Federated Learning Driven Sparse Code Multiple Access in Vehicular Communications

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***Abstract*—Sparse code multiple access (SCMA) is one of the competitive non-orthogonal multiple access techniques for the next generation multiple access systems. One of the main challenges is high computational complexity and the SCMA-aided codewords, that is, each terminal device maintains its local data and codewords, which has no incentive for model updating to accommodate rapidly changing vehicle communication environment. Federated learning (FL) proves its effectiveness through collaborative training their local neural network models with private data while protecting the individual SCMA-aided codewords. To select reliable and trusted codewords, this article provides an overview of the salient characteristics on the application of federated learning driven SCMA for vehicular communication and discusses its fundamental research challenges. Furthermore, we outline the advancement of federated learning driven SCMA scheme, and present a general framework with potential solutions to the challenges. Experimental results verify the effectiveness of the proposed framework. Finally, several future research directions and open issues are discussed for federated learning driven SCMA scheme.**

***Index Terms*—Federated learning, sparse code multiple access (SCMA), reconfigurable intelligent surfaces, vehicular communication.**

I. Introduction

WITH the upsurge of the number of wireless devices, various potential communication technologies are emerging in beyond 5G (B5G) and the sixth generation (6G) to provide high spectral efficiency, ultrahigh reliability, ultralow latency as well as higher connectivity. Considering limited frequency and time-domain resource, the multiple access scheme is developed as one of the most important technologies to meet various special requirements such as lower transmission latency and higher spectral efficiency [1]. However, the simultaneous accessibility of users is directly proportional to the availability of orthogonal resources. Facing the diverse multi-dimensional requirements of quality of service (QoS), the multiple access technology becomes the research focus of B5G/6G wireless communication, including multiple access with low-density spreading (LDS) [2], multiuser shared access (MUSA) [3], nonorthogonal multiple access (NOMA) [4], sparse code multiple access (SCMA) [5] and so on.

Among them, a promising code domain NOMA scheme, SCMA, is a codeword-based modulation and spreading strategy, which has attracted research attention from both academic and industrial communities [6]. In SCMA, multiple users can be served simultaneously by employing different sparse codewords. More specifically, for the transmitter, a mapping scheme is employed to assign data streams from multiple layers to multi-dimensional sparse complex codewords, which can share the same time-frequency resource. The sparse advantage of codewords allows for their nonorthogonal multiplexing within a single SCMA block, resulting in a significantly larger capacity than the number of available orthogonal resource. At the receiver, the maximum likelihood (ML) decoding or message passing algorithm (MPA) can be used to decode the received signal in the data recovering stage. Since the information bits can be mapped into multi-dimensional codewords, SCMA has been widely recognized as a promising technique towards Next Generation Multiple Access (NGMA) for 6G.

Although SCMA brings great benefits for wireless networks, there are still challenges for the application of the SCMA in vehicular network, namely vehicle-to-everything (V2X), which is diverse and pervasive. Due to the non-orthogonal properties of SCMA as well as the mobility and dense topology of a V2X communication, the design of the SCMA-based V2X communication becomes different from the conventional wireless communication system, as outlined in the following:

1) Low transmission latency connection: The SCMA technique usually requires more decoding computations in comparison to the classic multiple access framework. As the demand for diverse mobile services, the challenge in designing a reliable SCMA lies in developing viable encoding/decoding schemes to provide the low transmission latency requirements. To accelerate the convergence rate or reduce the required computations, it is necessary to develop low complexity of codewords generator for the design of SCMA systems.

2) Massive connectivity: Although SCMA allows multiple users to transmit simultaneously within the shared resources, the multidimensional codewords restrict the realtime operation of SCMAs. Specifically, for a multi-task learning structure of J tasks, if each task involves an M-dimensional input vector, the corresponding input dimension of single task learning structure will increase to M^J, leading to significantly high computational complexity.

3) SCMA-based codewords design: The performance of an SCMA heavily depends on the codewords design. However, the training codewords accuracy and dimension of codewords are two conflicting objectives, which is difficult to tradeoff. Therefore, the optimal SCMA codeword design remains an open problem.

