

Three-Tier Hierarchical Model of Dynamic Spectrum Sharing Based on Hybrid Authorization Using Geolocation Database and Cognitive Radio

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Abstract—Dynamic spectrum sharing (DSS) has been envisioned as a promising approach to address the imminent shortage of spectrum resources caused by the exploding growth of wireless traffic. Contrast to the existing DSS approaches which are either based on individual authorization using a geolocation database, such as Licensed Shared Access and Spectrum Access System, or general authorization using spectrum sensing techniques, such as Collective Use of Spectrum, in this paper, we propose a three-tier hierarchical model of DSS based on hybrid authorization, in which primary licensees (PLs) and secondary licensees (SLs) register with a geolocation database to guarantee predictable quality-of-service, and tertiary licensees (TLs) opportunistically access the small spectrum holes in time and space to further improve the spectrum usage. We provide a mathematical analysis of the optimal access strategy for each type of licensees in the proposed hierarchical model, such that the weighted sum throughput of SLs and TLs is maximized while the PL throughput is guaranteed. Simulation results show that the proposed hierarchical approach can highly increase the system performance, compared to the current database-driven approaches.

I. INTRODUCTION

Due to the massive growth of mobile broadband services and machine type communications, wireless traffic is expected to continue exploding in the 5G era. The increasing capacity requirement has imposed great demand pressure on spectrum resources, which necessitates a major paradigm shift in how we manage radio spectrum. Specifically, the legacy management policies with static and exclusive spectrum usage are expected to be replaced by dynamic spectrum sharing (DSS) approaches that share spectrum resources more intensively and dynamically among all types of wireless systems. The benefit of DSS has been widely recognized in terms of improving spectrum utilization, providing additional bandwidth, and lowering spectrum license fee [1], [2]. As an example, the widely studied cognitive radio can be seen as a promising DSS technique, which can improve the spectrum usage efficiency by allocating the radio resource flexibly [3]–[5].

Regulatory bodies have proposed various DSS models, including Licensed Shared Access (LSA) and Collective Use of Spectrum (CUS) from Europe, and Spectrum Access System (SAS) from the United States [6]. LSA and SAS are

based on individual authorization (IA) [7], in which each licensee is exclusively granted a particular part of spectrum for a predefined geographic area and time period, and therefore guarantees an interference-free environment and a predictable quality-of-service (QoS). However, the granularity of IA approaches can be highly restricted due to the cost of maintaining a real-time geolocation database, the communication range of different wireless services (e.g., fixed microwave services), and the willingness of IA licensees to give spectrum usage information (e.g., military and government users). Therefore, the QoS guarantee of IA approaches is achieved at the price of leaving a large number of small spectrum holes undetected and unutilized by potential users, such as commercial IoT devices requiring small scale transmissions in time and space.

On the other hand, general authorization (GA) approaches such as CUS [8] have no centralized or proactive control of the licensees sharing the spectrum. Each GA licensee is allowed to opportunistically access the idle frequency bands, as long as a set of predefined conditions (e.g., maximal transmit power, minimum spectrum sensing accuracy) is satisfied. In practice, GA approaches can be implemented by using “listen-before-talk” devices (such as cognitive radio and WiFi), which provide necessary techniques to ensure the harmonious sharing among coexisting GA licensees. However, the imperfect sensing capability of practical devices and the uncontrollable number of GA licensees lead to no performance guarantee of GA approaches, and thus, they are not suitable for traditional mobile broadband services with strict QoS requirements.

