[5], Investigated a mechanism for channel allocation protocol in CRN, namely DPM (Distribution probability matrix). The two basic components of the DPM mechanism, the allocation indicator matrix, and the effective duration were introduced, followed by the explanation of the typical usages of the DPM. The DPM was implemented as a channel allocation protocol in a multichannel CRN and the queueing analysis was carried out accordingly to acquire the performance metrics using DPM and reference protocols. The flexibility and adaptability of the DPM as channel allocation protocol, together with the comparisons with existing protocols were demonstrated by the numerical results. The assertion that the DPM has advantages as a channel allocation protocol and that DPM has the potential to provide references to determine the SU system settings to achieve the performance requirements are valid finally concludes besides working as a channel allocation protocol, the usage of the DPM mechanism to help design and evaluate channel allocation protocols with specific objectives as demonstrated by an implementation of a protocol, namely MT (Maximum throughput). A powerful queueing analytical framework that is capable of obtaining the performance metrics of each CR user independently was established based on DPM, to carry out the evaluations in a multi-user multi-channel CRN scenario. Through the framework, the MT protocol was analyzed and compared with reference protocols also aimed at maximizing the throughput of the CR system.

With the need to address the CSA on CRNs by malicious SUs, an algorithm for selecting spectrum holes in the primary spectrum will be developed using a channel occupancy pattern of the probability of ON-OFF.

2. Channel Selection Algorithm

In this paper, the algorithm is based on deriving the probability of being free from PU at a given instance in time. Hence, in this section, the probability of a channel being free from PU, given the ON-OFF time distribution of PU.

In a PU spectrum, it is randomly denoted that the probability of ON and OFF times on the channel, is the probability density function (pdf) which can be given many variables.

let us assume the process starts with PU being in OFF state K_i, followed by ON state Y_i. Noting that the ON-OFF cycle as the renewal cycle with $Z_i = K_i + Y_i$ with as K_i and Y_i are statistically independent of each other. Hence, the pdf of Z_i is the convolution of the ON time and OFF time distributions of PU, i.e., $f_Z = f_k * f_y$.

2.1 Probability of OFF time in PU

Suppose the SU's first sensing instant falls in OFF time of PU and the SU uses the channel for Δt duration, the next sensing instant of the secondary transmitter falls at $t_1 = t_0 + \Delta t$. For the channel to be free from PU at time t_1, the primary user activity in the channel should be either of the following cases:

i. There is no arrival of the PU in the interval $[t_0, t_1]$
ii. The primary user might have used the channel at least once in (t_0, t_1) but it would have left the channel by t_1.

2.2 Probability of idle channel given the last sensing instant falls in PU ON time

The probability of channel being free from PU given the last sensing instant falls in PU ON time, denoted as $P_{ON,OFF}(\Delta t)$, can be calculated in a similar manner as in the previous section. However, a simple approach was followed to calculate $P_{ON,OFF}(\Delta t)$, first by deriving $P_{ON,ON}(\Delta t)$ as follows:

Let $P_{ON,ON}$ denote the probability of channel being used by PU given the last sensing instant falls no PU ON times. Then the $P^*_{ON,ON}(s)$ is calculated by interchanging the role of f_k and f_y in $P^*_{OFF,OFF}(s)$.

2.3 Probability of idle channel for hyper-exponential distribution (HED) OFF time

This section covers the system model and a brief overview of the already existing predictive CSA framework for exponential ON-OFF time distribution as well as the derivation of the proposed CSA framework for heavy OFF time which is approximated as a Hyper-exponential Distribution (HED) through detailed inference. Evaluating the performance of the proposed CSA framework using a simple testbed implementation in MATLAB with a simple CRN MAC protocol was done, there are a number of articles that claim that the hyper-exponential distribution is a better representation of the idle time of PUs. The most obvious claim is that it is more realistic. Hence, forms the basis of this algorithm. Let the $p.d.f$ of HED be filled for a heavy failed PU OFF time.

The corresponding exponential ON-OFF time distribution can be derived easily from that of HED by setting N = 1, such that the parameters λ_{ON} and λ_{OFF} result.

2.4 CSA algorithm for independent and identically distributed channels

The following notations represent the conditional probabilities $P^a_{OFF,OFF}$ and $P^a_{ON,OFF}$ of channel a, respectively.

