Multi-user ALE for Future HF Radio Communication by Leveraging Wideband Spectrum Sensing and Channel Prediction

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Abstract. HF cognitive radio is considered to be one direction of fourth generation HF radios. In this paper, we investigate the problem of multi-user HF radio communication by leveraging the techniques of cognitive radio. In the presented system model, we consider the determination of optimal path between two points and propose a channel probing method based on coarse granularity wideband spectrum sensing as well as channel prediction. To cope with the problem of channel selection and link establishment, we adjust the channel selection strategy after every probing based on Stochastic Learning Automata (SLA) learning algorithm. The experimental results show that the channel selection based on SLA learning algorithm is better than random channel selection, and channel selection with predicted wideband spectrum sensing performs better in system performances than no-predicted narrowband spectrum sensing.

Keywords: HF radio communication · Multi-user · Channel probing · Channel selection strategy · SLA learning algorithm

1 Introduction

In the past 20 years, the telecommunication explosion has created an ever-expanding wireless communication applications and products, as well as spectrum congestion. With the burgeoning demand for communication services and capacity, more stringent requirements on the flexibility and adaptability are put forward on wireless communication equipment under the limited spectrum resources [1]. The High Frequency (HF) radio communication has been the earliest solution for wireless communication with the characteristics of long-distance transmission and wide coverage [2]. Limited by narrowband and unstable channel conditions, the development of HF communication has been restricted for a long time [3].

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Cognitive Radios (CR) have the potential to radically improve the performances, efficiency, and reliability of wireless networks and enable new applications such as dynamic spectrum access (DSA) to be developed [4]. In the past years, most of the researches in CR have been given to the frequency band above 30 MHz. Given the challenges in HF communication, scientists are taking the research of HF cognitive radios which can detect the frequency occupancy quickly [5]. Therefore, the goal of fourth generation HF communication system aims at selecting the optimal frequency adaptively and adjusting the waveform bandwidth automatically to realize fast Automatic Link Establishment (ALE) as well as high speed data transmission.

In order to extend functions in next generation HF radios, it's taking the exploration of adding some new elements to the ALE module such as propagation modeling, wideband spectrum sensing, available channel prediction. For example, the work in [6] use the ITS HF Propagation, an international mainstream HF link propagation model, to simulate the transmission path and power loss between two points. Shahid et al. [7] propose listen before transmit (LBT) in ALE based on cognitive radio sensing techniques to obtain ALE channels effectively. Haris et al. [8] introduce the Neural Network model to predict the likelihood of interference experienced by broadcast users and find the regularity in some channels.

This paper is a significant extension of previous works on HF channel selection of multi-transmitter to multi-receiver. The main contributions of this paper are summarized as follows.

– Present a HF wireless network model containing multiuser, and considering the determination of optimal path between transceiver.
– Propose a multi-user channel probing method combined coarse granularity wideband spectrum sensing and channel prediction.
– Develop a channel selection strategy based on SLA learning algorithm, and find the optimal channel for link establishment by the proposed strategy.

The reminder of the paper is organized as follows. The system model is presented in Sect. 2. In Sect. 3, a new channel probing method is proposed. In Sect. 4, we develop the channel selection strategy based on SLA learning algorithm. In Sect. 5, simulation results and discussion are presented, and we draw conclusions about this paper in Sect. 6.

2 System Model and Path Design

The system model is shown in Fig. 1, we consider the HF radio network consisting of N transmitting stations and n receiving stations ($n > N$). Assuming there is no coordinator in the network to enable interactions among radios, and the radio stations take the asynchronous ALE to realize point-to-point communication. The channel quality is entirely unknown at the beginning, and the transmitting station cannot initiate channel probing until know the station number of receiver.

