Subcarrier Index Modulation for Future Wireless Networks: Principles, Applications, and Challenges

Preprint · March 2020

DOI: 10.13140/RG.2.2.27842.94406

Qiang Li
South China University of Technology

Miaowen Wen
South China University of Technology

Bruno Clerckx
Imperial College London

Subcarrier Index Modulation for Future Wireless Networks: Principles, Applications, and Challenges

Qiang Li[†], Miaowen Wen[†§], *Senior Member, IEEE,*
Bruno Clerckx[‡], *Senior Member, IEEE,* Shahid Mumtaz[$], *Senior Member, IEEE,*
Anwer Al-Dulaimi[#], *Senior Member, IEEE,*
and Rose Qingyang Hu[◊], *Fellow, IEEE*

[†]School of Electronic and Information Engineering,
South China University of Technology, Guangzhou 510640, China

[§]National Mobile Communications Research Laboratory,
Southeast University, Nanjing 210096, China

[‡]Department of Electrical and Electronic Engineering,
Imperial College London, London SW7 2AZ, U.K.

[$]Instituto de Telecomunicações, Aveiro 3810-193, Portugal

[#]Center of Excellence, EXFO Inc., Quebec, QC G1M 2K2, Canada

[◊]Department of Electrical and Computer Engineering,
Utah State University, Logan, Utah 84322-4120, USA

Email: eeqiangli@mail.scut.edu.cn, eemwwen@scut.edu.cn, b.clerckx@imperial.ac.uk,
smumtaz@av.it.pt, anwer.al-dulaimi@exfo.com, rose.hu@usu.edu

Abstract

The unprecedented surge of mobile data traffic requires future wireless networks to support both high spectral efficiency and energy efficiency. To this end, index modulation (IM) emerges as a revolutionary modulation concept. As a realization of IM in frequency domain, subcarrier IM (SIM) has been receiving significant interest. In this article, we introduce the generic framework of SIM and its specific representatives. The potential applications of SIM are then investigated in a variety of scenarios, including cognitive radio, relay networks, downlink multiuser communications, and physical layer security. We finally discuss the challenges and possible research directions in SIM and its applications.

I. INTRODUCTION

Diverse services, secure communications, and high spectral/energy efficiency (SE/EE) are driving the development of wireless networks. According to the forecast of Cisco, by 2022 the number of devices connected to Internet protocol (IP) networks will be more than three times the global population, the traffic from wireless and mobile devices will account for 71% of total IP traffic, and the average mobile network connection speed will more than triple that in 2017. The challenges faced by future wireless networks are multifold.

- *Requirement of High SE/EE:* Due to the explosive increase in mobile data traffic, new groundbreaking physical layer technologies with high SE/EE and low transceiver complexity are highly demanding. Over the past 50 years, we have been persisting in the traditional digital modulation schemes by altering the amplitude, the phase, or the frequency of a sinusoidal carrier signal. High order modulation formats are required to meet the demand of high data rates, and meanwhile increased signal power or complicated channel coding shall be coupled for achieving targeted error performance.
- *Increasingly Random and Diverse Mobile Traffic:* Mobile traffic is distributed unevenly across space and time. Such an acute traffic fluctuation results in an obvious dilemma in the network planning: the network capacity is either insufficient for busy hour traffic demands or overabundant for average traffic loads. Moreover, mobile traffic becomes increasingly diverse with the development of various new applications/services that have different quality of service requirements. Since traditional cellular networks are designed to operate over expensive licensed bands and offer low-volume delay-sensitive services such as voice, it is very cost-ineffective to run high-volume delay-insensitive services such as non-real time sharing of video files over current wireless networks.
- *High Propagation Loss for High Frequencies:* Although both below and above 6 GHz spectrum are considered for future wireless networks, high frequencies, typically millimeter wave (mmWave), would be more essential due to the huge bandwidth it can offer. However, the major drawback of mmWave is that it has small coverage area and trouble in penetrating buildings. Small-cell deployment can address this issue to some extent, which, however, requires huge capital expenditures.
- *Serious Threats From Powerful Eavesdroppers:* Future wireless communications are expect-

ed to shape the industrial world as well as our daily life. People heavily rely on wireless networks for the transmission of critically important/private information, such as command and control messages. Security is a critical issue for the networks. As the computational ability of eavesdroppers increases, cryptography-based methods on the application layer, which entail key generation, distribution, and management, may no longer provide adequate security, especially in dynamic and heterogeneous networks with massive connectivity.

Standing up against the above challenges, cognitive radio, relay networks, and physical layer security (PLS) with high SE/EE are promising technologies for future wireless networks. Index modulation (IM) is a novel digital modulation technique that leverages upon the on-off state of the transmission entities such as antenna, subcarrier, spreading code, and signal constellation to convey information [1]. A prominent feature of IM is that the additional information is implicitly transmitted over the emitted signal at the cost of little or even no power, achieving significant benefits in terms of SE and EE. For these advantages, IM appears as a competitive candidate with the potential to interact with the technologies of cognitive radio, relay networks, and PLS with high SE/EE to shape future wireless networks. It is worth noting that the IM concept has been carried out in Long Term Evolution for hybrid automatic repeat request-acknowledgement (HARQ-ACK) and scheduling request (SR) reporting via physical uplink control channel (PUCCH) format 1a/1b. The HARQ-ACK is explicitly transmitted on the SR PUCCH resource, whose state implicitly conveys the SR.

Subcarrier IM (SIM) refers to a family of IM in the frequency domain that is performed over the orthogonal frequency division multiplexing (OFDM) subcarriers [2]. The principle of SIM originally appeared in 1999 [3], and it has attracted increasing interest after the emergence of [2]. The recent standardization that OFDM is deemed as both uplink and downlink waveforms of 5G wireless networks sets off a new wave of development of SIM. In comparison with classical OFDM, SIM has the potential to achieve higher SE/EE and lower peak-to-average power ratio (PAPR) with less medium resource occupation. The presence of empty subcarriers also facilitates the design of PAPR reduction methods. However, most of the existing works about SIM lay emphasis on performance-enhancing SIM schemes, while the applications of SIM are still waiting to be investigated extensively. In this article, first, we present a generic framework for SIM. Then, we unlock the potential of SIM in the applications to cognitive radio, relay network, downlink multiuser communications, and PLS scenarios. Finally, we point out interesting possible research directions on SIM. To the best of the authors' knowledge, this is the first magazine paper that describes SIM with a unified framework and investigates the potential applications of SIM in specific scenarios.

