Factor Graph Hopping Based FH-SCMA for Band-Limited and Large-Scale IoT Networks

Qi Zeng†, Kun Yang†, and Zilong Liu‡

†College of Electrical Engineering, Sichuan University, Chengdu, China
‡School of Computer Science and Electronics Engineering, University of Essex, UK
Emails: qzeng1@hotmail.com, 2417527781@qq.com, zilong.liu@essex.ac.uk

***Abstract*—In wireless Internet-of-Thing (IoT) networks, massive nodes/users congest in limited resource blocks (RB, i.e., time-frequency block). Sparse code division multiple access (SCMA) technology is a most potential solution for massive IoT access due to its superior resource utilization; however, the prototypical SCMA likely suffers from severe interference/ jamming because of lacking reliable transmission strategies. To address this issue, a reliable SCMA based on factor-graph (FG) hopping scheme (FG based FH-SCMA) is proposed for massive connectivity and band-limited IoT in this paper. To meet the sparsity of transmitted FH-SCMA codewords, a FG hopping pattern with long-period is designed via Bernoulli chaotic map. Through the proposed system design, physical RBs utilized by SCMA codewords are randomly hopped within one RB-group so as to obtain efficient RB utilization and robust transmission; meanwhile, iteration error in message-passing-algorithm (MPA) resulted from the hopping RB-collision in the SCMA receiver can be alleviated. The numerical and simulation results show that, under the jamming attack, the proposed FH-SCMA system can attain the reliable transmission performance, compared to the traditional SCMA and previous FH-SCMA systems.**

Keywords—System design, FH-SCMA, hopped factor-graph, BER, IoT.

I. INTRODUCTION

With the development of the Internet-of-Things (IoTs), plenty of wireless applications including WiFi, Bluetooth, Zigbee and so forth, operate within the limited band, such as, the industrial, scientific, and medical (ISM) radio bands. Sparse code division multiple access (SCMA), as an emerging technology in the fifth generation(5G) cellular and beyond, can support exponential growth of IoT nodes (users) over the limited and congested spectrum resource[1]-[2]. However in the traditional SCMA system, the users' codewords are sent over a few fixed resource-blocks (RBs), which imply that the traditional SCMA is vulnerable to interference/jamming threats and channels fading effect [3-4]. Therefore, it is necessary to adopt the reliable transmission and signal processing strategies in SCMA to overcome the challenges posed by wireless IoT networks.

The frequency-hopping (FH) technique has been adopted as a powerful solution to mitigating the interference/jamming in a variety of wireless applications, for example, FH based PUSCH in 5G NR [5], FH based multi-cluster communications [6]. To improve the robustness of SCMA, FH based SCMA (FH-SCMA) also has been proposed in recent years [7]–[9], where the operating frequency of SCMA codeword is hopped randomly according to the preassigned hopping pattern (cascade-manner). With the aid of FH, the SCMA has the capability to alleviate the effect of channel contamination including jamming and fading on the performance. Based on these studies, we proposed a multi-cell FH-SCMA network in our previous study [10], where the hopping pattern is referred to the cell address. The cascade of FH and SCMA indicates that the entire RBs (subcarriers) of SCMA codewords are hopped over a wide range of spectrum; which leads to waste a large portion of frequency resource. Thus, in the band-limited wireless IoT scenarios, the existing FH-SCMA infrastructures are not applicable.

