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Cooperative frequency competition model and the corresponding algorithms and protocols for improving the HF sky-wave electromagnetic environment

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REPORT ITU-R F.2484-0

Cooperative frequency competition model and the corresponding algorithms and protocols for improving the HF sky-wave electromagnetic environment

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Abbreviations/Glossary

2G-ALE Second-generation ALE

3G-ALE Third-generation ALE

ALE Automatic link establishment

ALOHA Additive links on-line Hawaii area

CAM Competition announcement message

CRM Competition reply message

DFS Dynamic frequency selection

ED External diseconomy

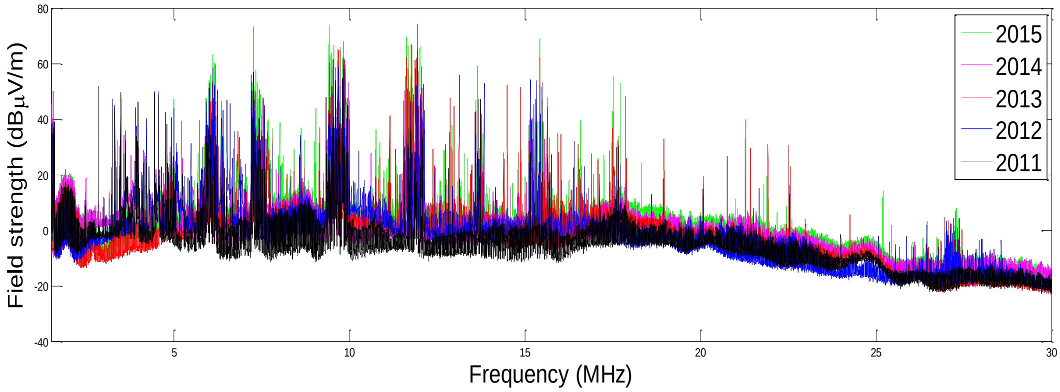
FOM	Frequency occupying message
HF	High frequency
IMT	International mobile telecommunications
TCP	Transmission control protocol

1 Introduction

As one of the first applied wireless systems, High Frequency (HF) radio systems have long been used for data transmission with many advantages such as flexibility, robustness and long transmission distance. Notable development has been achieved for HF radio systems over the last 100 years on frequency prediction, channel models, automatic link establishment (ALE) and hardware. Specifically, 4th generation ALE technologies are under development that will enable stations to select the channels and corresponding bandwidth adaptively, improving the robustness of the system and its ability to support various operational requirements. With increasing demand from users, HF communication technologies will develop towards the direction of intellectualization, broadband and integrated service. Under the service-based static frequency allocation framework of the current Radio Regulations, the power of the wanted and unwanted transmissions keeps rising to guarantee the performance of the HF radio systems. A vicious circle comes into being between the HF radio systems and the HF electromagnetic environment. The pollution of the HF electromagnetic environment deteriorates incessantly. A HF frequency spectrum record of each December between 2011 and 2015 measured at Hangzhou (Zhejiang province, China) HF Monitoring Station is shown in Fig. 1. It shows that the background noise increases every year, and the cumulative gain is about 5 dB following the criterion in Recommendation ITU-R SM.1753. Thus, the usability of the HF electromagnetic environment decreases, negatively impacting the performance of HF radio systems. Consequently, the actual link availability probability is low in many cases leading to the inability to support the increasing requirements from users for open channels of the links. The comparison of the noise factors of the 20th century and the first decade in this century at a representative rural district in south China is presented in Fig. 2. It can be observed that the noise factors of the first decade in this century increase remarkably in daytime compared with that of the same period of time in the 20th century, while no notable variation can be observed from the data of the night-time. For the disappearance of the E-level of the ionosphere, the absorbing of the noise decreases. As a result, the noise factors in the night-time are bigger than that in the daytime and the natural factor dominates the overall HF noise in the night-time. This indicates that the natural factor has not changed notably. On the other hand, the rising noise in the daytime, influenced by both natural factors and man-made factors, results mainly from man-made factors.

