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Large scale spectrum survey in rural and urban environments within the 50 MHz–6 GHz bands

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ABSTRACT

In-depth spectrum measurement was conducted in rural and urban locations, covering 50 MHz–6 GHz bands, during the weekdays and weekends. A modified duty cycle metric is presented by introducing a space variable into the existing metrics available today. An adaptive energy detection threshold technique was employed, the results indicate the average spectral occupancy of 0.18%, and 5.08% in rural and urban locations respectively during weekdays and 1.45% on weekends for urban locations. Furthermore, short and long term temporal variations of the duty cycle for each of the bands were studied, and it was found that GSM 900 shows significant temporal variation when compared with GSM 1800. It was also found that the choice of the detection threshold would significantly affect the duty cycle as GSM 900 and 1800 give exponential decay with increase in detection threshold while TV band shows very sharp exponential decay which becomes invariant after −85 dBm.

1. Introduction

The finite nature of the electromagnetic spectrum is continuing to pose immeasurable challenges to man, in the face of emerging new technologies that are deployed through the wireless medium. Political or governmental control naturally crept in and became an issue (i) to protect users so they have value for investment (ii) to take advantage of the desire for this natural resource, to generate revenue. Within the first half of this century, the wireless telephone emerged and has been evolving, over the year into what is, now to be known as the 5G (fifth generation). Pioneered, by Bell laboratories' development, of the cellular concept, in the 1960s, several mobile standards have been evolving, all over the world, being deployed in commerce, security, leisure, governance, transportation etc. A run through the evolutionary-history of wireless communication indicates that data speed had being the main driver of the evolutionary trend. To this end, this desire, for limitless services, with frequency spectral frugality, therefore, exposes man to the obvious choice of having to seek novel and more ingenious techniques of managing the spectrum, a finite resource with almost limitless demands. This scenario had brought through several ideas, prominent among which is frequency reuse, which, in turn, has given rise to such concepts as *spectral efficiency, spectral occupancy*, among a few others, which quantitatively measure the rate at which the frequency are utilized. However there is a misconception of the scarcity of radio spectrum, this has been opined to be attributed to the gap between spectrum allocation and usage [1]. Software Defined Radios (SDR) or Cognitive Radio (CR) have been proposed to improve on spectrum utilization and this is expected to bridge the gap and mitigate the spectrum scarcity problem. The CR would exploit the unused radio spectrum in non-interference basis, this require full understanding of the current spectrum usage and dynamic behavior of the primary users of the spectrum. Hence, calls for a deeper understanding of the characteristics of current spectrum utilization [2]. Therefore it is very essential to provide the true behavior of the actual spectral usage in a given environment; this would enable the development and wide scale deployments of future wireless communication systems that would efficiently maximize the usage of the underutilized spectrum.

The aim of this paper is to provide a more comprehensive and in-depth spectrum measurement in diverse environments spanning both rural and urban locations, covering the frequency bands of 50 MHz–6 GHz. In order to determine the duty cycle, an adaptive energy detection threshold technique was employed with a modified duty cycle metric where space variables are taken into consideration. In order to characterized the duty cycle, short and

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long term temporal variations of the duty cycle for each of the bands were investigated. The paper also investigated how the choice of detection threshold could affect the duty cycle.

The paper is organized as follows: Section 2 highlighted the global spectrum surveys conducted. Section 3 presents the material and method used to carry out the experiments. Theory of the spectrum occupancy metrics are presented in Section 4; Section 5 present the results and discussion. Finally Section 6 concludes the paper.

2. Global spectrum survey

The bid to address spectrum scarcity necessitated the global campaigns on spectrum usage, several spectrum measurements studies and analyses have been conducted aiming to provide the actual spectrum occupancies in various countries. A measurement campaign was conducted covering a total of 4500 km along a route from Denver, Colorado to Washington DC in the band 698–806 MHz, covering a variety of busy urban centers and quiet rural areas. The aim was to evaluate the actual spectrum usage, in the 700 MHz band, and to make to make available same information for researchers and SWR technology developers [3]. Measurements were conducted in South Africa to measure the spectrum occupancy in the UHF and GSM bands [4]. Results of their findings indicate the upper limits of 20%, 92% and 40% respectively for UHF, GSM 900 MHz and GSM 1800 MHz bands. However, the GSM bands occupancies vary between 10% and 20% according to time of the day. Qaraqe et al. [5] performed measurements in the 700–3000 MHz frequency band, over three consecutive days, at an indoor and outdoor location simultaneously. Their findings show that there are striking and quantifiable differences in the spectrum utilization profiles between indoor and outdoor environments. Spectrum utilization and signal-level between Continental United States and Western Europe were compared. It was concluded that the occupancy level of the 2–30 MHz band of the radio spectrum in Europe is higher than Continental United States with considerably more broadcast activity in the German city [6]. Spectrum occupancy measurement covering the frequency range of 75 MHz–3 GHz spanning a period of forty-eight (48) hours for each block of 500 MHz in the measured range was performed in Spain [7]. The results obtained showed high occupancy of 58.65% below 1 GHz and low occupancy of 5.89% between 1 GHz and 3 GHz. Schiphorst and Slump [8] provide a framework of mobile spectrum monitoring as against, the fixed spectrum monitoring for the purpose of spectrum governance. Horrold et al. [9], conducted an extensive spectrum occupancy measurement between 300 MHz and 4.9 GHz, with aim of obtaining information about spectrum occupancy, particularly focusing on time variation, short and long term channel availability. The obtained results shows that 13.8% of the spectrum measured falls under the category of 10% < *Tocc* < 90%, where *Tocc* is the percentage of time occupancy and therefore, considered to be suitable for cognitive reuse.

Mendes et al. [10], describes a modelling technique for spectrum occupancy of GSM 900 and DCS 1800 bands with respect to analogue and binary quantized power was described. They conclude that GSM 900 frequency has high spectrum occupancy, while the DCS1800 frequency has low spectrum occupancy to enable reuse. Wellens et al. [11], conducted an extensive measurement campaign covering 20 MHz–1.52 GHz, 1.52–3 GHz and 3–6 GHz frequency bands, to compare indoor and outdoor spectrum occupancy. It was observed that very high occupancy existed in the outdoor location and significantly less in indoor scenario due to less ambient noise. Patil et al. [12], carried out campaign on spectrum occupancy in India (Mumbai and Pune). The results of this research indicated that the average utilization of the spectrum was found to be 6.62%. Jayavalan et al. [13], focused on measurement and analysis of spectrum in the cellular and TV bands in Malaysia. The results indicate opportunity for secondary re-use of the frequency bands investigated with the TV bands showing less utilization and thus more opportunity for secondary users. Liang et al. [14] also quantified the usage of the spectrum in 4 diverse measurement areas in China. The results show considerable amounts of underutilize spectrum (white spaces) in particular, the TVWS (TV white space) that is vacant for prospective application of cognitive radio.