In the 5G era, the scarce spectrum should be used to provide massive capacity and high flexibility. Different spectrum usage methods are proposed to meet these requirements, including the aforementioned DSS approaches based on either IA or GA, cognitive radio technique, and the device-to-device communications [9]–[11]. In this paper, we propose a hierarchical DSS model that defines three types of spectrum licensees, namely, the primary licensee (PL), the secondary licensee (SL), and the tertiary licensee (TL). The proposed three-tier hierarchical model is based on hybrid authorization (HA), in which the PLs and the SLs are IA licensees that register with a geolocation database to ensure interference-free sharing, and the TLs are GA licensees that opportunistically access the spectrum without centralized control. The benefit of the proposed HA approach is twofold, firstly, it provides a predictable QoS for

This work was partially supported by the National Natural Science Foundation of China (61671233), the Jiangsu Science Foundation (BK20151389, BK20170650), the Postdoctoral Science Foundation of China (BX201700118, 2017M621712), and the Jiangsu Postdoctoral Science Foundation(1701118B).

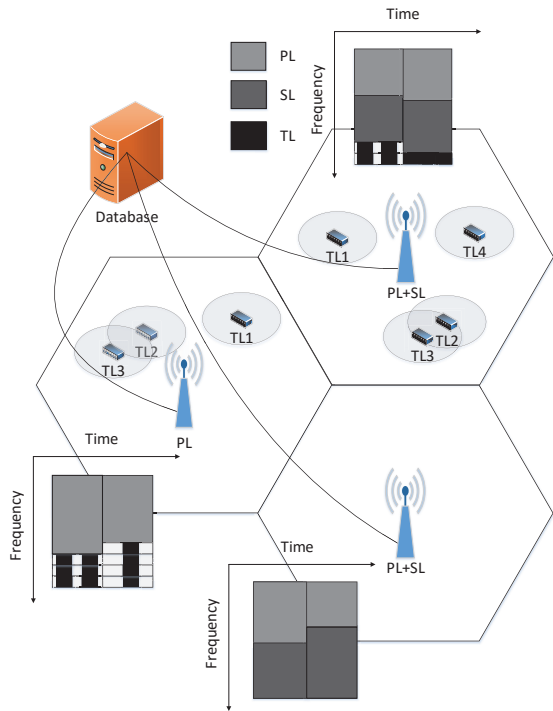


Fig. 1. Three-tier hierarchical model of dynamic spectrum sharing based on hybrid authorization.

PLs and SLs in a large scale of time and space, and secondly it further improves the spectrum utilization by allowing opportunistic access of TLs.

There are some related works that jointly using geolocation database and cognitive radio for DSS [12], [13]. However, their models are still based on pure IA, in which cognitive nodes are utilized as parts of a collaborative sensor network that aims at enhancing the accuracy of the geolocation database, instead of being treated as third-tier GA licensees that opportunistically utilize the small spectrum holes left by the geolocation database. Also, there are some works modeling and analyzing hierarchical DSS models with three access tiers [14]–[16]. Our work is different from them as their analysis is based on the SAS approach in which all three tiers are IA licensees that register with a geolocation database.

The remainder of this paper is organized as follows. In Section II, we provide a detailed description of the proposed HA approach. Section III gives a mathematical analysis of the optimal access strategy for each licensee type defined in proposed DSS model. Simulation results are provided in Section IV and we conclude our paper in Section V.

II. THREE-TIER HIERARCHICAL MODEL BASED ON HYBRID AUTHORIZATION

As shown in Fig. 1, the proposed DSS model defines three types of licensees, namely, PL, SL, and TL, each of which is explained as follows:

- **PL:** The PL has the right to periodically claim any part of the spectrum for a given geographic area and time

period, within which no SLs or TLs are allowed to access. The PLs can be traditional incumbent users with specific restriction zones, such as military radars and fixed satellite systems, or commercial users with more dynamic spectrum usage, such as mobile network operators.

- **SL:** The SL has the right to periodically claim any part of the spectrum unutilized by the PL for a given geographic area and time period, within which no TLs are allowed to access. Compared to the PL, the SL also has an exclusive usage of frequency bands for a specific area and time, but the amount of SL bands is not a guarantee. The SLs are usually commercial users requiring additional frequency bands for certain area and time, such as mobile network operators in hot spots and peak hours.
- **TL:** The TL can access any frequency band that is not claimed by a PL or an SL for a given geographic area and time period, as long as the specific band is idle. The TLs are suitable for services with a large number of local and temporary transmissions with no strict QoS requirement in capacity, latency, and reliability, such as massive IoT communications in the 5G era.