Therefore, it is imperative to examine effective and robust SCMA scheme in V2X network. In light of the advantages introduced by the adoption of Deep Learning (DL) techniques, various DL-aided SCMA codewords designs have been devel-

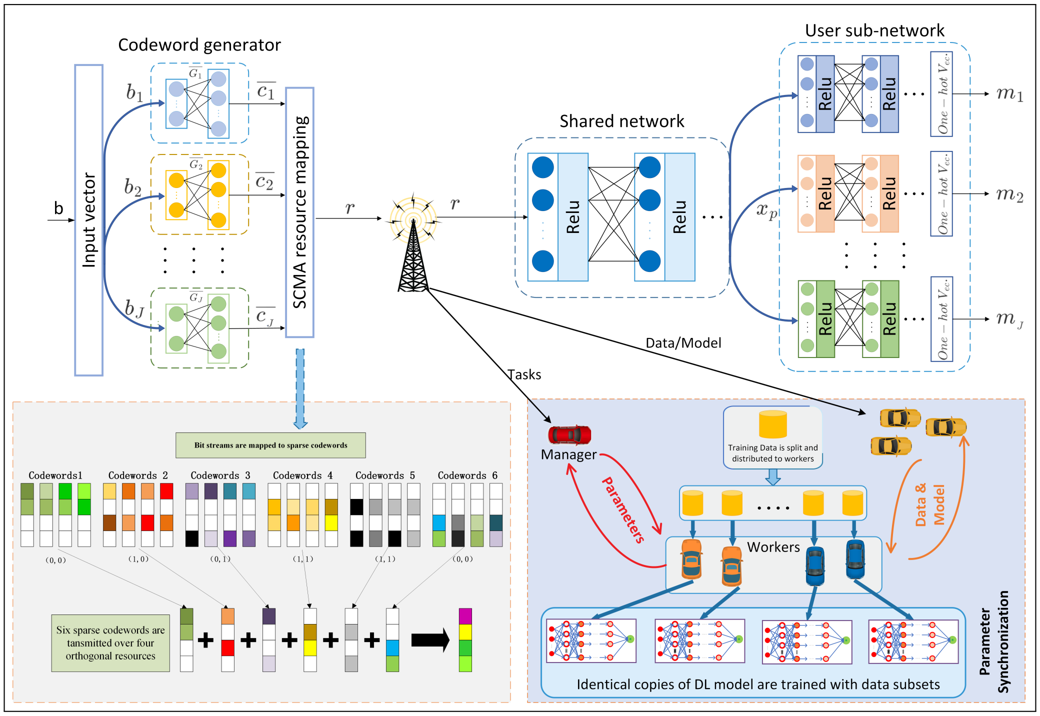

Fig. 1. Illustration of an uplink multi-user SCMA system

oped [7], [8]. Among them, a decentralized machine learning paradigm called federated learning (FL) has recently emerged, which can collectively train a system model using cooperation and feedback while preserving the privacy of training data by storing it locally on mobile clients [9]. In FL framework, multiple devices or clients can be adapted to collaboratively train a shared global model while each mobile client is allowed to train its own local model using its own local data. The local model is then sent to the central aggregator that synthesizes a global model instead of raw data, and the process repeats. FL significantly balances the transmission latency connection and the codewords design accuracy. In addition, reconfigurable intelligent surface (RIS) can also be adopted to improve the higher connectivity and the desired spectrum [10]. To this end, it is interesting to develop SCMA codeword construction combined with FL scheme by properly adjusting the reflecting element of RIS. Motivated by these facts, we specifically focus on the FL driven SCMA codewords design and the higher connectivity problem within the massive transmission links.

The main contribution of the paper is a lookahead vision that establishes the potential integration of SCMA and FL in V2X networks, and point out future research directions. In particular, the considered vision identifies the potential challenges, potential solutions and technological trends that can enable the realization of FL-aided SCMA architecture in V2X networks. We discuss the requirements that the proposed scheme is superior to conventional SCMA-based architecture. Finally, several implementation challenges and future work are highlighted for the FL technique at V2X networks.