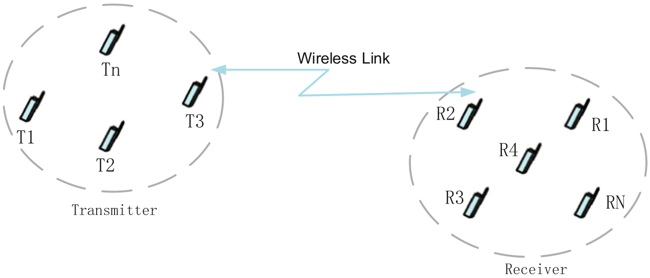


Fig. 1. System model.

ITS HF Propagation is a long-term frequency prediction software developed by National Telecommunications Bureau of the United State, the software can simulate transmission paths in ionosphere [9]. ICEPAC is one of the modules in the software usually used to predict the Maximum Usable Frequency (MUF), Circuit Reliability (REL), and Signal to Nosie Ratio (SNR) between two points [10]. To determine the path of transceiver station, we could analyze qualities of all possible links between two points to select the best path by ICEPAC. Details are described as follows.

Let φ define the set of $N \times n$ possible paths in the system model. We start by setting the system parameters including stations' locations, signal transmitting power, sunspot numbers, and a set of reference frequencies $I = \{f_1 \ \ f_2 \dots \ f_i\}$. The MUF of each path as well as the SNR and REL of each reference frequency in the path can be obtained by simulation. Define the quality indicator of path h as:

$$\lambda_h = \omega_1 \times MUF_h + \omega_2 \times \overline{SNR}_{h(REL>0.9)}, \quad \forall h \in \varphi \tag{1}$$

where $\overline{SNR}_{h(REL>0.9)}$ represents the average SNR of all frequencies with REL over 90% in I, ω_1 and ω_2 is the corresponding weight ($\omega_1 > \omega_2$). We sort all paths by the values of λ and pick N paths with good indicators. Therefore, we identify N users in the HF radio network and each user contains a pair of transceiver. After assigning the transceiver station, we could start probing channel.

3 Channel Probing of Multi-user

The refraction of electromagnetic waves by the ionosphere causes the frequency-selective in HF, thus the range of usable frequencies varies with time, season, space, weather and other factors [11]. One of the solution is to find the available frequency supporting ALE through channel probing. Figure 2 shows the channel probing process in the standard of MIL-STD-188-141A [12], the transmitter sends a probing signal at each frequency to update the scores in the LQA matrix then selects an optimal frequency to call for link establishment. However, there is no coordination in the network, when optimal frequency probed is same for multiple users, signal collision would occur in the process of ALE. Moreover,

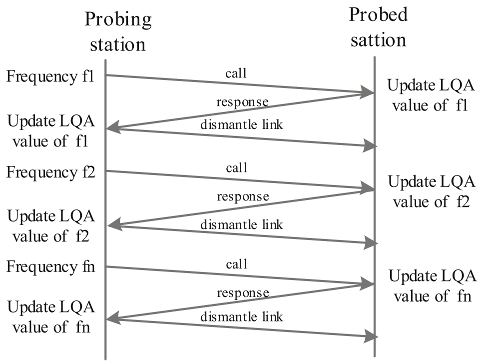


Fig. 2. Channel probing process in 2G-ALE.

the time spent on call and response of every frequency reduces the network throughput. To solve this problem, a new channel probing method of multiuser is proposed.

The method is based on coarse granularity wideband spectrum sensing and channel prediction. The narrowband spectrum sensing is opposite to wideband spectrum sensing using high spectral resolution to detect spectrum holes precisely at the cost of time delay, whereas the coarse granularity wideband spectrum sensing can find frequency band of low occupancy more quickly by reducing the sampling rate. Considering the time variability of HF, we can capture the trend in the variability of occupancy based on long-term wideband spectrum sensing results to predict relatively stable and idle channels at the time of link establishment. For example, we find the occupancy of certain frequency bands have 24-hour periodicity by weeks of spectrum sensing, which can predict the lowest occupancy bands when ALE. Moreover, combined the simulated MUF and predicted bands, we could determine the selectable channel set. The process of channel probing is shown in Fig. 3.