3. The Implementation protocol in MATLAB

The code was done in Matlab. The approach of this protocol is to ensure maximum throughput by maximally using the best channel. With the 3-phase hyper-exponential distribution of 5 channels at the inter-sensing time of 600ms the ON-OFF and OFF-OFF probabilities, with very close probabilities to the mean rate of the channel (as a hyper-exponential distribution can be seen as a parallel combination of m-exponential distributions at different probabilities. This was done analytically to approach the mean duty cycles chosen for the 5 channels used in testing the protocol. The hyper-exponential distribution for the 5 channels was considered at a maximum inter-sensing time of 2 seconds (2000 ms). The sequence of the protocol is as follows:

(i) Check if the back-off mode is activated (this is done when thorough sensing has not reviewed any free channel)
(ii) If back-off mode is not activated, check the belief vector for maximum idle probability and select the corresponding channel
(iii) Sense the selected channel and update the belief vector with the latest sense result for every channel.
(iv) If the sensed channel is free, transmit for 600 ms and sense if the selected channel is still free
(v) If the previously sensed channel is still free, transmit for another 600 ms
(vi) If the previously sensed channel is no longer free, sense all channels for free channel and update the belief vector, if at least a channel is free repeat the above steps else, enter back-off mode.

3.1 Implementation of energy detection of a single channel, time-domain in Matlab

One other analysis done was to embark on the observation that the energy detector in the time domain at different frequencies is important to develop a useful dynamic spectrum access protocol for the cognitive radio. This determines the rate of the idle time model used for the

PU activity. However, before developing into the DSA protocol, the purpose of this design was to test the accuracy of the energy detector for low and high SNR in the time domain shown in Matlab Figure 1.

The code is available in the Matlab of this study. The script starts with initializing parameters and RTL-SDR object to tune to a single frequency (user can change this parameter to see results). The time-domain analysis was done for 2 seconds as IEEE 802.22 standard requires the maximum interruption time of any primary user is 2 seconds. To capture a single FM station IQ, a sample of a minimum of 200 kHz is required and so we used a sample rate of 300 kHz (personal preference). To meet 2 seconds of measurement, the number of iterations for 4096 samples out of 300000 samples in a second will have to be 146. Noise estimate is still assumed to remain constant in the FM spectrum and the duty cycle (number of times the iteration turns out to be 'true' or 'ON' out of the total iteration) is computed in Matlab.

The predictive CSA code is given in Matlab of this study, for the simulation of an actual channel, a random variable sample of the hyper-exponential distribution was used for the 5 channels. The variable sampled was the wait time/idle time of the channel, if the idle time is lower than the inter-sensing time (600ms), the channel is sensed as 'busy' whereas if the idle time is greater than the inter-sensing time, the channel is sensed as 'free'. This is given by the "sensing_block" function. Also, the "updateVec" function is used to update the belief vector based on the recently updated "result" array, that is if the result is '1'. To simulate secondary user transmission, this study used a time scope showing the plot of the transmission when a channel is free and the breaks in between as shown in Matlab.

4. Result

4.1 Spectrum sweep using RTL-SDR

Figure 1, shows the spectrum sweep across the band of FM broadcast in latitude 6.3999 longitude 5.6138. The blue plot is the frequency plot whose amplitude is measured in dB relative to 50 Ohms load while the plot in orange is that of linear scale amplitude. This is to determine the channel to be used for the duty circle.