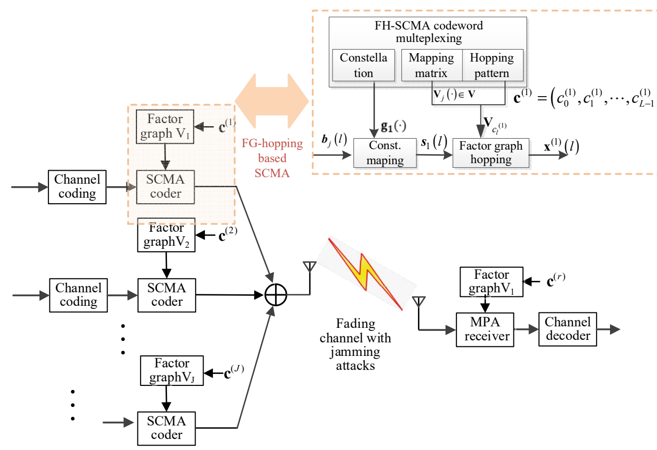

Fig.1 The transceiver model of the proposed FG hopping based FH-SCMA system

To address the aforementioned challenge in the resource-limited IoT networks, a novel factor-graph (FG) hopping based SCMA (FG hopping based FH-SCMA) system is proposed in this paper, where the physical RBs utilized by codewords are randomly hopped within a RB-group. Compared to the traditional SCMA, the user's codewords in the proposed scheme are no longer transmitted over the fixed RBs. The system model is as shown in Fig. 1, which will be depicted in details in Section II.

The hopping pattern in the proposed FH-SCMA is the most critical component, which heavily affects the performance of multi-user detection and the robustness of SCMA. For example, the hopping pattern should guarantee the specific sparsity of SCMA codebook so as to avoid the extra error diffusion of soft message passed over the users and RBs. In addition, the hopping pattern should possess the long period and the randomness, which helps to improve the anti-jamming capability of FH-

SCMA system. Thus, in this paper, we design a new hopping pattern by using the Bernoulli map based chaotic theory [14], and its construction algorithm will be presented in Section III. It is well noted that Bernoulli map can generate a more nearly uniform-distributed sequence than other chaotic maps including Logistic map. In our previous study concerning FH-SCMA in [11], the hopping pattern imposed within the RB group is designed via the *prime code* and interleaving technique, but with the limited period and the poor randomness.

In the receiver of the proposed FH-SCMA system, this paper adopts a log-domain message passing algorithm (MAX-log-MPA) to reduce the complexity of signal processing in the receiver [6]. The simulation performance of the proposed FH-SCMA system is presented in Section IV. Finally, the conclusion will be drawn in Section V.

II. System Model

In this section, we firstly recall the traditional SCMA system. The drawback of the current SCMA, which is vulnerable to jamming attacks and channel fading, can be straightway extracted. In order to address these issues, the new FG hopping based FH-SCMA system is proposed .

A. Traditional SCMA and problem descriptions

We consider a traditional SCMA in a single cell uplink, where J users are multiplexed to connect to base-station (BS) over a RB-group containing K contiguous RBs. The SCMA codebooks for these J users are properly designed, that is

$$\overrightarrow{\boldsymbol{CB}} = \left\{\boldsymbol{CB}_1, \boldsymbol{CB}_2, \dots, \boldsymbol{CB}_J\right\} \tag{1}$$

where each codebook $\boldsymbol{CB}_j = [\boldsymbol{x}_1^{(j)}, \boldsymbol{x}_2^{(j)}, \dots, \boldsymbol{x}_M^{(j)}]$ can be arranged as a $(K \times M)$ matrix, which satisfies $\mathrm{Tr}\left(\boldsymbol{CB}_j \boldsymbol{CB}_j^{H}\right) = M$. The column vector $\boldsymbol{x}_m^{(j)}$ with $(K \times 1)$ entries is called a codeword with low-density, which is denoted as $\boldsymbol{x}_m^{(j)} = (x_{m,1}^{(j)}, x_{m,2}^{(j)}, \dots, x_{m,K}^{(j)})^T$. The M-ary symbol $m \in \{1,2,3,\dots,M\}$ transmitted by the user j is mapped into a codeword $\boldsymbol{x}_m^{(j)}$ in $\boldsymbol{CB}_j$. The detailed codebook design method can be readily found in literature [12-14].

The channel gains corresponding to J users are assumed to be a set $\boldsymbol{h}$, which is denoted by

$$\boldsymbol{h} = \left\{\boldsymbol{h}_1, \boldsymbol{h}_2, \dots, \boldsymbol{h}_J\right\} \tag{2}$$

where $\boldsymbol{h}_j = [h_1^{(j)}, h_2^{(j)}, \dots, h_K^{(j)}]$ represents the channel-gains vector of the user j over K RBs. $h_k^{(j)}$ represents its channel-gain coefficient corresponding to the k-th RB. In practical, the channel-gain could be contaminated by jamming attacks or channel fading.