II. THE SIM FAMILY

There are various SIM schemes, including OFDM-IM [2], dual-mode (DM)-OFDM [4], zero-padded tri-mode (ZTM)-OFDM-IM [4], and multiple-mode (MM)-OFDM-IM [5], which differ in the ways of activating subcarriers and/or signal constellations (modes). All these schemes can be described in a unified framework by treating the idle state of a subcarrier as a null mode that only contains the symbol "0". In this sense, SIM relies on the indices of subcarrier mode patterns (SMPs) for extra information embedding.

In SIM, the information bits to be transmitted are split into index bits and constellation bits. The index bits are used to determine which SMPs are selected, and the constellation bits are mapped to conventional constellation symbols according to the selected SMPs. For an efficient IM, all subcarriers of an OFDM system are usually divided into several subblocks and the same IM procedure is performed within each subblock. We focus only on a single subblock unless otherwise noted. For a subblock of n subcarriers, the number of modes for SIM can be an arbitrary integer ranging from 2 to n. Suppose that the number of modes is m and the number of subcarriers modulated by the i-th mode is k_i, where $m \in \{2, \dots, n\}$, $i = 1, \dots, m$, and $k_1 + \cdots + k_m = n$. There are $\binom{n}{k_1}\binom{n-k_1}{k_2}\dots\binom{n-k_1-\cdots-k_{m-1}}{k_m}$ possible realizations of SMPs in total, where $\binom{\cdot}{\cdot}$ denotes the binomial coefficient. Hence, the system SE in terms of bits per second per Hertz (bps/Hz) is

$$\eta = \frac{1}{n}\left\lfloor \log_2\left(\binom{n}{k_1}\binom{n-k_1}{k_2}\dots\binom{n-k_1-\cdots-k_{m-1}}{k_m}\right)\right\rfloor + \frac{k}{n}\log_2(M), \tag{1}$$

where $\lfloor\cdot\rfloor$ denotes the floor function, k is the number of subcarriers modulated by non-null modes, and all non-null modes have the same cardinality M. The first and second terms on the right-hand side of (1) are contributed by the index bits and constellation bits, respectively.

SIM is a very flexible technique that can be embodied in a variety of specific schemes by judiciously adjusting the values of m, k, and $k_i, i = 1, \dots, m$. SIM also subsumes the classical OFDM as a special case with a single non-null mode. Fig. 1 illustrates the examples of index mapping and the bit error rate (BER) performance of four representatives of SIM, namely OFDM-IM, DM-OFDM, ZTM-OFDM-IM, and MM-OFDM-IM, which will be categorized into SIM with two modes and with multiple modes subsequently. In principle, any m signal constellations whose intersection is a null set can be chosen as the m modes. However, in order to facilitate symbol modulation/demodulation and achieve good BER performance, the m modes are usually obtained by partitioning phase shift keying (PSK)/quadrature amplitude modulation (QAM) constellations as described in [5].

A. SIM with Two Modes

1) OFDM-IM: In OFDM-IM, each subcarrier is modulated by either the conventional M-ary constellation or the null mode such that (1) reduces to $\eta = (\lfloor \log_2(\binom{n}{k_1}) \rfloor + k \log_2(M))/n$ as $m = 2, k_1 = n - k$, and $k_2 = k$. As shown in Fig. 1(a), part of subcarriers are inactive and the indices of subcarrier activation patterns convey extra information bits, i.e., index bits, via IM, thus enhancing the EE of OFDM. It is revealed in [4] that OFDM-IM outperforms classical OFDM in terms of BER for an SE below 2 bps/Hz. However, OFDM-IM fails to exhibit an explicit BER advantage over its OFDM counterpart for a higher SE. The presence of inactive subcarriers in OFDM-IM accounts for this deficiency as they themselves do not carry any information, and a higher SE has to be attained with a larger cardinality of the signal constellation.

2) DM-OFDM: DM-OFDM follows the same IM idea as OFDM-IM except that both modes in DM-OFDM are non-null ones, as presented in Fig. 1(b). For $M = 2$, the two non-null modes can be $\{-1, +1\}$ and $\{-j, +j\}$, where j is the imaginary unit. The SE of DM-OFDM is given by $\eta = \lfloor \log_2(\binom{n}{k_1}) \rfloor / n + \log_2(M)$. Hence, DM-OFDM has a higher SE than OFDM and OFDM-IM under the same cardinality of the modes.

B. SIM with Multiple Modes

1) ZTM-OFDM-IM: ZTM-OFDM-IM can be treated as the integration of OFDM-IM and DM-OFDM, possessing two non-null modes and one null mode, as shown in Fig. 1(c). It tries to leverage the spectrum-efficient DM-OFDM and the energy-efficient OFDM-IM with one more mode, capable of improving the EE of DM-OFDM and the SE of OFDM-IM.

2) MM-OFDM-IM: In MM-OFDM-IM, all subcarriers are activated to transmit M-ary symbols that are drawn from different signal constellations. Particularly, (1) can be simplified as $\eta = \lfloor \log_2(n!) \rfloor / n + \log_2(M)$ since $m = n$ and $k_1 = \cdots = k_m = 1$. The number of modes is n, and the full permutations of these distinguishable modes are utilized for IM purposes, enabling a factorial increase of the number of all possible modes. From the perspective of achieved SE, MM-OFDM-IM equivalently enlarges the symbol constellation by n/e times in comparison with classical OFDM, where $e = 2.7183$ is the Euler's number.