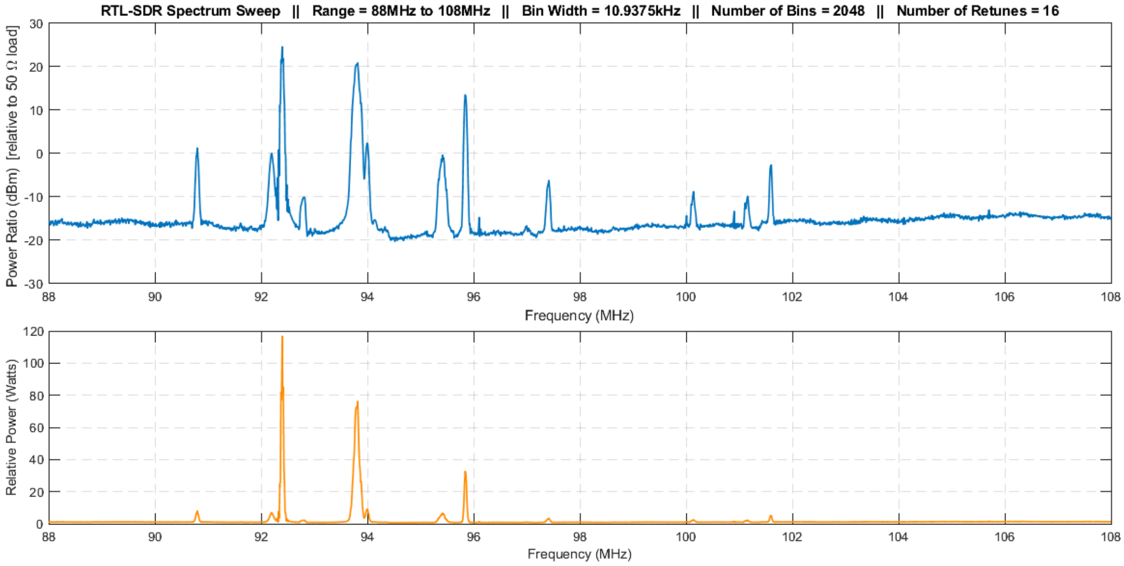

Figure 1: Spectrum sensing in the FM spectrum relative to 50 Ohms load

Presented are the results for the channel selection algorithm implemented in this study for improved SU performance. Figures 2 - 6 show the result of the selection algorithm for 5 channels of different duty cycles or channel usage generated from Matlab as shown in Figure 7.

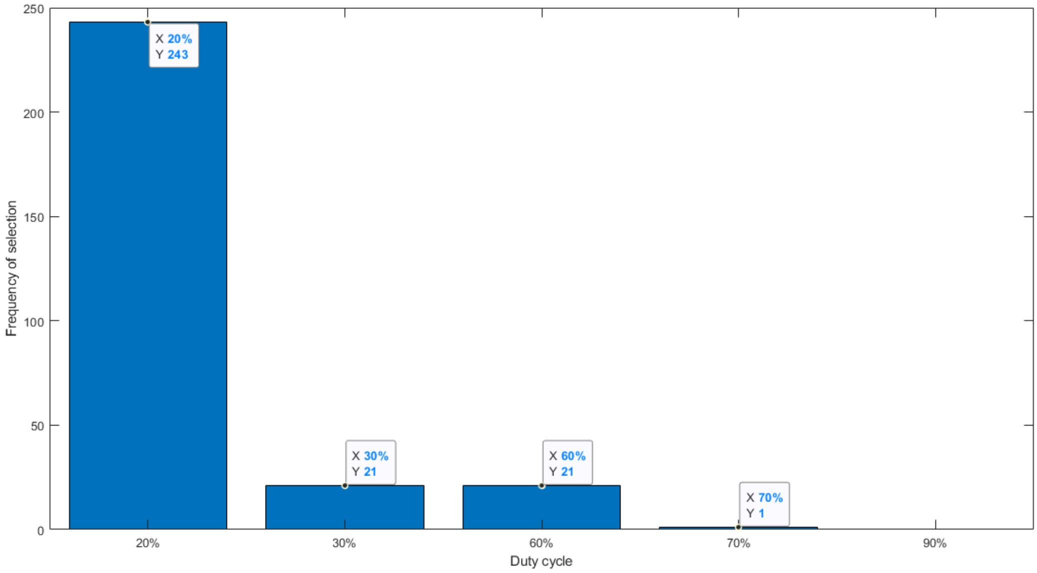

Figure 2: Frequency of selection using the predictive CSA on 5 different duty cycles