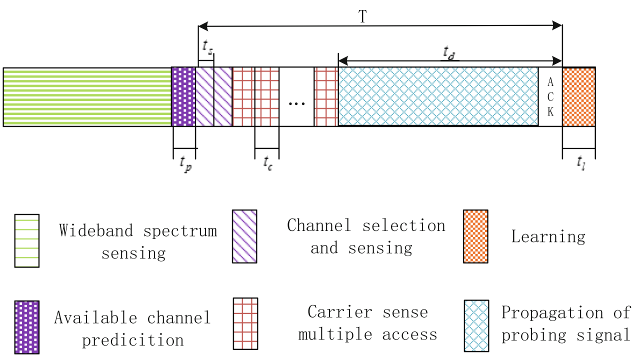


Fig. 3. Channel probing of multiuser.

Users have been in coarse granularity wideband spectrum sensing until ready to start establishing links. When preparing for ALE, the selectable channel set M_n of user n ($n \in N$) is determined by sensed low occupancy band and predicted channels. Define the time slot of probing one channel as T, the transmitting station chooses one channel in M_n at the beginning, if chose channel sensed occupied, reselects until finding an idle one. There is a carrier sense multiple access (CSMA) mechanism before probing, if more than two users select same free channel and send frames at same time, collision would occur, in that case, trying to compete again after the time of t_c until one user accessing the selected channel successfully. Suppose the propagation of probing signal requires a minimum time $t_{\min}$, once the signal is successfully transmitted, the receiver would send back an ACK to the transmitter, otherwise failure if ACK haven't received exceeding the time of $t_{\max}$. At the end of each slot, every user will receive a payoff, and then apply a learning algorithm to update the channel selection strategy next slot.

For the convenience of analysis, it is assumed that spectrum sensing and channel prediction are perfect. The precondition of receiving ACK is $t_{\min} < t_d < t_{\max}$, and the channel probing time of user n is expressed as:

$$t_d^n = T - \alpha_n t_s - \beta_n t_c \tag{2}$$

where α_n and β_n respectively represent the number of sensed channels before finding an idle one and the number of competitions during the conflict.

We know from Fig. 3 that longer time spent on sensing and competition, shorter time for user's probing. However, in asynchronous mode, the receiver scans frequencies at a rate that allows the dwell on each frequency to be long enough to detect a signal [13], therefore more time on t_d^n is better.

4 Channel Selection and ALE

At present, there are many learning algorithms used for channel selection, such as no-regret learning algorithm [14], logarithmic linear learning algorithm [15], and spatial adaptive algorithm [16]. But these algorithms require coordination mechanism which is not feasible in the considered multiuser HF radio network. In this section, we develop a channel selection strategy based on SLA learning algorithm and illustrate how to establish link by the strategy.

Stochastic learning automata (SLA) based channel selection algorithm can adjust current channel selection strategy on the basis of historical action rewards [17], usually used in non-cooperative opportunity spectrum access of dynamic environment. Denote the reward value of user n in slot j as:

$$r_n(j) = \frac{S_{ACK}}{N \log_{T-t_{\min}}^{(\alpha_n t_s + \beta_n t_c)}} \gamma_n ACK \tag{3}$$

where S_{ACK} represents received power of ACK, N is the local noise, γ_n indicates whether n successfully contends the selected channel or not, and ACK indicates whether the probed channel is idle or occupied in propagation.

Algorithm 1. SLA based channel selection algorithm

1: **Initialize:** Set $j = 0$ and initial channel selection probability vector $p_{nm}(j) = 1/M, \forall n \in N,\ m \in M$.
2: At the beginning of the jth slot, each user n selects a channel m according to its current channel selection probability vector $p_n(j)$.
3: In each slot, users perform channel probing. At the end of jth slot, each user n receives the reward $r_n(j)$ specified by (3).
4: All users update their channel slection probability vectors according to the following rule:

$$\begin{aligned} p_{nm}(j+1) &= p_{nm}(j) + b\tilde{r}_n(j)(1 - p_{nm}(j)), \quad m \in M \\ p_{nl}(j+1) &= p_{nl}(j) - b\tilde{r}_n(j)p_{nl}(j), \quad l \in M \,\&l \neq m \end{aligned} \tag{4}$$

5: where $0 < b < 1$, $\tilde{r}_n(j)$ is the normalized reward defined as follows:

$$\tilde{r}_n(j) = r_n(j)/R_{\max} \tag{5}$$

6: If $\forall n \in N$, there exists a component of $p_n(j)$ which is approaching one, stop; Otherwise, go to step 2).

