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A HYBRID UNDERLAY/OVERLAY SPECTRUM ALLOCATION STRATEGY IN COGNITIVE RADIO NETWORKS: MULTI-CHANNEL BASED PERFORMANCE OPTIMIZATION

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Abstract. *In cognitive radio networks (CRNs), it is important to achieve more effective utilization of existing spectrum without interfering with the primary users (PUs). In this article, in order to decrease the interference rate of PUs and the average delay of secondary user (SU) packets, we propose a hybrid underlay/overlay spectrum allocation strategy. If there is an idle channel, the SU packets will be transmitted in an overlay mode; otherwise, an underlay mode will be employed. We establish a two-dimensional Markov chain by considering the channel switching procedure in a multi-channel scenario. Then we give some required performance measures. Moreover, we provide theoretical and simulation experiments to verify the effectiveness of the proposed strategy and the accuracy of the performance estimation. Finally, we present an optimal design for setting the number of the channels in a spectrum.*
Keywords: Cognitive radio networks, Underlay/overlay, Channel switch, Multi-channel

1. **Introduction.** With the rapid development of wireless service, the radio spectrum is becoming a valuable and scarce resource. Cognitive radio (CR) is a promising technique to improve the spectrum utilization [1]. In CR, there are two kinds of users, primary users (PUs) and secondary users (SUs). PUs have pre-emptive priority to occupy the licensed spectrum, and SUs are allowed to opportunistically exploit the spectrum that is authorized to the PUs [1, 2].

In cognitive radio networks (CRNs) based on CR technology, there exist two spectrum-sharing technologies called overlay mode and underlay mode [3]. In an overlay mode, SUs opportunistically take up the channel when the channel is not used by PUs. In an underlay mode, SUs are allowed to share the channel simultaneously with PUs. However, in order to constrain the interference with PUs, the transmission power of SUs must be lower in an underlay mode than that in an overlay mode [4].

In [5], Masri proposed simple but effective modifications to the overlaid transmission technique in CRNs. They proved the technique can improve the system performances for both primary and secondary networks. In [6], an embedded Markov chain approach was adopted to illustrate the impact of system parameters on the underlaid CRNs. Nevertheless, just one single mode, overlay mode or underlay mode, was considered in the above literature.

Nowadays, some researches have been focused on the hybrid underlay/overlay structure. Zhao et al. considered a hybrid underlay/overlay spectrum sharing strategy. By building a discrete-time Markov chain, they gave the transition probability matrix of the system and derived the average delay of SUs [7]. Do et al. used an M/M/1 queueing model with heterogeneous arrivals and service to capture a hybrid underlay/overlay CRN. Numerical results demonstrated the accuracy of the derived expressions [8]. Unfortunately, in the hybrid underlay/overlay strategy mentioned above, single channel scenario was assumed for analysis simplicity.

In this article, by combining the merits for both the overlay and underlay mode, we propose a novel hybrid underlay/overlay strategy. By considering a multi-channel scenario, we establish a discrete-time Markov chain with channel switching procedure to capture the stochastic behavior of the proposed strategy. Moreover, we verify the effectiveness of the hybrid underlay/overlay strategy mathematically and numerically.

The remainder of this paper is organized as follows. A hybrid underlay/overlay strategy is proposed in Section 2. The two-dimensional Markov chain and the transition probability matrix are established in Section 3. In Section 4, we provide numerical experiment to estimate the system performance. We establish a system benefit function and optimize the number of channels in a spectrum in Section 5. Section 6 concludes the whole paper.

2. A Hybrid Underlay/Overlay Strategy and System Model.

2.1. A hybrid underlay/overlay strategy. For the purpose of improving the spectrum utilization without interfering with the transmission of PU packets, we propose a novel hybrid underlay/overlay strategy. We consider one spectrum composed of M channels, and each SU packet or PU packet is allowed to occupy one channel at a time.

PU packets are transmitted with pre-emptive priority. If all the channels are occupied by PU packets, a newly arriving PU packet will be blocked and depart from the system. That is to say, no buffer is prepared for PU packets. The transmission of PU packets is independent of the hybrid underlay/overlay strategy.

A newly arriving SU packet will firstly queue at the end of the system buffer. If there is at least one idle channel not being occupied by any packets, the SU packets queueing in the buffer will occupy the idle channels with a higher transmission power, i.e., the overlay mode is the first choice. Only if there is no idle channel in the system, the SU packets will occupy the channels being used by PU packets with a lower transmission power, i.e., the underlay mode is a secondary option.

