \tag{35}$$

where j^* shows the index of false alarm busy channel with maximum handoff delay, τ is indicating when sensing stops. In our scheme, we define a miss-detection probability according to the IEEE standard to protect the PU from harmful interference from the CR user transmission due to a miss-detection error. Similarly, to prevent a degraded performance of the CR user due to false alarm a CR user keeps an HIA of all channels within a safe radius of all PUs transmission range. This is to determine if the PU occupying the channel is a hidden PU node or coexistence PU node to avert harmful interference to a PU activity.

5. Simulation

5.1. Simulation set-up

In this work, we investigate the performance of the proposed SH algorithm by extensive MATLAB simulations. In Table 2, the simulation setup is presented.

5.2. Simulation result and performance comparison

In this section, we present simulation results to validate our proposed SH scheme. Hence, the following performance metrics, i.e., (1) communication latency, (2) number of SHs, and (3) throughput are used to validate the performance of the delay-PritSHS. In this paper, communication latency is defined as the period of time between the instant a CR user began transmission and the instant a CR user completes its transmission. Similarly, number of SHs is the total number of SHs from the start of a CR transmission to the end of CR transmission. Likewise, throughput represents data rate of CR node during CR transmission. During these periods, several interruptions may occur due to low SINR and/or the arrival of PU on the channels. We compare the delay-PritSHS with the following channel allocation schemes to test the efficiency of our approach:

5.2.1. Greedy nonpriority channel allocation schemes

In this scheme, CR users are not classified according to the priority of their QoS requirements. Therefore, when a CR user needs to perform handoff, the cognitive base station (CBS) allocates available channel on a first-in, first-out (FIFO) basis. The CBS checks for target channels in candidate channel list (CCL) upon receiving a handoff request from a CR user. If there are available channels in the CCL, the CBS allocates the first channel in the CCL to the CR user. However, before a CR user begins its transmission on the allocated channel, it senses the channel to make sure no active PU is on the channel at the beginning of the slot, to prevent harmful interference to the PU activity.

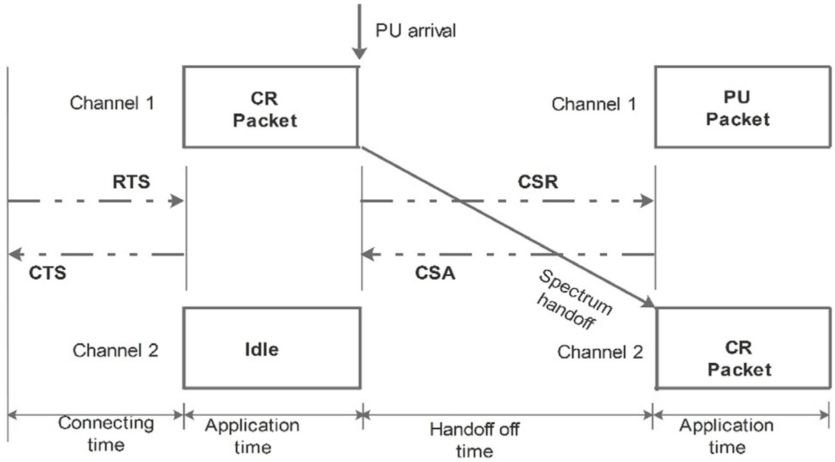

Fig. 4. The overhead of the spectrum handoff model.

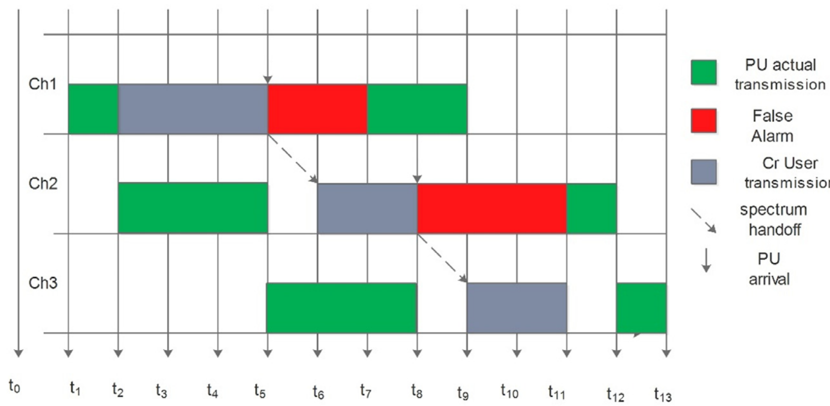

Fig. 5. Effect of false alarm on transmission time of a CR user.

Table 2
Simulation setup.