II. Fundamentals of SCMA-aided V2X Communication

A. SCMA Design Principles

This section briefly reviews the model of the SCMA-aid V2X Communication, where the implementation of SCMA transmission is depicted in Fig. 1. In the encoder, coded bits are modulated to the multidimensional sparse codewords consisting of the high-dimensional lattice points. As the grey box shown in Fig. 1, for each user, two bits are mapped to the four-dimensional sparse codewords, where the positions of zeros in different codebooks are distinct to facilitate the collision avoidance of any two users. Therefore, at most, $\binom{K}{N}$ users can be accommodated, where K is the total number of subcarriers and N denotes the number of nonzero entries. To enable the sparse structure of codewords, it is imperative to ensure that $N \ll K$. This reduces the probability of users encountering collisions within a single subcarrier and further simplifies decoding. Considering the four-dimensional codewords in the grey box, as depicted in Fig. 1, the maximum number of users is limited to six, whereas, due to the sparsity of codewords, the number of possible collisions among users is reduced to three per subcarrier.

B. SCMA-aided V2X Networks

Benefiting from widely deployed infrastructure of V2X, the SCMA has emerged as a promising solution to support V2X services, which enable ubiquitous interactions with vehicular environments including the infrastructures, devices, and participants. This facilitates the custom-designed vehicular services, while ensuring secure and convenient driving experiences. An

Performance Metrics	Mathematical Tools	Solutions	Technology
Network utility and diverse vehicle requirements e.g., spectral efficiency and energy efficiency	• Convex optimization • Nonlinear programming • Random search methodologies • Probability and statistics theory	• Codeword approaches • Heuristic approaches • Random search methodologies • Learning-based approaches	• Power allocation • User scheduling • Antenna association • Hybrid beamforming

Fig. 2. Overview of SCMA in V2X network.

overview of multiple access in V2X network is provided in Fig. 2. An immersible driving vehicular should be satisfied the following features:

1) Ubiquitous vehicular connectivity: To facilitate a wide range of personalized connected services, it is imperative to establish a ubiquitous, high-speed and affordable vehicular connectivity infrastructure for V2X network. However, a reliable vehicular connectivity is the foundational prerequisite for achieving the unique and tailored V2X network.

2) On-demand location services: As increasing number of RIS-based vehicular services, on-demand location services emerge as a pivotal competitive capability within V2X networks, which can be employed to enhance road safety, offer in-vehicle entertainment, and optimize transportation efficiency.

3) Human-vehicle interaction: With the advances of communication and automation technologies, human-vehicle interactions will be crucial to the intelligent transportation system, which can make transportation more inclusive and environmentally friendly. Intelligent transportation systems driven by effective human-vehicle interaction can exchange real-time data about road conditions, traffic congestion, weather, and more. This shared information can contribute to more informed decision-making, helping drivers choose optimal routes, which can reduce fuel consumption and lower emissions.

4) Real-time data sharing: To facilitate the sharing of more one word data, RIS can be deployed to provide more transmitting connection in V2X networks, which can facilitate the sharing of real-time vehicle driving status, such as speed, acceleration, braking, and location. This information can be valuable for enhancing safety and traffic flow management. For example, if a vehicle ahead suddenly brakes hard, this information can be communicated to vehicles following behind to trigger timely responses and avoid collisions.

5) In-motion multimedia networking: A more cost-effective and convenient vehicular driving experience will be made possible by in-motion vehicular multimedia networking, which involves the seamless sharing of multimedia content. Considering the strong interest in V2X networking, various internet-based onboard multimedia services will be regarded as an indispensable technology for connected vehicles driven.

III. Key Challenges of SCMA Design in V2X

The SCMA design is a modulation and multiple access technique that enables multiple users to share the same frequency resources by assigning specific codewords to each user. Due to the complexity of the SCMA design, finding the most appropriate design criterion and specific solution are still challenging, including maximizing data rate, minimizing interference, optimizing spectral efficiency, or achieving a balance between these factors. Thus, how to break the limitation of local codewords in the form of isolated islands and guarantee the reliable performance still face the challenge. Several research challenges arise and are listed in the following.

A. High Vehicle Mobility vs. Codewords Sharing Behavior

The availability of SCMA codewords is closely related with the various road topology, vehicle traffic condition and the demand for vehicular service. However, for different designated locations, SCMA-based codeword configurations may be different, including the number of SCMA-based codewords and phase shifts constraints, which lead to lower vehicle utilization. Furthermore, 6G V2X networks are subject to frequent spatio-temporal variations in their topologies due to the inherent challenges posed by high and variable relative vehicle speeds. Therefore, the high mobility of vehicular services would greatly affect the SCMA-based codewords sharing efficiency in vehicular communications, which become the main focus of the study in 6G V2X networks.