Then, the signal received at the BS can be expressed as

$$\boldsymbol{y} = \sum_{j=1}^{J} diag(\boldsymbol{h}_j)\sqrt{p_j}\boldsymbol{x}_m^{(j)} + \boldsymbol{n} \tag{3}$$

where p_j denotes the transmission power of user j, which is assumed that each user has the same transmission power. $\boldsymbol{n}$ is a $(K \times 1)$ vector with each element following the additional white Gaussian noise (AWGN).

For easy explanation, we take the traditional SCMA with J=6, K=4 as an example, of which preset factor graph $\mathbf{V}$ is given by the indicator matrix [3],

$$\mathbf{V} = [\boldsymbol{V}_0, \boldsymbol{V}_1, \dots, \boldsymbol{V}_5] = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}$$

where $\mathbf{V}_j$ indicates the RBs at which the j-th user sends the non-zero data.

According to the aforementioned FG $\mathbf{V}$, the j-th user (j=1 for example) in the traditional SCMA always sends the non-zero data on the 1st and 2rd RBs, as shown in Fig. 2, no matter which m-ary data is transmitted. In Fig. 2, each column vector represents a codeword vector $\boldsymbol{x}_m^{(j)}$ corresponding to the m-ary symbol.

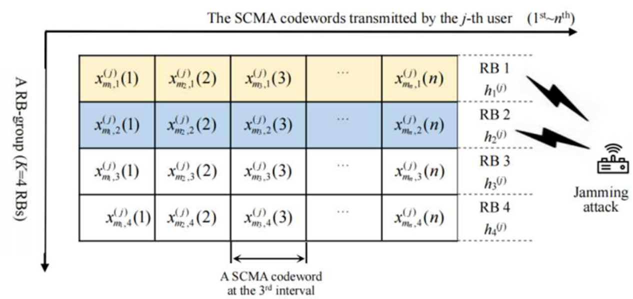

Fig. 1. The traditional SCMA system with 4 RBs under a jamming attack

The effect of jammed RBs on the performance of SCMA system is presented in Fig. 3. Under the jamming attacks where the 1st and the 2nd RBs are contaminated, the 1st user attains the worst performance since both #RB1 and #RB2 are jammed, while the 6-th user gets the best one due to the clean #RB3 and #RB4. In addition, in the iteration MPA decoder, the error diffusion of soft message due to the jamming attack is also spread over all the UEs and RBs. Thus, the users in the traditional SCMA with fixed factor graph are very vulnerable to the jamming attack or fading channels.

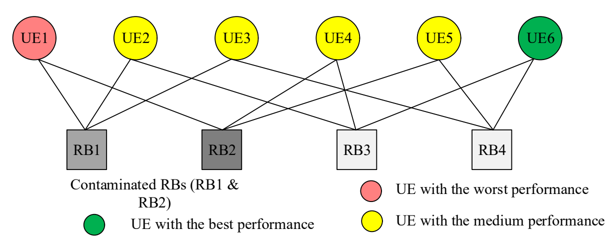

Fig. 2. The unbalanced performance of UE in traditional SCMA system with 2 jammed RBs.

B. The factor graph hopping based SCMA system

For the problems raised in the previous sub-section, a novel SCMA system based on the FG hopping scheme is proposed as shown in Fig. 1. The symbol stream at the l-th interval $\{ \boldsymbol{b}_j(l) \mid l=1,2,3... \}$ for the j-th user is input orderly into the proposed FG hopping based SCMA model, where the FG of the j-th user is changed by the assigned hopping pattern $\boldsymbol{c}^{(j)}$. Via the proposed FH-SCMA system, users' data is transmitted at the various RBs so as to avoid the contaminated channels and jamming attacks.