FIGURE 1

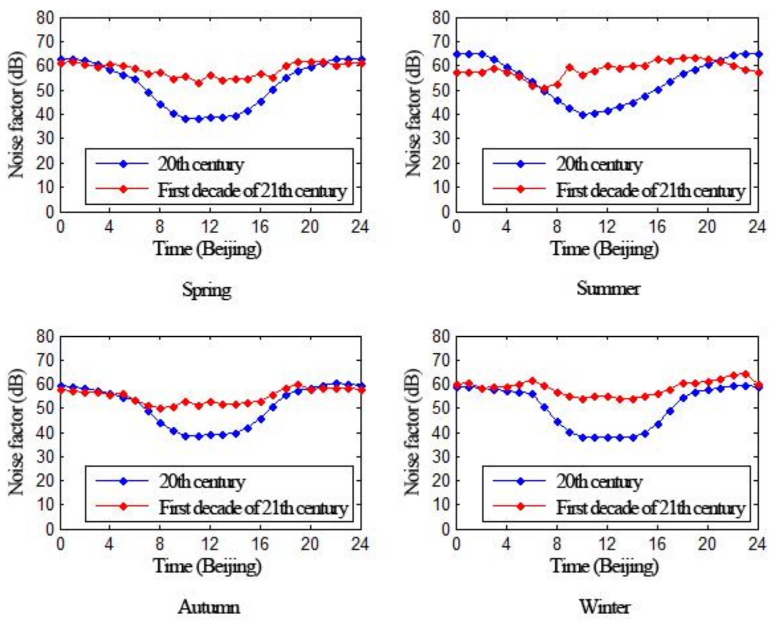
Spectrum record of HF band at country area of Hangzhou, China, between 2011 and 2015



Existing approaches to solve above problem include increasing the transmission power (within the authorized limit), cognitive radio, ALE, and transmitting and receiving with spatial division. The common feature of these technologies is that they all focus on the frequency and power adaptivity of a single system. While the performance of a system might be improved, the background noise is also increased and there is no contribution to the improvement of the HF electromagnetic environment. Furthermore, as the number of HF stations exceed the number of candidate usable licensed channels, these technologies cannot serve as the fundamental method for HF radio systems. On the other hand, the cooperation of intra-system and inter-systems has been rather popular in other wireless radio systems, such as the frequency sharing in the IMT Advanced systems as reported in Report ITU-R M.2292-0. As a result, the study and deployment of frequency cooperation between the increasing number of competing HF radio systems can serve as a fundamental approach to improve the HF electromagnetic environment, which also benefit the sustainable usability of the HF spectrum resource.

FIGURE 2

Noise factor comparison of 5.2 MHz of representative rural district in South China



To solve above problems, ITU-R developed Question ITU-R 258/5, "Technical and operational principles for HF sky-wave communication stations to improve the man-made noise HF environment". Techniques for evaluating the mutual interference, technical measures, and operational requirements for mitigating or avoiding mutual interference among HF skywave communication stations are two important problems that are to be studied by Question ITU-R 258/5. Focusing on these two problems, this Report will propose a cooperative frequency competition model and the corresponding algorithms and protocols for improving the HF skywave electromagnetic environment.

First, the current situation of HF skywave electromagnetic environment is investigated and modelled based on the External Diseconomy (ED) model in economics. On that basis, the necessity of the cooperative frequency cooperation among different HF radio systems is explained. Second, a cooperative frequency competition model to improve the HF skywave electromagnetic environment is proposed based on hypergraph theory as used in mathematics. It should be noted that ED theory and hypergraph theory are just used in the analysis and modelling, while the theories themselves are not in the scope of the Report. Finally, the algorithms and protocols for the model are discussed. The HF radio systems used in these studies are adaptive HF systems with frequency planning and adaptive management based on the obtained frequency through prediction and/or sounding. It is noted that ITU-R HF Handbook gives guidance on such systems, Recommendation ITU-R F.1110-2 specifies the general characteristics of adaptive HF systems, Recommendation ITU-R P.533-13 presents method for prediction of the performance of HF circuits, Recommendation ITU-R F.1778-1 specifies the channel access requirements for HF adaptive systems, and Recommendations ITU-R F.1611 and ITU-R F.1337 describe the prediction methods and sounding methods for adaptive HF systems respectively. The presented models and methods have considered and followed the above guidance and requirements.

