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Probability-Based Centralized Device for Spectrum Handoff in Cognitive Radio Networks

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ABSTRACT Wireless communication technology is the future of communication, but rapid growth in wireless technology has led to a scarcity in the spectrum. Thus, the world has moved away from fixed spectrum allocation to dynamic spectrum allocation. Cognitive radio technology is a rapidly growing technique that allows spectrum to be shared between licensed or primary users (PUs) and unlicensed or secondary users (SUs). The SUs are allowed to use the licensed channels in the absence of the PUs. Upon the arrival of a PU on the channel, the SU has to leave the channel and resume its transmission on another channel. This process is known as spectrum mobility, and the shift in the channel is known as spectrum handoff. Typical transmission of data using this technology requires numerous spectrum handoffs, leading to fluctuations in the spectrum allotted to SUs. Reducing the number of handoffs and providing SUs with a better transmission environment require choosing an efficient handoff strategy. The current handoff strategies face various drawbacks that reduce the efficiency of the network. This paper presents a probability-based centralized device for increasing the efficiency of spectrum handoffs in cognitive radio networks. The handoff strategy presented in this paper improves the accuracy in sensing the right channel for handoff, reduces the energy consumed in the process, reduces the handoff time, and speeds up the transmission of data. This paper presents a complete model of the system, along with the detailed study of its parameters that proves the effectiveness of the technique.

INDEX TERMS Cognitive radio, spectrum handoff, spectrum mobility, probabilistic logic, PRP M/G/1 queuing.

I. INTRODUCTION

Wireless communication technology is growing very rapidly due to increasing demand that has enormously increased the number of wireless devices. Due to the increase in the number of wireless devices, spectrum, which is a limited resource, has become scarce. Thus, wireless communication technology has moved away from fixed spectrum allocation schemes to dynamic spectrum allocation, through which multiple operators can use the same spectrum band. Efficiency in spectrum usage can be increased by using a more effective dynamic spectrum allocation technique. Cognitive radio is one such emerging technique that has proven to be efficient [1], [2].

Cognitive Radio Networks (CRNs) solve the problem of spectrum scarcity by allowing spectrum to be shared between licensed primary users (PU) and unlicensed secondary users (SU) [3]. SUs can temporarily use a particular licensed channel while PUs are absent. When a PU requests access to that channel, SUs must vacate that channel and find

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another for their transmission of data [4]–[6]. This process in CRNs requires four important functionalities: (i) spectrum sensing, (ii) spectrum management, (iii) spectrum sharing, and (iv) spectrum mobility or spectrum handoff [4], [7].

Spectrum sensing allows a SU to detect the presence of PUs and other SUs in the spectrum. It allows SUs to detect spectrum holes, or vacant space in the spectrum, where it can resume its unfinished transmission of data. Spectrum management deals with selecting the best channel out of the various vacant channels found during spectrum sensing. The coordination of the limited number of available channels among multiple users who compete for access is known as spectrum sharing. The phenomenon of the SUs switching channels on the appearance of a PU in a channel is known as spectrum mobility, and the process of switching is known as spectrum handoff [7]–[11].

This paper focuses on issues faced during spectrum handoff, presenting a novel, hybrid spectrum-handoff technique in which a centralized device uses a probabilistic approach to overcome shortcomings of the existing techniques for spectrum handoff. This approach centralizes the functionalities of the SUs in a single device, which allocates channels to SUs using a probabilistic approach in a sequence based on the PRP M/G/1 queuing model.

The rest of this paper is organized as follows. Section II reviews the literature related to spectrum handoff and spectrum mobility. The system architecture of the proposed model, including the complete probabilistic algorithm and PRP M/G/1 queuing model, is presented in Section III. Section IV analyzes the performance of the proposed system and compares the performance characteristics of the proposed model with existing approaches. Section V concludes.

II. SPECTRUM MOBILITY AND SPECTRUM HANDOFF

CRNs allow SUs, also called cognitive users, to use licensed channels in the absence of PUs. When a PU arrives on a channel, the cognitive user must vacate that channel to avoid interference between users. Through its function of spectrum sensing, the cognitive user then must sense the available channels and re-establish its link on another, best available channel. This phenomenon is known as spectrum mobility. The SU's process of switching channels is known as spectrum handoff [12].

Spectrum handoff is the process of continuing an ongoing communication between two users on another channel. It disrupts the transmission of the SU, increasing the total required transmission time due to the addition of the latency resulting from the spectrum-handoff process. Spectrum handoff can occur as a result of any of the following three activities [14], [15]: (i) arrival of a PU on the channel occupied by the SU for the transmission of data, (ii) spatial mobility of the SU, or (iii) degradation of link quality and signal to noise ratio (SNR).