Islam et al. [15], conducted a survey on occupancy measurement in Singapore, with the aim of evaluating the occupancy of the bands of diverse services and discover the possible candidate bands that can be for futuristic usage. The spectrum measurement result shows that the average utilization of the spectrum was established to be just 4.54% in Singapore. Analytical and simulation-based results were provided on wideband multidimensional spectrum occupancy measurement at 700–3000 MHz band to study the disparity in frequency spectrum over spatial, time and frequency concurrently, with the goal of discovering the utilization of the propose spectrum band [16]. The results revealed different occupancy rate at different location. The overall bandwidth utilization of the spectrum in all the four locations investigated varies within 4–15%. Measurements covering two different countries were taken by Valenta et al. [17], three locations in France and two locations in Czech Republic with the goal of correlating the measurements analysis of the two regions. The overall utilization from 400 MHz to 3 GHz in the locations investigated are 6.5%, 10.7% and 7.7%.

Lopez-Benitez and Casadevall [18] considered both outdoor and indoor areas at high points and ground level respectively in measurements (covering 75–7075 MHz) in Barcelona, Spain. The average duty cycle for the experiment was 12.10%. Najashi et al. [19] conducted indoor measurements of frequency between 800 MHz and 2000 MHz in Abuja, Nigeria. The measured frequency range was divided to seven blocks and the reading was taken between 9:00 am and 9:00 pm. It was found out that due to the high availability of unused spectrum it will be better and easier to develop a cognitive radio to manage the spectrum. Martian et al. [20], scanned the 25–3400 MHz band in Romania and the mean occupancy obtained was 12.19%. A similar campaign was conducted in Hull, United Kingdom between 180 MHz and 2700 MHz within 24 h [21]. The frequency was sub-divided into six groups. Results show that the most utilized sub-band was 880–960 MHz and the occupancy measured was 32.19%. But the mean spectrum occupancy of all the bands was 11.02%. Adediran et al. [22] used geospatial approach to quantify available frequencies in the TV band is provided. The study show that vast amount of spectrum in the TV band is unutilized.

An outdoor experiment was conducted in Ohio, USA from range 30–300 MHz [23]. It was found that almost 80% of the spectrum measured was free and it was further explained that in a rural location the spectrum occupancy percentage will decrease because of lesser traffic. Attard et al. [24], conducted a measurement campaign in different geographical locations, notably Finland and the United States, to provide a database of information on global spatial and temporal utilization. Similar measurement was also carried out in the 2.3–2.4 GHz band at Turku, Finland and the outcome was compared with the situation in found Chicago, USA [25]. The results show lower utilization in the Finland when compared to the US, but generally, there is some potential possibility for spectrum sharing. Dzulkifli et al. [26] reported based on their findings that spectrum occupancy in Malaysia is very low with majority of the spectrum above 1 GHz accounting for the low utilization level. They therefore concluded that opportunity for the deployment of cognitive radio is very high.

It should be noted that all the measurement surveys provided employed energy detection with pre-defined sensing threshold to determine the actual spectrum usage. However, as each channel has different noise power levels and it is paramount to use appropriate threshold to enable optimum decision. López-Benítez et al. [27], proposed and evaluated a new method to address the limitation in energy detection as a preferred technique for spectrum sensing. The improved method was able to preserve the attractions of the conventional energy detection methods namely, simplicity and applicability regardless of signal format and structure, while providing a better spectrum detection performance. Yucek and Arslan [28], highlighted the shortfall of present spectrum utilization measurements that focuses solely on frequency. The work introduced new dimensions, such as code, angle and angle of arrival.

Despite the spikes in growing spectrum occupancy measurements and survey, due to global demand for more spectral spaces to accommodate increase in wireless data services, significant works has not been carried out in Africa as most of the surveys were conducted in the USA, Europe and Asia. It is worth noting the research efforts [29–35], ranging from preliminary field survey to protocol and model developments, to improve on spectrum utilization so that secondary use of radio spectrum in the VHF and UHF bands in Nigeria is possible. Yet, the works did not provide substantial information about the spectrum usage for researchers and SDR technology developers. The sensing threshold for future CRs may not necessarily be the same across the globe due to differences in terms of geo spectral usage, subscriber behavior, noise levels, hidden node margins and terrain environment. It is therefore very essential; to characterize the actual spectral usage in a given environment as this would enable the development and wide scale deployments of future wireless communication systems that would efficiently maximize the usage of the under-utilized spectrum.

3. Material and method

3.1. Measurement setup and site locations

The spectrum occupancy measurement setup consists of Agilent N9342C spectrum analyzer with frequency range from 100 kHz to 7 GHz, a GPS, Omni directional antenna and 32 gigabyte storage device. The measurements were conducted outdoors at strategic urban and rural locations in Kwara state, Nigeria. For the urban locations, measurements were conducted on weekdays and weekend, while only weekdays measurements were conducted in the rural locations. Table 1 provides details of the locations visited and Fig. 1 shows the locations designated as LOC 1–16. For urban measurements, 11 strategic locations (LOC 6–11) were chosen as shown in Fig. 2 while, for rural measurements, 5 villages (LOC 1–5) were visited across four cardinal axes at an average distance of 30 km from the metropolis. Table 2 provides the service bands considered.

Table 1
Location overview.

Identifier	Location	Type	Coordinate
LOC 1	Adio village, Oke Oyi	Rural	4°29′42″E 8°46′40″N
LOC 2	Malete Village	Rural	4°28′32″E 8°42′44″N
LOC 3	Alamote Village	Rural	4°29′42″E 8°22′34″N
LOC 4	Odo Oke	Rural	4°31′55″E 8°17′09″N
LOC 5	Lajiki	Rural	4°33′02″E 8°16′46″N
LOC 6	University Quarters, Ilorin	Urban	4°38′47″E 8°27′49″N
LOC 7	University of Ilorin Campus	Urban	4°67′60″E 8°48′74″N
LOC 8	Pipe line Road	Urban	4°35′07″E 8°27′57″N
LOC 9	Kwara State Stadium	Urban	4°32′29″E 8°28′36″N
LOC 10	Offa road	Urban	4°34′34″E 8°27′31″N
LOC 11	KW diagnostic center	Urban	4°32′21″E 8°27′03″N
LOC 12	Oja-Oba	Urban	4°32′46″E 8°29′45″N
LOC 13	Post Office	Urban	4°33′52″E 8°29′19″N
LOC 14	Tanke Junction	Urban	4°35′27″E 8°29′10″N
LOC 15	ShopRite, Fate road	Urban	4°35′16″E 8°29′44″N
LOC 16	Al-Hikmah University	Urban	4°30′22″E 8°28′47″N

3.2. Data collection and processing

All raw data was collected by the analyzer in a matrix form with elements of the received signal powers $P(t_i, f_j)$ (in dBm), where f_j denotes the frequency and t_i the time slot. The process of evaluating the occupancy statistics comprises of three steps: raw data input, setting detection threshold, and computing the average duty cycle of each channel and for each location visited. The matrix, Y, of the data sets with the elements $P(t_i, f_j)$ is given by Eq. (1).

$$Y = \begin{pmatrix} P(t_1, f_1) & . & . & . & P(t_1, f_j) \\ . & . & . & . & . \\ . & . & . & . & . \\ . & .. & .. & . & . \\ P(t_i, f_1) & . & . & . & P(t_i, f_j) \end{pmatrix} \tag{1}$$

Eq. (1) can be written in matrix form as:

$$Y = y(n) \tag{2}$$

where $y\ (n)$ is a matrix of received power at each point n.