The integration of FG hopping technique and SCMA is described in details as following. The symbol $\boldsymbol{b}_j(l)$ is mapped into a complex constellation vector $\boldsymbol{s}_j(l)$ with (1×N) dimension. At the different symbol intervals, the user selects various FG $\tilde{\boldsymbol{V}}_j(\cdot)$ over the set $\tilde{\mathbf{V}}$ according to the hopping pattern $\boldsymbol{c}^{(j)}$, that is,

$$\tilde{\boldsymbol{V}}_j(\cdot) \in \tilde{\mathbf{V}} = \{\tilde{\boldsymbol{V}}_1(\cdot), \tilde{\boldsymbol{V}}_2(\cdot), \ldots, \tilde{\boldsymbol{V}}_J(\cdot)\} \tag{4}$$

The hopping patterns $\boldsymbol{C}$ controlling the changes of SCMA codebook for these J users are shown as

$$\boldsymbol{C} = \{\boldsymbol{c}^{(1)}, \boldsymbol{c}^{(2)}, \ldots, \boldsymbol{c}^{(j)}, \ldots, \boldsymbol{c}^{(J)}\} \tag{5}$$

$$\boldsymbol{c}^{(j)} = [c_0^{(j)}, c_1^{(j)}, \ldots, c_l^{(j)}, \ldots c_{L-1}^{(j)}] \tag{6}$$

where L denotes the length of sequence. Due to the design of FG hopping, the instantaneous SCMA codebook utilized by the j-th users over the l-th interval is controlled by $c_l^{(j)}$, which is denoted as

$$\mathbf{x}^{(j)}(l) = \tilde{\mathbf{V}}_{c_l^{(j)}} \boldsymbol{s}_j(l), \ \ c_l^{(j)} \in \{1,2,\ldots,J\}, \tag{7}$$

Then the multiplexed signals of all users under the jamming attack can be expressed as

$$r_l = \sum_{j=1}^{J} diag(\boldsymbol{h}_j)\sqrt{p_j}\mathbf{x}^{(j)}(l) + \boldsymbol{n} + \boldsymbol{J}_a(l) \tag{8}$$

where $\boldsymbol{J}_a(l)$ denotes the vector of jamming signal emitted on the portion of these K RBs. The channel-gain vector $\boldsymbol{h}_j$ of the user j over K RBs is as defined as (2).

At the receiver, the hopping pattern of the transceiver is assumed to be perfectly synchronized. According to the assigned hopping pattern $\boldsymbol{C}$, the FG of each user in the receiver is also changed accordingly, which is utilized for FG dehopping, and then a low complexity MAX-log-MPA is adoppted for SCMA decoding [6].

III. Design of FG Hopping Pattern for FH-SCMA System

To implement the optimal FG hopping based FH-SCMA under the jamming scenario, we find that the properties of hopping pattern are very critical to the performance of the multi-user detection. It is worthy noted that the FG is hopped according to the constructed hopping pattern, thus the specific sparsity of the SCMA codebook should be maintained at each hopping interval so as to be detected by the MPA successfully in the receiver. Aiming for performing both of the FG hopping and sparsity of codebook, in this paper we propose a cyclic shift operation on the given FG to implement the specific aims.

The construction of the FG hopping pattern (sequences) for FH-SCMA system consists of the following steps.

Step 1: Given a FG matrix **V** with (K×J) dimensions, which can be readily obtained from the previous studies [11-13]. Then **V** can be rewritten as a row manner, that is

$$\mathbf{V} = [\boldsymbol{V}_0, \boldsymbol{V}_1, \ldots, \boldsymbol{V}_{J-1}] \tag{9}$$

where $\boldsymbol{V}_j$ is a column-vector with (K×1) dimension.

Step 2: Constructing a pseudo random analogy sequence with the length L by using the Bernoulli map based chaotic theory [14]. The chaotic Bernoulli map applied here aims to improve the randomness and length of the hopping pattern, which is denoted as

$$z_{k+1} = \begin{cases} z_k/(1-\lambda), & z_k \in (0, 1-\lambda] \\ (z_k - 1 + \lambda)/\lambda, & z_k \in (1-\lambda, 1] \end{cases} \tag{10}$$

where z_k □ $\boldsymbol{I}$ = (0, 1). And the analogy sequence $\boldsymbol{Z}$ = [z_0, z_1, . . . , z_{L-1}] is obtained by setting the initial value z_0 and the λ parameter .