When an SU packet is being transmitted in an overlay mode with a higher transmission power, if a newly arriving PU packet appears at the same channel, the transmission of the SU packet will be continued in the original channel with a lower transmission power rather than being interrupted, i.e, an overlay mode will be switched to an underlay mode. Otherwise, the SU packet will always be transmitted in an overlay mode. When an SU packet is being transmitted in an underlay mode with a lower transmission power, when there is an idle channel in the system, the SU packet will switch to the idle channel and continue its transmission with a higher transmission power. If the PU packet being transmitted in the same channel leaves the system and no newly arriving PU packet appears at the channel, the transmission of the SU packet will be continued in the original channel with a higher transmission power. That is to say, an underlay mode will be switched to an overlay mode. Otherwise, the transmission of the SU packet will always be transmitted in an underlay mode. Therefore, with the proposed hybrid underlay/overlay strategy, at most M SU packets and M PU packets can be transmitted simultaneously in the spectrum; in addition, the transmission interruption of SU packets is eliminated.

2.2. System model. According to the slotted timing structure, we assume the arrivals of SU and PU packets follow Bernoulli processes with parameters λ_{su} $(0 < \lambda_{su} < 1,\ \bar{\lambda}_{su} = 1-\lambda_{su})$ and λ_{pu} $(0 < \lambda_{pu} < 1,\ \bar{\lambda}_{pu} = 1-\lambda_{pu})$, respectively. We assume the transmission time of an SU packet follows geometric distribution with parameters μ_l $(0 < \mu_l < 1,\ \bar{\mu}_l = 1-\mu_l)$ in an underlay mode, and μ_h $(0 < \mu_h < 1,\ \bar{\mu}_h = 1-\mu_h)$ in an overlay mode, respectively.

We assume the transmission time of a PU packet follows geometric distribution with parameter μ_{pu} $(0 < \mu_{pu} < 1,\ \bar{\mu}_{pu} = 1 - \mu_{pu})$.

We define the total number of SU packets in the system as the system level, and the number of PU packets in the system as the system phase. Let X_n be the system level at the instant n^+, Y_n be the system phase at the instant n^+. $\{X_n,\ Y_n\}$ constitutes a two-dimensional Markov chain. The state space of the Markov chain is given as follows:

$$\boldsymbol{\Omega} = \{(x, y) :\ x \geq 0,\ 0 \leq y \leq M\}.$$

Let $\pi_{x,y}$ be the stationary probability distribution for the two-dimensional Markov chain $\{X_n,\ Y_n\}$. $\pi_{x,y}$ is given as follows:

$$\pi_{x,y} = \lim_{n \to \infty} P\{X_n = x, Y_n = y\},\ x \geq 0,\ 0 \leq y \leq M.$$

3. **Model Analysis.** We define $\boldsymbol{B}_{uv}$ as the one step transition probability submatrix from the system level u to v, the element $B_{uv}\{i,\ j\}$ of $\boldsymbol{B}_{uv}$ as the one step transition probability when the system level changing to v from u and the system phase changing to j from i. $B_{uv}\{i,\ j\}$ is given as follows:

$$B_{uv}\{i,\ j\} = a_{ij} b_{uv}$$

where a_{ij} represents the one step transition probability from the system phase i to j, and b_{uv} represents the one step transition probability from the system level u to v.

We note that the transmission of a PU packet has nothing to do with the behavior of SU packets or the hybrid underlay/overlay strategy proposed in this paper. With a straightforward method, the one step transition probability a_{ij} of the system phase can be given as follows:

$$a_{ij} = \begin{cases} \bar{\lambda}_{pu} \mu_{pu}^{i} & j = 0,\ 0 \leq i \leq M \\ \lambda_{pu} \binom{i}{j-1} \mu_{pu}^{i+1-j} \bar{\mu}_{pu}^{j-1} + \bar{\lambda}_{pu} \binom{i}{j} \mu_{pu}^{i-j} \bar{\mu}_{pu}^{j} & 1 \leq j \leq \min\{i, M-1\},\ 1 \leq i \leq M \\ \lambda_{pu} \mu_{pu} \bar{\mu}_{pu}^{M-1} + \bar{\mu}_{pu}^{M} & i = j = M \\ \lambda_{pu} \bar{\mu}_{pu}^{i} & j = i + 1,\ 0 \leq i \leq M \\ 0 & \text{others.} \end{cases}$$

Considering whether there is a newly arriving SU packet or not, we discuss the one step transition probability b_{uv} of the system level. In order to clarify the description of the proposed hybrid underlay/overlay strategy, we call the system state before one step transition as the original state, and the system state after one step transition as the destine state. We define p as the number of SU packets being transmitted with a higher transmission rate μ_h at the original state, and q as the number of SU packets being transmitted with a lower transmission rate μ_l at the original state.