3.3. Energy detection with decision threshold

Several methods have been proposed to determine channel state and these include Energy detection (ED) method [36,37], Cyclostationary detection method [38], Matched filtering (MF) method [38], Wavelet transform based estimation [39] and Multi-taper spectrum estimation [40]. Each aforementioned methods has its merits and demerits, however, energy detection is found to be the most widely used sensing technique due to its less computational complexities and there is no need for prior knowledge of signal to be detected. ED has been adopted by many researchers globally [5–15] to mention few. ED is an optimal detector if the noise power is known, however noise power could be unpredictable, as it could be location and frequency dependent. ED is based on satisfying a certain hypothesis that the signal is present, if and only if the detected power is greater that a threshold λ $\{H_1\}$. If it is not greater than the threshold, it is suggested as noise $\{H_0\}$. This can be expressed mathematically in Eq. (3).

If Y is the energy output over m sensed samples, i.e.

$$Y = \sum_{i=n}^{m} |y(n)|^2 \tag{3}$$

The decision 'D' of Energy detection can be inferred by comparing the energy Y with a threshold λ, i.e.

$$D = \begin{cases} H_1, \text{if } Y > \lambda \\ H_o, \text{if } Y < \lambda \end{cases} \tag{4}$$

This implies, the detection is the test of the following two hypotheses:

$$\begin{aligned} H_1 &: Y[n] = X[n] + W[n] \text{ Signal present} \\ H_o &: Y[n] = W[n] \text{ Signal absent} \end{aligned} \tag{5}$$

n = 1, 2, 3… N; where N is observed interval.

False alarm and miss detection are major constraints in ED method, as selecting suitable detection threshold λ, could be challenging, since, value too low will increase the probability of false detection, weak signals may be treated as noise, thus would result

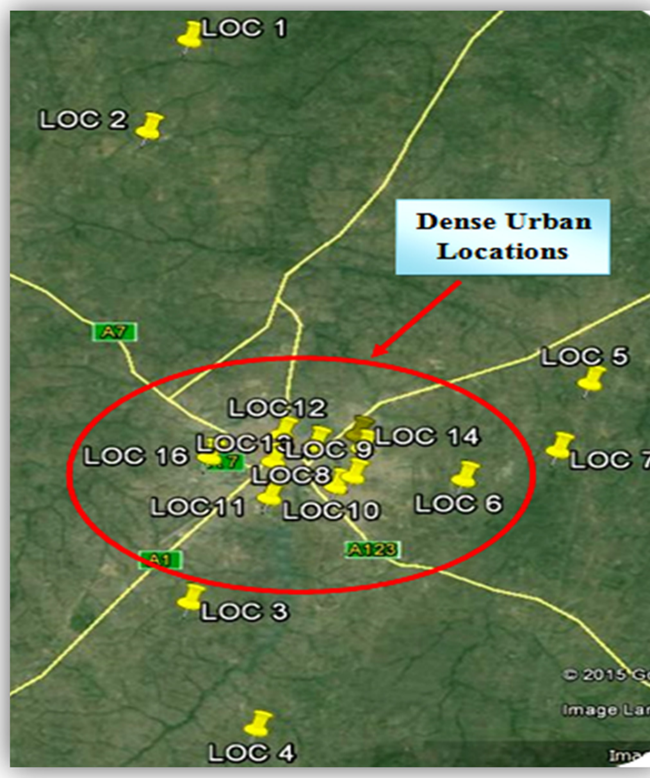

Fig. 1. Rural and urban measurement locations designated as LOC 1–16.

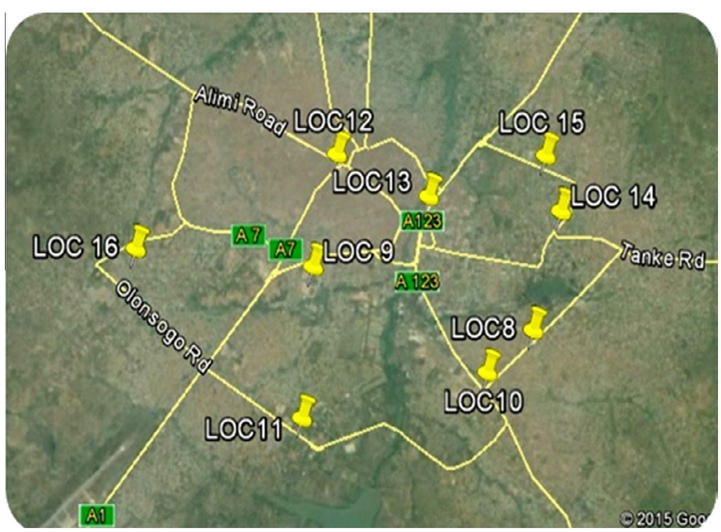

Fig. 2. Urban measurement locations designated as LOC 6–16.

in underestimation of the true occupancy. High values of λ could give high chance of miss detection as this could be caused by high amount of noise power samples chosen and lead to an overestimation of the average channel occupancy.

The analytical method which uses the Johnson–Nyquist [41] noise relations have been tested and found inefficient in this study. It was found that selecting a singular threshold λ value for all the bands was not a viable option, as the background noise varies as a function of the frequency and location. In this regard, an experiment was conducted to construe as suitable and more realistic threshold that will meet the PFA 1% criterion presented in [42]. An adaptive threshold is used; as each channel has different noise power levels, a threshold of 10 dB above the measured mean noise power is then set for each band for each location. In order to avoid uncertainty in choosing appropriate detection threshold, we also varied the decision threshold from −70 dBm to −100 dBm to examine its effects on the occupancy for each of the locations visited for some selected bands.

Table 2
Service bands considered.

Service bands	Frequency range	Bandwidth (MHz)
CDMA UL	825–835 MHz	10
CDMA DL	870–880 MHz	10
GSM 900 UL	885–915 MHz	30
GSM 900 DL	925–960 MHz	35
GSM 1800 UL	1710–1785 MHz	75
GSM 1800 DL	1805–1880 MHz	75
UMTS UL	1885–2025 MHz	125
UMTS DL	2110–2200 MHz	90
TV Band 1	48.5–92 MHz	43
TV Band 2	167–233 MHz	66
TV Band 3	470–566 MHz	96
TV Band 4	606–870 MHz	264
ISM	2.4–2.7 GHz	300
FIXED SAT	3.4–4.2 GHz	800
PMR Trunk	960–1429 MHz	469
Aeronautical, Radar	790–824 MHz	30
Aeronautical	5–5.85 GHz	850
Whole bandwidth	50 MHz–5.850 GHz	5800

4. Theory of occupancy metrics

The occupancy level of the various spectrum bands is quantified in terms of the duty cycle. The Duty cycle is obtained based on a finite set of discrete measurements collected along a range of frequencies:

$F_{span} = F_{stop} - F_{start}$ over a period of time: $T_{span} = T_{stop} - T_{start}$. The discrete time instant measured $t_i \in (T_{start}, T_{stop})$ and $T_{start} \leqslant t_i < T_{stop}$ is presented in [18] and is given by:

$$t_i = T_{start} + (i-1) \cdot T_r, i = 1, 2, \quad \ldots\ldots N_t \tag{6}$$

The discrete frequency points measure $f_j (F_{start} \leqslant f_j < F_{stop})$ is also presented in [18] and is given by:

$$f_i = F_{start} + (j-1) \cdot F_r, \quad j = 1, 2, \ldots\ldots N_f \tag{7}$$

T_r and F_r are the time and frequency resolution respectively, both depends on the input parameters on the analyzer. If $P = [P(t_i, f_j)]$ represents the matrix of measured power presented in Eq. (1). Therefore to obtain the duty cycle, we use the binary hypothesis presented in Eq. (5), a state of frequency band in a particular period of time, at a given location, x is defined as an indicator function $1_D(x)$: $P(t_i, f_j) \to \{0, 1\}$ given by:

$$\Omega_D(t_i, f_j) = \begin{cases} 0, \text{if } P(t_i, f_j) < \lambda_j \\ 1, \text{if } P(t_i, f_j) \geqslant \lambda_j \end{cases} \tag{8}$$

Then, the duty cycle can be obtained as:

$$\Psi_j = \frac{1}{N_t} \sum_{i=1}^{N_t} \Omega(t_i, f_j) \tag{9}$$

where Ψ_j represent the duty cycle and $\Omega(t_i, f_j)$ is a sample of power, when $P(t_i, f_j) > \lambda_j$. Ψ_j is computed for each frequency. Therefore the overall duty cycle $\Psi(x, t, f)$ for all the frequency N_f for a given location (x) is given by:

$$\Psi(x, t, f) = \frac{1}{N_f} \sum_{j=1}^{N_f} \Psi_j \tag{10}$$

By substituting (9) into (10) we have:

$$\Psi(x, t, f) = \frac{1}{N_t N_f} \sum_{i=1}^{N_t} \sum_{j=1}^{N_f} \Omega(t_i, f_j) \tag{11}$$

The total average duty cycles for rural and urban are given by:

$$\Psi'_R(x, t, f) = \frac{1}{n} \sum_{k=1}^{n} \Psi_k(x, t, f), \quad \text{for } k = 1, 2, \ldots n \tag{12}$$

$$\Psi'_U(x, t, f) = \frac{1}{n} \sum_{k=1}^{n} \Psi_k(x, t, f), \quad \text{for } k = 1, 2, \ldots n \tag{13}$$

$\Psi'_R(x, t, f)$, $\Psi'_U(x, t, f)$ and n are the total average duty cycle for rural, urban and number of locations visited.

5. Results and discussion

5.1. Urban and rural spectrum occupancy

5.1.1. Broadcasting TV bands

The duty cycle for TV broadcasting frequencies designated as bands 1, 2, 3 and 4 were obtained in both rural and urban locations. Figs. 3–5 provide results of the occupancy measurements conducted in the rural (LOC 1–5), urban-weekday (LOC 6–9) and urban weekend (LOC 10–16) respectively. For TV band 1 (48.5–92 MHz), LOC 9 has the highest occupancy of 7.23%. For TV band 2 (167–233 MHz) and TV band 3 (470–566 MHz) LOC 8 has the highest occupancy of 11.49% and 37.37% respectively. However for TV band 4 (606–870 MHz), LOC 6 has the highest occupancy value of 15.14%. These are all urban locations, although locations 3 and 5 which are rural villages show considerable occupancies of 14.91% and 20.26% respectively for band 3, while other locations (i.e. 1, 2 and 4) show 0%. However, in all the rural locations (i.e. LOC 1–5), the occupancy value of nearly 0% was obtained for TV band 4 (606–870 MHz) indicating about 100% white spaces in this band. TV band 1 in the other hand recorded the least occupancy across all the locations when compared with other bands this is because only one active transmitter (i.e. Unilorin FM radio, operating on 89.3 MHz frequency) in the VHF channels is allotted for FM radio broadcasting. Therefore, no significant activity was captured, although the experiment did not cover other bands, in which other radio transmitters such as royal FM transmitting on 95.1 MHz, harmony FM operating 103.5 MHz and midland FM 105.3 MHz are operating. TV band 3 recorded the highest occupancy value as up to 37% of the band is occupied during the period of the measurements. This value is expected to vary depending on time and usage. There was no much activity in the TV band 4 as only about 15% of the band is occupied and considering the frequency band of 606–870 MHz which is UHF band, this would be suitable for secondary network deployment with high capacity. However, the duty cycle for LOC 7 was 2.61% in TV band 1 which is very low compared to other urban locations in spite of its closeness to the radio transmitter of about 100 m. The observed low duty cycle is accounted for, by the phenomenon of near far effects. Fairer occupancies values were observed during the weekend measurements for urban locations 10–16 as shown in Fig. 5. A maximum occupancy of 13.66% was obtained in LOC 14. The underutilizations vindicates the weekend schedules of the broadcasting stations and apparent active transmitters in the state, where there were only two televisions broadcast stations (i.e. Kwara TV, operating on 583.28 MHz and NTA Ilorin, operating on 203.25 MHz).

5.1.2. Digital cellular bands

Digital cellular services in Nigeria consist of the second generation (2G) and third generation (3G) network. The 2G network are mainly built using the Global System for Mobile Communication (GSM) standard operating in the 900 MHz and 1800 MHz region and few Code division multiple access technologies (CDMA) can also be found. In Fig. 3 the duty cycles in the rural environments were found to be very low, with occupancy reaching 0% in the five locations, this was not surprising due to the scare population and sparse dispersion of base stations. GSM 900 DL was discovered to have the highest occupancy amongst these technologies in the rural environment with 6.91% in LOC 2; this location is where the state university is situated. CDMA band in these locations is

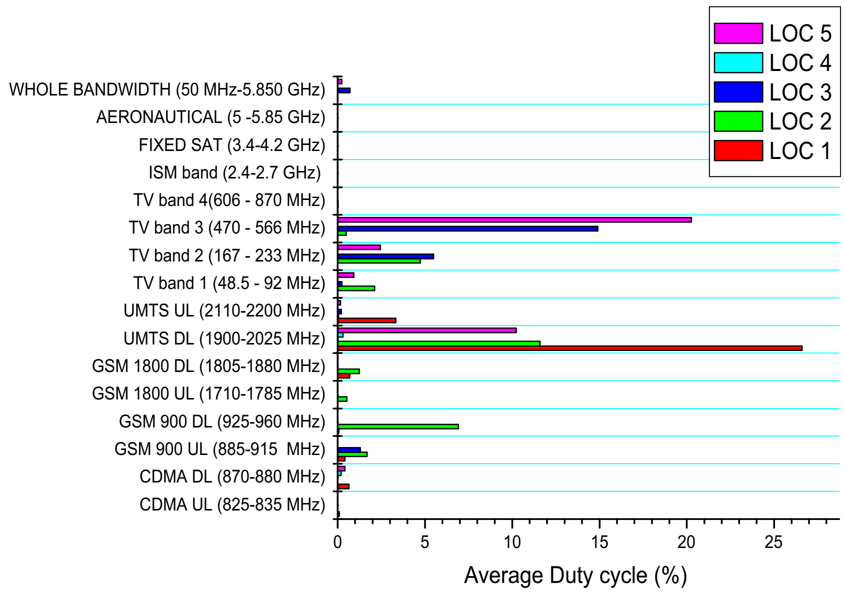

Fig. 3. Comparison of duty cycle for rural locations.