In a typical implementation of the proposed hierarchical model, there are usually one PL, multiple SLs, and massive TLs. The specific spectrum sharing scheme can be determined by both technical and commercial considerations. Here, we assume that the PL and the SLs register with a geolocation database, which maintains the real-time information of spectrum claims so as to guarantee the exclusive band usage. Moreover, to protect the QoS of SLs, the PL is not allowed to reclaim any frequency bands from the SLs during a claimed period, which is different from traditional incumbent users as defined in LSA or SAS. The TLs are not pure “listen-before-talk” devices, but also receive guiding information from the geolocation database, such as the frequency bands available for TL transmissions and the number of TLs in a specific frequency band.

III. OPTIMAL SPECTRUM ACCESS

For simplicity, we assume that there are one PL, one SL, and sufficiently many TLs. Thus, there is no competition among SLs. The spectrum is segmented into L orthogonal frequency bands with the same bandwidth, each of which provides a constant data rate λ_0 for all types of users. The data packets arrive at Poisson process, where the arrival rates of PL, SL, and TL are denoted by λ_p , λ_s , and λ_t , respectively. For the PL and the SL, the packet size is assumed to follow a negative exponential distribution with mean normalized to 1, and the TL packet has a constant size of 1. We denote l_p and l_s as the number of bands claimed by the PL and the SL, and n_t is the number of TLs in each frequency band.

We try to obtain the optimal $\{l_p^*, l_s^*, n_t^*\}$ to maximize the weighted sum throughput of the SL and the TLs while guaranteeing the PL throughput. The optimization task can be

formulated as follows:

$$\max_{l_p, l_s, n_t} \alpha_s R_s + \alpha_t R_t, \quad (1a)$$

$$s.t. Pr\{d_p \geq D\} \leq P_0, \quad (1b)$$

$$Pr\{d_s \geq D\} \leq P_0, \quad (1c)$$

$$l_p + l_s \leq L, \quad (1d)$$

$$l_p, l_s, n_t \in \mathcal{N}, \quad (1e)$$

where R_s and R_t represent the SL throughput and the total TL throughput, respectively; α_s and α_t represent the weight factors of SL and TL, respectively; d_p and d_s are the packet delay of PL and SL, respectively; D is the delay threshold, and P_0 is the probability threshold. Thus, (1b) and (1c) guarantee QoS requirement, that is the probability that the PL/SL packet delay exceeds the delay threshold D is below the threshold P_0 . We assume that $\alpha_s + \alpha_t = 1$.

A. Primary Licensee

Consider that the PL packets are sequentially transmitted using the total l_p frequency bands. Thus, the transmission time of a PL packet follows a negative exponential distribution with mean $1/(\lambda_0 l_p)$. The PL can then be formulated as an $M/M/1/\infty$ queueing system with the arrival rate λ_p and the service rate $\mu_p = \lambda_0 l_p$ [17]. We assume $\lambda_p < \lambda_0 L$ such that there always exists enough number of PL bands $l_p \leq L$ to ensure the occupation rate $\rho_p = \lambda_p / \mu_p < 1$.

For any PL packet arriving at the PL, the probability that there are n packets in the system is given by:

$$p_n = (1 - \rho_p) \rho_p^n, n \geq 0. \quad (2)$$

The delay of the arriving packet is then given by the total service time of $n + 1$ PL packets. As the service time of each PL packet follows a common negative exponential distribution with mean $1/\mu_p$, the total service time follows an Erlan- $(n + 1)$ distribution with mean $(n + 1)/\mu_p$, and the cumulative distribution function is given by:

$$F_{n+1}(t) = 1 - \sum_{k=0}^n \frac{(\mu_p t)^k}{k!} e^{-\mu_p t}, t \geq 0. \quad (3)$$