Spatial mobility could cause an SU to leave transmission coverage and arrive in another channel already occupied by a PU. To avoid interference between users, spectrum handoff must occur. PUs always have higher priority than SUs. The high-priority PUs determine the distribution of load between PUs and SUs. An excess number of PUs can reduce SUs' link quality and SNR, which results in a lack of effective transmissions that result in increased spectrum handoffs.

Spectrum handoff is a cyclic process in two phases: (i) the evaluation phase and (ii) the link maintenance phase. The first phase involves the evaluation and thorough examination of the spectrum environment, as the SU observes parameters to decide whether or not a handoff is required. Once an SU makes the decision to perform a spectrum handoff, it moves into the second, link maintenance phase, in which the SU first pauses its transmission, hands over the channel to the demanding PU, and then resumes its transmission of data on another channel. The SU then leaves the link maintenance phase, and the same cycle continues [15], [16].

A. TYPES OF SPECTRUM HANDOFF

The main objective of spectrum handoff is to help SUs find the most suitable channel for the transmission of data. Spectrum handoff procedures are divided into three types based on target channel selection [17]: (i) reactive spectrum handoff, (ii) proactive spectrum handoff, and (iii) hybrid spectrum handoff.

With reactive spectrum handoff, the SU senses the channels only after the event triggering the handoff takes place. Once the spectrum handoff is required, a target channel is selected by instantaneous wide-band sensing of all available channels in a random order. This wide-band sensing process involves visiting all the available channels and stops its search when a vacant channel is obtained [18], [19].

Proactive spectrum handoff requires maintaining a prepared target channel sequence before the actual event triggering the handoff occurs. SUs periodically sense all channels in order to obtain their channel usage characteristics. Based on these channel usage statistics, the SU creates a target channel sequence depending on the availability duration of the channels. Then, when an actual handoff is required, the SU re-establishes its link on the pre-selected target channel. Figure 1 shows the order of processes in both reactive and proactive spectrum handoffs. Hybrid spectrum handoff combines both reactive and proactive spectrum handoffs in any manner [20]–[23].

Reactive spectrum handoff attains greater accuracy than proactive spectrum handoff, since the spectrum-sensing process happens in the most relevant spectrum environment. This accuracy is attained at the cost of high spectrum latency, the time required to sense the available spectrum after the event triggering the handoff takes place. In cases where accuracy is required without any limitations on the handoff latency, the reactive scheme is used [19].

Proactive spectrum handoff procedures overcome the high latency of reactive spectrum handoffs by keeping a target channel ready even before the handoff-triggering event takes place. But this affects the accuracy of the procedure in selecting the best channel, since the chosen target channel could be

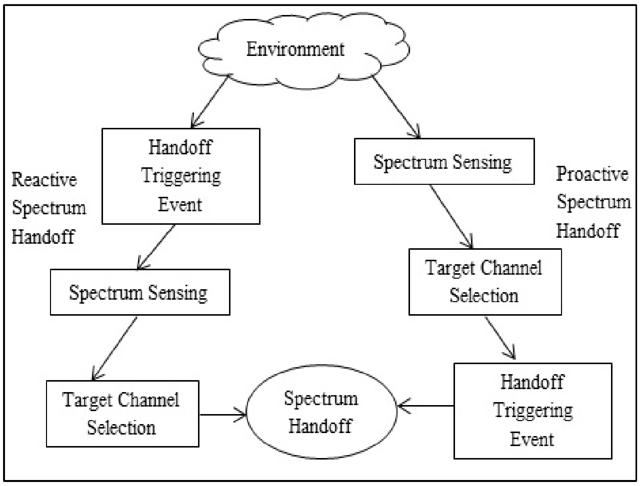

FIGURE 1. Reactive and proactive spectrum handoffs.

already occupied by a PU or SU at the time of handoff. Thus, channel usage statistics are very important to determine the best channel.

Consider the time an SU takes to sense a single channel, T_S, and the time an SU takes to switch to another channel, T_H. Then the minimum time for a reactive spectrum handoff to take place, which depends on the spectrum environment, is:

$$T_{Rmin} = T_S + T_H. \tag{1}$$

The maximum time for a reactive spectrum handoff is:

$$T_{Rmax} = N * T_S + T_H \tag{2}$$

where N is the total number of channels in the system.

T_{Rmin} will be the required time when a handoff takes place to the first-sensed channel, whereas T_{Rmax} will be the required time when the handoff takes place to the last-sensed channel. This could enormously increase the handoff latency.