Step 3: Mapping the analogy sequence $\boldsymbol{Z}$ to a J-ary sequence. The value range **I** = (0, 1) is uniformly divided into J non-overlapping partitions $\mathbf{E}_0$ = (0, 1/J], $\mathbf{E}_1$ = (1/J, 2/J], ..., $\mathbf{E}_{J-1}$ =((J-1)/J, 1) . The mapping algorithm is presented as

$$\boldsymbol{Z} = [z_0, z_1, \ldots, z_{L-1}] \xrightarrow{Mapping} \boldsymbol{C} = [c_0, c_1, \ldots, c_{L-1}]$$
$$\text{Mapping algorithm: } c_l = j, \text{ if } z_l \in \mathbf{E}_j, l = 0,1,..,L-1 \tag{11}$$

Then, the J-ary sequence $\boldsymbol{C}$ is obtained.

Step 4: Cyclic v-digit(s) shift on the row-manner **V**. At the l-th interval, the instantaneous FG is changed/hopped by performing the cyclic c_l-digit(s) shift on **V**, that is,

$$\tilde{\mathbf{V}}_l = [\boldsymbol{V}_{c_l}, \boldsymbol{V}_{c_l+1}, \ldots, \boldsymbol{V}_{J-1}, \boldsymbol{V}_0, \boldsymbol{V}_1, \ldots, \boldsymbol{V}_{c_l-1}] \tag{12}$$

where the first column-vector to the last one are accordingly assigned to the 1-st user to the J-th user. Thus, the newly obtained FGs $\tilde{\mathbf{V}}_l, l = 0,1,2,\ldots$ guarantee the sparsity of the SCMA codebook at any hopping intervals, and its randomness is controlled by the chaotic Bernoulli map.

The parameters and features of various hopping patterns are concluded in Tab. 1. For the completely random hopping strategy, the active RBs of SCMA user is hopped arbitrarily, which results in multiple RBs collisions, thus ruining the sparsity of SCMA codebook. As for our previous study [10], it is noted that the RB-hopping pattern of FH-SCMA is constructed by prime code, which has the limited length of

$\tilde{\mathbf{V}}_l$

hopping pattern. Thus these previous hopping patterns are not applicable to the complex IoT scenarios.

TAB. I THE PARAMETERS AND FFEATURES OF VARIOUS HOPPING PATTERNS

Types of hopping patterns	Seed seq.	length	RB-hits	Appl. cond.	Constr. compl.
Our proposed	Bernoulli chaotic seq.	L, unlimited	0	No	Mod.
Hopping pattern in [10]	Prime code	p, a prime integer	0	K=p-1	High
Random hopping pattern	No	L, unlimited	1/K	No	Low

IV. SIMULATION AND DISCUSSIONS

In this section, we will evaluate the BER of the FG hopping SCMA by simulations. In the following simulations, it is assumed that the receiver of the proposed system has been perfectly synchronized with the transmitter in the wireless IoT networks. The parameters of SCMA are set as follows: the number of RBs is 4 ($K = 4$), the number of users equals to 6 ($J = 6$), the codebooks in [3] with the dimension of $(K \times M) = (6 \times 4)$ are utilized. The wireless channels adopts the flat Rayleigh fading with AWGN model. In addition, the jammer emits the contaminated signal at the fixed RBs.

The BER of the proposed FG hopping based FH-SCMA system is evaluated in Fig. 3. We assume that two RBs (#1 RB and #2 RB) are constantly attacked by the jammer with SJR= 0 dB. As the baseline, the traditional SCMA without hopping technique are also studied. In this figure, it can be observed that the #6 UE obtains the best BER while the #1 UE gets the worst one; that is, UEs in the traditional SCMA system have the unbalanced BER performance under the jamming attacks. This phenomenon can also be explained by Fig. 3 and preset fixed FG **V**. However, in our proposed FH-SCMA system, the physical RBs utilized by codewords are randomly hopped within a RB-group, thus the proposed system can offer consistent BERs for all users, of which curve lies between "the best" and "the worst" curves. It is also verified that the FG hopping SCMA proposed in this paper can help all IoT users attain the stable and acceptable BER performance.