Let F_{uv} be the one step transition probability when there is no newly arriving SU packet. For this case, the original system level u and the destine system level v satisfy $0 \leq v \leq u \leq M$.

Given that $0 \leq u \leq M$ and $v = 0$, i.e., all the SU packets, if any, leave the system. If the original system phase i satisfies $0 \leq i \leq M - u$, all the SU packets being transmitted with a higher transmission rate leave the system with probability μ_h^p. If the original system phase i satisfies $M - u + 1 \leq i \leq M$, all the SU packets, including p SU packets being transmitted with a higher transmission rate and q SU packets being transmitted with a lower transmission rate, leave the system with probability $\mu_h^p \mu_l^q$.

Given that $1 \leq u \leq M$ and $1 \leq v \leq u$, if the original system phase i satisfies $0 \leq i \leq M - u$, all the SU packets will be transmitted with a higher transmission rate. If the original system phase i satisfies $M - u + 1 \leq i \leq M$, there are p SU packets being transmitted with a higher transmission rate and q SU packets being transmitted with a lower transmission rate. We denote a ($a = \min\{u - v,\ q\}$) and b ($b = \max\{0,\ u - v - q\}$) as the most and the least departure number of the SU packets being transmitted with a higher transmission rate, respectively. We denote k as the total departure number of SU packets being transmitted with a higher transmission rate, and c ($c = u - v - k$) as the total departure number of SU packets being transmitted with a lower transmission rate. Since we cannot determine which SU packets leave the system, we need to take account of all the possibilities when k changes to a from b.

F_{uv} is then given as follows:

$$F_{uv} = \begin{cases} \mu_h^p & 0 \le i \le M - u,\ 0 \le u \le M,\ v = 0 \\ \mu_h^p \mu_l^q & M - u + 1 \le i \le M,\ 0 \le u \le M,\ v = 0 \\ \binom{u}{v} \mu_h^{u-v} \bar{\mu}_h^v & 0 \le i \le M - u,\ 0 \le u \le M,\ v \le u,\ v \ge 1 \\ \sum_{k=b}^{a} \binom{p}{k} \mu_h^k \bar{\mu}_h^{p-k} \binom{q}{c} \mu_l^c \bar{\mu}_l^{q-c} & M - u + 1 \le i \le M,\ 0 \le u \le M,\ v \le u,\ v \ge 1. \end{cases}$$

Let S_{uv} be the one step transition probability when there is a newly arriving SU packet. For this case, the original system level u satisfies $0 \le u \le M$, and the destine system level v satisfies $1 \le v \le u + 1$. The derivation of S_{uv} is similar to that of F_{uv}. S_{uv} is given by

$$S_{uv} = \begin{cases} \bar{\mu}_h^p & 0 \le i \le M - u,\ 0 \le u \le M,\ v = u + 1 \\ \bar{\mu}_h^p \bar{\mu}_l^q & M - u + 1 \le i \le M,\ 0 \le u \le M,\ v = u + 1 \\ \binom{u}{v-1} \mu_h^{u-v+1} \bar{\mu}_h^{v-1} & 0 \le i \le M - u,\ 0 \le u \le M,\ v \le u,\ v \ge 1 \\ F_{u,v-1} & M - u + 1 \le i \le M,\ 0 \le u \le M,\ v \le u,\ v \ge 2 \\ F_{u,1} & M - u + 1 \le i \le M,\ 0 \le u \le M,\ v = 1. \end{cases}$$

The one step transition probability b_{uv} of the system level can be summarized as follows:

$$b_{uv} = \lambda_{su} S_{uv} + \bar{\lambda}_{su} F_{uv}.$$

Up to now, all the probabilities for possible transitions in the Markov chain are addressed. We note that the sub-matrix $\boldsymbol{B}_{uv}$ begins to be repeated in the one step transition matrix $\boldsymbol{P}$ when the original system level $u \ge M$. By employing the matrix-geometric solution method, we can get the steady-state distribution $\pi_{x,y}$ with numerical experiments.

