Quality of Service Aware Channel Allocation for White Spaces Radio Networks

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***Abstract*—The growing demand for high-speed and ubiquitous connectivity continues to present new challenges for efficient usage, management and sharing of radio frequency spectrum. Dynamic spectrum access concept, enabled by cognitive radio technology, allows heterogeneous wireless networks to share white spaces or unused RF spectrum without compromising quality of service (QoS) for secondary users. In this paper, a QoS Aware White Spaces Allocation (QAWSA) scheme is proposed for bandwidth constrained white space radio networks. We assume white space channels are identified using a geo-location spectrum database (GLSDB) combined with a reactive spectrum sensing technique. Such combination of GLSDB and reactive spectrum sensing ensures that correct white spaces are selected and assigned for communication at a desired QoS levels. Analytical results showed that our proposed QAWSA scheme performed better than the sequential white space allocation, especially in guaranteeing the QoS requirements for secondary users. The proposed scheme can be used in the deployment of dynamic spectrum access aware wireless networks such as the television white spaces for broadband communication and narrowband connectivity networks in both especially in rural areas.**

***Index Terms*—bandwidth, cognitive radio, dynamic spectrum access, quality of service, white space, wireless networks**

I. Introduction

According to the 2021 International Telecommunication Union (ITU) statistics, there was only 63% of the global population using the internet; and in Africa, the total population of internet users was at 33% by 2021 [1]. When compared to fixed line telecommunication networks (such as fibre-to-the home or business networks), wireless broadband communication networks remain the most reliable, efficient and cost effective way to bridge the digital divide gap, which does not show any sign of narrowing, especially in developing countries [2]. These growing number of heterogeneous wireless networks can only be supported by the availability of usable and suitable radio frequency (RF) spectrum. If the RF spectrum is not carefully coordinated and managed among different wireless technologies (in the most intelligent of dynamic means), users may experience poor quality of service (QoS) due to harmful interference [3]. There is a need to develop intelligent solutions that will improve the usage and sharing of RF spectrum, which is the scarce natural resource.

Cognitive radios (CRs) and software defined radios (SDRs) have been studied as promising technological solutions towards the realisation of dynamic spectrum access (DSA) concept, which allow the management and sharing of RF spectrum among heterogeneous wireless networks [4], [5], [6]. Wireless networks that make use of DSA and CR technology to intelligently manage RF spectrum are commonly known as white space radio networks (WSRNs). In such networks, SDRs with CR capability should detect unused spectrum opportunities or white spaces for exploitation using the DSA concept. DSA plays a crucial enabling rule in today's wireless communication environment characterised where there is co-existence of terrestrial and satellite (and other space based communication) technologies for provision of broadband connectivity in remote and rural areas.

This paper proposes a quality of service aware white spaces allocation or QAWSA scheme for bandwidth constrained WSRNs. The remainder of this paper is organised as follows; Section II reviews the related work on channel allocation and selection. The systems model and problem formulation is presented in Section III. Section IV presents the proposed QAWSA scheme. The numerical results of QAWSA scheme are provided in Section V. The conclusion and possible further work are presented in Section VI.

II. Related Work

When allocating channels to WSRNs, it is important to consider critical factors such as channel bandwidth in order to meet the QoS requirements for the SUs. This paper builds on our previous work on spectrum decision in heterogeneous wireless broadband networks [4], by focusing on the spectrum allocation in bandwidth constrained wireless networks.

In [7], a channel scheduling model which takes into consideration different sizes of the available bandwidth for CR networks is proposed. Ali et al. [8] proposed a channel allocation scheme for CR enabled internet of things networks which aims to enhance SU QoS using a priority-based dynamic channel reservation approach. A study by Li and Zhu [9] investigate different strategies for spectrum allocation in CR networks for vehicular ad-hoc networks based on QoS requirements. To maximise the network throughput, they proposed a greedy algorithm for their challenge allocation scheme.