For users, the probability of selecting every channel is same at first slot, if user n selects channel m ($m \in M$) randomly and gets the $r_n(j)$ after probing, then the probability of selecting m next slot is updated as:

$$p_{nm}(j+1) = p_{nm}(j) + br_n(j)(1 - p_{nm}(j)) \tag{6}$$

and the probabilities of selecting other channels l ($l \in M \,\&\, l \neq m$) are updated as:

$$p_{nl}(j+1) = p_{nl}(j) - br_n(j)p_{nl}(j) \tag{7}$$

where b represents the iteration step. The detail of SLA learning algorithm is shown in Algorithm 1 [15].

At the end of each slot, every user would apply the SLA learning algorithm to update all channels' selection probabilities. After learning for many time slots, the probabilities eventually converged to nearly one or zero. The optimal channel corresponds to the probability approaching one, then the user can start calling and responding of asynchronous ALE in the optimal channel.

We assume the spectrum environment is stable in T_{sta} that the transmission rate of every channel remains constant. Define $T_{\cos}^n$ as the time from getting out of the wideband spectrum sensing to establish the link successfully, which is called ALE preparation time. So the system throughput is given by:

$$\begin{aligned} U &= \sum_{n=1}^{N} \{(T_{sta} - T_{\cos}^n) \times R_n\} \\ T_{\cos}^n &= jT + T_{shake} \end{aligned} \tag{8}$$

where j is the number of time slots before reaching the convergence, T_{shake} is the time of "three-way handshake", R_n is the transmission rate of the probed channel by user n.

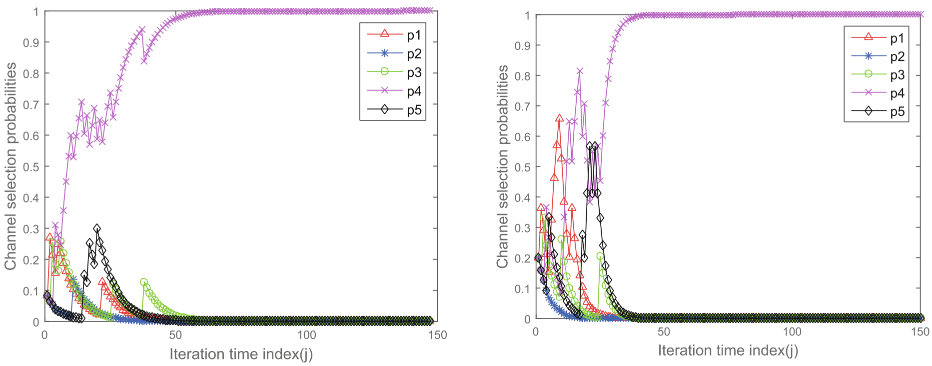
In contrast to 2G-ALE, the proposed ALE is carried out through the convergence of channel selection probability. The convergent speed of each user is different, the user with fast convergence can start link establishment firstly, decreasing the collision between users.

5 Simulation Results and Discussion

In the simulation, we set $T = 100$ ms, the time for narrowband spectrum sensing is $t_s = 5$ ms, and the waiting time when conflicts occur is $t_c = 5$ ms. Besides, $T_{sta} = 30$ s, $t_{\min} = 20$ ms, $t_{\max} = 80$ ms, $T_{shanke} = 780$ ms, and $b = 0.15$. In [18], the signal is detected as long as SNR reach at least 6 dB. We set the SNR of channels range from 6 dB to 10 dB, so every channel has different transmission rate. Moreover, the number of users $N = 8$, the total number of channels $F = 12$, and the number of available channels $S = 5$.