Parameter	Value
Network model	
Network radius	100 m
PU coverage radius	50 m
CR user coverage radius	35 m
Propagation-loss exponent, n_p	$2 \le n_p \le 3$ (obstructed industrial environment)
Number of PUs	10
CR user of class α type	5
CR user of class β type	5
CR user of class j type	5
Unlicensed band	
Frequency	2.4 GHz ISM band
Transceiver	CC2420
Bandwidth	50 KHz
Number of channel (N)	$2\le N \le 10$
Packet rate	Poisson distribution
SINR	5 dB
Licensed band	
Frequency	470–890 MHz
Number of channel	5–20
Packet rate	Poisson distribution
SINR	1–15 dB
Probability of sensing idle channel	$P_{min} = 0.9, P_{max} = 0.95$
Time slot	10 ms

5.2.2. Fair proportional channel allocation schemes

In this scheme, CR users are categorized into different priority classes according to the QoS requirements. However, the CBS reserves and allocates an equal number of channels to the different priority classes of CR users according to the total number handoff request. Here, the quality of the channel and the priority of a CR user class are not given any strict consideration.

The number of priority classes of CR user connections is CR-IWSN i, CR user j and CR user $j+1$, where CR-IWSN i has higher priority than both CR user j and $j+1$ respectively. In this set of experiments, we conduct a performance comparison in terms of number of SHs, Latency, and Throughput between these three schemes through simulations. Performance evaluation of the proposed SH scheme as a function of the services time of CR users on the occupied target channels are presented.

5.2.2.1. Number of handoffs. In terms number of SHs performed during the CR-IWSN i node total transmission time (owing to non-preemptive periods of the other CR users and expected handoff delays on the available target channels) as a function of the packet service rate of CR users on the available channels. As illustrated in Fig. 6, the delay-PritSHS outperformed both the greedy non-priority scheme and fair proportional scheme respectively. This can be attributed to the fact that, in the delay-PritSHS, the transmission of the CR-IWSN i nodes cannot be interrupted by low priority CR users, and target channel are selected based on the estimated handoff delay. Whereas in the fair proportional scheme, the CR-IWSN node i transmission is susceptible to several interruptions by other CR users in its class, which resulted in

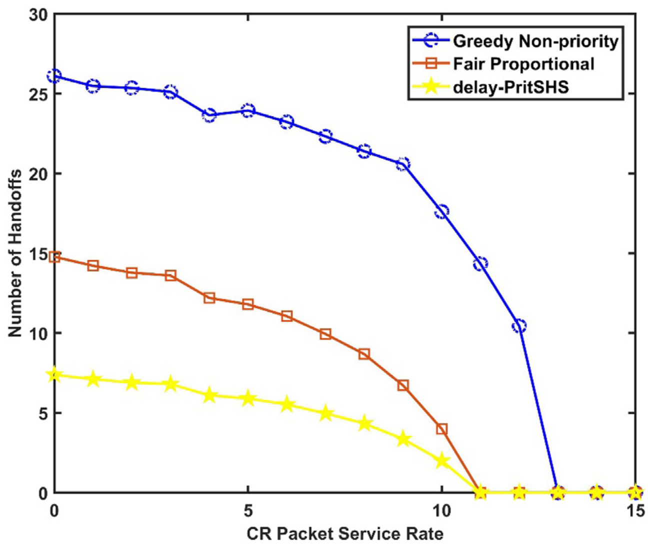

Fig. 6. Number spectrum handoffs as a function of CR packet service rate.

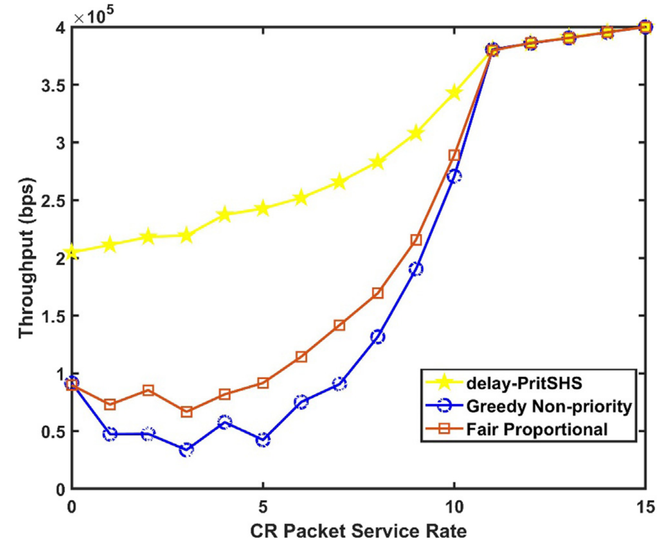

Fig. 8. Throughput as a function of CR packet service rate.