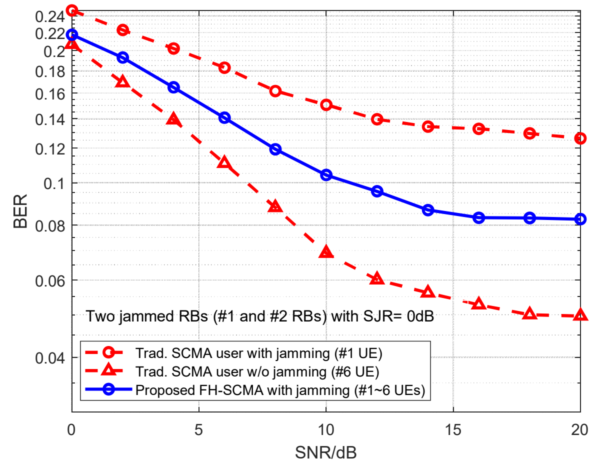

Fig.3. BER comparisons between proposed FH-SCMA and traditional SCMA under the jamming attacks

The effects of various hopping patterns on the proposed FH-SCMA system are presented in Fig. 4. The parameters of systems and jammer are as shown as Fig. 3. Here the random hoppping pattern is generated over the given K RBs. Observed from this figure, the average BERs of the FH-SCMA system with the random hopping pattern is poorer than that with our developed one in Sect. III. The reason lies on that the random hopping pattern can not avoid the RB-hits, while for the proposed FG hopping pattern, all FGs $\{\tilde{\mathbf{V}}_l\}_{l=0,1,\dots L-1}$ keep the sparsity in the MPA decoder for any ls, and does not bring the extra RB-hits and BER increase, as shown in Tab. 1.

The BERs of the proposed FG hopping based SCMA system with various SJRs are plotted in Fig. 5. The parameters are set as the same as those in Fig.3. We find that the proposed FH-SCMA gets the worse BER as the SJR decreases, but attains an acceptable performance under the strong jamming attack.

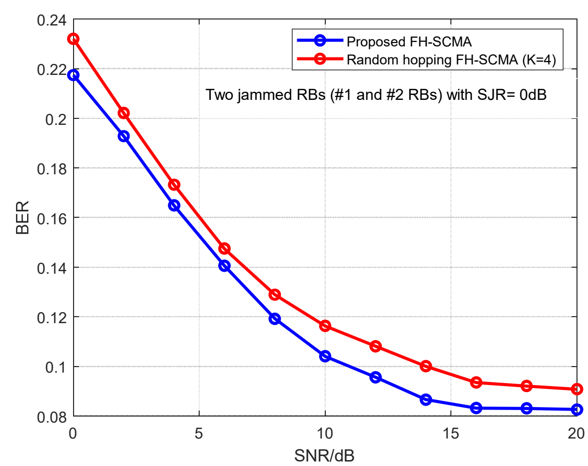

Fig. 4 BERs of the proposed FG hopping based SCMAs using the random hopping pattern and the proposed one (SJR= 0dB).

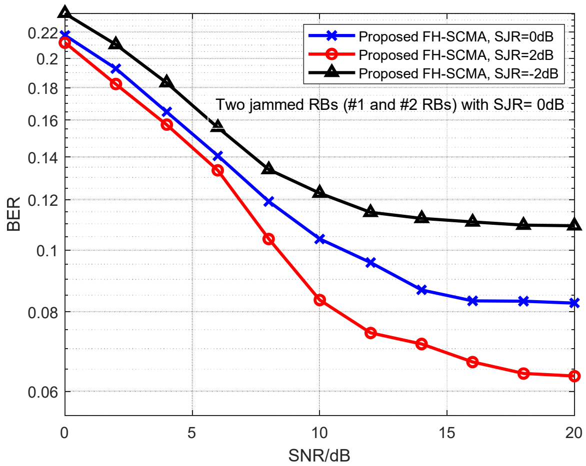

Fig. 5 BER of the proposed FG hopping based FHSCMA system under jamming attack with various SJRs.

V. Conclusions

The traditional SCMA transmits the codewords over the fixed RBs, it is vulnerable to the external jamming threats in the IoT scenarios. In addition, our previous FH-SCMA system, where the entire SCMA symbol is hopped over the wider band, wastes the time-frequency resource seriously. In this paper, a novel SCMA system based on FG hopping scheme is proposed, where instantaneous RBs utilized by users' codewords are randomly hopped within a RBs-group. To meet the sparsity of transmitted FH-SCMA codewords, a FG hopping pattern is designed via Bernoulli chaotic map. The developed hopping pattern controls the the change rule of FGs. Such a FG hopping pattern guarantees the sparsity of SCMA codewords and also improves the utilization efficiency of RBs. The simulation results reveal that, under the jamming attack, the proposed FH-SCMA system can attain the reliable transmission performance, compared to the traditional SCMA and random hopping based FH-SCMA systems, which is more suitable for the band-limited IoT networks with massive connectivity.