5.1 Algorithm Convergence Analysis

To show the evolution of channel selection probability of the SLA learning algorithm, Fig. 4 compare two channel selection methods based on SLA algorithm. The traditional SLA method refers to selecting channels one by one through narrowband spectrum sensing and having no prediction of available frequency band before probing, whereas the proposed SLA method is expressed in this paper, which reduces the selectable channels through wideband spectrum sensing and channel prediction.



(a) Tradional SLA method. (b)Proposed SLA method

Fig. 4. Evolution of the channel selection probability of arbitrary user.

The different lines in Fig. 4 represent the selection probability of arbitrary user on the available channels. It's seen that, the user finally chooses channel 4 for link establishment, which proves the convergent SLA algorithm is applicable to the system model. Meanwhile, the proposed SLA method has fewer iterations and faster convergence speed than traditional SLA method, because the method with no-predicted narrowband spectrum sensing costs more time in channel sensing and selecting.

5.2 System Performance Analysis

To analyze the impacts on system performances, the simulation scenario is in the same spectrum environment and each channel can only be accessed by one user.

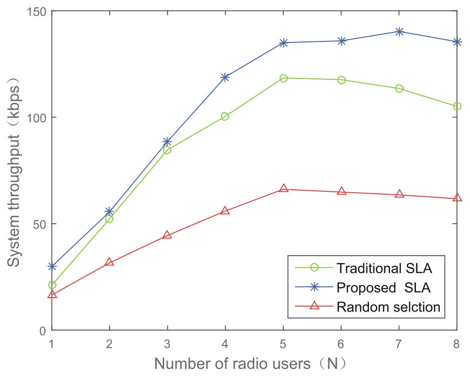


Fig. 5. System throughput with different number of users.

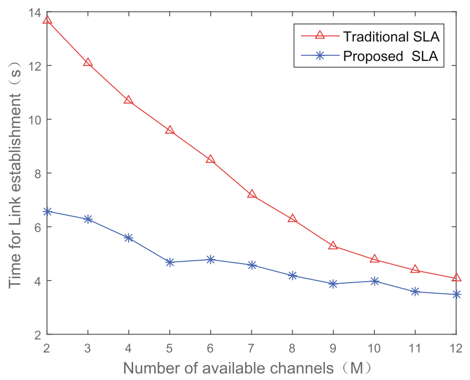


Fig. 6. Link establishment time with different available channels.

Figure 5 compare the system throughput of random channel selection, traditional SLA channel selection, proposed SLA channel selection with different number of users. We observe that, random channel selection would cause channels with low transmission rates selected by multiusers simultaneously, so performs worst in the throughput. In SLA learning algorithm, users tend to select channels with higher transmission rates, especially the proposed SLA channel selection method, faster convergence speed leaves more time for data transmission, thus the throughput is maximum. Besides, throughput increases with the number of users while $N < 5$, once the number of users exceed the number of available channels ($N > 5$) severe competition lead to slower convergence speed, which results in the throughput degradation.

A further comparison on link establishment time of two SLA channel selection method under different number of available channels is shown in Fig. 6. The results suggest the proposed SLA method is better while the available channels are few, and the differences between two methods become small as the number of available channels increase. As a result, channel selection with predicted wideband spectrum sensing performs better in system performances than no-predicted narrowband spectrum sensing.

6 Conclusion

In this paper, we propose a HF wireless network model containing multiuser, the optimal path between transceiver is determined by a long-term link propagation model in unknown channel statistics. Moreover, a new channel probing method for multiuser is presented which combines coarse granularity wideband spectrum sensing and channel prediction. To select optimal channel for ALE, we develop the channel selection strategy based on SLA algorithm. The simulation results prove that the channel selection based on SLA learning algorithm is better than random channel selection, and channel selection with predicted wideband spectrum sensing performs better in system performances than no-predicted narrowband spectrum sensing.