Therefore, the probability that the delay of the arriving packet exceeds the threshold D is given by

$$\begin{aligned} Pr\{d_p \geq D\} &= \sum_{n=0}^{\infty} p_n [1 - F_{n+1}(D)] \\ &= \sum_{n=0}^{\infty} \sum_{k=0}^n \frac{(\mu_p D)^k}{k!} e^{-\mu_p D} (1 - \rho_p) \rho_p^n \\ &= \sum_{k=0}^{\infty} \sum_{n=k}^{\infty} \frac{(\mu_p D)^k}{k!} e^{-\mu_p D} (1 - \rho_p) \rho_p^n \\ &= \sum_{k=0}^{\infty} \frac{(\mu_p \rho_p D)^k}{k!} e^{-\mu_p D} \\ &= e^{-\mu_p (1 - \rho_p) D}. \end{aligned} \quad (4)$$

Substituting (4) into constraint (1b), we have the optimal number of PL bands is given by

$$l_p^* = \lceil \frac{1}{\lambda_0} \left[\lambda_p + \frac{1}{D} \ln\left(\frac{1}{P_0}\right) \right] \rceil. \quad (5)$$

B. Tertiary Licensee

For any frequency band that is not claimed by the PL or the SL, the TLs can opportunistically access the band by using spectrum sensing techniques. The sensing capability is characterized by the false alarm probability p_f and the miss detection probability p_m , which is assumed to be the same for all SLs. We assume that all TLs are synchronized in time slots, the size of which is defined as the transmission time of one TL packet, i.e., $1/\lambda_0$. Also, we assume that the considered geographic area is a circle area with radius R and all TLs have the same interference radius r , i.e., any two transmitting TLs can interfere with each other only if their distance is within r .

Consider a frequency band with total n_t TLs. We denote p_{tran} as the probability that a TL transmits in a time slot, and p_{idle} as the probability that the band is decided to be idle during a time slot. For simplicity, we assume that detection of different TL signals are independent from each other. Thus, we have

$$p_{idle} = \left[\left(1 - \frac{r^2}{R^2}\right) + \frac{r^2}{R^2} p_{tran} p_m + \frac{r^2}{R^2} (1 - p_{tran})(1 - p_f) \right]^{n_t - 1}. \quad (6)$$

For the Poisson process of TLs, the probability that n packets arrive at a TL during a time slot is given by

$$q_n = \frac{(\lambda_t / \lambda_0)^n}{n!} e^{-\lambda_t / \lambda_0}. \quad (7)$$

We denote $\pi_n, n = 0, 1, \dots$ as the steady probability that the TL has n packets in the buffer at the beginning of each time slot, and $p_{i,j}$ as the transition probability from state π_i to state π_j . Thus, we have

$$p_{i,j} = \begin{cases} q_j & i = 0, \\ q_0 p_{idle} & i \geq 1, j = i - 1, \\ q_{j-i+1} p_{idle} + q_{j-i} (1 - p_{idle}) & i \geq 1, j \geq i, \\ 0, & \text{others,} \end{cases}$$

and the corresponding transition matrix is defined as

$$\mathbf{P} = \begin{bmatrix} p_{0,0} & p_{1,0} & p_{2,0} & \dots \\ p_{0,1} & p_{1,1} & \dots & \\ p_{0,2} & \dots & & \\ \vdots & & & \end{bmatrix}. \quad (8)$$

Thus, we have that the steady probability vector $\pi = (\pi_0, \pi_1, \dots)^T$ satisfies

$$\pi \mathbf{P} = \pi, \quad (9)$$

and

$$\pi \mathbf{1} = 1, \quad (10)$$

where $\mathbf{1} = (1, 1, \dots)^T$. Combining equations (9) and (10), the steady probability π_n can be numerically calculated as a function of p_{idle} , i.e., $\pi_n(p_{idle})$, and thus, as a function of p_{tran} , i.e., $\pi_n(p_{tran})$. Note that the probability that the TL needs to transmit in a time slot is given by $1 - \pi_0$. We have

$$(1 - \pi_0)p_{idle} = p_{tran}. \quad (11)$$

Therefore, p_{tran} can be numerically calculated from (11), and the value is determined by the number of TLs n_t , i.e., $p_{tran}(n_t)$.