4. Performance Measures and Experiment Illustrations.

4.1. Performance measures.

The channel utility δ is defined as the ratio for the number of channels being occupied to the total number M of channels in a spectrum. δ is then given as follows:

$$\delta = \sum_{y=0}^{M} \pi_{0,y} \frac{y}{M} + \sum_{x=1}^{M} \left(\sum_{y=0}^{M-x} \pi_{x,y} \frac{x+y}{M} + \sum_{y=M-x+1}^{M} \pi_{x,y} \right) + \sum_{x=M+1}^{\infty} \sum_{y=0}^{M} \pi_{x,y}.$$

Delay of an SU packet is defined as the time duration from the arrival instant of an SU packet to its departure instant. With Little's formula, the average delay γ_{su} of SU packets is given as follows:

$$\gamma_{su} = \frac{1}{\lambda_{su}} \sum_{x=1}^{\infty} x \sum_{y=0}^{M} \pi_{x,y}.$$

The normal throughput ξ_{pu} of PU packets is defined as the average number of PU packets transmitted successfully per slot. When all the channels are occupied by PU packets, the newly arriving PU packets will be blocked and leave the system. ξ_{pu} is then given as follows:

$$\xi_{pu} = \lambda_{pu} \left(1 - \sum_{x=0}^{\infty} \pi_{x,M} \bar{\mu}_{pu}^{M} \right).$$

4.2. **Experiment illustrations.** In this section, we evaluate the influence of the system parameters on the system performance in the proposed hybrid underlay/overlay strategy with numerical experiments. We demonstrate the change of the system performances such as the channel utility δ, the average delay γ_{su} of SU packets and the normal throughput ξ_{pu} of PU packets with analysis and simulation. By referencing the parameters used in [9], the common parameters in the numerical experiments are set as follows: $\mu_h = 0.40$, $\mu_l = 0.20$ and $\mu_{pu} = 0.70$.

Figure 1 illustrates the influence of channel number M in a spectrum upon the channel utility δ for different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

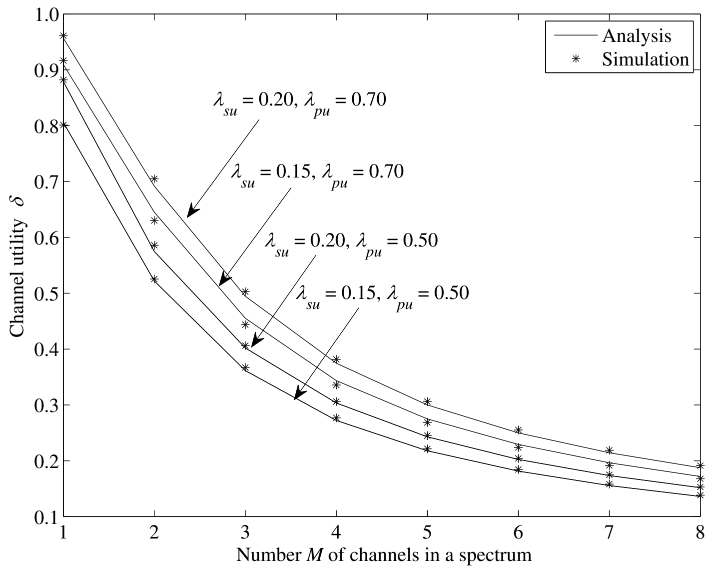

Figure 1. The channel utility

As shown in Figure 1, for the same arrival rates of SU packets and PU packets, the channel utility δ will decrease as the number of channels in a spectrum increases. This is because the bigger the number of channels in a spectrum is, the bigger the probability for the channel to be idle. For the same number of channels in a spectrum, if the arrival rate of SU packets (resp. PU packets) is given, the channel utility δ will increase with the increase in the arrival rate of SU packets (resp. PU packets). This is because with the increase in the arrival rate of SU packets (resp. PU packets), the channels are more possible to be occupied by SU packets (resp. PU packets), and that improves the channel utility.

The influence of the number M of channels in a spectrum upon the average delay γ_{su} of SU packets for different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets is shown in Figure 2.