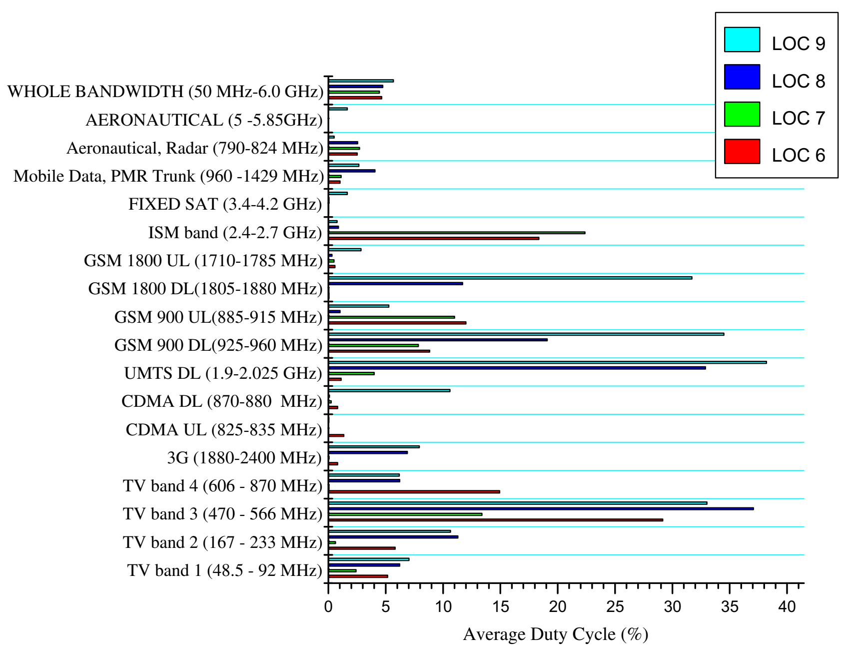

Fig. 4. Comparison of duty cycle for urban locations.

completely empty. The urban results as expected were found to have greater occupancies; with GSM 900 DL having average duty cycles of 9.04%, 8.04%, 19.28%, and 34.69% for LOC 6–9 respectively in the week days. GSM 900 UL was also fairly occupied with 12.2%, 11.2%, 1.21%, and 5.47% utilization for the locations accordingly indicating considerable activities in the band. Location 9 which is the Kwara Stadium, appeared to have the highest occupancy in the DL however, more activities in the UL were captured in locations 6 and 7 (i.e. the university campus area). GSM 1800 showed utilization of 0.78%, 0.68%, 0.52%, and 3.05% for UL and 0.12%, 0.1%, 11.89%, and 31.90% for DL to the locations accordingly. CDMA has the lowest occupancy with 1.55%, 0.066%, 0.03%, and 0.1% for UL and 1.01%, 0.438%, 0.3%, and 0.8% for DL, for LOC 6–9 respectively. Although about 8.81% duty cycle was recorded in location 14 (i.e. Tanke Junction), this is a band bank area and presumably, the banks might be utilizing this band for their services as this is the only location out of the sixteen locations visited where the duty cycle is above 1.5%. The 3G network in Nigeria used the IMT-2000 standard: Universal Mobile Telecommunication Standard (UMTS). Surprisingly, the duty cycle in this band was quite high in rural location when compared to GSM band with DL duty cycle of 26.6%, 11.6%, 0%, 0.31%, and 10.23% for the rural locations 1–5 respectively while urban duty cycle were 1.32%, 4.204%, 33.08% and 38.4% for location 6–9. The following occupancies were recorded in locations 10–16 during the weekend campaign. In the GSM 900 band: 14.64%, 4.64%, 17.6%, 7.35%, 8.68%, 12.4% and 9.44%; In the GSM 1800 band: 9.55%, 17.5%, 10.67%, 3.54%, 1.51%, 1.3% and 8.02%; In the UMTS band: 3.58%, 4.11%, 1.97%, 5.58%, 1.51%, 1.84% and 0.22%. Apparently, the weekend measurement still has effects on the downlink duty cycle for cellular bands but the effect is more pronounced in the case of the TV bands.

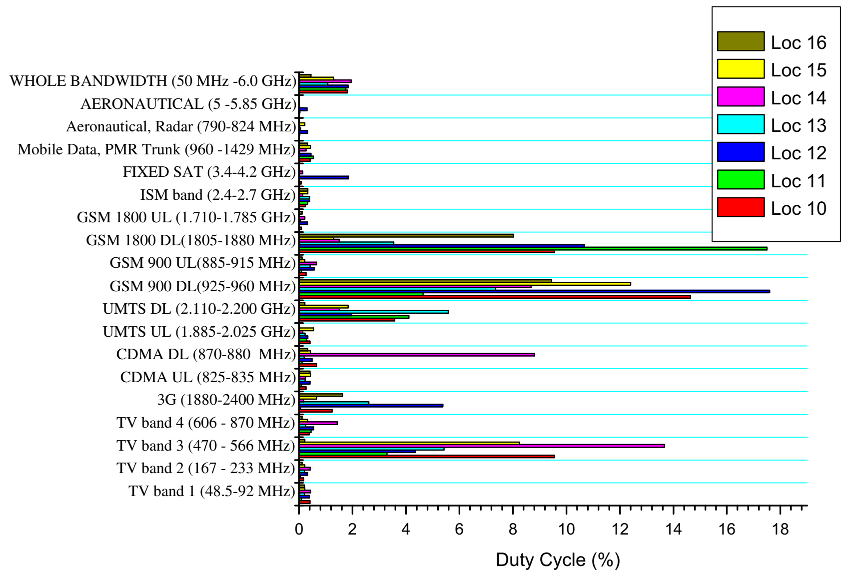

Fig. 5. Comparison of duty cycle for urban locations weekend measurements.

5.1.3. Radar, maritime navigation and trunk radio services

In these services, 0% duty cycle in rural environment were measured as shown in Fig. 3 and near near zero occupancy in the urban environment as shown in Fig. 4. However, the aeronautical mobile service band has a maximum occupancy of 2.9%. The aeronautical mobile refers to the air-to-ground or ground-to-air communications between the airport command center and aircrafts. The duty cycle profile in this band shows "on/off" utilization. The trunk radio services are services such as the PMR (Personal Mobile Radio) which occupies frequency range of 960–1429 MHz. The duty cycles in this band are 0.215%, 1.315%, 4.27%, and 2.86% for LOC 6–9 consequently which were all urban environments and 0% was observed across all the rural locations. The duty cycle observed during weekend measurements was found to be very much lower than the week days; maximum occupancies of 0.22% and 0.3% were recorded for trunk and aeronautical bands respectively.