Now, for a proactive spectrum handoff, the minimum and maximum times for handoff, respectively T_{Pmin} and T_{Pmax}, may be given as follows.

$$T_{Pmin} = T_H \tag{3}$$

T_{Pmin} is the elapsed time when the first channel itself in the sequence is empty and the handoff occurs.

$$T_{Pmax} = (N - 1) * T_H \tag{4}$$

T_{Pmax} is the time elapsed when switching to the last channel numbered in the sequence; $(N - 1)$ handoffs must take place since (N) channels in the spectrum are already occupied at the time of handoff. Though this case is rare, since channel-usage statistics are accurate enough, it is an important theoretical case to study. These equations of time latency show the advantages of the proactive scheme compared to a reactive one, since T_{Pmin} is more common than T_{Rmin}. A hybrid scheme can overcome the flaws of accuracy and handoff latency of both systems. This paper presents such a system.

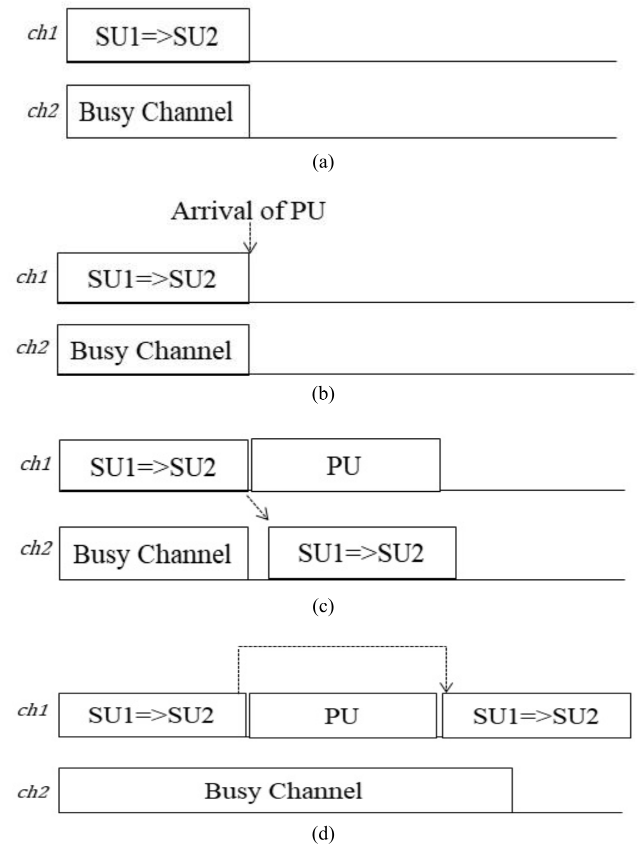

FIGURE 2. Steps of spectrum-handoff mechanism. (a): Transmission between SU1 and SU2. (b): Arrival of PU at channel occupied by SU. (c): Change of channel by SU. (d): SU stays on same channel.

B. SPECTRUM-HANDOFF MECHANISM

Spectrum handoff takes place immediately when a PU arrives on a channel occupied by an SU. The SU then moves from its current channel to a target channel. The mechanism of spectrum handoff is divided into various steps, as follows [15], [21], [24].

(1) First, assume two channels, $ch1$ and $ch2$. Two secondary users SU1 and SU2 communicate through $ch1$, and the other channel, $ch2$, is also busy, as shown in Figure 2(a).

(2) Now, Figure 2(b) shows a PU arriving on the channel, which is a handoff-triggering event. SU1 pauses its transmission, and also informs SU2.

(3) Now, the SUs need to re-establish their link on an available channel to continue with the remaining transmission. Thus, the SU moves to a pre-selected target channel, for a proactive handoff, or to an instantaneously sensed target channel, for a reactive handoff. The change in channel from $ch1$ to $ch2$ is shown in Figure 2(c).

(4) Another option for the SU is to wait for the PU's transmission to complete on $ch1$ and then continue on the same channel. In this case, the SU stays on the same channel, as shown in Figure 2(d). This option is selected when the PU has very little data to transmit. The SU chooses to stay on the same channel when the time taken by the PU on the channel is very less or negligible compared to the time required by the

SU on the channel. In that case, this method is more efficient in terms of time than switching channel.

(5) A single SU might be interrupted by PUs at various times during its transmission of data, resulting in multiple handoffs. In each case, the same process repeats.

These five steps determine the mechanism of spectrum handoff, as elaborated in Figure 2.

C. CHALLENGES FACED IN SPECTRUM HANDOFF

Spectrum handoffs in CRNs represent a developing area of research, with various issues yet to be solved. These challenges must be investigated to make this system even more efficient. Several challenges faced in spectrum handoff are mentioned below [14], [25]–[31].