Acknowledgement

The work of Qi was support by Sichuan Science and Technology Program, China, under Grant 2023NSFSC0480 and in part by Open Fund for Key Laboratory of Internet of Things Standards and Applications in Ministry of Industry and Information Technology, China, under Grant 202303.

The work of Z. Liu was supported in part by the UK Engineering and Physical Sciences Research Council under Grants EP/X035352/1 and EP/Y000986/1.

References

[1] M. Vameghestahbanati, I. D. Marsland, R. H. Gohary and H. Yanikomeroglu, "Multidimensional constellations for uplink SCMA systems—a comparative study," *IEEE Commun. Survey & Tutorials*, vol. 21, no. 3, pp. 2169-2194, third quarter 2019.

[2] K. Lai, J. Lei, Y. Deng and et al., "Analyzing uplink grant-free sparse code multiple access system in massive IoT networks," *IEEE Int. Things J.*, vol. 9, no. 7, pp. 5561 - 5577, Sept. 2022.

[3] Z. Liu and L.-L. Yang, "Sparse or dense: a comparative study of codedomain NOMA systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 4768 - 4780, Mar. 2021.

[4] F. Wei, W. Chen, Y. Wu, and et al., "Toward 5G wireless interface technology: enabling nonorthogonal multiple access in the sparse code domain," *IEEE Vehi. Tech. Mag.*, vol. 13, no. 4, pp. 18-27, Dec. 2018.

[5] E. Dahlman, S. Parkvall, J. Skold, *5G/5G-Advanced The New Generation Wireless Access Technology*, London: Academic Press, 2023.

[6] Q. Zeng, Z. Liu and G. Gabriele, "Optimal quasi-orthogonal FH sequences with adaptive array receiver for massive connectivity in asynchronous multi-cluster networks", *IEEE Trans. Wireless Commun.*, vol.21, no. 8, pp. 5730 – 5743, Aug. 2022.

[7] S. Maric and L. Z. Velimirovic, "Optimal frequency hopping patterns for FH-SCMA," 2018 IEEE 5G World Forum (5GWF), 2018, pp. 377-382.

[8] Z. Bai, B. Li, M. Yang, Z. Yan, X. Zuo and Y. Zhang, "FH-SCMA: frequency-hopping based sparse code multiple access for next generation internet of things," 2017 IEEE Wireless Communications and Networking Conference (WCNC), 2017, pp. 1-6.

[9] Q. Zeng, Z. Liu, X. Liu, J. Zhong and P. Xiao, "Frequency-hopping based SCMA for massive connectivity in multi-cell networks," 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 2021, pp. 1-6.

[10] K. Yang, Q. Zeng, X. Liu and et al, "Design and analysis of inter-RBs hopping SCMA system under jamming attacks," IEEE 22nd International Conference on Communication Technology, Nanjing, China, Nov.11-14, 2022.

[11] Y. -M. Chen and J. -W. Chen, "On the design of near-optimal sparse code multiple access codebooks," *IEEE Trans. Commun*, vol. 68, no. 5, pp. 2950-2962, May 2020.

[12] Z. Hou, Z. Xiang, P. Ren and B. Cao, "SCMA codebook design based on divided extended mother codebook," *IEEE Access,* vol. 9, pp. 71563-71576, 2021.

[13] C. Huang, B. Su, T. Lin and Y. Huang, "Downlink SCMA codebook design with low error rate by maximizing minimum Euclidean distance of superimposed codewords," *IEEE Trans. Vehi, Technol*, vol. 71, no. 5, pp. 5231-5245, May 2022.

[14] J. Jung, and J. Lim, "Chaotic standard map based frequency hopping OFDMA for low probability of intercept," *Commun. Lett.*, vol.15, pp. 1019–1021, 2011.