5.1.4. ISM and fixed satellite broadcast bands

The fixed satellite bands are unoccupied in the rural areas and very low occupancies of less than 2% in the urban locations as shown in Fig. 4. For the ISM band, the duty cycle of 0% was obtained in all the rural locations. This result signifies that the band is completely unoccupied. This is an indication of the low penetration of devices that operate in this band in a typical rural Nigeria settlement that has little or no wireless network infrastructures. However, it is worth noting that even in urban locations ISM band is heavily underutilized, although, low occupancy values where obtained in some locations. Surprisingly the duty cycle of the locations i.e. LOC 6 and LOC 7 are quite higher than for other dense urban locations i.e. LOC 8–16. The occupancy values of 18.56% and 22.56% respectively were measured in LOC 6 and 7, while occupancy of 1.08%, 0.95%, 0.24%, 0.32%, 0.39%, 0.40%, 0.14%, 0.33% and 0.33% obtained in locations 8, 9, 10, 11, 12, 13, 14, 15 and 16. The result is not far-fetched because the locations described as LOC 6 and LOC 7 are campus areas where a lot of wireless LAN devices connect to the institution's internet connection, while other locations are residential and commercial areas of Ilorin. Location 12 is a central city center of the capital, called "*Ojo-Oba*" meaning the "*King's market*" yet the occupancy in this band is still below 1%.

5.1.5. Whole bandwidth

The whole bandwidth considered was from 50 MHz to 6 GHz to have a wide view on the overall spectrum usage. The whole bandwidths occupancy in the rural environment was zero percent in rural locations except from LOC 3 and 5 which yielded near zero utilization of 0.71% and 0.23% respectively. This is portrayed in Fig. 3. The percentage occupancies obtained in the urban environment across various locations were 4.85%, 4.65%, 4.95% and 5.87% during the weekdays with average value of 5.08%, while for weekend measurements, the occupancies were 1.81%, 1.75%, 1.84%, 1.08%, 1.95%, 1.3% and 0.44% with an average value of 1.45%. Fig. 6 provides a comparison between our measurement results and some other results obtained from various locations globally, Qatar [5], Spain [7], Bristol, UK [9], Germany [11], India [12], Singapore [15], Czech Republic [17], France [17], Spain [18], Romania [20], and Hull city, United Kingdom [21], Malaysia [26] and in China [2]. However, not all of these cited papers covers the whole band up to 6 GHz. For example, Bristol [9], Spain [18] and Singapore [15] measurement campaigns cover 300 MHz–4.9 GHz, 70 MHz–7 GHz and 80 MHz–5.8 GHz respectively, other's measurements scope were within the range of 20 MHz–3 GHz. Spain** as used in Fig. 6, indicate the results of measurement conducted in

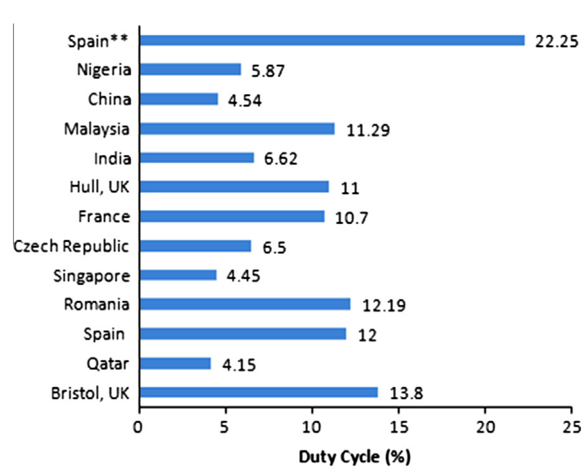

Fig. 6. Comparison with global duty cycle measurement results.

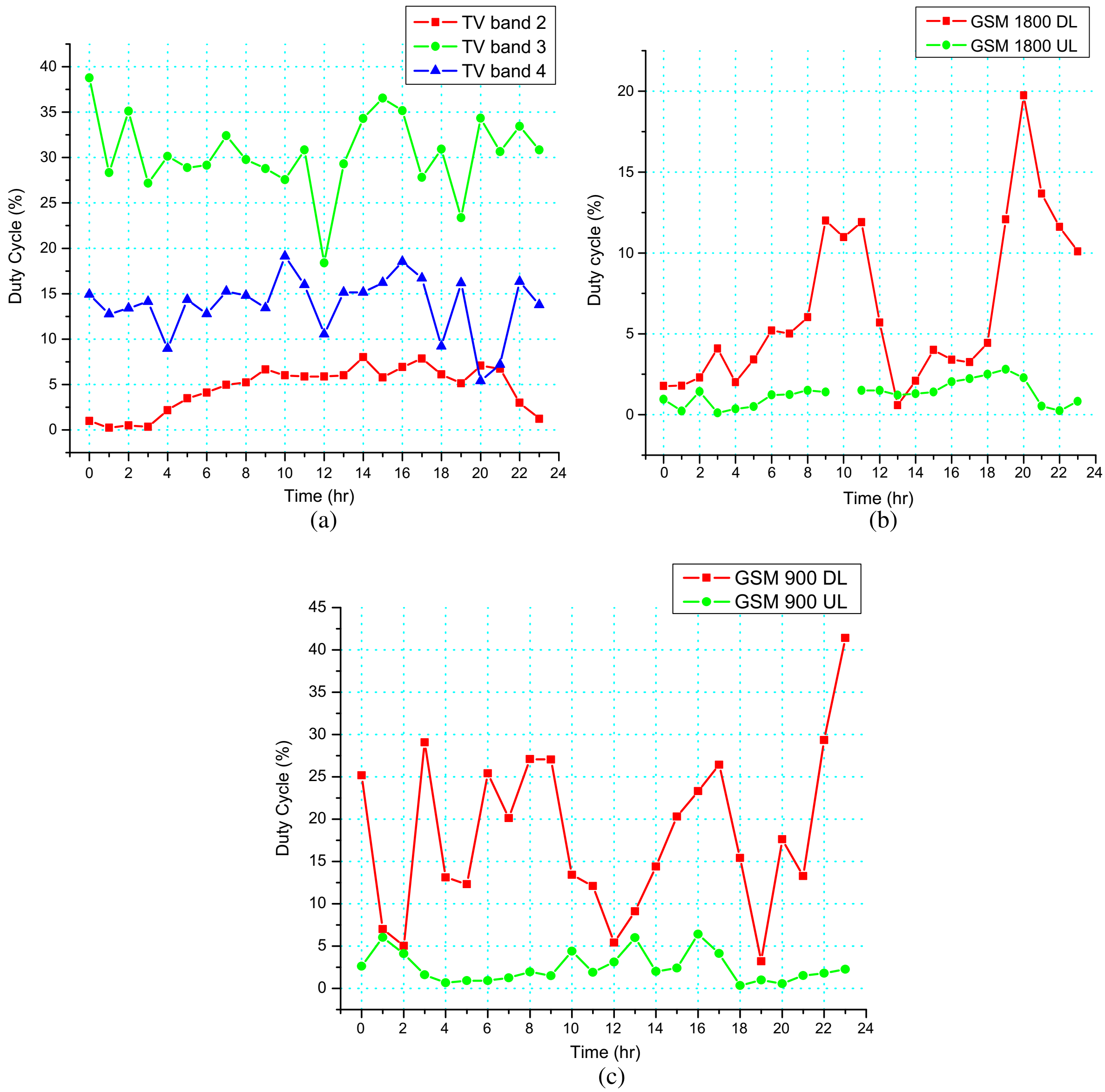

Fig. 7. Hourly temporal variation of duty cycle for LOC 6 (a) for TV band 2, 3 and 4 (b) GSM1800 UL and DL and (c) GSM 900 UL and DL.