2 The necessity of HF skywave frequency cooperation

The discordant competition of HF radio systems resembles ED in economic activity and has indivisibility feature of the terrain and the electromagnetic resource, i.e. the skywave transmission of the stations all over the world share the same ionosphere. Thus, it is feasible to investigate and construct the ED model in the HF electromagnetic environment to solve the problem following an analogical methodology.

2.1 External diseconomy in HF electromagnetic environment

In economics, ED is a familiar economic phenomenon denoting that the activity of an individual incurs negative impact on the exterior scope and cannot be compensated from the individual. The fundamental reason of that is indivisibility of the terrain and the environmental resource, i.e. the resource is shared by individuals in different terrains.

Result from the worldwide indivisible feature of the skywave HF frequency, the inter-system interference is serious, and the background noise level keeps increasing. As a result, all HF stations suffer from the poor HF radio environment. Yet no HF station can be traced or disciplined if no existing rule is violated. This is the ED phenomenon in HF radio environment. Mathematically, the utility function can be formulated as the exterior factors for a HF sky-wave radio system j with ED as:

$$F_j = f\left(x_1^n, x_2^n \ldots, x_m^n, x_1^a, x_2^a \ldots, x_k^a\right) \qquad (j \neq k) \tag{1}$$

where i is the factor index, x_i^n $(i = 1, 2, ..., m)$ represents the natural factors such as the variable ionospheric density, meteorological factors, and geographical factors, x_i^a $(i = 1, 2, ..., k)$ stands for the artificial factors such as the influence from other stations and industrial factors. To enhance the performance of HF radio systems, there have been many efforts devoted to the natural factors. This study focuses on the artificial factors, especially the inter-interference among HF radio systems. For an artificial factor x_i^a, if $\partial f / \partial x_i^a < 0$, it turns out that *j* is the embracer of the activity of *i*. Since there is no cooperation of different HF radio systems, this effect is hard to be managed.

2.2 Necessity of the cooperation among HF radio systems

Cooperation is the process of groups of organizations working or acting together for common, mutual, or some underlying benefit, as opposed to working in competition for selfish benefit. Its main ideology is to achieve all-win through accordant activity of the participants. In an ecosystem, cooperation is one of the fundamental approaches to keep viability and competition for populations. Even among different individuals and populations, reciprocity is a common cooperation mode. Enlightened by the cooperation in ecosystem as well as in human society, cooperation has been widely applied in the design of other kinds of wireless networks, such as TCP (Transmission Control Protocol) and ALOHA (Additive Links On-line Hawaii Area) for protocol level cooperation of the users. Although these cooperation protocols have been effectively applied in the optimization of mobile communications, ad hoc networks, and internet, only cooperation between the transmitter and receiver of the same system is applied in HF radio systems including the developing 4th generation HF ALE technologies. Taken as an analogy into the ecosystem, existing cooperation in HF radio systems can be regarded as cooperation within each individual rather than different individuals and populations. As a consequence, the HF stations have to improve their link performance through ALE or increasing the transmission power within the authorized limit. Because the inter-system interference is severe, the background noise keeps increasing. Therefore, for all existing systems, the HF radio environment continues to degrade, and operations become more difficult.