A comprehensive survey on different multiple access schemes in CR networks and detailed analysis of advanced futuristic multiple access schemes is provided in [10]. While the above works claimed to focus on providing higher throughput or meeting the QoS for the SUs, their work is limited to single type or homogeneous wireless networks. Hence, this paper explore channel allocation in multiple types of (or heterogeneous) white space networks with different QoS requirements.

III. Network System Model and Problem Formulation

A. System Model

As shown in Fig. 1, we consider a central entity (CE) that is responsible for spectrum management in multiple heterogeneous WSRNs. Each WSRN has a static (not mobile) white space device (WSD) that can act as a base station or access point to several SUs. Each WSD deploys CR techniques through SDR and has multiple transceivers to allow data transmission and spectrum sensing over a wide frequency band.

We assumed the regulator mandated the use of GLSDB for WS discovery to provide minimum protection to licensed network users against interference. As the main entity responsible for spectrum management, the CE is tasked with discovering WS channels from an authorised GLSDB before implementing an intelligent WS selection and allocation to every WSDs. Only the CE has access to GLSDB and is capable of querying WS from a GLSDB on behalf of WSDs. We assume a reliable link connecting the CE with WSDs and GLSDB for control channels. WSDs can perform reactive-spectrum sensing only when instructed to do so by the CE. Unlike proactive spectrum sensing, reactive sensing operates on-demand whereby a WSD can perform sensing only when it has some data to transmit [11]. We assumed that there exists a perfect spectrum-sensing mechanism and that the spectrum-sensing results are perfect [12]. Thus, the actual implementation of spectrum sensing and GLSDB are beyond the scope of this work.

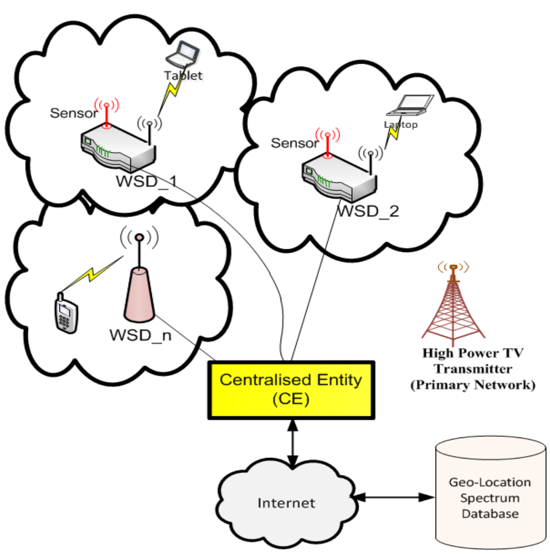


Fig. 1. Considered system model

Our proposed QAWSA scheme was executed within the CE that had knowledge of the Geographical Positioning System locations of all associated WSDs. Coexistence of heterogeneous WSRNs operating within the same geographical vicinity was assumed. In such an environment, there is a high possibility for multiple WSDs requesting WS spectrum at the same time, and if uncoordinated, may lead to interference among WSDs and PUs. Hence, the CE has the ability to identify conflicting WSDs in the most reliable manner. Depending on network topology and distances among WSDs, some WSDs might have overlapping radio coverage and if they are using the same WS channels, they will interfere among themselves.

Suppose there are N different categories of WSDs each belonging to a different wireless technology standard. For example, WSD^1 can belong to a wireless regional area network (WRAN) standard for rural broadband, WSD^2 to a family of wireless local area network (WLAN) standards and WSD^3 to a family of narrow-band and low power machine-to-machine (M2M) networks, such as the internet of things networks [12]. However, more than one WSD belonging to the same category of standards can exist at a given time such that, WSD_n^u represent WSD n of category u. In such cases, QoS requirements for WSDs falling under same category u are treated the same. Hence, we assumed that each WSD has backlogged SUs with traffic of similar QoS requirements.