Accuracy in selecting target channels is a major challenge. The algorithm the cognitive device uses to determine the best available channel plays a major role. For proactive spectrum handoffs to have the best results, channel-usage statistics must be very precise and accurate.

Excess handoff latency is another major issue for spectrum handoffs. The time it takes to sense channels increases transmission time and degrades SU performance. Multiple handoffs in a single transmission lead to excess switching time, reducing the efficiency of the system. The need to sense channels after the handoff-triggering event increases handoff latency in reactive spectrum handoffs. The sequence in which SUs and PUs are served should many incidents of interference happen simultaneously can also increase latency. How the algorithm determines the sequence of high- and low-priority users will directly affect latency. Faulty sequencing can lead an SU to wait for longer than other, newly interfering SUs. Older interfering SUs should be given higher priority than newly interfering SUs.

Energy consumed in the process of spectrum handoff is a major parameter. Every SU, as a cognitive device, periodically utilizes spectrum-sensing capabilities. The decentralization of cognitive abilities among SUs increases the energy used by the system. An effective system model must be devised to better utilize energy. This paper aims to solve these challenges in spectrum handoff.

The most popular and relevant models proposed for an efficient spectrum handoff process are Pre-emptive resume priority model, greedy target channel selection scheme and the Markov transition model. These models propose different architectures and algorithms for the process of spectrum handoff in cognitive radio networks. The challenges faced by these popular models are low accuracy and high handoff latency. The Pre-emptive resume priority model and the Markov transition model face the challenge of high handoff latency while the greedy target channel selection scheme has low accuracy [11].

III. SYSTEM ARCHITECTURE

The various challenges in spectrum handoff can be solved through a new system architecture, with a new algorithm to determine the target channel accurately and with low latency. The system architecture comprises a centralized cognitive device, a probabilistic algorithm for spectrum sensing, and a PRP M/G/1 queue used to prioritize handoff requests.

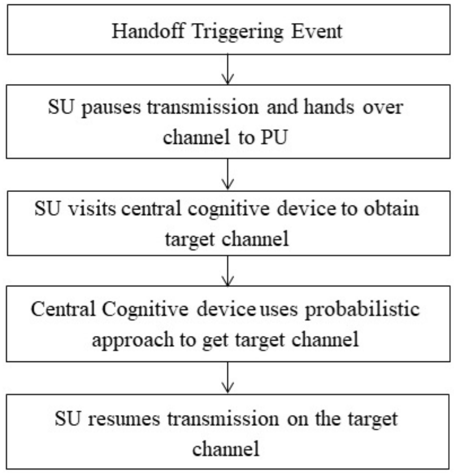

FIGURE 3. System model.

A. SYSTEM MODEL

The system uses a centralized cognitive device, taking the cognitive ability away from the SUs. This saves an enormous amount of energy that would otherwise be consumed by the individual cognitive devices. SUs communicate on a channel in the absence of a PU. Upon the arrival of a PU, a spectrum handoff is needed, which follows the following five steps. The steps of the system model are shown in Figure 3.

(1) A handoff triggering event takes place which indicates that the channel has to be vacated immediately.

(2) The SU pauses its transmission and hands the channel over to the PU. The SU also informs the receiving SU of the handoff.

(3) Now, the SU visits the central cognitive device to identify the target channel. The SU must cross the PRP M/G/1 queue (Section III C) before requesting assistance from the central cognitive device.

(4) The central cognitive device, using its probabilistic algorithm (Section III B), finds the best available channel and allots it to the SU.

(5) The SU then resumes its transmission of data on the allotted channel. The cycle continues in the case of multiple handoffs.

This model improves performance parameters including accuracy, handoff latency, and energy consumed.

B. PROBABILISTIC ALGORITHM

A probabilistic algorithm for selecting the best available target channel structures the core of this system architecture. The best available channels are selected using the concept of idle probability. A channel's idle probability is the probability that channel will be vacant at the time of handoff. Consider a particular channel, ch_i, sensed by the cognitive device N_{trials} times in time t. Then, if N_{idles} times out of the sensed N_{trials}

times the particular channel be idle and vacant, the idle probability of the particular channel i is:

$$(P_{idle})_i = \frac{(N_{idles})_i}{(N_{trials})_i} \quad \forall 1 < i < N \tag{5}$$