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References

1. Koski, E., Furman, W.N.: Applying cognitive radio concepts to HF communications. In: The Institution of Engineering and Technology, International Conference on Ionospheric Radio Systems and Techniques (IET), pp. 1–6 (2009)
2. Prouvez, R., Baynat, B., Khalife, H., Conan, V., Lamy-Bergot, C.: Modeling automatic link establishment in HF networks. In: Proceedings IEEE Military Communications Conference, Tampa, FL, pp. 1630–1635 (2015)

3. Jorgenson, M.B., Cook, N.T.: Results from a wideband HF usability study. In: Proceedings IEEE Military Communications Conference, Tampa, FL, pp. 1454–1459 (2015)
4. Shukla, A.K., Jackson-Booth, N.K., Arthur, N.K.: “Cognitive radios” and their relevance to HF radio systems. In: Proceedings 12th IET International Conference on Ionospheric Radio Systems and Techniques (IRST 2012), York, pp. 1–6 (2012)
5. Vanninen, T., Linden, T., Raustia, M., Saarnisaari, H.: Cognitive HF - new perspectives to use the high frequency band. In: Proceedings 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Oulu, pp. 108–113 (2014)
6. Zhao, J., Zhao, N.: An overview of the international HF transmission link simulation model and its application analysis. China Radio **1**, 47–49 (2017). (in Chinese)
7. Shahid, A., Ahmad, S., Akram, A., Khan, S.A.: Cognitive ALE for HF radios. In: Proceedings Second International Conference on Computer Engineering and Applications, Bali Island, pp. 28–33 (2010)
8. Haralambous, H., Papadopoulos, H.: 24-hour neural network congestion models for high-frequency broadcast users. IEEE Trans. Broadcast. **55**(1), 145–154 (2009)
9. Tian, X., Lu, J.: Shortwave propagation over oceans and HF propagation prediction model. In: Proceedings IEEE International Conference on Computational Intelligence and Software Engineering, pp. 1–4 (2009)
10. Shang, H., An, J., Lu, J.: HF ground-wave over rough sea-surface and HF propagation prediction model ICEPAC. In: Proceedings IEEE Global Mobile Congress, pp. 1–4 (2009)
11. Johnson, E.E.: Staring link establishment for high-frequency radio. In: Proceedings IEEE Military Communications Conference, Tampa, FL, pp. 1433–1438 (2015)
12. Wang, J.: Research and Development of HF Digital Communications, pp. 1–4. Science Press, Beijing (2009). (in Chinese)
13. Xu, Y., Wang, J., Wu, Q., Anpalagan, A., Yao, Y.D.: Opportunistic spectrum access in unknown dynamic environment: a game-theoretic stochastic learning solution. IEEE Trans. Wireless Commun. **11**(4), 1380–1391 (2012)
14. Hart, S., Mas-Colell, A.: A simple adaptive procedure leading to correlated equilibrium. Econometrica **68**(5), 1127–1150 (2000)
15. Xu, Y., Wu, Q.: Opportunistic spectrum access using partially overlapping channels: graphical game and uncoupled learning. IEEE Trans. Commun. **61**(9), 3906–3918 (2013)
16. Xu, Y., Wang, J., Wu, Q.: Opportunistic spectrum access in cognitive radio networks: global optimization using local interaction games. IEEE J. Sel. Top. Signal Process. **6**(2), 180–194 (2012)
17. Bilal, A., Sun, G.: Automatic link establishment for HF radios. In: Proceedings 8th IEEE International Conference on Software Engineering and Service Science (ICSESS), Beijing, pp. 640–643 (2017)
18. Zhang, Y., Xue, W., Luo, W.: A signal detection method based on auto-correlation for the listen-before-transmit. In: Proceedings 3rd International Conference on Computer Science and Network Technology, Dalian, pp. 858–862 (2013)