Our proposed QAWSA scheme sought to address in heterogeneous WSRNs the following two objectives:

a) *To satisfy QoS requirements for every WSD*. This was achieved for as long as a suitable WS channel was allocated to the correct WSD. By suitable WS channel we refer to the RF spectrum which features that met the WSD minimum requirements.
b) *To increase WS spectrum utilisation.* This ensured that no WS spectrum wastage existed when channels with wider bandwidths were reused and shared among narrow-bandwidth- and wide-bandwidth WSRNs.

B. Problem formulation

Suppose there are N number of heterogeneous WSDs wishing to access a WS spectrum. They all send their spectrum request to a CE which then requests WS channels from a GLSDB using the Protocol to Access White Space (PAWS) [13]. Given the heterogeneity of the WS channels, each portion of WS channels exhibit different characteristics. WS characterisation is performed within the local channel classifier module of our proposed Adaptive spectrum decision framework (ASDF) as discussed in the previous section.

Let matrix $\mathbf{C}$ be an $m \times k$ real matrix of WS channels, where m represents the number of WS channels and k is the number of criteria used to classify each WS channel, $k = 1, \ldots, k$. It is worth noting that matrix $\mathbf{C}$ is the output of local channel classifier module from the ADSF proposed in [4]. We assumed that WS channels were available in portions of three different values. For the bandwidth criterion, each WS channel was available in one of these sizes: 8 MHz, 5 MHz or 2 MHz. The channel event time was provided in one of the three periods:

1440, 720, or 360 minutes (which is equivalent to 24, 12 or 6 hours, respectively). And the permitted transmission power was classified into three levels: 36, 30 and 20 dBm. Table I demonstrates typical WS channels as classified by the local channel classifier where there are 8 WS channels to select from.

Once WS channels are found and classified $\mathbf{C}$ according to their key parameters, we implemented the Analytic Hierarchy Process (AHP) to evaluate each portion of WS spectrum against WSD QoS requirements. The AHP technique produced a vector of global priority values $\mathbf{g}$ which scored the WS spectrums according to their importance with respect to the WSDs. WS channels with the highest score in $\mathbf{g}$ were verified through reactive-spectrum sensing and, finally, suitable channels were allocated to WSDs.

WS channel allocation is then performed on verified WS channels. Using the global priority vector ($\mathbf{g}$), we built a $N \times M$ binary matrix $\mathbf{S} = \{s_{n,m} | s_{n,m} \in \{0, 1\}\}_{N \times M}$ that represented a sorted and ranked WS channel availability:

$$s_{n,m} = \begin{cases} 1, & \text{WS channel } m \text{ is available at WSD } n, \\ 0, & \text{otherwise.} \end{cases}$$

More than one WS channel can be available at a single WSD and $S(n) = \sum_{m=1}^{M} s_{n,m}$ was the total number of WS channels available at WSD n.

Let an $N \times M$ binary matrix: $\mathbf{Q} = \{q_{n,m} | \in \{0, 1\}\}_{N \times M}$, represent a QoS aware WS allocation such that:

$$q_{n,m} = \begin{cases} 1, & \text{WS spectrum } m \text{ is assigned to WSD } n, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

where N represents the number of heterogeneous WSDs waiting for WS channel allocation and M represents the number of verified WS channels. QAWSA scheme aims at finding a solution to the bandwidth optimisation problem (2):

$$\begin{aligned} &\text{minimise} \quad b_{n,m} = \quad q_{n,m} \cdot s_{n,m} \\ &\text{subject to:} \end{aligned} \tag{2}$$

$$\sum_{m=1}^{M} b_{n,m} \leq B_{tot} \quad (n = 1, 2, \ldots, N), \tag{3}$$

$$b_{n,m} = b^{n}_{min}, \tag{4}$$

$$s_{n,m}, b_{n,m} > 0, \quad for\ all\ n, m. \tag{5}$$

where B_{tot} is the total available bandwidth to be shared by all coexisting WSRNs, $b_{n,m}$ is the size of WS channel m bandwidth allocated to WSD n, and b^{n}_{min} denotes minimum bandwidth required by a WSD n. The objective function in (2) allowed proportional sharing of WS channels to WSDs under the minimum bandwidth constraint. Constraint in (3) ensures that allocated bandwidth does not exceed total bandwidth B_{tot}. The size of B_{tot} depends on the number of factors which include assignment and utilisation of incumbent spectrum by PUs. The value of B_{tot} can vary from few mega-Hertz (MHz) to tens of MHz of contiguous or non-contiguous spectrum bands. The total bandwidth B_{tot} was calculated from a list of all verified WS channels.