C. BER Performance of SIM

Both the M-ary symbols and the SMPs should be detected for SIM. In the literature, various detectors, including the optimal maximum-likelihood (ML), log-likelihood ratio, and sequential detectors, are developed for SIM schemes [1], [4]. In Fig. 1(e), we show the BER performance of classical OFDM, OFDM-IM, DM-OFDM, ZTM-OFDM-IM, and MM-OFDM-IM with $n = 4$ and perfect channel state information (CSI) at the receiver, assuming ML detectors over frequency selective Rayleigh fading channels. The parameters are chosen carefully for all schemes to achieve the SEs as close as possible. At medium to high signal-to-noise ratio (SNR), OFDM-IM achieves about 3 dB SNR gain over classical OFDM at an SE of 2 bps/Hz. DM-OFDM and ZTM-OFDM-IM even outperform classical OFDM with binary PSK (BPSK). MM-OFDM-IM performs the best among all schemes, even with a higher SE than classical OFDM with BPSK, DM-OFDM, and ZTM-OFDM-IM. In particular, an up to 6 dB SNR gain can be achieved by MM-OFDM-IM over classical OFDM at an SE of 2 bps/Hz.

III. APPLICATIONS OF SIM

How to explore the two information-carrying units and partial inactive subcarriers that are unique in SIM systems for potential applications is an interesting open problem. In this section, we answer this problem by limiting our focus on the promising applications, including cognitive radio, relay networks, downlink multiuser communications, and PLS.

A. SIM in Cognitive Radio

Cognitive radio allows unlicensed (secondary) systems to opportunistically use the idle spectrum owned by licensed (primary) systems, thereby improving spectrum utilization significantly and providing a solution to cope with explosive, random, and diverse mobile data traffic [6]. Underlay, overlay, and interweave are three main spectrum access strategies in cognitive radio. In classical OFDM, to share a frequency band concurrently, the secondary user has to minimize the detrimental interference on the primary user. For SIM, the interference incurred by the secondary user may be turned into helpful side information to boost the performance of the primary user. There has been an attempt to explore the potential of OFDM-IM in overlay OFDM-based cognitive radio networks [7]. Therein the primary transmitter (PT) transmits classical OFDM signals, and the secondary transmitter (ST) employs OFDM-IM to forward the PT's information via constellation symbols and convey its own information through SMPs. However, due to the decrease in the number of active subcarriers at the ST, the ST has to use a larger constellation size than the PT. Next, we will discuss some novel SIM-based cognitive radio models with overlay and interweave strategies. Here, only the relay-aided cognitive radio is studied. Actually, since there still exist two information-carrying units and/or inactive transmission entities in non-relay scenarios, SIM can also be applied to the cognitive radio without relaying.

1) Overlay Paradigm: In this paradigm, the secondary users access the primary spectrum at the cost of sacrificing part of their power to facilitate the primary transmission through cooperative amplify-and-forward (AF) or decode-and-forward (DF) relaying, as illustrated in Fig. 2(a). Based on the model, both OFDM and OFDM-IM are supported for the PT, and AF and DF relaying protocols are both feasible at the ST.

- When the PT employs OFDM, for DF relaying, the ST decodes the received signal, and then encodes the decoded data and its own information into MM-OFDM-IM signals, in which the constellation bits and index bits are dedicated for the primary receiver (PR) and the secondary receiver (SR), respectively; for AF relaying, the ST performs phase rotation on the received signal, where the index of the rotation angle carries the information of the ST via IM.
- When the PT employs OFDM-IM, for DF relaying, the ST decodes the received signal and then forwards a DM-OFDM signal by modulating the inactive subcarriers with its own data; for AF relaying, the ST senses the received signal and then superimposes its own signal on the inactive subcarriers of the received signal, outputting a DM-OFDM signal as well.

Obviously, thanks to the unique feature of SIM, the primary users do not need to spare frequency/time resources for the transmission of the secondary information in the SIM-based overlay cognitive radio.

2) Interweave Paradigm: In this paradigm, the secondary users exploit spectrum holes, which are spectrum resources assigned to a primary user but not being occupied by that user, for transmission. A potential application of SIM-based interweave cognitive radio is depicted in

Fig. 2(b), where the primary users rely on the dual-hop OFDM-IM AF relaying for priority transmission and the secondary users exploit spectrum holes of the primary network for opportunistic communications. Specifically, in the first phase, the PT broadcasts OFDM-IM signals to an AF relay and the ST. Upon the received signal, the ST measures the SNR and performs spectrum sensing. In the second phase, relay amplifies and forwards the received signal to the PR. Meanwhile, if the SNR of the PT-to-ST link is above a predefined threshold, the ST transmits its own information on those inactive subcarriers of the primary network to the secondary receiver (SR); otherwise, the ST stays in silent mode.

It should be noted that the PR (SR) suffers from the interference from the ST (PT). Fortunately, the interference can be transformed into performance gains, provided that the CSI of the secondary (primary) network is available at the PR (SR).

B. SIM in Relay Networks

Cooperative relaying is an effective technique to extend the wireless coverage and improve the performance of cell edge users. Apart from traditional dual/multi-hop AF/DF relaying [8], [9], more advanced relaying techniques, such as relay selection [10] and full-duplex relaying [11], can be also incorporated into SIM systems. Here, we propose to apply SIM to subcarrier mapping (SCM)-aided and two-way relay networks for improving the system capacity and SE.

1) SCM-Aided Relaying: In multi-carrier relay networks, the system capacity and end-to-end error performance can be significantly improved by means of SCM. With SCM, the incoming and outgoing subcarriers at the relay can be completely different depending on their SNRs [12]. The subcarrier reordering information is thereby required at the destination to recover the original transmitted messages. The existing schemes for signaling the reordering information occupy extra subcarriers, thus inevitably degrading the system SE.

SIM offers an effective tool to solve the signaling overhead problem from an alternative perspective. The basic principle is to transfer the subcarrier permutation to the mode permutation that can be implicitly transmitted via a constructed MM-OFDM-IM signal at the relay without consuming additional spectrum resource [13]. Let us take the dual-hop OFDM DF relaying as an example, as shown in Fig. 3(a). Given the CSI of both hops, the relay calculates the subcarrier reordering function according to the mapping rule, such as best-to-best (namely the best subcarrier of the first hop is paired with the best subcarrier of the second hop, second best with second best, and so on) or best-to-worst (namely the best subcarrier of the first hop is paired with the worst subcarrier of the second hop, second best with second worst, and so on) matching. After decoding all symbols carried on the received OFDM signal in the first phase, the relay re-encodes the symbols and maps the subcarrier permutation to the mode permutation based on the MM-OFDM-IM principle, outputting a constructed MM-OFDM-IM signal in the second phase. At the destination, the mode permutation and scrambled symbols are detected, from which the transmitted symbols can be recovered in correct order.