On the other hand, a feasible solution is to develop the dynamic codewords sharing demand by utilizing real-time traffic planning and RIS-assisted vehicular information. Since the quality of radio channels depend on the diversity of vehicle distribution, different types of codewords will be exploited to support different RIS-assisted vehicular services. Therefore, to achieve better 6G V2X resource utilization and RIS-assisted vehicular services, it is necessary to jointly study the dynamic SCMA-based codewords sharing behavior under the impact of high vehicle mobility, which is the key challenge of 6G SCMA-based codewords sharing in FL-driven vehicular communications.

B. Vehicular Service Diversity vs. SCMA-based Codewords Performance

SCMA-based vehicular communications have been envisioned to play an important role in the successful implementation of diverse tailor-made connected vehicular services ranging from traditional vehicular applications to unique applications. For ubiquitous vehicular connectivity environments, more and more diversified and personalized demand for services are the basic to realize the realtime traffic management and vehicular safety-related applications, such as traffic alert and collision avoidance. Therefore, how to provide efficient SCMA codewords over 6G spectrum bands by considering

Technology / Metric	Conventional FL	Parallel FL	Combined FL	Hybrid FL
Flexibility	Easy to deploy	Easy to launch	Harder to deploy	Easy to launch
Complexity	Limited computation	Medium computation	High computation	Medium computation
Modeling	Data-parallel	Data-parallel	Data-parallel + model-parallel	Data-parallel + model-parallel
Stability	Unstable	Stable	Stable	Stable

Fig. 3. Comparison of different paradigms of FL.

the complexities of vehicular mobility patterns and the various vehicular application demand is a key research issue.

In addition, massive vehicular connectivity disruptions would be occurred frequently due to the dynamics of SCMA-based codewords topology. Therefore, dynamic and seamless interworking of vehicular data is another issue for the vehicular diversified service requirements.

C. Radio Resource Heterogeneity vs. SCMA-based Codewords Sharing Efficiency

Modern smart vehicles require multiple wireless access techniques operating on different spectrum bands, which is becoming increasingly important in ensuring efficient and reliable vehicular communications. In this circumstances, the performance of dynamic SCMA codewords are eventually determined by the operating capability of a system in multiple frequency bands. Note that vehicle devices are requested to change working mode flexibly and can be compatible with all kinds of equipment under different systems and standards, which brings numerous limitations to the processing of V2X network. Therefore, it is necessary to coordinate different vehicle devices to maximize the spectrum utilization for different codewords sharing demands and spectrum heterogeneity.

IV. Federated Learning Driven SCMA of V2X Network

FL is a distinct type of distributed learning to tackle multidimensional values exhibiting nonlinear characteristics, which is an ideal solution for the SCMA-based codebook design. Fig. 3 summarizes the features of the discussed FL-based SCMA schemes. The core idea is to collaboratively learn a shared prediction model, wherein all training data remains localized on individual vehicles. Consequently, the design of an appropriate SCMA codeword significantly affects the overall detection performance.

Although FL can reduce the SDMA decoding complexity, the FL is still identified as a black box. The relationship between a network structure and the decoding process is rarely explored, leading to a lack of interpretability in the network model. On the other hand, instead of sending the raw data to a central data center for training, the data is trained locally on each device, reducing the risk of exposing sensitive information, which is particularly useful to dealing with privacy-sensitive or large datasets [11]. However, the performance depends on codewords design, when the parameters of the SCMA system change, the original codewords may suffer from the problem of performance degradation.

To further improve the performance of codewords, we propose the FL empowered SCMA scheme for distributed learning in V2X networks. There are three types of SCMA codewords that can be developed for V2X network: parallel-model mechanism, combined-model mechanism, and hybrid-model mechanism. The scheme can be further used for facilitating SCMA-based codeword sharing and content caching among vehicles. Instead of using a vulnerable centralized server, the federated vehicle learning is exploited to design SCMA codewords, which can provide permission control over participating users and secure data encryption. The above mentioned three types of SCMA codewords have their own features, which can significantly enhance the security and privacy of parameters in FL framework. In the next section, we will provide the comprehensive methods to support diverse services and applications in future 6G networks.