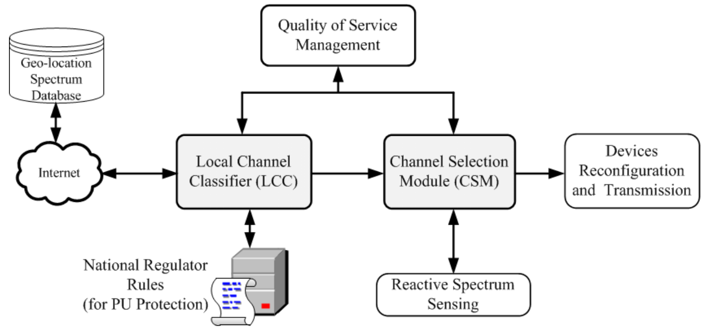


Fig. 2. Adaptive spectrum decision framework for WSRNs showing local channel classifier and channel selection modules

Constraint in expression (4) ensured that every WSD was allocated a WS channel that met its required minimum bandwidth. Minimum required bandwidth is important for allowing a WSD to operate. If the bandwidth is less than the WSD requirements, no communication will be established. This constraint makes sure that our scheme is QoS aware as we use WS channel bandwidth as our main QoS metric. Details of QAWSA scheme development and the entire procedure is demonstrated in the next section.

IV. Quality of Service Aware White Space Allocation

The proposed QAWSA scheme relies on the outputs of the local channel classifier module of the adaptive spectrum decision framework, as shown in Fig. 2. As proposed in [4], the local channel classifier module produces a vector of global priority values which characterise each WS channel based on SUs QoS requirements and the category of WSRNs supported by WSDs. QAWSA represents a novel scheme for selecting and allocating WS channels to WSDs belonging to heterogeneous WSRNs under the QoS constraint.

Fig. 3 demonstrates the overall operation of QAWSA scheme. WS channels discovered using GLSDB and the global priority vector of these channel are inputs to the QAWSA scheme. Using these inputs, the proposed QAWSA scheme is then achieved through the following steps: (1) ranking of WS channels based on their AHP global priority vector, (2) performing reactive spectrum sensing on selected WS channels and (3) allocation of WS channels to suitable WSDs.

A. Ranking and Scoring of WS channels

To allocate suitable WS channels to heterogeneous WSDs, the proposed QAWSA scheme ranked WS channels based on the global priority vector ($\mathbf{g}$) generated using AHP technique. WS channels were then ranked in decreasing order and channels with the highest score were at the top and represented the most preferred WS channels. Ranking of WS channels helped

TABLE I
TYPICAL PRESENTATION OF WS CHANNELS AND CLASSIFIED BASED ON THEIR CHARACTERISTICS

Spectrum Parameter	Ch.1	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6	Ch.7	Ch.8
Bandwidth (MHz)	5	8	5	2	5	5	8	2
Channel Time (minutes)	360	1440	720	1440	360	1440	720	1440
Tx Power (dBm)	20	30	20	36	30	20	30	36