2) Two-Way Relaying: In conventional two-way relay networks, four time slots are required to complete an information exchange. Based on SIM, a novel two-way relaying system saving one transmission phase can be established.

An example is given in Fig. 3(b), where Source 1 and Source 2 employ OFDM-IM to communicate with each other with the aid of the relay. In the first phase, Source 1 sends its own data to the relay via an OFDM-IM signal, and the relay decodes the signal to obtain the index bits and constellation bits for Source 1. Similarly, in the second phase, Source 2 sends its own data to the relay via an OFDM-IM signal, and the relay obtains the index bits and constellation bits for Source 2. In the third phase, the relay broadcasts the decoded data across the two phases to Source 1 and Source 2, through an MM-OFDM-IM signal, in which the SMPs are determined by the concatenation of the two decoded index bit streams. Finally, Source 1 (Source 2) detects the received MM-OFDM-IM signal for the message from Source 2 (Source 1), completing the information exchange.

C. SIM in Downlink Multiuser Communications

The study of IM-based multiuser communications is still in its infancy. One intuitive idea is to modulate part of the information bits for each user by activating a specific time slot (subcarrier) among all available orthogonal time slots (subcarriers) and use that time slot (subcarrier) to transmit an M-ary symbol [14]. In this way, however, severe inter-user interference arises when there are a large number of users to accommodate. By introducing SIM into OFDM access, we can facilitate the design of broadcasting systems that provide the services of both unicast streams and a multicast stream simultaneously without incurring inter-user interference.

A feasible architecture is presented in Fig. 4, where the base station transmits an MM-OFDM-IM signal to serve T users simultaneously with unicast streams $b_1, \ldots, b_T$ and a multicast stream

b_0. At the base station, T unicast streams are scheduled and conveyed within different subblocks to avoid mutual interference. Notice that the subcarrier assignment can be as flexible as that in OFDM access systems to accommodate different user requirements. Each subblock is generated by multiple-mode SIM, i.e., the multicast stream determines the SMP and the unicast streams are mapped to M-ary symbols following the selected modes. At each user side, the SMPs associated with that user are first detected for the transmitted multicast stream, and then the unicast stream is extracted from the subcarriers assigned to that user. Note that in classical OFDM, the transmission of the multicast stream needs extra spectrum/time resources.

D. SIM in Physical Layer Security

PLS has emerged as a new powerful security alternative that can complement cryptography-based approaches. To this end, a PLS-based OFDM-IM scheme by randomizing the mapping rules for index bits and constellation bits based on the shared CSI between the legitimate transmitter and receiver appears [15]. In this scheme, however, the subcarrier selection as a degree of freedom particular to SIM is neglected. In classical OFDM, subcarrier selection cannot even be performed. The M-ary symbols in SIM are confined to the active subcarriers. Therefore, the PLS in SIM is different from that in OFDM. In what follows, we propose a CSI-based PLS technique for OFDM-IM systems, which improves the security and error performance simultaneously.

Fig. 5(a) shows the system model of the proposed secure OFDM-IM, in which a legitimate transmitter (Alice) wants to send confidential messages via OFDM-IM signals to an intended receiver (Bob), preventing information leakage from an eavesdropper (Eve). We assume that Eve is spatially separated from Bob, such that they experience different fading channels. Since the receiver structures of Bob and Eve are similar to those in existing SIM systems, we only highlight the transmitter structure of Alice in Fig. 5(a) and describe it below.

Let b_0 index bits and b_1 constellation bits first pass through the conventional OFDM-IM modulator, outputting OFDM-IM subblocks. Each created subblock is then processed according to the CSI feedback from Bob. More specifically, if the channel phase of a subcarrier is larger than 0, the signs of the real and imaginary components of the symbol on that subcarrier is reversed; otherwise, the symbol remains unchanged. The reason why the threshold is set to 0 is that the channel phases are uniformly distributed over $(-\pi, \pi]$. After sign reverse, the subblock is fed into a mode variation module, which transforms the non-zero symbols into those drawn from different modes. Note that this mode variation is also performed according to the channel phases of the n subcarriers. In other words, the subcarrier with the largest channel phase employs the first mode, second largest employs second mode, and so on. Finally, the symbols in the resulting subblock are rearranged so that the non-zero symbols are transmitted over those subcarriers with largest channel amplitudes. For ease of understanding, an example of secure subblock generation is given in Fig. 5(b).

Since Bob knows the CSI, he naturally has the positions of the active subcarriers. Hence, Bob only needs to detect the symbols on k strongest subcarriers as well as their associated modes. After obtaining them, the original active subcarriers indices and symbols can be constructed according to the channel phase and amplitude information. The picture at Eve, however, is completely different. Although Eve may detect correctly the indices of active subcarriers and the symbols on them at high SNR, it cannot recover the original indices and symbols because of the lack of the CSI of the legitimate link. Let us consider an example to evaluate the successful attack probability that Eve correctly estimates the mapping rules in the secure OFDM-IM. If the total number of subcarriers $N = 128$, $n = 4$, and $k = 2$, the successful attack probability is given by $1/2^{kN/n} \times ((n-k)!/n!)^{N/n} \approx 1.6 \times 10^{-54}$, which is negligibly small.

E. Discussions and Remarks

Classical OFDM has inevitable drawbacks when applied to the above-mentioned scenarios. Specifically, in the cognitive radio, the secondary user has to exert interference on the primary user to share a frequency band concurrently; in the relay networks, extra spectrum/time resources are required for the relay to convey signaling information or data symbols to the destination; in the downlink multiuser communications, the transmission of the multicast stream needs extra spectrum/time resources; in the physical layer security, coding/diversity gains resulting from the subcarrier selection are lost. On the contrary, due to the unique feature, SIM can obtain special benefits. Table I gathers the superiority of SIM over OFDM counterparts for each scenario.

IV. CHALLENGES AND FUTURE WORK

As a newly emerging research field for SIM technologies, there still exist numerous potential challenges and open research problems in SIM applications. Besides, SIM itself deserves further study for facilitating the applications of SIM.