A. Parallel Mechanism

The data-parallel processing approach has emerged recently, in which the original data is generally divided according to the number of vehicles. Each vehicle processes a unique part of the model by exploiting the FL-based algorithm separately. Since the computation capacity of vehicles is much greater than that of mobile phones, more flexible ML algorithm should be developed to process both data and model in parallel. The same or different model is replicated to all vehicle services. It is worth noting that the data sets in the existing model-parallel approach can be shared within all vehicle services. Each vehicle is responsible for a unique part of the model, rather than a specific portion of the data set. However, this method is limited to specific ML algorithms, as it cannot accommodate model parameters that are inherently interdependent and cannot be learned separately. Consequently, it significantly affects the convergence and communication overhead.

The blue box shown in Fig. 4 illustrates the proposed parallel mechanism and flow, where RIS is deployed to provide

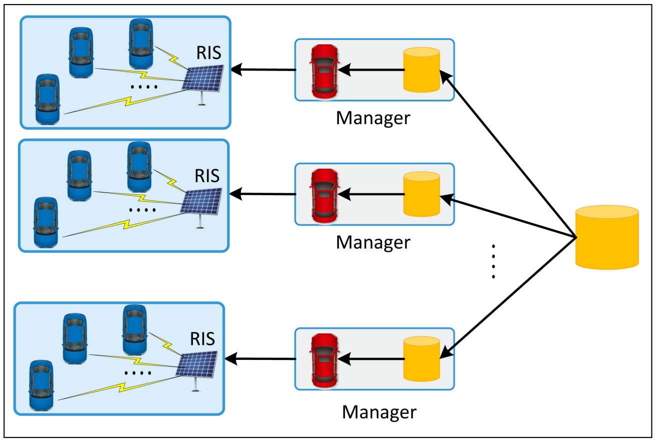

Fig. 4. Combined schemes. A larger partition of the dataset is allocated to worker group (manager) that each worker group is responsible for a unique part of the model.

more connectivity options to vehicle nodes. To update the aggregating and averaging of parameters, a designated vehicle (red car icon) is designed as the parameter server that behaves as the manager. Each vehicle within the network serves as a client node, denoted by the blue car icon. The data collected by the vehicles, the specific computational tasks as well as the corresponding models are shared between client node and venue infrastructure. Each worker node focuses on a distinct partition of the dataset for parallel processing, then the FL-based SCMA algorithm is employed to perform the computational tasks. As a result of learning and training, these changes are sent back to the designated vehicle. The venue infrastructure acts as a resource manager, denoted by the cell tower icon, which makes sure that the allocation of specific data set partitions is assigned to each vehicle. At the start of each iteration, the data set is divided into several sections, which is equal to the number of vehicles participating. After the end of the iteration, the resource manager consolidates all modifications, including acquired learned parameters. Subsequently, the averaged changes is sent to the participating vehicles in response to an updated model.

The proposed mechanism has several desirable advantages. Firstly, high-tech vehicles are more resourceful, and have larger battery capacity than conventional mobile devices. Each vehicle can be regarded as a fundamental computational and storage unit to improve the system capability. Secondly, compared to prior vehicular clouds/networks, FL-aid SCMA framework is available to heterogeneous network for high-bandwidth transmission of data, and the concept of RIS is introduced to enhance coverage area and exchange/update data efficiently. Thirdly, integrating venue infrastructure into SCMA-assisted V2X networks not only can lead to enhanced interaction with clients and provide incentives for various parties involved, but also provide seamless interaction with clients, particularly in the context of Beyond 5G and 6G.

B. Combined Mechanism

Compared with the parallel mechanism, the main difference in the combined approach is to split participating vehicles into "worker groups". By exploiting the RIS, each worker group is responsible for handling a specific partition of the dataset. As depicted in Fig. 4, a model-parallel approach is employed to facilitate the acquisition of model parameters within their designated dataset. To achieve this, each worker group focuses on a specific part of the model, which is responsible for handling a specific partition of the dataset. The corresponding combined approach for FL-aid SCMA is managed in Fig. 4.