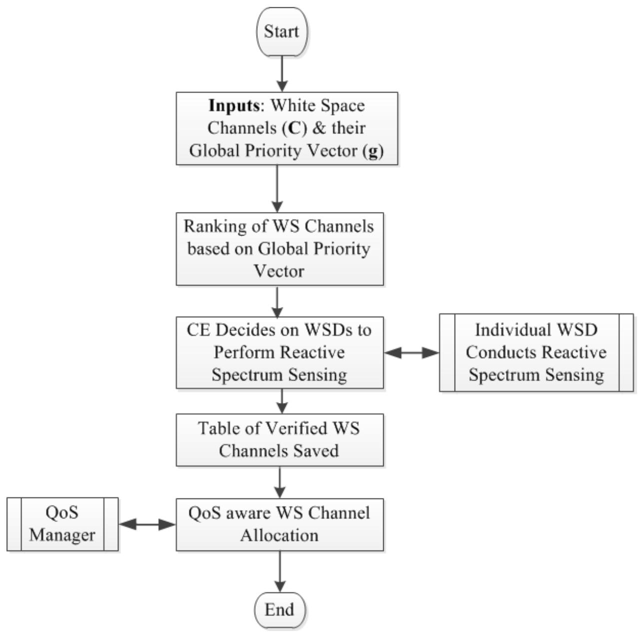


Fig. 3. Flowchart demonstrating AHP and QAWSA scheme

TABLE II
TYPICAL PRESENTATION OF REACTIVE SPECTRUM SENSING RESULTS SHOWING MAIN SENSED CHANNELS WITH THEIR $m \pm 1$ ADJACENT CHANNEL STATUS

GLSDB Channels	Reactive Spectrum Sensing Results						
	WSD 1			. . .	WSD N		
Ch. Number	Lower Adj. Channel	Main Ch.	Upper Adj. Channel	. . .	Lower Adj. Channel	Main Ch.	Upper Adj. Channel
Ch. 1	0 or 1	0 or 1	0 or 1	0 or 1	0 or 1	0 or 1	0 or 1
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
Ch. M							

the CE in deciding whether to verify all WS channels through reactive sensing or to sense the top WS channels only.

B. Reactive Spectrum Sensing

There is a general understanding that usage of GLSDB provides protection to PUs against interference that might arise from WSRNs. Thus, for as long as WSRNs operated within WS channels identified using GLSDB, there shall not be any interference between PU and WSD signals. Reactive sensing is only conducted to verify results from GLSDB. Such verification is crucial since the potential for errors may be high depending on the dataset used to build the GLSDB [14].

Depending on the number of WSDs waiting for channel allocation, the CE will decide on the number of WS channels to be verified as well as number of WSDs to be instructed to perform reactive sensing. For example, if there are five WSDs waiting for channel allocation, and ten channels were provided by the GLSDB, a CE might request each of the five WSDs to perform sensing on all ten WS channels. Each WS channel is sensed together with its upper and lower adjacent channels ($m \pm 1$). Reactive sensing is only interested on verifying WS channels discovered by the GLSDB to be vacant/available. This process is not expected to be time consuming when compared to the normal proactive spectrum sensing [14].

Once the WSDs completed their reactive-spectrum sensing, they will send their individual results to the CE. Such results will inform the CE as to whether sensed WS channels plus their adjacent channels are available (0) or unavailable/occupied (1). Depending on the sophistication of the sensing process, the sensing results can also indicate whether a channel is occupied by other WSDs or PUs. Table II shows a typical reactive spectrum sensing results. For every WS channel discovered using a GLSDB, a sensing results table will show whether such channel was verified to be vacant or occupied, as well as the status of the adjacent channels. Mechanisms to implement reactive-spectrum sensing are beyond the current scope of work.

C. WS Channel Allocation

After receiving sensing results from WSDs, the CE builds a WS channel-availability-matrix using expression (1). Then a WS channel allocation is achieved using the bandwidth-optimisation problem defined in expression (2).

We adopted the proportional fairness for our optimisation problem, expression (2). Proportional fairness aims at maximising the total reward or system utility for every WSD based on its communication capabilities as well as its minimum QoS requirements. In our case, minimum WS channel bandwidth was used as the main QoS metric. We used channel bandwidth because irrespective of the allowed transmission power and channel holding time, without minimum spectrum bandwidth, a WSD will not be able to communicate. Furthermore, the size of bandwidth is also useful for every WSD to achieve its maximum throughput. The sum of right elements in our optimisation problem ($\sum_{m=0}^{M} q_{n,m} \cdot s_{n,m}$) is equivalent to throughput allocated to every n WSD.