The value of idle probability ranges from 0 to 1 theoretically but practically the extreme cases are not possible due to the fact that a channel can never be busy or vacant throughout time. The practical values of the idle probability lie between 0.2 and 0.8. Assume that there are N channels in the system. The cognitive and evice maintains an idle probability matrix P_{idle} of dimension $(1 \times N)$ for all N channels. When an SU requests a handoff, the central cognitive device senses all N channels. Upon sensing a particular channel, the N_{trials} value of that particular channel is increased by one in the N_{trials} matrix of dimension $(1 \times N)$. Thus, once all channels are sensed, the N_{trials} value for every channel will increase by one, thus remaining the same for all channels.

$$(N_{trials})_i = (N_{trials})_i + 1 \quad \forall 1 < i < N \tag{6}$$

If a particular channel is found idle at the time of sensing, its N_{idles} value is incremented by one. N_{idles} is also a $(1 \times N)$ matrix.

$$(N_{idles})_i = (N_{idles})_i + 1 \quad \textit{if channel is idle} \quad \forall\ 1 < i < N \tag{7}$$

$$(N_{idles})_i = (N_{idles})_i \quad \textit{if channel is busy} \quad \forall\ 1 < i < N \tag{8}$$

Using the values of N_{trials} and N_{idles}, the idle probability matrix is calculated as in equation (5). This matrix contains accurate data as to which channels have the maximum probability of being vacant at the time of handoff.

The idle probability matrix is the backbone of this algorithm. Now, the idle probability matrix is used to find the channel with the maximum idle probability, $(P_{idle})_{max}$, as follows:

$$(P_{idle})_{max} = \max\left\{(P_{idle})_i\right\} \quad \forall 1 < i < N \tag{9}$$

If the channel with the maximum idle probability is vacant at the time of handoff, that particular channel is then allotted to the requesting SU. If that channel is busy, the channel with the next-highest idle probability is allotted, again on the condition that it is vacant. This process repeats until the SU is allotted a channel. Usually, the cognitive device would allot the channel on the first try.

The procedure of sensing all channels would apply only to the first n handoffs, after which the idle probability matrix would be filled for all channels, giving an initial approximation. The value of n would depend on the number of users in the cluster and the number of channels in the system. After these n handoffs, only those channels with maximum idle probability will be sensed, so only their idle probabilities will be updated in the matrix. After $n + 1$ trials, not all channels will be sensed, reducing latency while retaining the same accuracy. The systematic approach of this algorithm is shown in Figure 4.

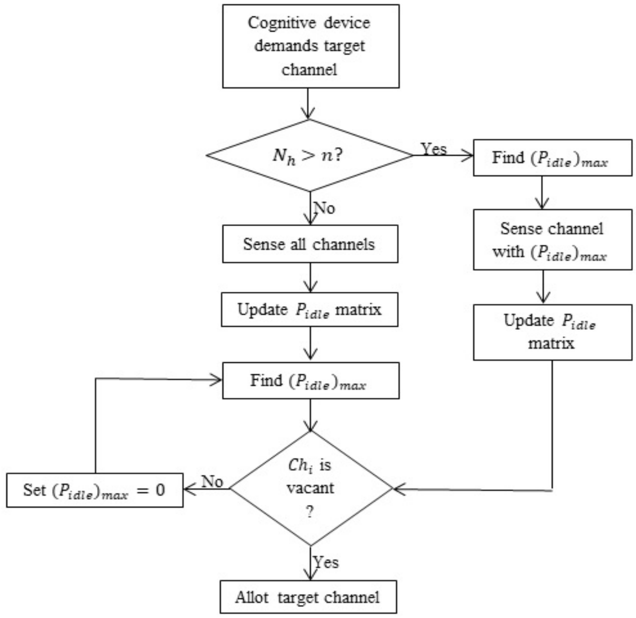

FIGURE 4. Probabilistic algorithm.

The first n handoffs fill the idle probability matrix for all available channels, giving an initial approximation. Later, only the channel with the maximum idle probability will be sensed, updating the status of the same, whether vacant or busy, in the idle probability matrix. If the channel with the maximum idle probability is vacant, that will be allotted to the requesting SU; otherwise, the cognitive device will find the next maximum. This would change the mathematic formulae as shown in equations (10) and (11). Let the number of handoffs be denoted N_h, then:

$$(P_{idle})_i = \frac{(N_{idles})_i}{N_{trials}} \quad \forall 1 < N_h < n \tag{10}$$

$$(P_{idle})_i = \frac{(N_{idles})_i}{(N_{trials})_i} \quad \forall N_h > n \tag{11}$$

For the first n handoffs, N_{trials} will remain the same for all channels, since all channels will be sensed, whereas the value of N_{trials} for all channels will vary when the number of handoffs exceeds the value of n. These equations are presented here without the loss of generality. This algorithm decreases handoff latency by sensing channels in order from most expected to least expected to be idle. The sensing and handoff times are reduced, since the number of channels sensed and the number of handoffs are at their minima.