3 Cooperative competition model based on hypergraph

For the open feature of skywave transmission, HF stations with large transmission power may interfere other neighbouring HF receivers. Furthermore, with more and more stations deployed, HF radio systems at different locations with different transmitting channels can interfere with each other and the competition becomes more drastic. The degradation of the HF radio environment that results from the out-of-order competition makes the deployment and operation cost of HF radio systems much higher than they could be. To improve the HF radio environment, as well as the performance of HF radio systems, it is essential to investigate the correlation of different stations on frequency occupancy. Hypergraph is a powerful mathematical tool that can be used to model and analyse this kind of multi-member relationships.

Hypergraph is firstly proposed by C. Berger in 1970. Hypergraph is regarded as the most generalized framework in discrete mathematics and has been widely applied in information science, life sciences, etc. In this section, an analysis is presented on the correlations of the frequency occupancy of skywave stations based on Hypergraph theory leading to the corresponding approach of constructing the cooperative competition scheme with external economy.

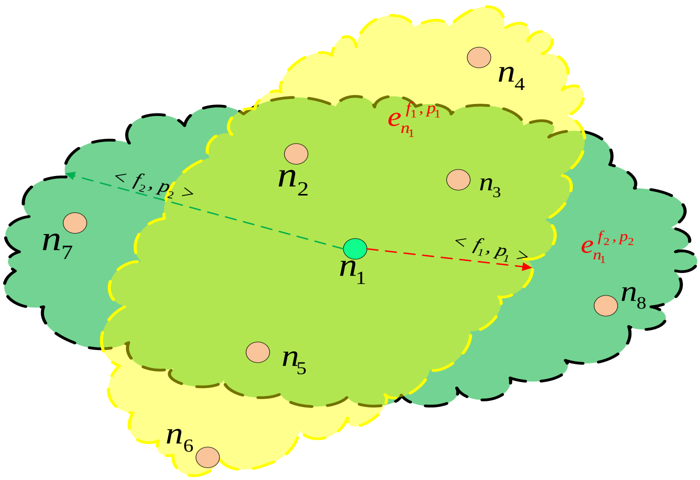
In skywave radio systems, HF stations select channels and adopt corresponding transmission power according to the spectrum allocation. Let $F = \{f_1, f_2, ..., f_F\}$ be the usable channel set, $P = \{p_1, p_2, ..., p_P\}$ denote the candidate power set, and $N = \{n_1, n_2, ..., n_N\}$ denote the HF station set. Then the Hypergraph model of the skywave radio systems is given by:

$$H = (N, E) \tag{2}$$

where N is the set of vertices and $E = \{e_n^{f,p} \mid n \in N, f \in F, p \in P\}$ is the set of undirected hyperedges. The hyperedge $e_n^{f,p}$ connects all the vertices influenced by vertex n transmitting on channel f with power p. The influenced area of an HF skywave station can be computed by the covered range with signal power bigger than a given threshold. An example of the Hypergraph model is depicted in Fig. 3. The yellow area within the dotted line denotes the influenced area of the couple $< f_1, p_1 >$ and the green area within the dotted line denotes the influenced area of the couple $< f_2, p_2 >$. Then the two hyperedges are given by $e_{n_1}^{f_1,p_1} = \{n_1, n_2, n_3, n_4, n_5, n_6\}$ and $e_{n_1}^{f_2,p_2} = \{n_1, n_2, n_3, n_5, n_7, n_8\}$ respectively. The Hypergraph model is an optimal way to analyse HF skywave radio systems with large influenced range and many influenced stations.

FIGURE 3

Hypergraph model of HF skywave radio systems



In the Hypergraph model, vertices with different transmitting channel and power correspond to different hyperedges and the connected vertices correspond to the influenced area. The influenced extent can be represented by the power of the hyperedges. According to the optimization requirements of the HF channels, the power can be set to the coverage area, covered vertices numbers, or the summation of the signal power of all the influenced vertices. In this study, the hyperedge power to the summation of the signal power is defined as:

$$w(e_n^{f,p}) = \sum_{n' \in e_n^{f,p} \setminus n} p_{n,n'}^{f,p} \tag{3}$$

In which $p_{n,n'}^{f,p}$ denotes the signal power at vertex n' transmitted from vertex n on channel f with transmitted power p.

