Toward Spectral and Energy Efficient 5G Networks Using Relayed OFDM with Index Modulation

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ABSTRACT

Next generation wireless networks are expected to provide much higher data throughput and reliable connections for a far larger number of wireless service subscribers and machine-type nodes, which result in increasingly stringent requirements of spectral efficiency (SE) and energy efficiency (EE). Orthogonal frequency-division multiplexing with index modulation (OFDM-IM) stands out as a promising solution to satisfy the SE requirement with a reasonable increase in system complexity. However, the EE of OFDM-IM is still required to be enhanced. Moreover, diversity gain is hardly harvested from the frequency domain without affecting the SE for OFDM-IM systems, which hinders further reliability enhancement. In this regard, relay assisted OFDM-IM, as a promising joint paradigm to achieve both high SE and EE, was proposed and has been studied since last year. The objectives of this paper are to summarize the recent achievements of this joint paradigm, articulate its pros and cons, and reveal the corresponding challenges and future work. More importantly, we provide a full picture and insights into the implementation of this new paradigm in next generation networks.

Keywords: Index modulation, OFDM, cooperative relaying, multi-hop transmission, multi-carrier systems, 5G communications, spectral efficiency, energy efficiency.

1 INTRODUCTION

Current studies have foreboded the tendency that data throughput and the number of connected nodes in next generation wireless networks will tremendously increase, which results in increasingly stringent requirements of spectral efficiency (SE) and energy efficiency (EE) (Andrews et al. (2014); Dang et al. (2020)). To meet these two requirements, orthogonal frequency-division multiplexing with index modulation (OFDM-IM) was proposed to introduce another modulation domain and an extra degree of freedom (Basar et al. (2013)). Different from conventional amplitude-phase modulation (APM) schemes, OFDM-IM employs an *index domain* in addition to the classic amplitude-phase constellation diagram, so as to form a three-dimensional modulation scheme, which considerably enhances the SE under proper system configurations (Wen et al. (2016); Ishikawa et al. (2016)). In particular, by OFDM-IM, only a subset of orthogonal subcarriers will be activated to form a unique subcarrier activation pattern (SAP), which can be generated by subcarrier grouping and inverse fast Fourier transform (IFFT) (Xiao et al. (2014)). Consequently, one can shrink the number of legitimate SAPs to a power of two, and resort to the index of SAP to modulate extra bit stream in addition to the bit stream modulated by data constellation symbols carried on active subcarriers. In this way, under appropriate system configurations, OFDM-IM is superior to plain OFDM in terms of SE and/or error performance. The verification of OFDM-IM in practical communication systems has also been carried out, and the results given illustrate that OFDM-IM is feasible for practical implementation (Gokceli et al. (2017)). Due to the advantageous properties, OFDM-IM attracts researchers' attention and is regarded as one of the most appealing modulation candidates for next generation networks (Basar et al. (2017); Ishikawa et al. (2018); Mao et al. (2019)).

Due to the stringent requirements of SE for next generation networks, various enhanced OFDM-IM schemes are proposed to further improve SE. To be more specific, various efficient subcarrier/subblock mapping schemes are introduced and proposed to improve the SE of OFDM-IM through numerous techniques. To efficiently utilizing the subcarriers allocation, a simple subcarrier-level interleaving strategy by enlarging the Euclidean distances among the modulated symbols is proposed resulting in achieving better system performance than conventional OFDM-IM (Xiao et al. (2014)). Moreover, assigning different numbers of active subcarriers for carrying constellation symbols and performing independent index modulation on the in-phase and quadrature components of each subcarrier become two efficient methods to gain higher SE (Fan et al. (2015)). In addition, a hybrid technique that explores the I- and Q-dimensions jointly for index modulation through the transmission of more index modulation bits per subcarrier group is well implemented to achieve a higher SE (Wen et al. (2017b)). Meanwhile, a selection strategy with multiple distinguishable modes and their full permutations is regarded as an available move to convey information leading to a higher SE (Wen et al. (2017a)). Besides, a power allocation technique combining with OFDM-IM, where the two groups of subcarriers per subblock are set with different M-ary modulation and different power levels, is able to eliminate the limits of SE (Zhang et al. (2017)). Furthermore, dividing subcarriers into multiple layers can also carry more IM bits. Based on this, a layered OFDM-IM (Li et al. (2019)) is designed and outperforms the conventional OFDM-IM scheme, especially in SE.