For any TL, the probability that the band is correctly decided to be idle is given by

$$p_{idle}^+ = \left[\left(1 - \frac{r^2}{R^2}\right) + \frac{r^2}{R^2}(1 - p_{tran})(1 - p_f) \right]^{n_t-1}, \quad (12)$$

The total throughput of n_t TLs is then given by

$$r_t(n_t) = n_t \lambda_0 \cdot (1 - \pi_0) \cdot p_{idle}^+. \quad (13)$$

Therefore, the optimal number of TLs in a single frequency band is given by

$$n_t^* = \operatorname{argmax} r_t(n_t). \quad (14)$$

Denote $r_t^* = r_t(n_t^*)$ as the maximal throughput of a single TL band, the total TL throughput is given by

$$R_t = (L - l_p - l_s)r_t^*. \quad (15)$$

C. Secondary Licensee

Consider that the SL packets are sequentially transmitted using the total l_s frequency bands. Thus, the transmission time of an SL packet follows a negative exponential distribution with mean $1/(\lambda_0 l_s)$. In order to guarantee the delay performance of the SL packets, as given in (1c), a finite buffer size K is applied and the SL is formulated as an $M/M/1/K$ queueing system with the arrival rate λ_s and the service rate $\mu_s = \lambda_0 l_s$ [17]. We also define $\rho_s = \lambda_s/\mu_s$ as the occupation rate.

For any SL packet arriving at the SL, the probability that there are $n \in [0, K]$ packets in the buffer is given by

$$w_n = \rho_s^n \frac{1 - \rho_s}{1 - \rho_s^{K+1}}, 0 \leq n \leq K. \quad (16)$$

The delay of the arriving packet is then given by the total service time of $n + 1$ SL packets. As the service time of each SL packet follows a common negative exponential distribution with mean $1/\mu_s$, the total service time follows an Erlan- $(n+1)$ distribution with mean $(n+1)/\mu_s$, the cumulative distribution function of which is given by:

$$G_{n+1}(t) = 1 - \sum_{k=0}^n \frac{(\mu_s t)^k}{k!} e^{-\mu_s t}, t \geq 0. \quad (17)$$

TABLE I
SIMULATION PARAMETERS

$R = 1000\text{m}$	Radius of the considered area
$r = 500\text{m}$	Interference range of TLs
$L = 150\text{m}$	Total number of frequency bands
$\lambda_0 = 1/40$	Capacity of a single frequency band
$\lambda_p = 1$	Arrival rate of PL packets
$\lambda_t = 1/400$	Arrival rate of TL packets
$D = 3$	Delay threshold
$P_0 = 0.2$	Probability threshold

Therefore, the probability that the delay of the arriving packet exceeds the threshold D is given by

$$\begin{aligned} Pr\{d_s \geq D\} &= \sum_{n=0}^K w_n [1 - G_{n+1}(D)] \\ &= \sum_{n=0}^K \sum_{k=0}^n \frac{(\mu_s D)^k}{k!} e^{-\mu_s D} \rho_s^n \frac{1 - \rho_s}{1 - \rho_s^{K+1}} \\ &= \sum_{k=0}^K \sum_{n=k}^K \frac{(\mu_s D)^k}{k!} e^{-\mu_s D} \rho_s^n \frac{1 - \rho_s}{1 - \rho_s^{K+1}} \\ &= \sum_{k=0}^K \frac{(\mu_s D)^k}{k!} \frac{\rho_s^k - \rho_s^{K+1}}{1 - \rho_s^{K+1}} e^{-\mu_s D}, \end{aligned} \quad (18)$$

which is an increasing function of the buffer size K . Substituting (18) into (1c), we can numerically calculate the maximum buffer size $K_{max}(l_s)$ for the SL system.