TABLE I

THE SUPERIORITY OF SIM OVER CLASSICAL OFDM FOR EACH SCENARIO.

Scenario	SE	Key advantages
Cognitive radio	High	No requirement for extra frequency/time resources and/or transformation of interference into performance gains
Relay networks	High	Saving signaling overhead or one transmission phase
Downlink multiuser communications	High	No requirement for extra frequency/time resources
PLS	Medium	Achieving coding/diversity gains resulting from the subcarrier selection

A. *SIM Itself*

One future direction is the exploration of novel SIM schemes that achieve high SE/EE. In particular, increasing the proportion of the index bits to the constellation bits is of great interest in the design of SIM schemes. The mapping/demapping between index bits and SMPs is a peculiar process in SIM systems. Low-complexity mapping/demapping methods are crucial for the efficient implementation of SIM systems. The error performance enhancement, especially the performance improvement of index bits, is also an important research direction for SIM.

B. *SIM in Relay Networks*

Relay assisted SIM provides a degree of freedom at the relay for subcarrier permutation. For SIM with inactive subcarriers, the relay can place constellation symbols over the subcarriers with good channel conditions, achieving the diversity gain. Moreover, by deploying multiple relays in parallel, one can use the index of an active relay to convey additional information or perform various relay selection schemes to harvest a coding gain and/or even a diversity gain. SIM also offers an opportunity for (physical layer) network-coded relaying in light of inherently inactive subcarriers.

C. *SIM in Multiuser Communications*

Since each user should occupy at least two subcarriers for IM, the design of SIM-based multiuser networks with high SE and without inter-user interference is still an open issue.

Moreover, the integration of non-orthogonal multiple access (NOMA) and SIM could be another solution to multiuser communications. By adjusting the number of active subcarriers for each user, NOMA-SIM can be used as a means of limiting interference.

D. SIM in Simultaneous Wireless Information and Power Transfer

Simultaneous wireless information and power transfer (SWIPT) enables the transmission of information and energy simultaneously. A simple yet effective SWIPT prototype can be easily implemented based on the framework of OFDM-IM. Specifically, the indices of active subcarriers are used for wireless information transfer as in OFDM-IM, while deterministic power waveforms are transmitted on the active subcarriers for wireless power transfer. In this way, time switching or power splitting at the receiver side can be completely avoided.

E. Hybrid IM Schemes and Their Applications

As discussed previously, IM can be implemented in a number of domains. Combining SIM with other IM techniques, such as (generalized) spatial modulation, time IM, and media-based modulation [1], can further increase the SE/EE. However, due to the increase in information-bearing dimensions, the design of low-complexity detectors is one of key issues for hybrid IM schemes. Hybrid IM also provides enormous opportunities in, but not limited to, cognitive radio, relay networks, multiuser communications, and PLS, which deserve further investigation.

V. CONCLUSIONS

In this article, we have introduced the SIM family by a unified framework, and discussed some representatives of SIM schemes. In light of the challenges faced by future wireless networks, we have revealed the promising potential of SIM in cognitive radio, relay networks, downlink multiuser communications, and PLS. Finally, we have outlined the challenges and opportunities on SIM applications for future work. This article has shown that SIM provides an alternative to classical OFDM in network design, and achieves potential benefits in terms of SE/BER compared with classical OFDM. The research trends of SIM include how to improve the SE/EE, support massive connectivity, and combine with massive multi-input-multi-output.

VI. ACKNOWLEDGEMENT

This work was supported in part by the Pearl River Nova Program of Guangzhou under Grant 201806010171, in part by the National Natural Science Foundation of China under Grant 61871190, in part by the Natural Science Foundation of Guangdong Province under Grant 2018B030306005, and in part by the open research fund of National Mobile Communications Research Laboratory, Southeast University under Grant 2020D03.

REFERENCES

[1] X. Cheng, M. Zhang, M. Wen, and L. Yang, "Index modulation for 5G: Striving to do more with less," *IEEE Wireless Commun. Mag.*, vol. 25, no. 2, pp. 126–132, Apr. 2018.

[2] E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5536–5549, Nov. 2013.

[3] P. K. Frenger and N. A. B. Svensson, "Parallel combinatory OFDM signaling," *IEEE Trans. Commun.*, vol. 47, no. 4, pp. 558–567, Apr. 1999.

[4] T. Mao, Q. Wang, Z. Wang, and S. Chen, "Novel index modulation techniques: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 315–348, 1st Quart., 2019.

[5] M. Wen, E. Basar, Q. Li, B. Zheng, and M. Zhang, "Multiple-mode orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Commun.*, vol. 65, no. 9, pp. 3892–3906, Sep. 2017.

[6] X. Hong, J. Wang, C.-X. Wang, and J. Shi, "Cognitive radio in 5G: A perspective on energy-spectral efficiency trade-off," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 46–53, Jul. 2014.

[7] Q. Ma, P. Yang, L. Dan, X. He, Y. Xiao, and S. Li, "OFDM-IM-aided cooperative relaying protocol for cognitive radio networks," in *Proc. IEEE 18th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Sapporo, Japan, Jul. 2017, pp. 1–5.

[8] S. Dang, J. Li, M. Wen, S. Mumtaz, and Z. Zhang, "OFDM-IM based dual-hop system using fixed-gain amplify-and-forward relay with pre-processing capability," *IEEE Trans. Wireless Commun.*, vol. 18, no. 4, pp. 2259–2270, Apr. 2019.

[9] S. Dang, J. P. Coon, and G. Chen, "Adaptive OFDM with index modulation for two-hop relay-assisted networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1923–1936, Mar. 2018.

[10] J. Crawford and Y. Ko, "Cooperative OFDM-IM relay networks with partial relay selection under imperfect CSI," *IEEE Trans. Veh. Tech.*, vol. 67, no. 10, pp. 9362–9369, Oct. 2018.

[11] J. Zhao, S. Dang, and Z. Wang, "Full-duplex relay-assisted orthogonal frequency-division multiplexing with index modulation," *IEEE Systems Journal*, vol. 13, no. 3, pp. 2320–2331, Sep. 2019.