Although OFDM-IM can gain a higher SE, its EE is still required to be enhanced. In addition, diversity gain is hardly harvested from the frequency domain without affecting the SE, which hinders further reliability enhancement for OFDM-IM systems. To manage these rising issues with OFDM-IM and achieve high SE and EE simultaneously, cooperative multi-hop architecture consisting of relay(s) is incorporated with OFDM-IM systems (Mrkic et al. (2017); Wang et al. (2018)), and the resultant relay assisted OFDM-IM has sparked the research interest in academia within a short period of time. A number of papers have shown that the reliability of OFDM-IM can be improved by incorporating the cooperative multi-hop architecture, and a higher degree of system flexibility is obtainable (details will be given in the next section). In particular, the optimization and design dimensions can be extended from the frequency domain to the spatial domain, which facilitates more advanced techniques to be employed, for example cognitive radio (CR), subcarrier permutation (SP), power allocation (PA), relay selection (RS), and full-duplex (FD) relaying. Based on the milestones, the objectives of this paper are to summarize the recent achievements of relay assisted OFDM-IM, articulate pros and cons of this new paradigm, and reveal the corresponding challenges and future work for further research activities. Overall, we aim to provide a full picture and insights into the implementation of relayed OFDM-IM in next generation networks.

To illustrate the pros and cons of relayed OFDM-IM in a clear manner, we resort to numerical simulations for demonstration. For the sake of simplicity, in this paper, we only focus on a single group of N subcarriers and adopt the simplistic look-up table method with a fixed number of K active subcarriers for bit-to-SAP mapping. The APM scheme is assumed to be M-ary phase-shift keying (PSK). The numbers of hops and relays in a single hop are denoted as L and T, respectively.

The rest of this paper is organized as follows. In Section 2, we first provide an overview and the application scenarios of relayed OFDM-IM for next generation networks. Then, we summarize and review the state-of-the-art achievements and milestone papers related to relayed OFDM-IM in Section 3. Based on the existing research works, we discover the advantages and disadvantages of this novel paradigm and give a case study for quantitative comparison purposes in Section 4. In addition, we present several challenges and future work associated with relayed OFDM-IM in Section 5. Finally, the paper is summarized in Section 6.

2 OVERVIEW AND APPLICATION SCENARIOS

The basic principle of relay assisted OFDM-IM is similar to classic/plain OFDM supported by cooperative multi-hop architecture. However, only a subset of subcarriers will be received and forwarded by relay(s) to the destination. A complete system diagram of a typical decode-and-forward (DF) relay assisted OFDM-IM system is pictorially presented in Figure 1. For amplify-and-forward (AF) relay assisted OFDM-IM, the receiving part from ‘Down conversion’ to ‘Data output’ modules can be simply replaced by a signal amplifier that could also be supported by channel state information (CSI) depending on whether fixed-gain AF or variable-gain AF relaying protocol is applied.

Depending on the design of cooperative multi-hop structure, we can have a number of system models for applying relay assisted OFDM. There are three main cooperative multi-hop structures that are practical for relay assisted OFDM-IM systems:

- Cooperative multi-hop structure with relays in series
- Cooperative dual-hop structure with relays in parallel
- Cooperative dual-hop structure for overlay CR

Most of other structures for relay assisted OFDM-IM can be regarded as special cases or combinations of these three major structures. For clarity, we illustrate them in Figure 2, and expatiate on their features as follows.

2.1 Cooperative Multi-Hop Structure with Relays in Series

The cooperative multi-hop structure with $L-1$ relays in series (i.e., L hops) is suited for enabling long-distance transmission of OFDM block, and assumes transmission links only exist between two adjacent nodes. This structure is the most common structure for relay assisted OFDM-IM. By such a multi-hop structure, ideally, the network coverage can be extended to arbitrarily large as long as a sufficient number of relays are deployed in a proper manner. As a consequence, relay assisted OFDM-IM supported by the cooperative multi-hop structure with relays in series would have a higher SE and EE. On the other hand, if DF relaying protocol is adopted over this structure, error propagation issue should be taken into consideration (Bhatnagar (2012)), since the correct detection at the destination is based on the prerequisite that all $L-1$ relays must correctly detect the received OFDM block, which becomes less likely when the number of hops is large. On the contrary, if AF relaying protocol is adopted, noise amplification and nonlinear distortion caused by amplification saturation would be severe (Simmons and Coon (2016)), especially for large L.