Note that w_K represents the probability that the buffer is full, or the packet blocking probability. Then the SL throughput is given by

$$R_s = \lambda_s(1 - w_K) = \lambda_s(1 - \rho_s^K \frac{1 - \rho_s}{1 - \rho_s^{K+1}}), \quad (19)$$

which is an increasing function of the buffer size K . Thus, the maximal SL throughput is achieved with the maximum buffer size K_{max} , and we rewrite (19) as follows:

$$R_s(l_s) = \lambda_s(1 - \rho_s^{K_{max}} \frac{1 - \rho_s}{1 - \rho_s^{K_{max}+1}}). \quad (20)$$

Therefore, the weighted sum throughput defined in (1a) can be rewritten as

$$R_{total}(l_s) = \alpha_s R_s(l_s) + \alpha_t R_t(l_s), \quad (21)$$

and the optimal number of SL bands can be numerically calculated as

$$l_s^* = \operatorname{argmax}_{0 \leq l_s \leq L - l_p^*} R_{total}. \quad (22)$$

IV. NUMERICAL RESULTS

In this section, we provide the simulation results of the proposed three-tier hierarchical model. The SL packet arrival rate λ_s , the ratio α_s/α_t , and the sensing capability p_f, p_m are considered as the influencing factor of the weighted sum throughput of the SL and TLs. We also compare with a database-driven approach, in which each band frequency is exclusively claimed by an IA licensee. The simulation parameters are given in Table I.

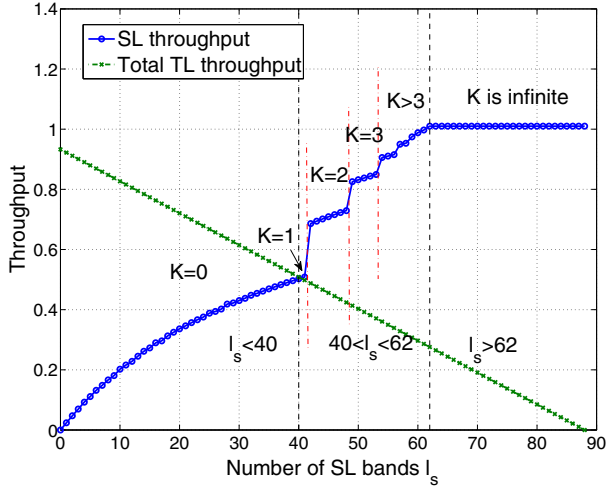


Fig. 2. The SL throughput R_s as well as the total TL throughput R_t as a function of the number of SL bands l_s in a network with $\lambda_s = 1$ and $p_f = p_m = 0.01$.

In Fig. 2, the SL throughput R_s and the total TL throughput R_t are shown as a function of the number of SL bands l_s , where the sensing capability is given by $p_f = p_m = 0.01$ and the SL traffic is given by $\lambda_s = 1$. We see that the SL throughput R_s increases with l_s by taking multiple steps, and the total TL throughput R_t decreases linearly with l_s . For the curve of total TL throughput, we note that the maximal throughput of each TL band is given by r_t^* , which is independent from the number of SL bands l_s . Thus, the total TL throughput R_t is proportional to the number of TL bands $l_t = L - l_p - l_s$, and therefore, decreases linearly with l_s , as shown in Fig. 2.

The curve of the SL throughput is segmented into three different zones. In zone $0 \leq l_s \leq 40$, we have the occupation rate $\rho_s \geq 1$, i.e., the SL bands cannot support the transmission of SL traffic. Thus, the buffer size is set as $K = 0$ and the SL throughput increases smoothly with l_s . In zone $40 < l_s \leq 62$, we have the occupation rate $\rho_s < 1$, i.e., the SL bands can support the transmission of SL traffic. However, a finite buffer size $K < \infty$ is required to guarantee the delay constraint given in (1c). Thus, the SL throughput increases with l_s by taking multiple steps, each of which corresponds to a specific buffer size K . In zone $l_s > 62$, the SL bands are more than sufficient for the SL traffic such that all SL packets can be transmitted and the delay constraint is always satisfied. Thus, we have the infinite buffer size $K = \infty$, and the SL throughput stays unchanged at $\lambda_s = 1$.