The proposed QAWSA scheme ensures that QoS requirements for WSDs are met. In cases where interference is not an issue, the QAWSA scheme can be sufficient for WS allocation in heterogeneous WSRNs. However, most practical WSRNs are expected to coexist within a geographical area and interference management will remain a concern. In such cases, an optimal WS allocation scheme should also consider interference and spectrum efficiency. Such channel allocation schemes with interference and spectrum efficiency constraints were developed in our previous work [4].

V. Results Analyses and Discussions

A. Numerical Analyses on Generated WS channels

We start by showing WS spectrum channels used in our analysis. These channels were randomly generated by QoS management unit and classified by the local channel classifier module of our proposed ASDF. The aim is to first validate the operation of our AHP model and its ability to prioritise and rank WS channels according to their parameters and QoS requirements.

Fig. 4 illustrates WS channels that were randomly generated and arranged according to the three parameters (bandwidth, event time, and permitted transmission power). Up to 15 WS channels were found to be available. The x-axis represents three parameters and the y-axis represents WS channel numbers. WS channels were numbered sequentially, and their numbering does not reflect standard channel numbering of any wireless technology, such as TV channel numbering. The z-axis shows the quantity of three parameters, which are MHz for bandwidth, hours for time and dBm for transmission power.

Fig. 4 (a) shows WS channels provided by a GLSDB. These are WS channels that were predicted by GLSDB using the WSDs parameters as provided by the CE. Fig. 4 (b) shows verified WS channels. The verification process is done through reactive spectrum sensing. The CE selected a set of WSDs to perform reactive spectrum sensing on each one of the WSD from a GLSDB. Only two WS channels, number 4 and 5, were confirmed to be unavailable for secondary usage during reactive sensing. Such results means that our GLSDB was almost perfect in predicting WS channels because it achieved the accuracy of over 87% and only two WS channels were found to be a false negative.

B. WS channel verification analysis

Based on the discovered WS channels, we then applied our AHP-based WS spectrum-ranking algorithm to produce the global priority vectors for each category of WSDs. These global priority vectors, depicted in Fig. 5, represent the score for each WS channel based on the criteria used per category of WSDs. Fig. 5 (a) shows global priority vectors for GLSDB-predicted WS channels before verification and Fig. 5 (b) shows the global priority vector of verified WS channels. It can be seen from Fig. 5 (a) that WRAN based WSDs preferred (meaning the WS channel with the highest global priority value) WS channels 4, 6, 7 and 11 because of their high bandwidth size when compared to other WS channels. After WS channel verification, it happened that channel 4 (which was among the top ranked for WRAN of WSDs category), was found to be unavailable. As such, WRAN-based WSDs will have to settle for the remaining three best WS channels.

For WLAN category, WS channel 5 is the most preferred, followed by WS channels 8, 13, 9, 12 and 1. Since WS channel 5 was a false negative, only five WS channels will be considered for allocation as the best available channels for WLAN category of WSDs. On the other hand, the top WS channels for M2M networks is WS channel 5 followed by WS channel 8 and 3. These WS channels offer the longest channel event time (24 hours), although they do not have the smaller bandwidth. WS channels that do not satisfy QoS requirements for any category of WSDs are ranked the lowest as they had the smallest global priority values.