Spain [7] which covers 75 MHz–3 GHz, while the measurement scope of the experiment conducted in Spain which was presented in [18] covers 75–7075 MHz. Measurement with narrow band may influence the occupancy value and this may not provide actual spectrum usage when a wide band is used. The results presented in [7,18] demonstrate this.

5.2. Short term temporal variation of duty cycle

5.2.1. Hourly-temporal variation

Temporal variation is regarded as time evolution of duty cycle at a particular frequency band. The temporal duty cycle measurement was taken in two scenarios: firstly, the hourly occupancy measurements over a period of 24 h and secondly, the minute wise occupancy measurements for the same 24 h period in which the average duty cycle of every minute was analyzed. Each frequency range exhibits a change in occupancy observed at each hour but it is more distinct in some bands and at certain time of the day. To this end, only GSM 900 and 1800, TV broadcast band 2, 3, and 4 bands were considered. Frequency bands above 2.5 GHz are excluded in this measurement by the reason of low levels of occupancy. Fig. 7(a)–(c) demonstrate a simple characterization of the temporal behavior of the service bands. Hour "0" represent the start time (T_{start}) or the beginning of the day (24:00 h) proceeding to the hour "24:00" (T_{stop}) of the next day.

A dynamic time variance of occupancy is observed. The TV broadcast bands shows an incessant change in occupancy that defines no particular pattern except from the sudden decrease that occurs in the late hours as shown in Fig. 7(a), basically because of the ON and OFF epochs the TV transmitters, although sharp drop in duty cycle were observed around 12 h for both TV band 3 and 4. However, for TV band 2, the band was completely empty from 24:00 h till 03:00 h, the duty cycle start increasing and become near static for about 9 h, thereafter a sudden fall was observed at around 23:00 pm. The temporal activity is consistent for the cellular bands as shown in Fig. 7(b) and (c), steady increasing in the early hours, reaching peak values at working hours and drastically decreasing in utilization at late hours. GSM 900 shows significant temporal variation when compared with GSM 1800.

5.2.2. Minutes-temporal variation

Unlike the hourly variation, the minute's variation involves a continuous acquisition of the duty cycle over a period of 24 h (i.e. non-stop). Minute "0" represents the first minute of the day, i.e. 24:00 h. The bands exhibit an oscillating pattern along time. Short interleaved time stamps can be notice, which implies opportunistic access to these bands can be done by an intellectual radio. For example, in Fig. 8(a) low duty cycle was observed within 0–300 min window and thereafter the duty cycle increases, this feature is similar to the one exhibited in Fig. 7(a).

For most of the bands studied, every minute have a different *instantaneous* duty cycle Ψ_j it can be observed that in some instances the change in the *instantaneous* duty cycle $\Delta\Psi_j$ is larger than others. However it is worth to note that GSM 1800 band's cycle exhibits periodicity over time. This implies that future algorithms of CR for smart spectrum access can use these results to provide additional guidance for sensing strategies, which in this case should be focus on the use of busty data that can make good use of the short time frame between a high and low occupancy states without interference. Thus, as an upshot, short term continues measurement can still state an acceptable estimate of the real occupancy rates irrespective of the start time. This deduction is valid for broadcast channels of cellular mobile systems and in general for transmitters with a sequential temporal activity such as TV and FM broadcast stations.

5.3. On effect of detection threshold on duty cycle

The concept of duty *cycle* will be extremely ambiguous if the decision threshold amplitude is not clearly stated. A threshold is a fixed value the signal amplitude by which, when exceeded by the result of an actual measurement of the signal duration, one decides that the signal is present and vice versa. There are different means of choosing a detection threshold as discussed earlier. It may be analytical or empirical; however, according to ITU chooses 10 dB above the noise power as a suitable threshold. An investigation was carried out using the data set of LOC 7–9, the threshold was varied between −100 dBm and −70 dBm for some selected bands. It was discovered that occupancy rates are inversely proportional to the threshold. However, the damping of the duty cycle varies as a function of the band and location.

In Fig. 9, TV bands 3 and 4, GSM 1800 and 900 for LOC 7 give exponential decay in their duty cycles with increase in detection threshold. TV band 3 show very high duty cycle and goes to about zero percent only when the threshold reaches −70 dBm. TV band 4 show very sharp exponential decay and becomes invariant after