The SCMA-aided V2X network is a more suitable alternative compared to edge, fog and cloud solutions, wherein training tasks are offloaded to edge or fog computing nodes. In SCMA-aided combined mechanism, the sensitive data can be trained on the on-board units of their own vehicles without data sharing and collaboration capabilities. Compared to the recent concept of fog computing-enabled self-driving learning that focuses mainly on the communication perspective, FL-aided SCMA consider a highly competitive federated V2X architecture by employing a combination of heterogeneous network, SCMA and FL, which can improve the shared model without exposing individual data [12]. Finally, the integration of V2X systems allows FL-aided SCMA to mitigate malicious behaviors. By virtue of parallel processing of combined mechanism, SCMA decoding based on FL-aid networks can reduce computational complexity compared to conventional iterative decoding algorithms.

Driven by the imperatives of faster connection and durability, the combined mechanism requires workers to iteratively update models. As shown in Fig. 4, the data is split into a series of patches on the basis of manager (red car icon), and each worker node deals with a different patches of data through RIS-assisted connection. It is essential to note that different from the parallel mechanism, the combined mechanism requires each worker to use exactly the same ML algorithm for the model training.

C. Hybrid Mechanism

To support a high overloading factor, a hybrid SCMA mechanism is investigated. As shown in Fig. 5, a hybrid mechanism provides a basic idea of exploiting the FL to the concept of SCMA-aid V2X network. The architecture of such mechanism is divided into two part: inner and outer layers. To facilitate remote vehicles access, RIS is employed to connect the outer network. K near vehicles (NVs) adopted high-frequency SCMA codewords to design the inner layer structure, while J far vehicles (FVs) adopt low-frequency SCMA codewords for the transmission of the outer layer.

To improve the performance of SCMA, FL-aided learning model is exploited to design the hybrid SCMA codewords: one for NVs symbol detection, and the other for FVs symbol detection. Then, a trained offline strategy is employed to the designed mode by using the simulated data and applied for online symbol detection. Compared to conventional SCMA schemes, the proposed hybrid SCMA framework can be broken up into the FL network used, parallelism, and the resource heterogeneity design, which guarantees a good error rate performance.

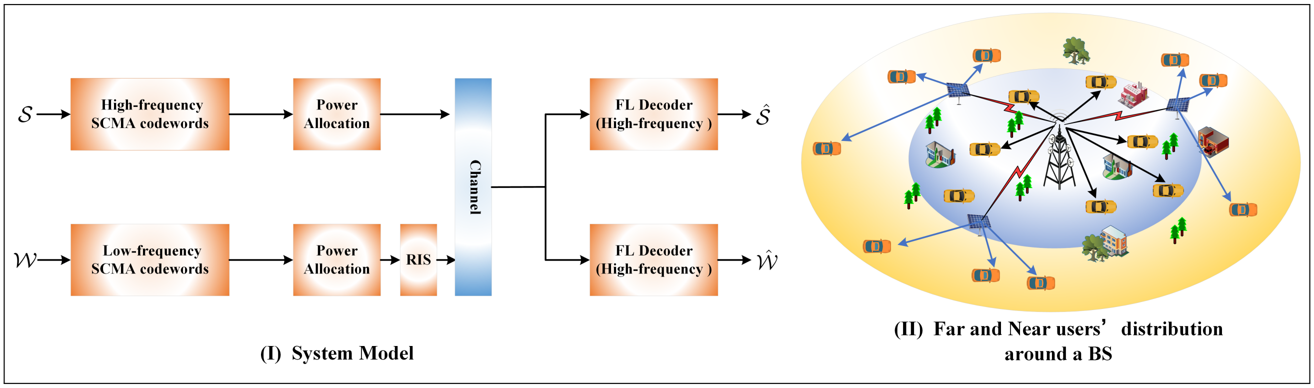

Fig. 5. Hybrid SCMA mechanism. (I) System model. (II) Far and near distribution around a BS.

V. Performance Evaluation

A. Simulation and Results

To evaluate the performance of the proposed FL-aid SCMA schemes in terms of Bit Error Ratio (BER), we perform simulation on Python and Network X for a federated vehicle learning, a network simulator library in Python. For SCMA-based federated vehicle learning, the training sets of the well-behaved vehicles are randomly generated, which follow a uniform distribution over 12 classes. The BER qualification index is used to measure the learning performance by minimizing the model aggregation error. The networking parameters settings are determined based on the Third Generation Partnership Project (3GPP) Release LTE document [13].