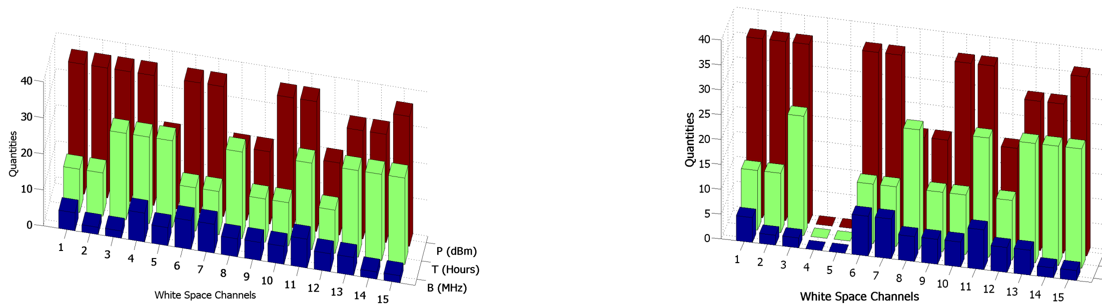
To check the consistency of our AHP algorithm, we repeated AHP evaluations using Microsoft Excel as well as human judgement for construction of pairwise comparison matrices. We also used an on-line AHP tool [15] to verify our results. In all cases, our module was found to be consistent and producing similar results. Based on this validation techniques, we can conclude that our system was capable of performing AHP evaluation since the results were similar to the expected results.

C. Analysis on Classified WS Channels

Next we investigated WS allocation from the classified WS channels. Fig. 6 (a) illustrates the sequential white space allocation (SWSA) scheme when the number of WS channels was equal to the number of WSDs. Since channels are already ranked according to their relevance to WSDs of different categories, we implemented a baseline SWSA scheme. This scheme is similar to the first-come-first-serve channel allocation used by some TV band WSD manufacturers that we used during the TVWS trials. This type of white space allocation lacks some intelligence and leads to poor QoS delivery to WSDs at the bottom end of the list. It also leads to high interference among WSRNs due to double allocation of common WS channels to more than one WSDs belonging to different WSRNs.

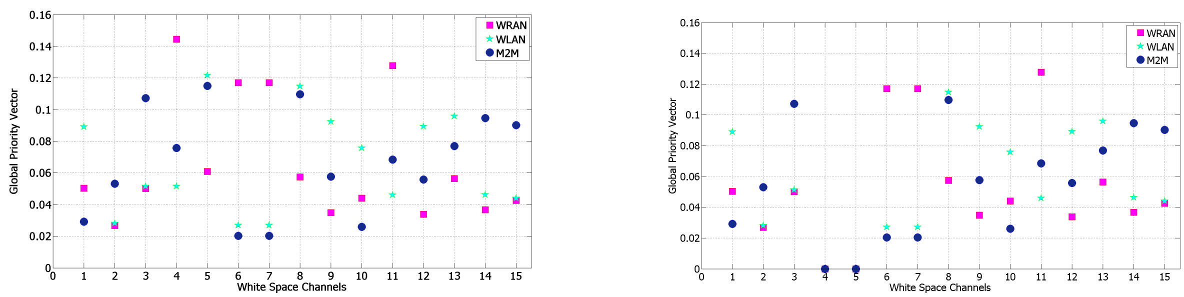
Fig. 6(a) can be read as follows. A WSD number of the x-axis is assigned a channel number of the y-axis. For example, WS channel number 5 is allocated to to WSD number 1 in both WRAN and M2M categories of WSDs. Fig. 6(b) illustrates QAWSA matrix whereby WS channel availability is 1 if WS channel m is available and allocated to WSD n.

Comparing the sequential first come first serve scheme in 6(a) and sequential QAWSA scheme in 6(b), we can see that there are number of advantages in using our scheme (6(b)) when compared to the uncoordinated WS allocation scheme. One of the advantages is that our scheme allocates suitable WS channels to the right WSDs. Instead of allocating a WS channel which a bandwidth of 2 MHz to a WRAN type of WSD (which requires a minimum of 8 MHz), our scheme considered the WSD QoS requirements and allocated channels only so as to allow the WSD to operate. If there were not enough WS channels to allocate to WSDs, other multiple access techniques could be employed, or the WSD may have to try in a different band. We find this mechanism to be preferred above just allocating WS channels even if they were not going to be used by WSDs. Our solution avoids wasteful efforts when