In Fig. 3, the weighted sum throughput R_{total} of the proposed approach and the database-driven approach are shown as a function of the ratio α_s/α_t , where the sensing capability is given by $p_f = p_m = 0.01$ and the SL traffic is given by $\lambda_s = 1$. We see that R_{total} first decreases and then increases with α_s/α_t in the proposed approach, while R_{total} increases monotonously with α_s/α_t in the database-driven approach.

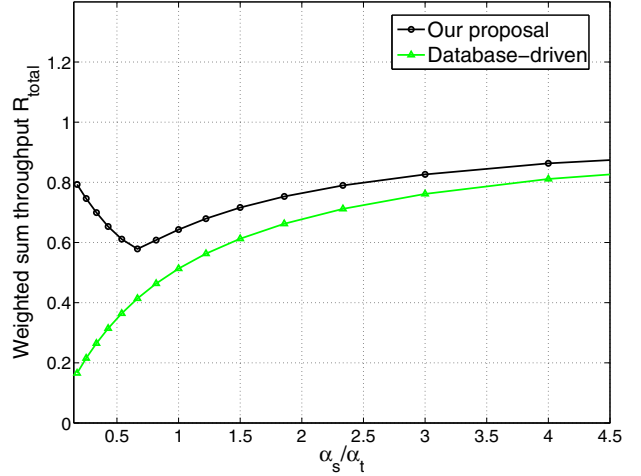


Fig. 3. The weighted sum throughput R_{total} of the proposed approach and the database-driven approach as a function of the ratio α_s/α_t in a network with $p_f = p_m = 0.01$ and $\lambda_s = 1$.

And also, our proposed algorithm outperforms the database-driven approach by 20% ~ 200%. For the database-driven approach, each frequency band is exclusively utilized. The TL band efficiency λ_t is much lower than the SL band efficiency $\lambda_s/l_s \approx \lambda_0$. Thus, the number of SL bands is maximized, and the SL traffic occupies a large portion of R_{total} . Therefore, R_{total} increases monotonously as the SL weight α_s goes up, as shown in Fig. 3.

For the proposed approach, the small spectrum holes in TL bands can be efficiently utilized, and the TL band efficiency is comparable with the SL band efficiency ($n_t \lambda_t \approx \lambda_0$). Thus, as the ratio α_s/α_t goes up, the gains of SL throughput may not compensate the loss of TL throughput. Thus, the weighted sum throughput R_{total} first decreases with α_s/α_t , as shown in Fig. 3 with $\alpha_s/\alpha_t < 3/7$. When α_s/α_t is sufficiently large, the SL throughput achieves the maximal value λ_s and the number of SL and TL bands stay unchanged. Thus, the weighted sum throughput R_{total} increases with α_s/α_t , as shown in Fig. 3 with $\alpha_s/\alpha_t > 3/7$.

In Fig. 4, the weighted sum throughput R_{total} of the proposed approach and the database-driven approach are shown as a function of the SL traffic λ_s , where the sensing capability is given by $p_f = p_m = 0.01$ and the weight factors are given by $\alpha_s = \alpha_t = 0.5$. We see that R_{total} increases with λ_s by taking multiple steps, and the proposed approach outperforms the database-driven approach when λ_s is low. When the SL traffic is low, there are sufficiently enough frequency bands to serve all SL packets, i.e., $l_s < L - l_p$, and the rest bands are utilized for TL transmissions. As the proposed approach has a much higher TL band efficiency, it outperforms the database-driven approach, as shown in Fig. 4 with $\lambda_s < 2.1$.