2.2 Cooperative Dual-Hop Structure with Relays in Parallel

To mitigate the disadvantages of cooperative multi-hop structure with relays in series and provide a higher degree of network design flexibility, the cooperative dual-hop structure with T relays in parallel is in use, when the distance between source and destination is moderate. Another benefit of the cooperative dual-hop structure with relays in parallel is that a variety of RS schemes can be performed to harvest a coding gain and/or even a diversity gain (Yang and Cai (2011)). On the contrary, the rising issue of this structure is the increasing system complexity and signaling overhead caused by multi-relay coordination and synchronization (Huang et al. (2010)). First, in order to select appropriate relay(s), full or partial CSI must be known by the source node in a certain way. This can be achieved by a centralized manner via a central node (e.g., base station (BS) and access point (AP)) or a timer-based distributed manner that waits for the response from relays (Bletsas et al. (2006)). The former would require an extra feedback channel exclusively used for selected relay indication and latter could cause an additional delay. The synchronization issue comes from the fact that multiple relays are spatially distributed and operate in different oscillators.

2.3 Cooperative Dual-Hop Structure for Overlay CR

The cooperative dual-hop structure for overlay CR considers both primary and secondary user pairs (Ma et al. (2017)). Specifically, in the first phase, the primary transmitter (PT) transmits its information to both primary receiver (PR) and the secondary transmitter (ST). The ST acting as a relay for the primary transmission re-transmits the signal from the PT to the PR. However, different from conventional CR cooperative networks, OFDM-IM is utilized at the ST, and the ST split the transmission space into the classic phase-amplitude constellation domain and the index domain. The information required to be re-transmitted is modulated in the classic phase-amplitude constellation domain, while the information intended to be transmitted to secondary receiver (SR) is encoded in the index domain via the SAP. Therefore, the OFDM block transmitted by the ST in the second phase can both help the decoding process in the PR for the primary transmission, and concurrently piggyback information for the secondary transmission to the SR. The mutual interference between primary and secondary transmissions can thus be alleviated.

3 STATE-OF-THE-ART ACHIEVEMENTS

It has been pointed out that due to the low implementation cost and improved SE as well as extended coverage, cooperative communications would be a helpful ally of OFDM-IM, and the combination of both prototypes is worth investigating (Basar (2016); Cheng et al. (2018); Li et al. (2020b)). The initial work introducing the cooperative dual-hop architecture with a single DF relay to OFDM-IM systems is published by Mrkic et al. (2017). Only numerical results generated by Monte Carlo simulations are shown in this work to testify the performance superiority of this combination. From these preliminary results, several key properties of relay assisted OFDM-IM can be observed and it is thus summarized that relay assisted OFDM-IM would be considered as an intriguing solution for both long-range energy-efficient communications and high data rate communications on cell edges. Besides DF protocol, as for the AF protocol in dual-hop OFDM-IM relaying systems, Wen et al. (2019) proposes a novel signaling scheme to eliminate additional spectrum resources consuming by transferring the subcarrier permutation to the mode permutation. It is clear that different relay protocols have great research prospects for OFDM-IM relaying systems.

In the meantime, OFDM-IM-aided cooperative relaying protocol for CR networks is proposed by Ma et al. (2017), in which the cooperative dual-hop structure for overlay CR is in use. Upper bounds on bit error rate (BER) of both primary and secondary transmissions are derived in single-integral form and the achievable rates of the proposed system with a variety of finite-size constellations are also analyzed. Numerical results verify the analysis presented and meanwhile confirm that the error performance of both primary and secondary user pairs is improved by adopting OFDM-IM over the cooperative dual-hop structure for overlay CR. Moreover, in the OFDM-IM-aided CR networks model, Li et al. (2020a) shows the research on exploring the potential of reusing inactive subcarriers for a secondary system aiming at improving OFDM-IM. To be specific, To be specific, the idle subcarriers can be utilized to transmit signals to the secondary receiver by the secondary user in this scheme. In this case, the asymptotically tight upper bound on BER is also obtained and evaluated. As for the AF relay protocol in above model, a novel opportunistic spectrum sharing scheme is proposed from primary transmitter to secondary transmitter. The simulation result corroborate the superiority on BER and SE compared with OFDM-CR and OFDM-IM-AF (Li et al. (2020c)).