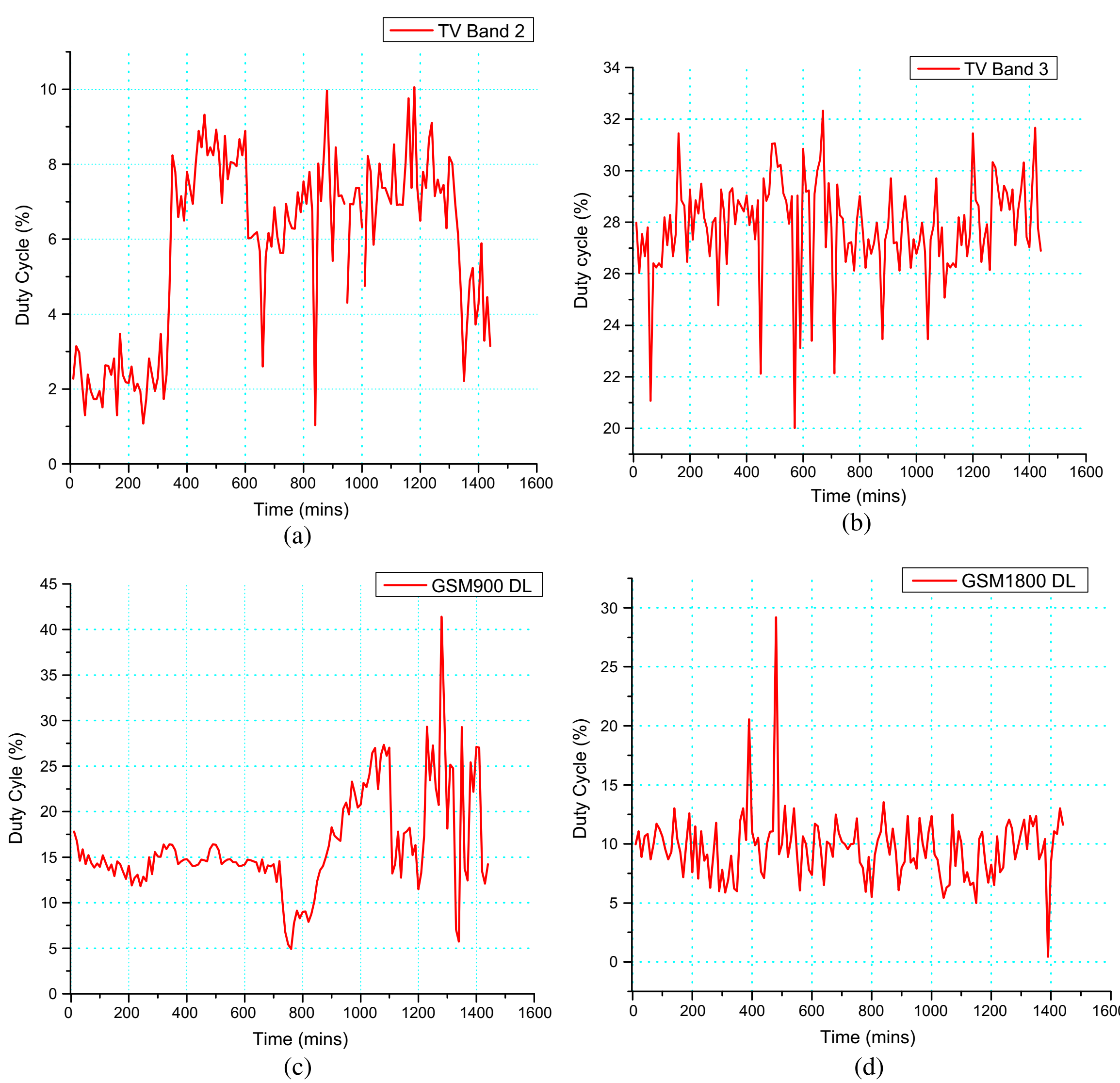

Fig. 8. Minutes temporal variation of duty cycle for LOC 6 (a) TV band 2 (b) TV band 3 (c) GSM 900 DL and (d) GSM 1800 DL.

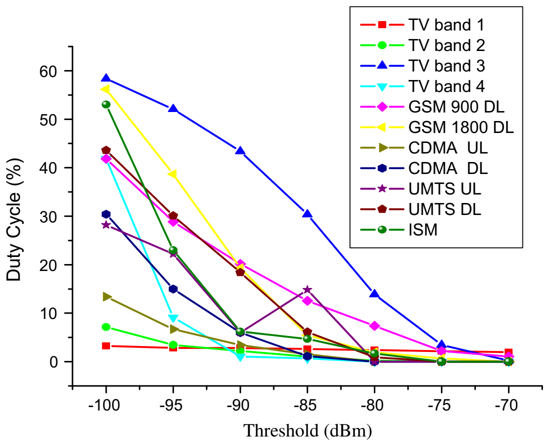

Fig. 9. Effect of detection threshold on duty cycle for LOC 7.

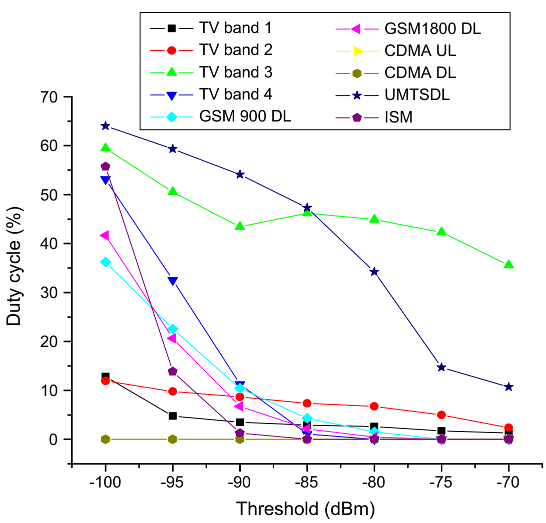

Fig. 10. Effect of detection threshold on duty cycle for LOC 8.

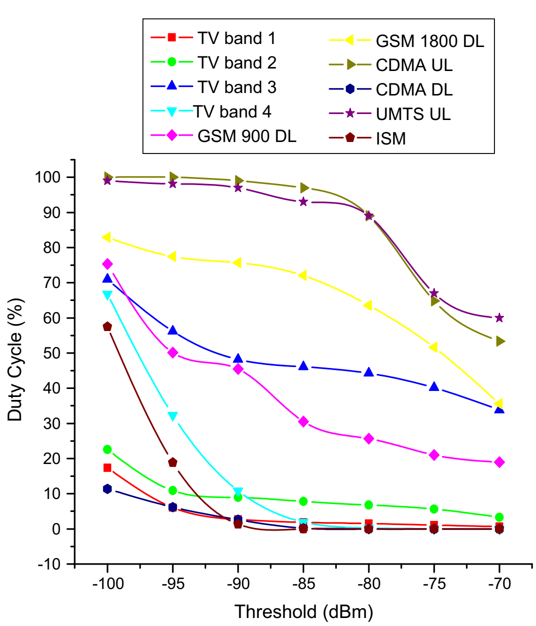

Fig. 11. Effect of detection threshold on duty cycle for LOC 9.

−85 dBm. The ISM band also exhibits these features. On the other hand, TV bands 1 and 2, and CDMA band show linear changes in the duty cycle with increase in the threshold, although when rescaled, we may observe linear decrease for TV band 2 since the duty cycle goes to about zero percent when the threshold is −80 dBm. For LOC 8, similar results were observed except for TV band 3 and UMTS where non-zero duty cycles were observed across the entire threshold as shown in Figs. 10 and 11 provides results for LOC 9.

6. Conclusion

In this work, a more comprehensive and in-depth spectrum occupancy measurements was conducted in both rural and urban locations spanning from 50 MHz to 6 GHz. The results obtained show that the whole band is immensely underutilized and there is, therefore, ample opportunity for the deployment of cognitive radio devices in the investigated band on account of low usage manifested by low occupancy in both rural and urban locations. Measurement results indicate the actual spectral occupancy over the frequency band studied was found to be virtually empty in the rural locations and fairly occupied in the urban locations. The lower and upper bound occupancies for TV, GSM 900, GSM 1800, UMTS, ISM, CDMA, Aeronautical, PMR and Fixed Satellite bands are 0.00–37.37%, 0.31–34.69%, 0.1–31.90%, 0–38.4%, 0.00–22.56%, 0.00–8.81%, 0.00–2.90%, 0.00–4.27% and 0.00–2.0% respectively. The experimental results also show that the spectrum band assigned for broadcast television band (470–566 MHz) is the highest occupied band with 16.6% on average for all locations. The bands allocated for UMTS, GSM 900 and 1800 and digital mobile communication have fairly low occupancies. However CDMA band has the lowest occupancy in all the locations. Frequencies above 1 GHz are relatively underutilized except for the cellular bands and wireless ISM bands in urban areas. The short and long term temporal variations of the duty cycle for each of the bands were provided, and it was found that GSM 900 shows significant temporal variation when compared with GSM 1800. The work investigated the impact of detection threshold on the duty cycle. It was found that GSM 1800 and 900 give exponential decay in their duty cycles with increase in detection threshold. TV band shows very sharp exponential decay and becomes invariant after −85 dBm. The ISM band was also found to exhibits these features across all locations.

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