[12] Y. Li, W. Wang, J. Kong, and M. Peng, "Subcarrier pairing for amplify-and-forward and decode-and-forward OFDM relay links," *IEEE Commun. Lett.*, vol. 13, no. 4, pp. 209–211, Apr. 2009.

[13] M. Wen, X. Chen, Q. Li, E. Basar, Y.-C. Wu, and W. Zhang, "Index modulation aided subcarrier mapping for dual-hop OFDM relaying," *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6012–6024, Sep. 2019.

[14] S. Althunibat, R. Mesleh, and T. F. Rahman, "A novel uplink multiple access technique based on index-modulation concept," *IEEE Trans. Commun.*, vol. 67, no. 7, pp. 4848–4855, Jul. 2019.

[15] Y. Lee, H. Jo, Y. Ko, and J. Choi, “Secure index and data symbol modulation for OFDM-IM,” *IEEE Access*, vol. 5, pp. 24959–24974, 2017.

BIOGRAPHIES

Qiang Li (eeqiangli@mail.scut.edu.cn) received the B.S. degree from the Inner Mongolia University of Science and Technology, Baotou, China, in 2013, and the M.S. degree from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2016. He is currently pursuing the Ph.D. degree with the South China University of Technology, Guangzhou, China. From 2018 to 2019, he was a Visiting Student Research Collaborator with Princeton University, Princeton, NJ, USA. His current research interests include index modulation, non-orthogonal multiple access, and reconfigurable intelligent surfaces.

Miaowen Wen [SM’18] (eemwwen@scut.edu.cn) received his Ph.D. degree from Peking University, China, in 2014. From 2012 to 2013, he was a Visiting Student Research Collaborator with Princeton University, USA. He is currently an associate professor with South China University of Technology, China, and a post-doctoral fellow with The University of Hong Kong, China. He has authored a book and more than 70 IEEE journal papers. He was the recipient of Best Paper Awards at IEEE ITST’12, ITSC’14, ICNC’16, and ICCT’19. He served as a Guest Editor for IEEE JSAC, IEEE JSTSP, and IEEE Access. His research interests include index modulation, non-orthogonal multiple access, physical layer security, and molecular communications.

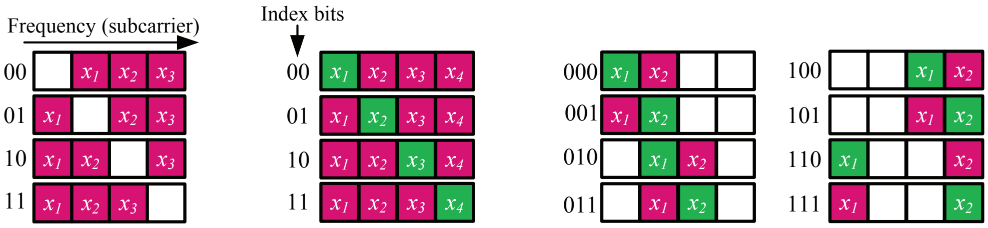
Bruno Clerckx [SM’17] (b.clerckx@imperial.ac.uk) is currently a Reader, the Head of the Wireless Communications and Signal Processing Lab, and the Deputy Head of the Communications and Signal Processing Group, within the Department of Electrical and Electronic Engineering, Imperial College London, London, U.K.. He is the author of 2 books, 180 peer-reviewed international research papers, and 150 standards contributions, and the inventor of 75 issued or pending patents among which 15 have been adopted in the specifications of 4G standards. His area of expertise is communication theory and signal processing for wireless networks.

Shahid Mumtaz [SM’16] (smumtaz@av.it.pt) is an ACM Distinguished Speaker, EiC of *IET*

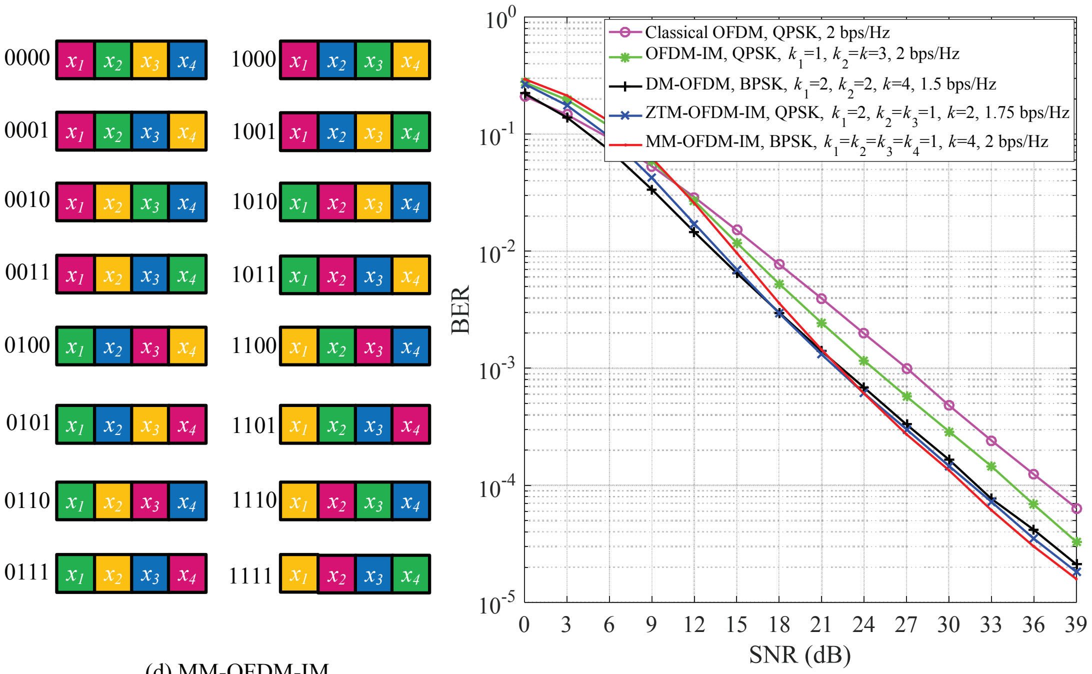
Journal of Quantum Communication, Vice Chair of the Europe/Africa Region-IEEE ComSoc: Green Communications & Computing Society, and Vice-Chair for IEEE Standard on P1932.1: Standard for Licensed/Unlicensed Spectrum Interoperability in Wireless Mobile Networks. He has more than 12 years of wireless industry/academic experience. He received his M.S. and Ph.D. degrees in electrical & electronic engineering from Blekinge Institute of Technology, Sweden, and the University of Aveiro, Portugal, in 2006 and 2011, respectively. He has been with Instituto de Telecomunicações since 2011, where he currently holds the position of auxiliary researcher and adjunct positions with several universities across the Europe-Asian Region. He is also a visiting researcher at Nokia Bell labs. He is the author of 4 technical books, 12 book chapters, and 150+ technical papers in the area of mobile communications.