Following these pioneering papers, dual-hop relay assisted OFDM-IM with SP is analyzed by Dang et al. (2018b). In particular, the codebook mapping incoming bits to SAPs is dynamically changed according to CSI, and it is allowed to perform SP at the relay node. In this way, the end-to-end performance consisting of two hops can be decoupled and a higher degree of freedom is achievable, which leads to an enhanced reliability and a frequency diversity gain. The analysis pertaining to outage performance, error performance and network capacity is provided and corroborated by numerical results. PA is further incorporated in the dual-hop relay assisted OFDM-IM with SP by Dang et al. (2017), and the formulated power allocation problem over active subcarriers can be solved based on the Karush-Kuhn-Tucker (KKT) conditions. A similar optimization structure has also been adopted to allocation transmit power between source and relay nodes for a dual-hop relay assisted OFDM-IM system with AF relaying (Zhou et al. (2020)).

The cooperative dual-hop model is generalized to cooperative multi-hop model by Wang et al. (2018). Because of the employment of DF relaying, the bottleneck effect will yield a constraint on the number of hops, as with an increasing number of hops, the outage and error performance will be considerably degraded. An ingenious analytical methodology based on the concept of end-to-end link is used so as to facilitate the performance analysis of relay assisted OFDM-IM in cooperative multi-hop networks. In addition, as a minor contribution, the transmission rate of relay assisted OFDM-IM is analyzed in depth. To mitigate the bottleneck effect, AF relaying protocol is integrated into OFDM-IM with a multi-hop transmission structure and analyzed thoroughly in Dang et al. (2019). Meanwhile, in order to harvest spatial diversity gain for relay assisted OFDM-IM systems in multi-hop cooperative networks, two multi-carrier relay selection schemes are employed and greatly improve the system reliability (Yang and Mu (2020b)).

Multi-relay assisted OFDM-IM enhanced by RS are investigated in numerous studies. In general, most studies adopt the cooperative dual-hop structure with relays in parallel and employ multi-carrier RS schemes. Crawford and Ko (2018) assumes that only the CSI in the first hop is accessible at the source for RS purposes, so that a partial RS (PRS) scheme based on centralized control is formed. To be realistic, the channel estimation error is taken into consideration in this paper, which yields imperfect CSI for PRS. Dang et al. (2018a, 2019); Sheng et al. (2019) suppose that full CSI is perfectly known and thereby the end-to-end channel power gain can be adopted as the indicator for RS. As a result, two common multi-carrier RS schemes for classic OFDM systems, bulk and per-subcarrier (PS) RS schemes are applied. Sheng et al. (2019) in particular involves the AF relaying protocol with multi-relay selection in relay assisted OFDM-IM. All aforementioned papers have shown that spatial coding and/or diversity gains for relay assisted OFDM-IM can be harvested by RS.

All aforementioned papers adopt half-duplex DF relaying as the forwarding protocol at relay(s). Apart from half-duplex relaying, full-duplex DF relay assisted OFDM-IM is proposed and analyzed by Zhao et al.

(2018), in which residual self-interference (RSI) at the full-duplex relay node is investigated and its power is modeled as an exponentially distributed random variable. The analysis is extended to multi-relay scenarios with bulk and per-subcarrier relay selections (Yang and Mu (2020a)). Most different from half-duplex relay assisted OFDM-IM, the transmission in full-duplex relay assisted OFDM-IM will be affected by previous transmission attempts, which cause a difference in RSI over frequency bands because different SAPs are employed in different transmission attempts. Moreover, the cooperative non-orthogonal multiple access (C-NOMA) system based on OFDM-IM also grows up as a potential research direction, especially with relaying systems. To mitigate the inter-user interference, Chen et al. (2020a) works on this system to use two different information-bearing units of OFDM-IM to convey messages. The simulation results of BER validate the superiority of the scheme and further demonstrate the prospect of this technique. Besides, different IM bits allocation for each cell-edge user and different modulation modes are analyzed in the system, where the techniques of C-NOMA and IM are integrated based on the OFDM framework (Chen et al. (2020b)). The improvement of the system performance in terms of both BER and SE verifies the potential benefits in the future and provides a possible alternative to classical technique like conventional OFDM-IM or conventional NOMA.