To minimize the influence of a HF skywave station to the HF radio environment, the station should choose the setting with least corresponding hyperedge power on the condition of satisfying its performance requirement. For the unitary consideration of the HF radio environment, multiple stations competing for same channel should optimize satisfying their operational requirements along with incurring the least composited influence on the environment as the objective.

For a given channel f , let the competing vertices set be $\Psi \subset N$. Denote the obtained hyperedges set through centralized optimization or distributed coordination by $E_s = \{e_n^{f,p} \mid n \in \Psi\}$ and let $\boldsymbol{e}_{Es} = \bigcap_{\boldsymbol{e}_n^{f,p} \in \boldsymbol{E}_s} \boldsymbol{e}_n^{f,p}$. Then the optimization model with external economy is given by

$$e_{Es} = \arg\min\{w(e_{Es})\} \tag{4}$$

There should be the performance constraints for equation (4). And different constraints may be added for different radio parameters and operational environmental constraints. In general, the problem is in the form of combination optimization and cannot be solved thoroughly in a short time.

Based on the proposed Hypergraph model of the skywave HF radio systems, efficient near optimal algorithms of cooperative competition may be designed with other factors taken into consideration such as the usable channel prediction and the networking structure.

4 Discussion on the cooperative competition algorithms and protocols

4.1 The relationship between the executing speed and the usability of the algorithms

For the variable HF radio environment, the executing speed of the algorithms is important for their usability. It is understood that algorithms with long execution times will not be practical.

4.2 The relationship of the overhead and usability of the protocols

Although much improvement has achieved for HF radio systems, the transmission rate in the HF band is much lower compared with a higher frequency band. Thus, it is essential for the cooperation protocol to run with as little overhead as possible.

5 Algorithm and protocol design

5.1 The cooperative competition scheme

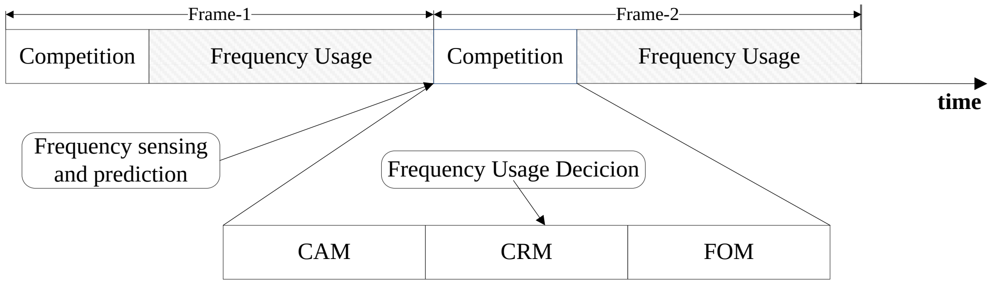
A cooperative competition scheme is proposed based on the model introduced in § 3. The basic idea of the scheme is to let the user choose the frequency with least negative influence on the competitors.

The frame structure of the proposed scheme is presented in Fig. 4. The participant nodes of the cooperative competition are denoted by $\mathbf{N} = \{1, 2, \cdots, N\}$. The system is synchronous, and all participant nodes start with frequency sensing and prediction to ascertain the usable frequency set. The usable frequency set of node $n \in \mathbf{N}$ is denoted by $\mathbf{C}_n = \{c_1, c_2, \cdots, c_{n_k}\}$. With that, the capacity $EC^c_{n_1,n_2}$ of the link between node n_1 and node n_2 on common frequency $c \in \mathbf{C}_{n_1,n_2} = \mathbf{C}_{n_1} \bigcap \mathbf{C}_{n_2}$ can be computed. All the following messages during the cooperative competition are exchanged on a predefined control channel $c_0 \in \mathbf{C}_n, \forall n \in \mathbf{N}$.