When the SL traffic is high, all frequency bands left by the PL is utilized for the SL traffic, i.e., $l_s = L - l_p$. Thus, both approaches achieves the same performance. Note that the

V. CONCLUSIONS

In this paper, we proposed a novel three-tier hierarchical model of DSS based on HA, where PLs and SLs register with a geolocation database to achieve guaranteed QoS, and TLs opportunistically access the idle frequency bands to utilize small scale spectrum holes. We analyzed the optimal access strategy for PL, SL, and TL, respectively, to maximize the weighted sum throughput of SL and TL while guaranteeing the QoS requirement of PL. Numerical results shown that our proposed approach can significantly improve the system performance as compared to database-driven approaches.

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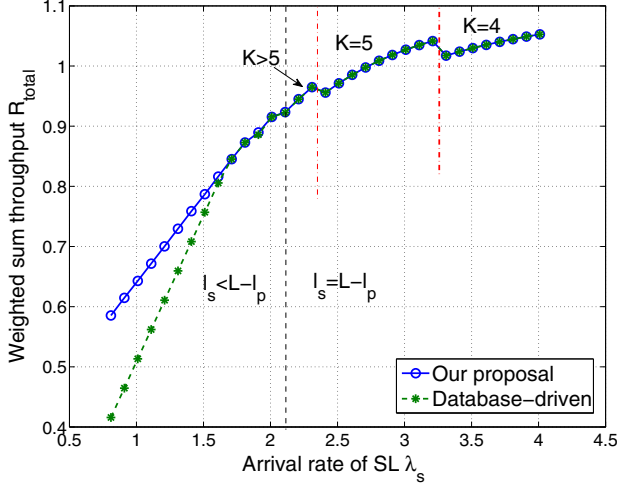


Fig. 4. The weighted sum throughput R_{total} of the proposed approach and the database-driven approach as a function of the SL traffic λ_s in a network with $p_f = p_m = 0.01$ and $\alpha_s = \alpha_t = 0.5$.

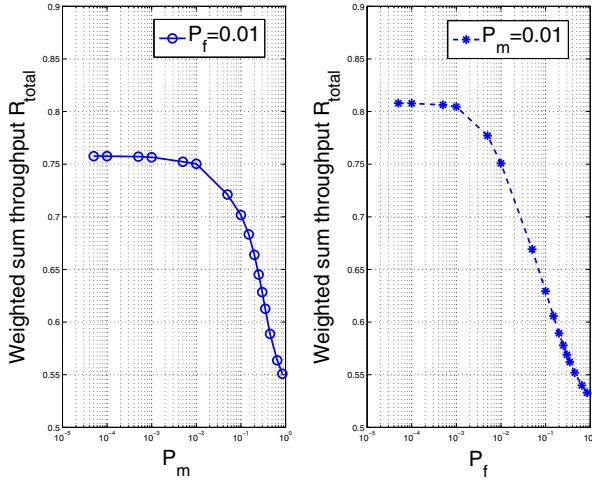


Fig. 5. The weighted sum throughput R_{total} of the proposed approach as a function of p_f with $p_m = 0.01$, and as a function of p_m with $p_f = 0.01$ in a network with $\alpha_s = \alpha_t = 0.5$ and $\lambda_s = 1$.

maximal buffer size K_{max} decreases with the SL traffic, such that the delay constraint in (1c) is satisfied. The weighted sum throughput R_{total} , or equivalently, the weighted SL throughput $\alpha_s R_s$ increases with λ_s by taking multiple steps corresponding to different buffer size K , as shown in Fig. 5 with $\lambda_s > 2.1$.

In Fig. 5, the weighted sum throughput R_{total} of the proposed approach is shown as a function of the false alarm probability p_f and the miss detection probability p_m , respectively, where the weight factor is given by $\alpha_s = \alpha_t = 0.5$ and the SL traffic is given by $\lambda_s = 1$. We see that R_{total} decreases dramatically with both p_f and p_m , and the false alarm probability p_f has a greater influence on R_{total} , compared to the miss detection probability p_m .