4 ADVANTAGES AND DISADVANTAGES

From an engineering perspective, any technology/paradigm can gain in one aspect at the cost of the other. The same rule applies to relay assisted OFDM-IM. As we have more or less mentioned earlier, we elaborate the main advantages and disadvantages of relay assisted OFDM-IM infra, so as to provide a full picture of this new paradigm. Subsequently, simulation results for a case study are demonstrated to provide quantitative information and an insight into various relay assisted OFDM-IM systems.

4.1 Advantages

4.1.1 Diversity and Coding Gains

Without involving channel coding techniques, the diversity gain of relay assisted OFDM-IM systems can be harvested from the frequency domain and/or the spatial domain by SP and RS, respectively. Both diversity and coding gains can enhance OFDM-IM systems in terms of outage and error performance.

4.1.2 Energy Efficiency

Since the radio wave propagation distance can be effectively shrunken from a complete one to L segments by cooperative relaying, the required transmit power to achieve a given quality of service (QoS) is much smaller than that without support of relays. As a consequence, the EE superiority of relay assisted OFDM-IM can be easily deduced from the Friis transmission equation.

4.1.3 Spectral Efficiency

The SE of OFDM-IM systems can also be further enhanced as a concomitant of EE enhancement by introducing cooperative relaying. This is simply because the reduction of transmit power will allow the reuse of the same spectral resources among multiple users in proximity. From a holistic viewpoint, the network throughput is enlarged without utilizing extra spectral resource and thereby the SE rises.

4.2 Disadvantages

4.2.1 Transmission Delay

To decouple the transmission over L hops and hence prevent the cross-hop interference, L orthogonal time slots for one complete transmission from source to destination are required, for half-duplex relaying.

This would result in a considerable transmission delay. Also, if DF relaying is adopted as the forwarding protocol at relays, an additional delay is yielded by the decoding and re-encoding process.

4.2.2 Complexity and Signaling Overhead

The implementations of cooperative multi-hop architecture and multiple relays inevitably render a higher system complexity and signaling overhead. First, time and frequency synchronizations are required among multiple nodes and the multi-relay coordination on a distributed basis is demanding. Second, channel estimation in cooperative multi-hop networks is also difficult and causes extra signaling overhead, especially when channels are volatile. Depending on the network protocol and application scenario, multiple replicas are received at the destination and shall be combined before processing, which again rises the system complexity.

4.2.3 Error Propagation

Error propagation is a unique issue for DF relay assisted OFDM-IM only, indicating the scenario that an erroneously decoded OFDM block by an intermediate DF relay is re-transmitted and detected by the posterior relay(s) and the final destination. This also refers to the bottleneck effect of DF relaying and should be dealt with carefully.

4.2.4 Nonlinear Distortion

Contrary to error propagation for DF relay assisted OFDM-IM, nonlinear distortion is an exclusive arduousness for AF relay assisted OFDM-IM. Nonlinear distortion is caused by the amplification saturation to the nonlinear region. Because most electronic components can only operate linearly within a limited power region, this phenomenon might yield severe inter-channel interference (ICI) and a deleterious impact on signal detection.

For clarify, we provide qualitative comparisons of a number of crucial properties among plain OFDM, classic OFDM-IM and relay-assisted OFDM-IM in Table 1.

4.3 Case Study

To pictorially illustrate the performance superiority of relay assisted OFDM-IM and reveal the effects of different network structures and system configurations, we carried out a series of simulations regarding block error rate (BLER), BER, outage probability (OP), and throughput in bit per channel use (bpcu) for various cases. To simplify the simulations and restrict our discussions within a reasonable scope in this paper, we make the following assumptions when carrying out simulations:

- A sufficiently long CP and perfect synchronizations in time and frequency are implemented, so as to eliminate inter-symbol interference (ISI) and ICI.
- Instantaneous CSI is perfectly accessible to all nodes to facilitate RS (if required) and estimation.
- Free space is supposed to be the signal propagation environment and the path loss exponent is thereby $\alpha = 2$.
- All nodes are physically stationary, and there is no correlation among hops and subcarriers.
- Nodes can only communicate with their adjacent nodes, and cross-hop communications do not take place.
- Half-duplex relaying is in use for all relays in all cases.