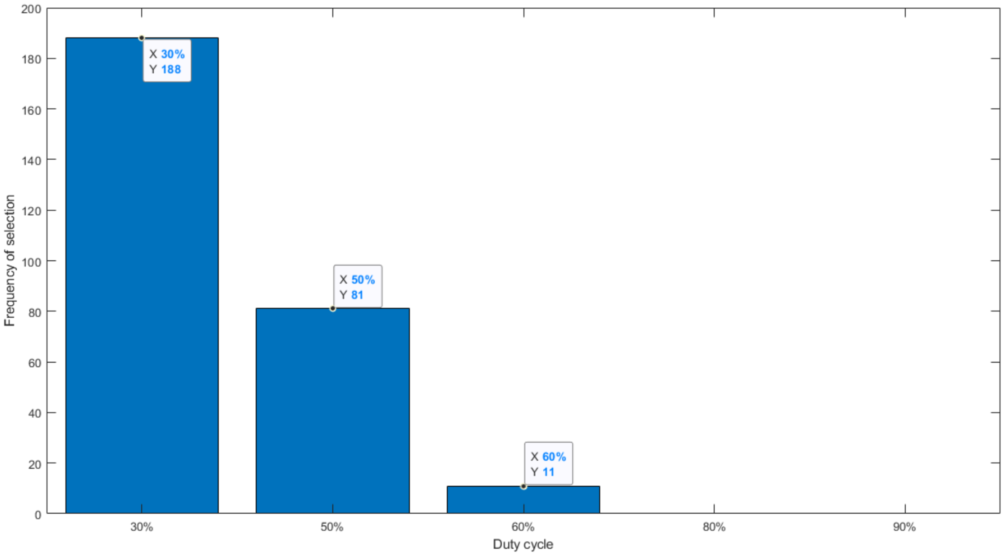

Figure 3: Frequency of selection using the predictive CSA on 5 different duty cycles

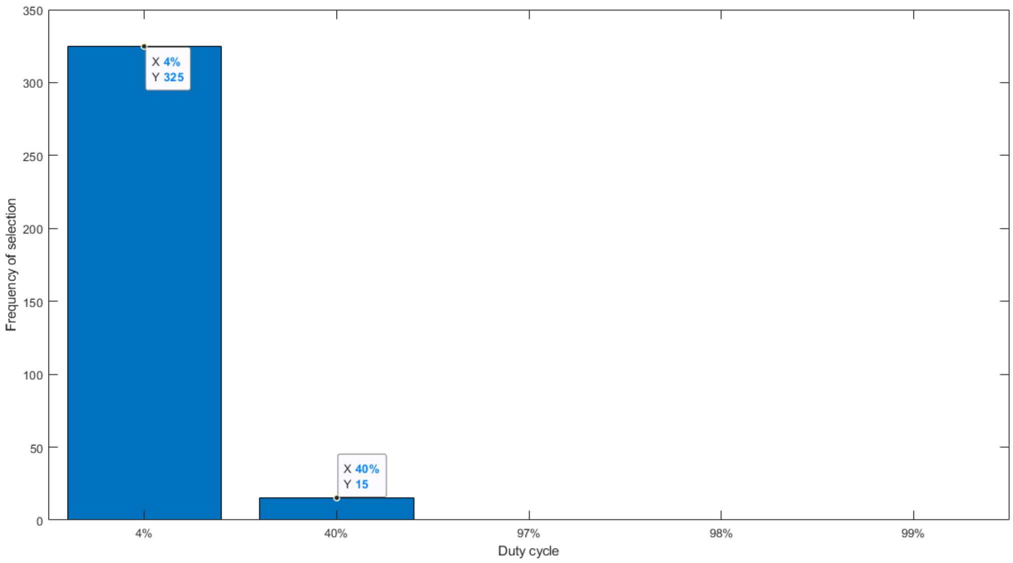

Figure 4: Frequency of selection using the predictive CSA on 5 different duty cycles

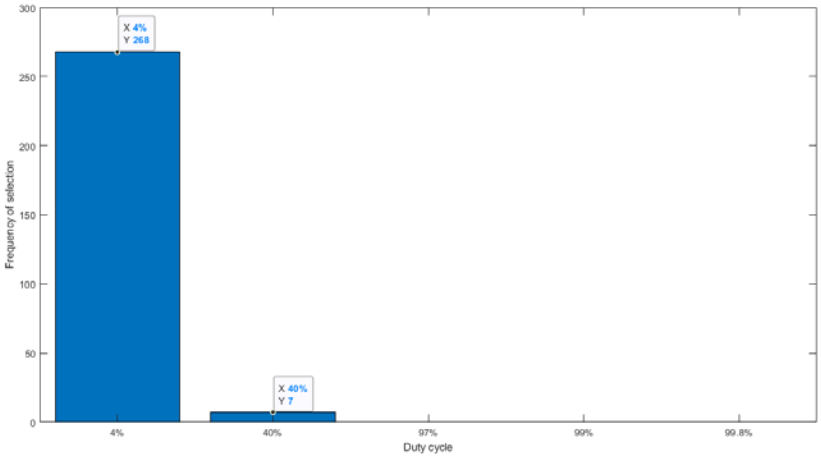

Figure 5: Frequency of selection using the predictive CSA on 5 different duty cycles