From Figure 2, we note that for the same arrival rates of SU and PU packets, the average delay of SU packets will decrease with the enlargement for the number of channels in a spectrum. The reason is that the larger the number of channels in a spectrum is, the less the number of SU packets queueing in the buffer or being transmitted with a lower transmission rate will be. For the same number of channels in a spectrum and the same arrival rate of SU packets, the average delay of SU packets will increase with the increase

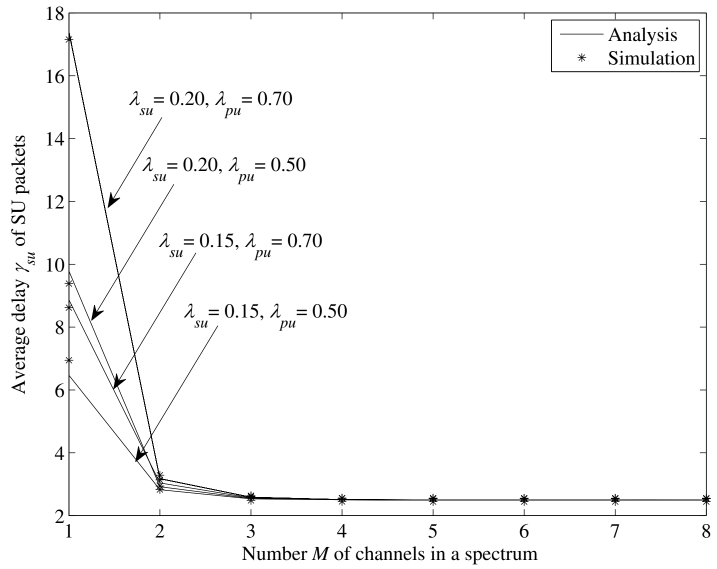

FIGURE 2. The average delay of SU packets

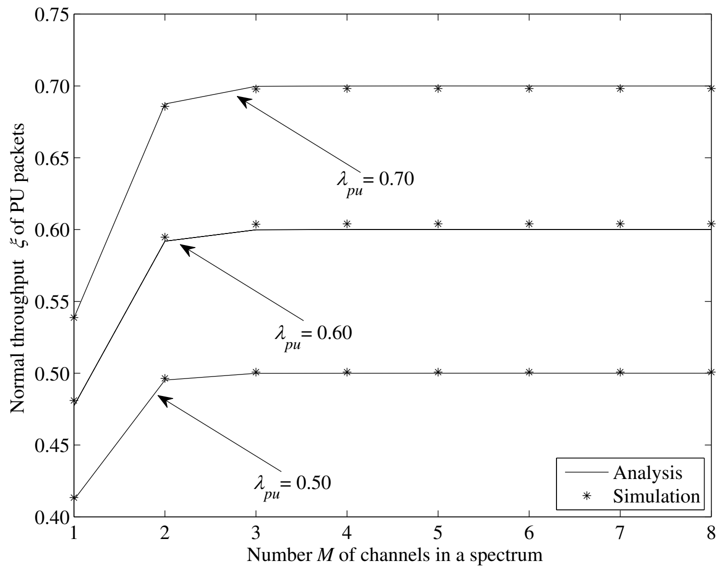

FIGURE 3. The normal throughput of PU packets

in the arrival rate of PU packets. This is because a greater arrival rate of PU packets will make more SU packets queue in the buffer or to be transmitted with a lower transmission. For the same number of channels in a spectrum and the same arrival rate of PU packets, the average delay of SU packets will increase with the increase in the arrival rate of SU packets. This is because the bigger the arrival rate of SU packets is, the more the SU packets will queue in the buffer, the longer the SU packets will wait in the buffer. So the average delay of SU packets will be greater.

The influence of the number M of channels in a spectrum upon the normal throughput of PU packets for different arrival rates λ_{pu} of PU packets is shown in Figure 3.

As can be seen in Figure 3, when the number of channels in a spectrum is fixed, the normal throughput of PU packets will increase with the increase in the arrival rate of PU packets. When the arrival rate of PU packets is fixed, the bigger the number of channels in a spectrum is, the greater the normal throughput of PU packets will be. With the enlargement for the number of channels in a spectrum, PU packets have more opportunities to occupy the channels at the same time, more PU packets will be transmitted successfully.