First, the node $n_s \in \mathbf{N}$ that wants to transmit initiates a competition announcement message (CAM), in which the destination node $n_d \in \mathbf{N}$, expected capacity $EC^c_{n_s,n_d}$ on each usable channel $c \in \mathbf{C}_{n_s,n_d}$, and the end time of the competition reply message (CRM) transmitting period t_s is embodied.

FIGURE 4

Frame structure of the cooperative competition scheme



Second, in the following competition reply period, the destination node n_d that has received CAMs sends a CRM that includes the information of all the received CAMs after a random waiting time.

Third, the initiating node n_s constructs a cooperative competition hypergraph $H_n = (\mathbf{N}_n, \mathbf{E}_n)$ based on the received CAMs and CRMs, in which $\mathbf{N}_n$ is the competing node set to n_s and n_d, and $\mathbf{E}_n = \{e_n^c \mid c \in \mathbf{C}_{n_s,n_d}\}$ is the hyperedge set connecting all nodes that may compete with n_s and n_d for channel c. Then the negative influence factor of each hyperedge can be computed by $NF_{e_n^c} = \sum_{m \in e_n^c} \delta_m^c$,

in which $\delta_n^c = \dfrac{EC_{n_s,n_d}^c}{\sum_{c' \in C_{n_s,n_d}} EC_{n_s,n_d}^{c'}}$ denotes the essentiality of channel c to n_s and n_d.

In the fourth period, all initiating nodes compete based on the aforementioned computing in the previous steps. Competing node n_s first waits a random period, selects a non-occupying frequency with least influence factor as an occupying frequency, and broadcasts a frequency occupying message (FOM). On receiving the FOM, the destination node n_d reply an acknowledge message. Then the frequency can be occupied by the two nodes.

Through the simple message exchange, the cooperative competition can be achieved. Furthermore, although the system is synchronous, the asynchronous nodes can also join the competition if some related messages are also received.

5.2 Cooperative competition scheme integration with adaptive HF radio systems

5.2.1 Current adaptive HF systems

Applications of adaptivity techniques in HF radio systems have improved the performance of HF radios by addressing problems such as variable propagation, which leads to questionable reliability of links and the lowering of the data bandwidth. Resolution **729 (Rev.WRC-07)** provides framework for adaptive use and frequency sharing of HF systems. The ITU-R HF Handbook gives guidance on such adaptive HF radio systems, Recommendation ITU-R F.1110-2 specifies their general characteristics, Recommendation ITU-R P.533-13 presents method for prediction of the performance of HF circuits and Recommendations ITU-R F.1611 and ITU-R F.1337 describe the prediction methods and sounding methods for adaptive HF systems respectively. Specifically, Recommendation ITU-R F.1778-1 recommends that frequency-adaptive HF systems should use the minimum number of active frequency channels and use the dynamic frequency selection (DFS) scheme to minimize interference to and from other systems.

Under the layered model, adaptivity techniques in adaptive HF radio systems can be classified into system-level frequency management and control, network level adaptive routing, flow control and handshaking, link level frequency management control, transmission level adaptive data rate, waveform and power, for example. It should be noted that, optimized frequency usage relates mainly to system level and link level.

The integration of the proposed cooperative competition scheme with adaptive HF radio systems is investigated with respect to the system level and link level frequency management and control under current guidance and recommendations on such kind systems.

5.2.2 Candidate integration with ALE

Developed in the late 1970s and early 1980s, the ALE systems enable automatic frequency selection from several preassigned frequencies. The second-generation ALE (2G-ALE) systems, standardized in 1986 in MIL-STD-188-141A, Appendix A for military use and FED-STD-1045 for U.S. civilian use, adopts asynchronous mode for link establishment. The latest, third-generation ALE (3G-ALE) systems, standardized in MIL-STD-188-141B Appendix C, supports more reliable and capacity efficient synchronous mode, while mandating interoperability with 2G-ALE. These two generations of ALE standards have become the *de facto* worldwide standard. Recently, new techniques such as spectrum sensing and spectrum aggregation have been researched in the development of the next generation of ALE systems. It can be foreseen that the frequency competition will become more intense with more frequency agile HF radio systems.