C. PRP M/G/1 QUEUING AND SECONDARY USER CLUSTERING

A realistic system contains various numbers of channels to share among PUs and SUs. Thus, at a given time, many handoffs may be requested from the central cognitive device. This increases the load on the cognitive device at any given time.

PRP M/G/1 queuing and SU clustering are two techniques to help manage load on a single cognitive device.

A PRP M/G/1 queue is considered in this model to overcome the condition when the arrival of users to the cognitive device forms a Poisson distribution. A Poisson distribution is formed in the case when the load on the system increases all of a sudden during the peak traffic hours and then reduces all of a sudden. Since one cluster has a central cognitive device, the load on the device could increase greatly. Also since a cognitive device could be in an area with excess load, thus this case is also considered. A resume discipline is considered due to the fact that the processor requires time to allot the channels.

PRP M/G/1 queuing arranges incoming request from SUs for handoffs at the same time. When a number of SUs visit the central cognitive device, they form a queue in the order of handoff occurrence. New SUs can also visit the cognitive device to obtain a channel for transmission. Interrupted SUs are always higher priority than newly joining SUs. Thus, another high-priority queue is formed specifically for interrupted SUs. Whenever an interrupted SU arrives, it is inserted at the end of the high-priority queue, while newly joining SUs are inserted at the end of the low-priority queue, as shown in Figure 5.

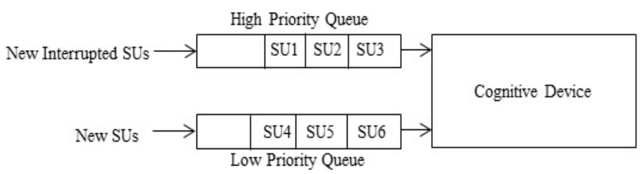

FIGURE 5. PRP M/G/1 queuing.

Even after forming a PRP M/G/1 queue, the number of SUs demanding handoff can be very large compared to what the queue can handle. The technique of clustering can be used to decrease the load on a single cognitive device. Clustering involves grouping various SUs under a single cognitive device and having many such cognitive devices. The number of SUs under a particular cognitive device will depend on the number of SUs that require handoff at a particular time instant. This is known as instant handoff density, or the load on the cognitive device at that instant. Management of load through PRP M/G/1 queuing and SU clustering makes the architecture more effective and efficient with respect to the associated latency.

IV. PERFORMANCE ANALYSIS

The system accurately allots the target channel to a SU with reduced handoff latency. Sensing the channels probabilistically from maximum idle probability to least reduces latency and increases accuracy by sensing a channel in the most relevant environment. Consider a system with five channels, $ch1$, $ch2$, $ch3$, $ch4$, and $ch5$. Assume five instances in time when a handoff is required, $N_h = 1, 2, 3, 4,$ and 5. Table 1 shows the status of the channels at these five time instances.

TABLE 1. Status of all channels at five different time instances.

Channel	N_h=1	N_h=2	N_h=3	N_h=4	N_h=5
$ch1$	0	1	1	1	0
$ch2$	1	0	0	1	0
$ch3$	1	0	0	1	1
$ch4$	1	1	0	1	1
$ch5$	0	1	1	0	1

TABLE 2. Idle probabilities of all channels at five different time instances along with the target channel selected by probability value and channel status.

Channel	N_h=1	N_h=2	N_h=3	N_h=4	$N_{□}$=5
$ch1$	1	0.500	0.333	0.333	0.333
$ch2$	0	0.500	0.667	0.500	0.600
$ch3$	0	0.500	0.500	0.333	0.333
$ch4$	0	0	0	0	0
$ch5$	1	0.500	0.500	0.667	0.500
Target Channel Selected	$ch1$	$ch2$	$ch2$	$ch5$	$c□2$

In Table 1, 0 represents an idle channel, and 1 represents a busy channel. After passing the status of channels from the system, the target channel output from the system is shown in Table 2, along with the idle probability for each channel. The target channel is determined by both the idle probability and the present status of channels at a particular time instant.

The value of n considered here is 2. Thus, after $N_h = 2$, the system senses only that channel with the maximum probability in order to allot it to an SU. Table 2 presents probability values, always between 0 and 1.

The idle probabilities can be visualized using the graph of the system simulation (Figure 6). The graph is plotted against the number of handoffs and the idle probability at each instance for all available channels. The situation can be elaborated in the following way. At the time of the first handoff, the cognitive device senses all the channels, obtaining all idle probability values for future use. Then, the channel with the maximum vacant probability, $ch1$ in the first case, is allotted. The same process occurs during the second handoff, and $ch2$ is allotted.