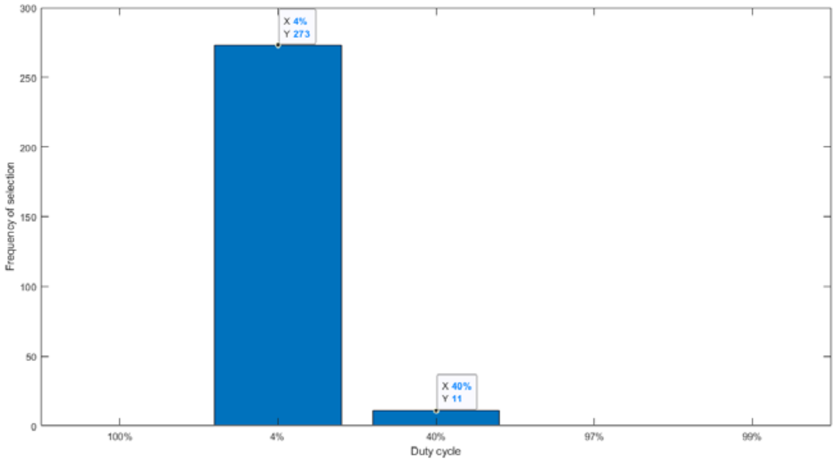

Figure 6: Frequency of selection using the predictive CSA on 5 different duty cycles

Figure 7, shows the probability distribution plots in time for the predictive probabilities $P_{OFF-OFF}$ and P_{ON-OFF} respectively. The channel selection algorithm as was discussed predicts the OFF state or idleness of a channel by modeling its OFF time as an exponential function with a defined rate. As expected, the plot in Figure 7, shows how quickly the channel returns to an OFF state from an ON state and how long it remains in an OFF state for a given duties cycle. Considering the case of 20% duty cycle, the blue plot has a higher $P_{OFF-OFF}$ in time because due to the 20% duty cycle in 2secs, it has a higher tendency to remain in the same state over time at a 20% decay rate. Also, if the initial state is an ON state, the 20% duty cycle channel will tend to quickly leave that state to an idle state at an 80% rate. So, the blue plot quickly approaches 1 compared to other higher duty cycles and less quickly compared to the 10% duty cycle (the orange plot).