For 2G-ALE and 3G-ALE HF radio systems with asynchronous mode, the cooperation competition on frequency may be implemented during the transmission channel selection. The called user selects the channel in the candidate channel pool, obtained through frequency prediction or sounding, with minimal negative influence factor. Benefits of this assignment lie in two aspects, first, the channel selection will incur the least negative influence on other users, thus the network capacity will be improved, and second, the potential interference from other users is also minimized as the occupied channel will be less likely to be reserved.

For 3G-ALE HF radio systems under synchronous mode, the cooperation competition on frequency can be implemented in the system-level frequency planning as well as in the channel selection in the link establishing process. During system-level frequency planning, the channels in the active channel pool with less negative influence factors should be preferred to be assigned as calling channels. During the link-level frequency assignment and control, similar preference should be adopted for the selection of transmission channels.

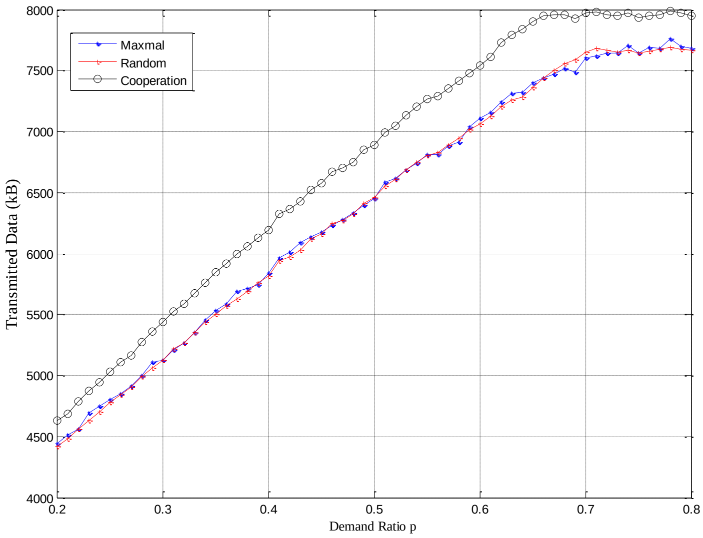
It should be noted that no revisions on frequency prediction, channel sounding, or ALE protocols is needed in this integration framework scheme.

5.3 Performance evaluation

To evaluate the performance of the proposed cooperative competition scheme, a simple scenario is simulated in which there are three HF users with usable channel set $\mathbf{C}_1 = \{1,2,3\}$, $\mathbf{C}_2 = \{1\}$, and $\mathbf{C}_3 = \{1\}$, respectively. Optimal capacity of each channel is 2.4 kbit/s and capacity of each channel is randomly generated between 80%~100% of the optimal value, considering the randomness of the HF channel. In each slot, each user receives a transmission request with length of 1 to 6 slot following a binomial distribution with probability p. The length of each slot is normalized to 1s. The total transmitted date throughput of the users in 10 000 slots are simulated and the proposed cooperative competition scheme are compared with maximal throughput strategy and random selecting method. Two-hundred simulations were conducted, and the averaged result is presented in Fig. 5. This Figure shows that there is a notable improvement in using the cooperative competition scheme when compared with the two other simple schemes. Note that the adoption of more flexible access technologies such as channel aggregation in the simulation is not assumed, therefore more total throughput of HF users is expected for those users with more flexible channel access capability.

FIGURE 5

Comparison on the amount of transmitted data



6 Summary

For the deteriorating HF skywave radio environment and low link available probability, this Report explained on the necessity of cooperation among different HF radio systems and proposed a cooperative competition model based on Hypergraph theory. The features of the candidate algorithms and protocols for cooperative competition are briefly discussed. Simulation results demonstrate that necessary improvement can be obtained with the proposed cooperative competition scheme even under the scenarios used in this process. Thus, it is preferable to adopt cooperative competition rather than non-cooperation.