Anwer Al-Dulaimi [SM'17] (anwer.al-dulaimi@exfo.com) received the Ph.D. degree in electronic and computer engineering from Brunel University, London, U.K., in 2012. Currently, he is a technical product owner (R&D) in the Center of Excellence at EXFO, Montreal, Canada. His research interests include 5G networks, cloud networks, V2X, and Internet of Things. He is the chair of the IEEE 1932.1 Working Group "Standard for Licensed/Unlicensed Spectrum Interoperability in Wireless Mobile Networks" and an IEEE Distinguished Lecturer. He is an associate fellow of the British higher education Academy and registered as a Chartered Engineer by the Brutish Engineering Council.

Rose Qingyang Hu [F'20] (rose.hu@usu.edu) is a professor in the Electrical and Computer Engineering Department and Associate Dean for research at the College of Engineering at Utah State University. She also directs the Communications Network Innovation Lab at Utah State University. Her current research interests include next-generation wireless system design and optimization, Internet of Things, cyber physical systems, mobile edge computing, V2X communications, artificial intelligence in wireless networks, wireless system modeling and performance analysis. She is an IEEE Communications Society Distinguished Lecturer Class 2015-2018. She was a recipient of prestigious Best Paper Awards at IEEE GLOBECOM 2012, IEEE ICC 2015, IEEE VTC Spring 2016, and IEEE ICC 2016. She is a member of the Phi Kappa Phi Honor Society.



(a) OFDM-IM (b) DM-OFDM (c) ZTM-OFDM-IM



(d) MM-OFDM-IM (e)

Fig. 1. Index mapping examples for (a) OFDM-IM ($m = 2, k_1 = 1, k_2 = k = 3$); (b) DM-OFDM ($m = 2, k_1 = 1, k_2 = 3, k = 4$); (c) ZTM-OFDM-IM ($m = 3, k_1 = 2, k_2 = k_3 = 1, k = 2$); (d) MM-OFDM-IM ($m = 4, k_1 = k_2 = k_3 = k_4 = 1, k = 4$), where $n = 4$, the blank elements are modulated by the null mode, and the differently colored elements are modulated by different non-null modes to carry constellation symbols x_l; (e) BER performance of classical OFDM, OFDM-IM, DM-OFDM, ZTM-OFDM-IM, and MM-OFDM-OM with $n = 4$, perfect CSI at the receiver, and ML detectors over frequency selective Rayleigh fading channels.

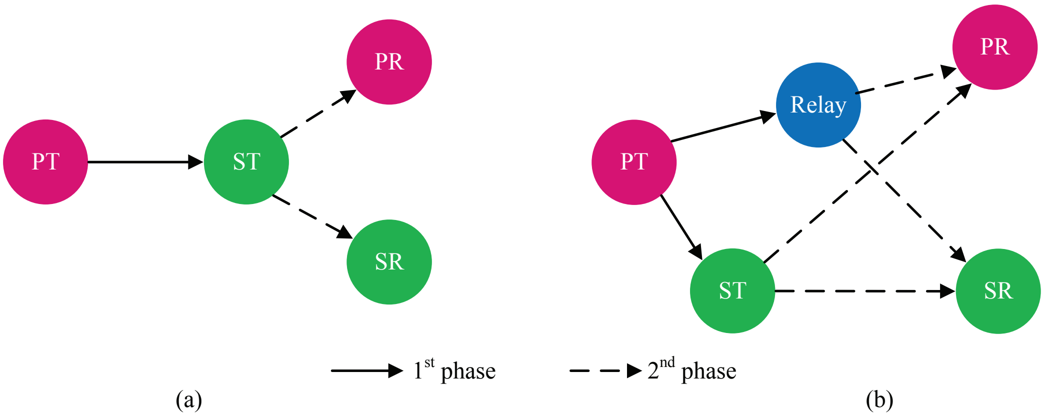


Fig. 2. SIM-based cognitive radio: (a) overlay paradigm; (b) interweave paradigm.