From the above experimented results, we find that the number of channels in a spectrum, the arrival rates of SU packets and of PU packets have a deep influence on the system performance. Moreover, we find that with the increase for the number of channels in a spectrum, the average delay of SU packets decreases and the normal throughput of PU packets increases. That is to say, there is a tradeoff when setting the number of channels in a spectrum.

5. **Performance Optimization.** In this section, in order to trade off different performance measures, we establish a system benefit function R as follows:

$$R = r_1\xi_{pu} - r_2\gamma_{su} + r_3\delta - r_4 M.$$

where r_1 is the reward for transmitting a PU packet successfully, r_2, r_3, r_4 are the costs per slot due to the delay of an SU packet, the benefit for the channel utility reaching to 1, and the expenditure for the network manager to provide one channel, respectively.

In numerical results of the system benefit, we set the system parameters as follows: $r_1 = 0.60$, $r_2 = 1$, $r_3 = 0.01$, $r_4 = 1$, $\mu_h = 0.40$, $\mu_l = 0.20$ and $\mu_{pu} = 0.70$.

Figure 4 shows the variation of the system benefit function R with the number M of channels in a spectrum for different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

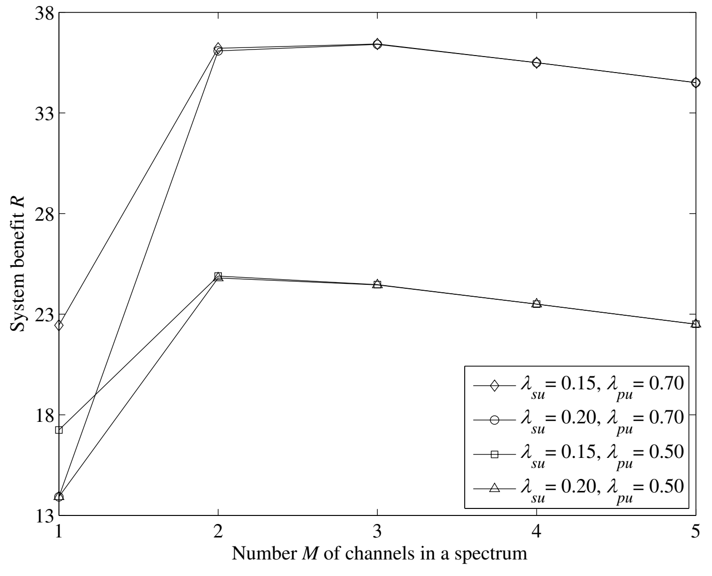

Figure 4. The system benefit function

From Figure 4, we note that for different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets, the system benefit function R will increase firstly and then decrease with the enlargement of the number of channels in a spectrum. During the ascent stage, the main factors influencing the system benefit are the normal throughput of PU packets and the average delay of SU packets. The greater the number of channels in a spectrum is, the higher the normal throughput of PU packets and the less the average delay of SU packets are, so the greater the system benefit will be. During the descent stage, the main factors influencing the system benefit are the channel utility and the expenditure for the network management. The greater the number of channels in a spectrum is, the higher the expenditure for the network management and the less the channel utility is, so the system benefit will decrease.

Table 1. Optimal number M^* of channels in a spectrum and the maximum system benefit R^*

Arrival rate λ_{su} of SU packets	Arrival rate λ_{pu} of PU packets	Optimal number M^* of channels in a spectrum	Maximum system benefit R^*
0.15	0.70	3	36.4245
0.20	0.70	3	36.4044
0.15	0.50	2	24.8938
0.20	0.50	2	24.7993

It is obvious that there is a maximum system benefit when the number of channels in a spectrum is set to an optimal value. Table 1 shows the optimal number M^* of channels in a spectrum and the maximum system benefit R^* with different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

6. **Conclusions.** In this paper, making comprehensive use of the merits for underlay and overlay mode, we proposed a hybrid underlay/overlay spectrum allocation strategy. Considering the channel switching, we presented the transition probability matrix by establishing a two-dimensional Markov chain in a multi-channel scenario. We derived the formulas for some important measures to evaluate the system performance mathematically. Moreover, we provided experiments to demonstrate the change trend of the utility of channels, the average delay of SU packets, and the normal throughput of PU packets. Finally, by constructing a benefit function, we optimized the number of channels in a spectrum. In the future research, we will analyze the hybrid strategy by considering the imperfect channel sensing.

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