The downlink SCMA system with J users is considered to communicate over K orthogonal resources. Then, we choose the benchmark as the learning performance of Huawei codewords without any distortion. A wide range of training $\mathrm{E_b/N_0}$ values are selected. The codeword generator is implemented with $\log 2(M)$ input nodes and $2 \times K$ output nodes. Since the values of $\mathrm{E_b/N_0}$ in training influence the BER performance, we investigate the system performance versus the influence of training samples generated with different $\mathrm{E_b/N_0}$ values, as depicted in Fig. 6. We compare the BER performance of the proposed FL-aided SCMA scheme with the parallel, combined and hybrid scheme, and the conventional SCMA scheme with Huawei codeword [14]. The results show that the advantage of the proposed FL-aid SCMA becomes more remarkable, compared to conventional Huawei schemes. The reason is that the reliable and designated vehicle nodes provide high-quality training data, which have positive impacts on the accuracy.

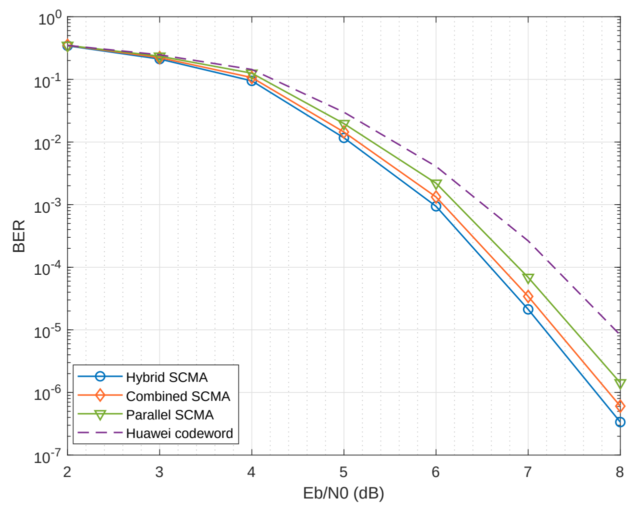

Fig. 6. The BER performance of different codebooks.

VI. Open Research and Challenges

The framework of FL-based SCMA exhibits considerable potential for substantial enhancement in the capacity of V2X networks with different overloading factors. However, there are still several open issues and challenges to be solved in V2X network. Some future research directions are outlined as follows.

1) Anti-Interference SCMA Resource Allocation: In future B5G/6G V2X scenarios, the channel interference between vehicles is inevitable, which is a fundamental bottleneck for significant error rate performance enhancement. As a result, designing an anti-interference SCMA power allocation algorithm to realize efficient spectrum access of diversified vehicles is necessary.

2) Large-Scale SCMA Decoding Scheme: An SCMA scheme with higher data rate and massive connectivity should be developed. The traditional SCMA codebook design lacks the scalability, which limits the applicability of SCMA in large-scale systems. Thus, considering both the communication priority and quality of service (QoS) of vehicle devices, an adaptive SCMA decoding order should be developed to provide massive connectivity in the high speed the V2X networks.

3) SCMA-aid Integrated Sensing and Communication (ISAC): In SCMA-aided ISAC scenarios, SCMA can support more communication and radar links simultaneously, which could lead to radar-communication beamforming interference in coexisting interference and spectrum sharing in underlay spectrum access. FL driven SCMA can be deployed on-demand for enhancing the throughput of ISAC network. Thus, the FL-aid SCMA codewords should be further investigated to promote vehicular diversified services for further V2X communications.

VII. Conclusion

This article reviewed the potential of FL-aid SCMA technologies of vehicular networks. We have specifically highlighted three key performance enhancing techniques by utilizing FL scheme and SCMA techniques, which can tackle the challenge of limited vehicular communication for the future V2X network. We showed how a proper FL-based model design as well as the dynamic codewords construction can promote an improved vehicle communication. The article also highlighted some of the key open issues including the design of FL-based SCMA model, optimal design of codewords. It is hoped that the proposed FL-SCMA will help pave the way for researchers to implement the federated vehicular learning in future 6G V2X communications.

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Biographies