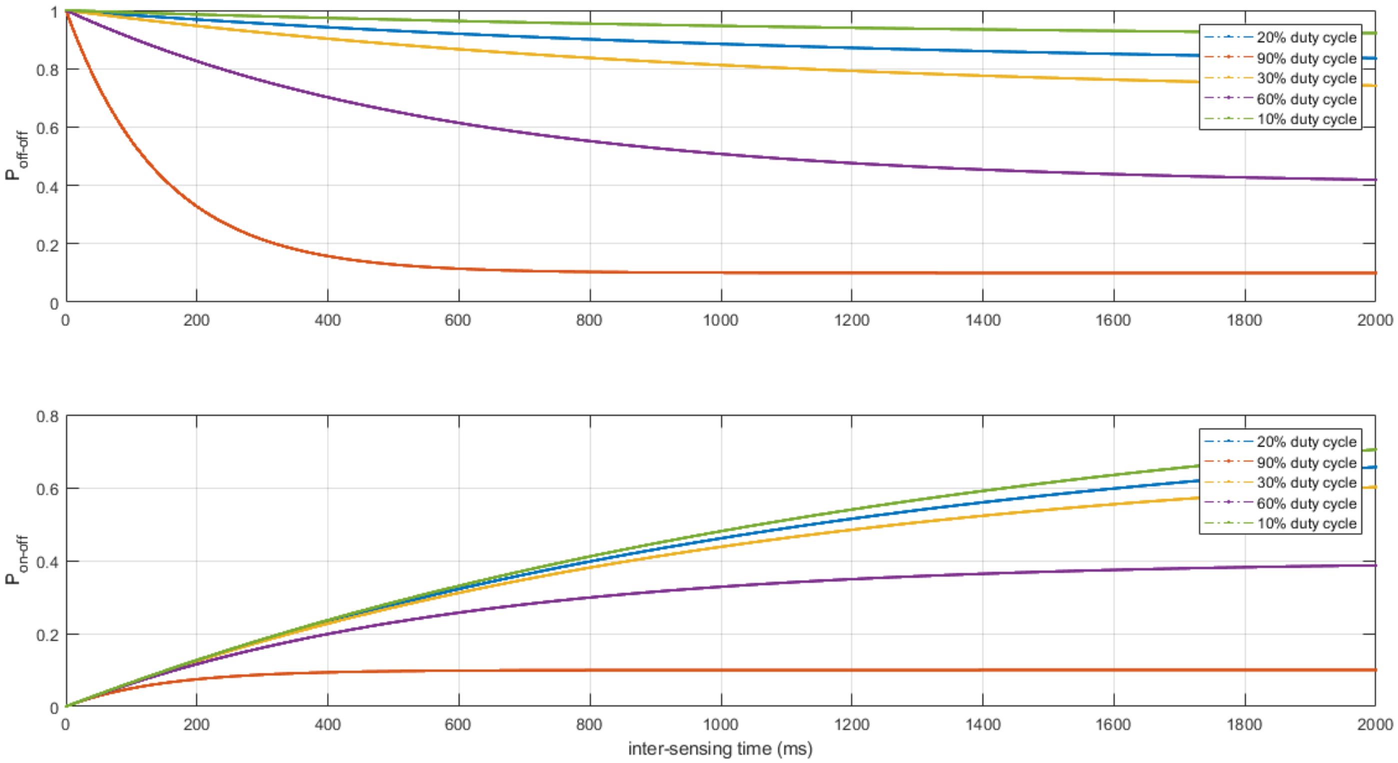

Figure 7: Exponential probability distribution for 5 different duty cycles or PU activity

The results from the MAC protocol implemented in MATLAB for the duty cycles as shown in Figures 2 - 6. Figure 2, shows the frequency of selection for a set of 5 different duty cycles, 20%, 30%, 60%, 70%, and 90% respectively. The first point that was established here is that the MAC protocol maximizes the best channel; hence it was noticed that the frequency of selection, select the best channel to exceed the rest by a large factor. The results for this combination of duty cycles is that the best channel is used 243 times while that of 30% and 60% duty cycle is used 21 times. Also, it was noticed that 70% duty cycle is only used once and there is no usage of the 90% duty cycle channel.

For another set of duty cycles, 30%, 50%, 60%, 80% and 90%, the frequency of selection is 188, 81, 11, 0 and 0 respectively as shown in Figure 3. Again, the best channel is maximized, however, in this scenario the next two best channels are also maximized leaving out the two most occupied channels unused. The sum of the selected frequency is given as 280 which is approximately the average amount of selection that was gotten from simulation. The same analysis applies to the next 3 sets of duty cycles shown in Figures 4, 5, and 6.

From the analysis it was determined how best the selection works at selecting the best channel, then a ratio relationship deduced which can be expressed as 243:43, 183:92, 325:15, and 268:7 respectively for the considered cases. Another test was carried out for a wide range of the set of duty cycles chosen randomly to determine the number of selections for a given number of steps in the simulation. It was observed that a higher percentage selection of 55.44554455 for case 123 where the duty cycles are 0.30514, 0.75311, 0.61739, 0.70019, and 0.0076076 respectively which show a fairly active channel set with 30.5% and 0.76% activity for two channels. In addition, for the simulation, the sensing block is a random generator depending on the mean OFF time of the channel set chosen, and as such the idlest channels will have the highest selection.

5. Conclusion

The system that was designed, determine channel selection for five stations, to determine if the design is good, the five stations that were chosen had been analyzed as shown in Figure 1, where present and absent stations had been recorded. To validate the design as shown in Figures 2 – 6 from the analysis done using Spectrum sweep using RTL-SDR shows that the result for various duty cycles was able to select the perfect station.

The predictive channel selection algorithm for maximizing the best channel selection performed as expected showed great dependence on the computed probabilities (probability of staying idle and the probability of returning to a used case). Hence, a better channel selection algorithm updates these probabilities in real-time. With higher processing computer systems and high-performing software, the throughput of the SU can be improved with smaller inter-sensing time as the ON-OFF, OFF-OFF probabilities show usable values with smaller inter-sensing time than with larger inter-sensing time.

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