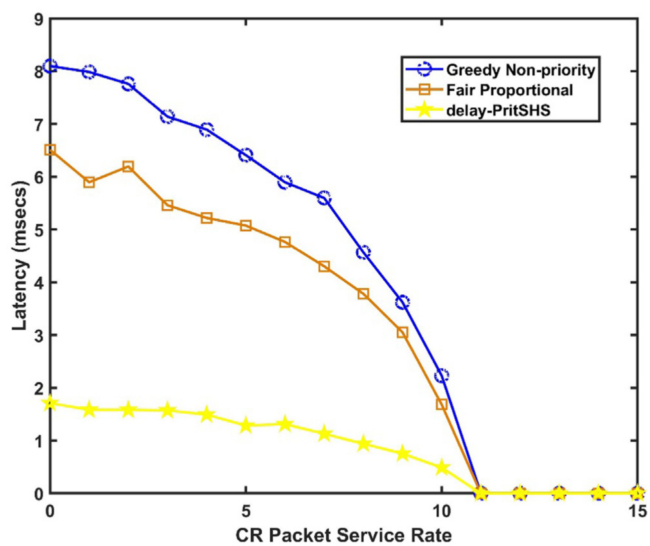

Fig. 7. Latency as a function of CR Packet service rate.

more SHs than the delay-PritSHS as shown in Fig. 6, the explanation for this is that equal amount of channels are allocated to priority classes, and priority is not considered outside a class. However, in the greedy non-priority scheme, channel is allocated arbitrarily as channel become available to the first CR user that request for it irrespective of its class. As a result of this, as presented in Fig. 6, the greedy non-priority scheme has the highest number of SHs performed.

5.2.2.2. Latency. Fig. 7 Presents the latency in the CR-IWSN node i transmission as a function of packet service rate of CR users on the channels.

The delay-PritSHS outstrips the other schemes in terms of lower latency. This significant reduction can be attributed to the fact that, in the delay-PritSHS, the CR-IWSN nodes i estimates the expected handoff delays associated with its current channel and the expected handoff delays associated with the potential target channel, and can only switch channel if the handoff delay in the target channel is lower than the expected handoff delay in the current channel. This is not usually considered in the fair proportional and greedy non-priority scheme respectively. The delay-PritSHS scheme reduced handoff latency by 92% compared to the typical delay budget of 25 ms for time critical system, and by 76% and 77% compared fair proportional and greedy non-priority schemes respectively. Therefore, the overhead of the delay-PritSHS scheme has not negatively impacted the overall latency. As a result, we can conclude that the overhead of the delay-PritSHS scheme has minimal effect on the overall latency.

5.2.2.3. Throughput. The throughput performance in Fig. 8, shows a better performance in terms of throughput by the delay-PritSHS in comparison to both the fair proportional and the greed non-priority scheme respectively. The reason for this is that, in the delay-PritSHS, while CR-IWSN i selects and transmits only on channels with the best characteristics, still, it transmission cannot be interrupted by low priority CR users. Whereas in the fair proportional scheme, though the CR-IWSN i transmits on the channels with the best characteristics, its transmission is predisposed to frequent interruptions by other CR users in its class, this is due to the fact that no priority is given to the CR-IWSN i transmission, since equal amount of channels are allocated to all priority classes. On the other hand, in the greedy non-priority scheme, channel is allocated arbitrarily SH request basis only and not based on priority of the class user. Similarly, channel quality is not considered when a CR user selects channel, and the CR-IWSN node transmission can be interrupted at any time by other CR users. As a result of this, as presented in Fig. 6, the greedy non-priority scheme has the lowest throughput performance.

6. Conclusion

In this paper, an SH scheme that implements spectrum sensing using channel statistical information to increase the likelihood of finding a channel that will remain idle during an opportunistic node transmission is presented. Similarly, this scheme deploys a reward system to rank the channels and introduces a cost function to optimize the probability of selecting a channel with the best characteristics in order to prevent the selection of poor quality channels. Finally, this scheme implements an integrated preemptive/non-preemptive priority scheme to allocate channels according to the priority of a user application to enhance spectrum utilization efficiency. A performance comparison in terms of number of SHs, Latency, and Throughput between the delay-PritSHS and the fair proportional allocation scheme and the greedy non-priority allocation scheme was conducted. The delay-PritSHS showed significant performance improvement in terms of the evaluated performance metrics in comparison to other schemes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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