Now at the value of $n = 2$, the algorithm works as follows. Only the channel with maximum probability is sensed, and its idle probability values are updated. For the case of $N_h = 3$, the previous idle probability matrix has four channels of equal idle probability, namely $ch1$, $ch2$, $ch3$, and $ch5$. The first channel $ch1$ is sensed; since it is busy, its probability value is changed. Then, channel $ch2$ is sensed, which is vacant; its probability value changes. The idle probabilities of the other channels remain the same, as they are not sensed. The same process can be visualized in the horizontal sections of the graph in Figure 6, symbolizing that particular channels were not sensed during the interval, thus leaving equal idle probabilities in subsequent handoffs. A similar

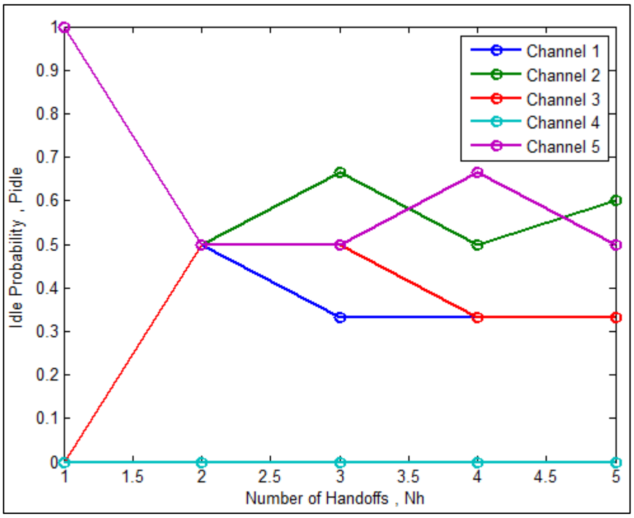

FIGURE 6. Number of handoffs vs. idle probability.

algorithm occurs in further handoffs to determine the best target channel.

The improvement attained by using this system may be seen in the changes in performance characteristics like accuracy, handoff latency, and energy consumption.

A. ACCURACY

The central cognitive device senses the channel with the maximum idle probability instantaneously before allotting the channel. The sensing of channels occurs in the most relevant environment at the time when the handoff is to take place. Thus, this architecture replicates the accuracy in target channel selection of a reactive-based system, reducing multiple handoffs and improving SU performance compared to a proactive-based system.

B. HANDOFF LATENCY

The sequence in which channels are sensed greatly contributes to the handoff latency of the SU. The channels are sensed from most probably to least probably vacant, reducing the time incurred for sensing channels compared to sensing in a random sequence. This also reduces the time incurred for handoff, as the central cognitive device checks the status of the allotted channel before the handoff.

Let T_{CCD} be the total time required for handoff with a central cognitive device. Then, the average time of handoff for this technique can be given as:

$$(T_{CCD})_{avg} = T_S + T_H. \tag{12}$$

The $(T_{CCD})_{avg}$ expression can be compared with the expressions for the proactive and reactive schemes given in equations (1) to (4). The scheme with a central cognitive device clearly performs better than the reactive scheme in terms of channel sensing time and better than the proactive scheme in terms of time switching between channels. The challenge of high handoff latency is thereby overcome using the central cognitive device scheme. Thus, the central cognitive device and overall architecture help reduce total handoff latency, thereby improving the ability of the SU to transmit data efficiently.

C. ENERGY CONSUMPTION

Consumption of energy is a major factor in any wireless technology. A system is more efficient with less energy consumed. The drawback of all spectrum-handoff strategies is the excess usage of energy, which, like spectrum, is a limited resource that needs to be conserved. Reactive and proactive spectrum-handoff strategies both face this major issue of excess energy consumption.

Consider a system with N SUs, and let E be the total energy consumed by a single cognitive device in the process. In the reactive and proactive spectrum handoff techniques, all SUs are cognitive devices and consume equal amounts of energy. Then, the system's total energy consumption in reactive and proactive techniques is as follows, respectively:

$$E_{reactive} = E_{proactive} = N * E \tag{13}$$

The energy consumed by the reactive and proactive systems is the same and can be written as E_{RE}.

$$E_{reactive} = E_{proactive} = E_{RE} \tag{14}$$

The power consumed by the central cognitive device scheme can be calculated in the same manner. Consider that N SUs are divided into clusters of n SUs, each with one central cognitive device. This helps reduce the number of cognitive devices, which in turn reduces the consumption of energy. The total energy consumed by the central cognitive device scheme can be given as:

$$E_{CCD} = \frac{N}{n} * E. \quad 0 < n < N \tag{15}$$

The energy consumed in the central cognitive device scheme is reduced by n times. The larger the value of n, the larger will be the consumption of energy in the central cognitive device scheme.

$$\frac{E_{RE}}{E_{CCD}} = n \tag{16}$$

Consider a system with 100 SUs. Let the energy consumed by a single cognitive device be 1 Joule. Then, Figure 7 shows that the energy consumed by both the reactive and the proactive schemes is equal and constant. A comparison is made between E_{RE} and E_{CCD} for different values of n. The following observations can be made.