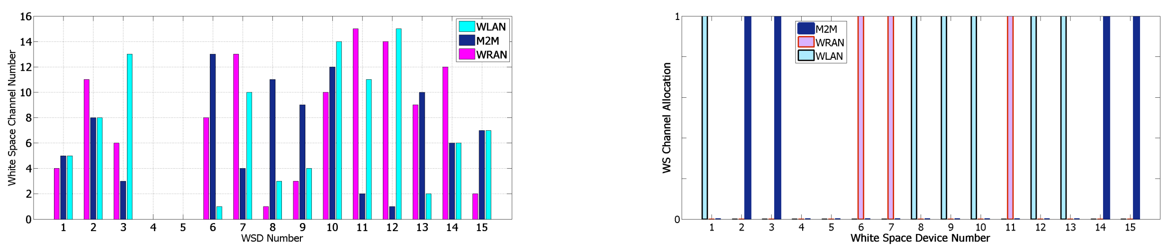
(a) (b)

Fig. 4. Randomly generated WS used in our analysis. (a) WS channels from GLSDB; (b) WS channels verified through reactive sensing



(a) (b)

Fig. 5. Global priority values computed from WS channels per WSRN type (a) Before WS verification; (b) After WS channels verified through reactive sensing



(a) (b)

Fig. 6. Sequential white space channel allocation: (a) without QoS; (b) QoS aware

it comes to WS channel allocation by knowing, before hand, the minimum required bandwidth per WSDs.

Finally, we observed the bandwidth distribution as the number of WSDs increased. Fig. 7 illustrates how the amount of WS spectrum bandwidth decreases with an increase in the number of WSDs for each category. Based on verified WS channels, there is 24 MHz (3 x 8 MHz) available for WSDs of WRAN category to share. Since this category requires a minimum bandwidth of 8 MHz to operate, a total of three WSDs can share the available WS spectrum. Three became the threshold for WRAN WSDs. WSDs of category WLAN have a high number of WS channels to share among themselves. The total WS spectrum bandwidth for WLAN devices is 30 MHz, which is due to 6 x 5 MHz WS channels. Thus, upto six WSDs can share the spectrum and be able to provide minimum QoS. For WSDs under the M2M category, there is a total of 8 MHz (which is 4 x 2 MHz WS channels). This total means that upto four WSDs can receive channels to provide minimum required QoS for M2M type network deployments.

VI. Conclusion

This paper attempted to address the problem of spectrum management in WSRNs by proposing QAWSA scheme. To improve the WS channel prediction, reactive spectrum sensing functionality is introduce to validate each WS channel before it can be selected. Based on numerical analysis, the proposed QAWSA scheme performed better than the SWSA scheme. Moreover, our proposed scheme was found to perform as expected for QoS-aware WS spectrum management in coexisting heterogeneous WSRNs. In cases where all WS channels had similar properties,and the number of WSDs was equal to the

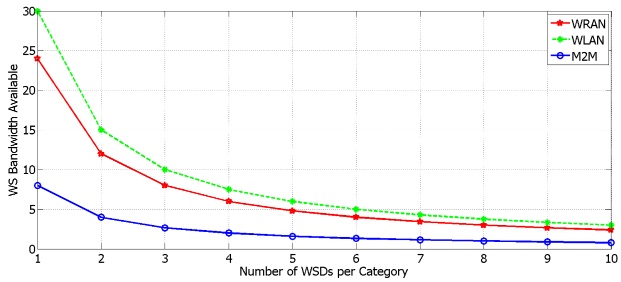


Fig. 7. Available white space spectrum bandwidth for WSD per category

number of WS channels, the QAWSA performance may be found to be on par with SWSA scheme. However, in most practical scenarios, the number of WSDs are expected to be more than the number of WS channels.

Some weakness from our QAWSA scheme include poor spectrum efficiency, as well as a lack of interference mitigation or management techniques. Thus, further work would include the investigation of QoS aware channel allocation schemes with intelligent WS sharing schemes to improve the spectrum efficiency and interference mitigation, especially in densely populated areas.

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