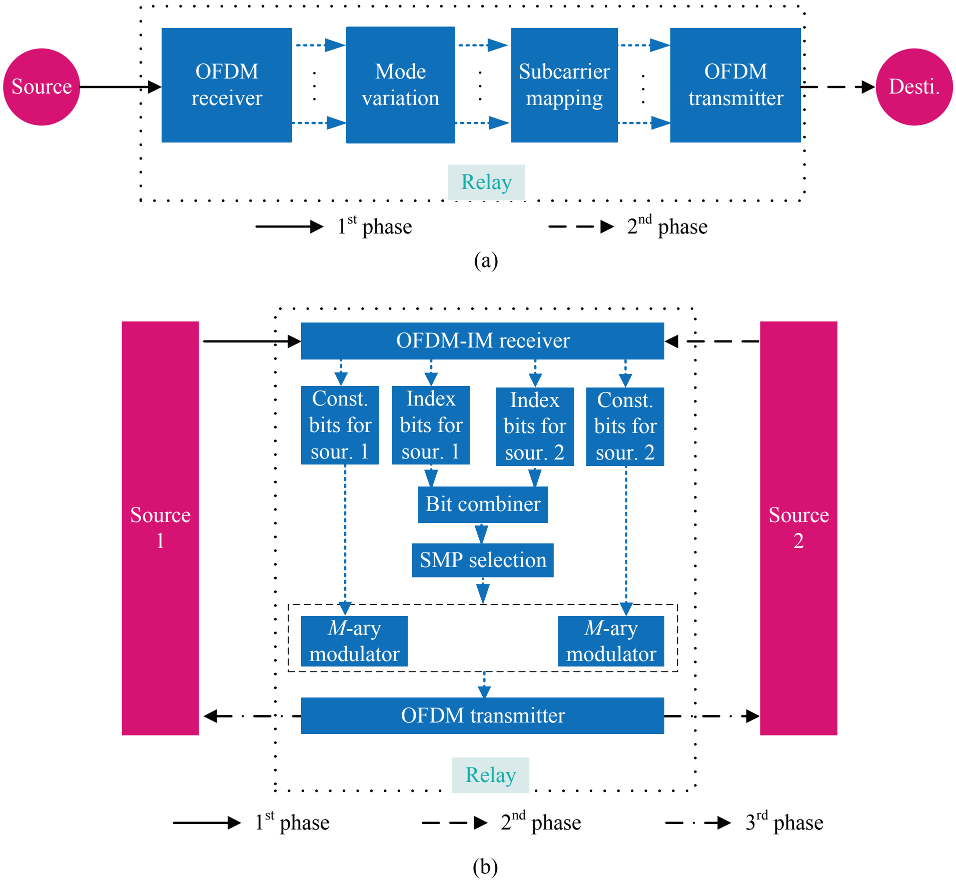


Fig. 3. SIM-based relay networks: (a) SCM-aided relaying; (b) two-way relaying.

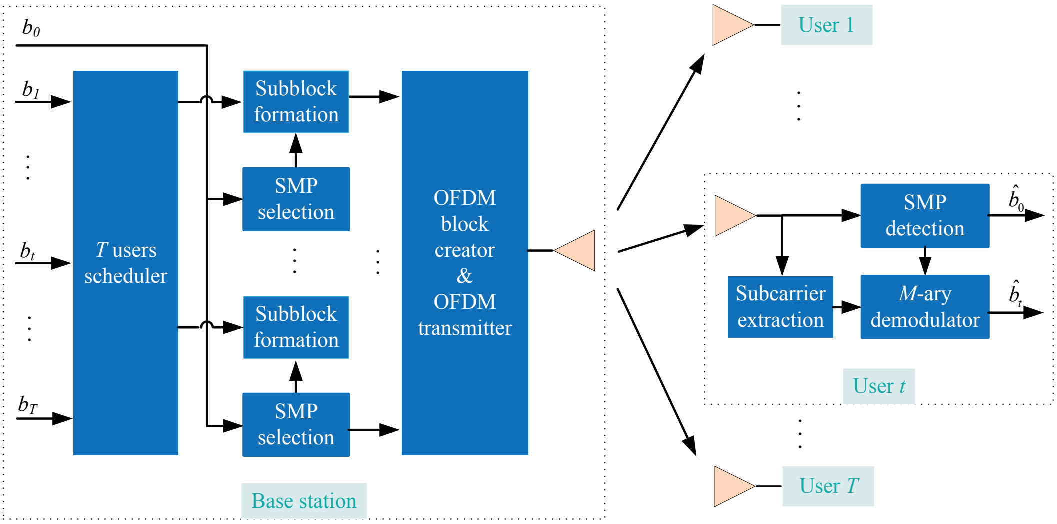
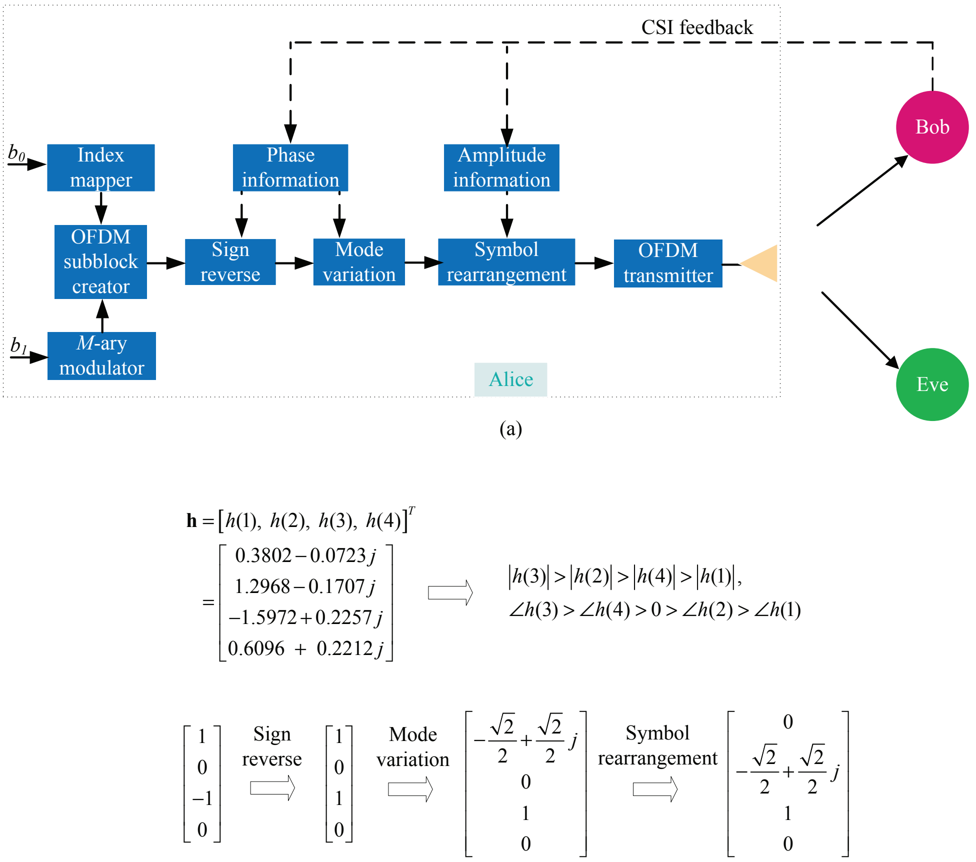


Fig. 4. SIM-based downlink multiuser communications with unicast streams and a multicast stream, where b_0 is the multicast stream for all users, and b_t is the unicast stream for User t.



(a)

(b)

Fig. 5. Secure OFDM-IM: (a) system model; (b) an example of secure subblock generation, where $n = 4, k = 2$, $M = 2$, and the mode selection strategy with PSK signaling in [5] is adopted.