(1) The energy consumed by proactive and reactive schemes is always greater than that consumed by a central cognitive scheme which is due to the fact that every SU acts as a cognitive device and uses its own energy to function.

(2) As the value of the cluster size, n, increases, the energy consumed in the central cognitive scheme decreases further.

(3) The central cognitive device scheme consumes less energy than the other two schemes.

Figure 7: Comparison of energy consumed in proactive, reactive, and central cognitive device schemes

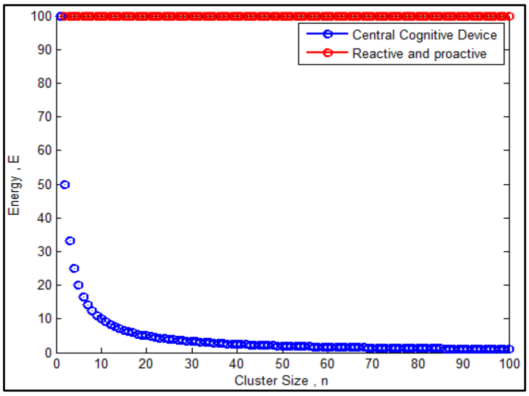

FIGURE 7. Comparison of energy consumed in proactive, reactive, and central cognitive device schemes.

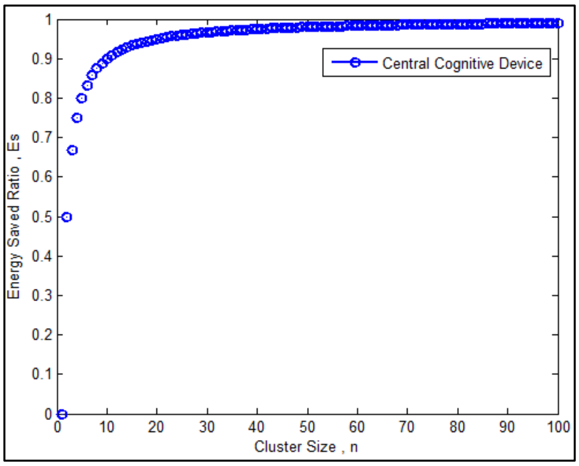

FIGURE 8. Relation between cluster size and energy-savings ratio.

(4) The energy consumed by the proactive, reactive and the central cognitive device schemes overlap when the cluster size is zero, indicating the fact that all the SUs act as a cognitive device.

The amount of energy the central cognitive device scheme saves compared to the reactive and proactive schemes is given as follows:

$$E_s = \frac{E_{RE} - E_{CCD}}{E_{RE}} \tag{17}$$

$$E_s = \frac{N * E - \frac{N}{n} * E}{NE} \tag{18}$$

$$E_s = 1 - \frac{1}{n} \tag{19}$$

The energy saved ratio, E_s lies within the limits 0 and 1. Larger values of n make the ratio $1/n$ smaller, thereby increasing the energy saved through this system, as shown in equation (20). Considering the same case of 100 SUs in a system, the relation between the ratio E_s and n is shown in Figure 8. As the cluster size increases, the energy-savings ratio also increases.

V. CONCLUSION

Increasing usage of wireless communication leads to a scarcity of spectrum, which has to be used opportunistically. A new spectrum-allocation technique is the only solution to this problem. CRNs have emerged as the best solution for this problem. All aspects of CRNs must be investigated and perfected to implement such systems efficiently. This paper proposes a unique approach to obtain better efficiency in spectrum handoff in a network. This paper presented a system architecture with complete system model, probabilistic algorithm, and other novel techniques, like SU clustering and PRP M/G/1 queuing. It is analytically proven that the system performs better than existing schemes in terms of accuracy, handoff latency, and energy consumption. The improvement in these system performance parameters supports our claim that this approach best on a centralized cognitive device is the best solution for CRNs.

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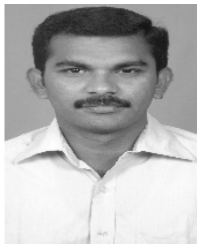

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