Base on these assumptions, we set the simulation platform with a fixed network topology as follows. The source and destination are separated by $d_{SD} = 10$ m without direct transmission link. Depending on the number of hops L, nodes are uniformly distributed over the straight line connecting the source and destination with separation d_{SD}/L. Transmit power P_t adopted at all nodes will be uniformly distributed over K active subcarriers. Binary PSK (BPSK) is used for APM over each individual active subcarrier ($M = 2$); there are $N = 4$ subcarriers in total, from which $K = 2$ subcarriers will be activated each time for transmission and indexing purposes. Varying the target parameter P_t/N_0 can help to derive the comparison among different configurations, in which N_0 denotes the noise power. Small-scale fading variation, noise power, and outage threshold are all normalized. The numerical results based on this simulation platform are generated by Monte Carlo methods and presented in Figure 3, 4, 5, and 6 in terms of BLER, BER, OP, and throughput respectively.

By observing the simulation results presented in Figure 3, 4, 5, and 6, we can find a series of key properties of relay assisted OFDM and explore the effects of system configurations on performance. First, it is obvious that the curves represented no relaying always achieve the worst or the second-worst performance in terms of all four indices. Especially, there are significantly recognized differences with high P_t/N_0. Meanwhile, focusing on the DF relaying curves, the curves with $L = 3$ always outperforms the curves with $L = 2$. For most cases, cooperative relaying is beneficial to OFDM-IM, because a longer propagation distance can be split into L segments and for each segment, the large-scale fading caused by path loss can be mitigated. Second, DF and AF curves display distinct performance compared with each other. Only in terms of OP, AF curve and DF curve are hard to be distinguished while DF is significantly better in terms of other indices. In a word, forwarding protocols are crucial and should be elaborately selected. Different requirements for each practical scenarios can be well adopted by different relaying protocols. DF relaying owns better performance than AF relaying at the cost of a higher complexity and instantaneous CSI. On the other hand, AF relaying could deteriorate the error performance of OFDM-IM, since the noise will also be amplified and could lead to a considerably distorted received OFDM block at the destination and thus a more error-prone system. Besides, when d_{SD} is given, a larger number of hops L will result in better performance, as more communication resources (relay nodes and power) are invested to handle the transmission.

Meanwhile, by applying three different RS schemes, one can also have an insight into the effects of RS on the performance of relay assisted OFDM-IM. The simulations in terms of all four indices get similar trending and results exhibits that the PS RS curve is the best, while the PRS one seems always the worst. PRS scheme only considering the channels over the first hop cannot achieve a diversity gain for relay assisted OFDM-IM, but a coding gain is attainable. Because bulk and PS RS schemes view the fading in an end-to-end manner, a diversity gain equaling the number of relays for selection can therefore be harvested. Furthermore, because PS RS scheme has a higher degree of freedom by allowing selecting multiple relays, a higher coding gain is obtained than that of bulk RS scheme.

5 CHALLENGES AND FUTURE WORK

As relay assisted OFDM-IM is a young-born paradigm and has attached researchers' attention since 2019, there still exist a number of challenges and interesting research topics awaiting exploration. We summarize them as follows to accelerate further related research activities.

5.1 Optimal Deployment of Relay Nodes

In current literature, the deployment related issues of relay nodes, including geographical distributions and locations are neglected. As relays might not always bring benefit to OFDM-IM systems without an appropriate deployment scheme, these deployment related issues are of high importance. Poisson point process (PPP) would be utilized to model the random distribution of relay nodes over a two-dimensional plane. Mode selection between direct transmission and cooperative transmission modes should also be enabled subject to relays' physical locations and CSI. Besides, as there exists a performance trade-off in the number of hops L, how many hops should be involved for one complete transmission by relay assisted OFDM-IM is still an open optimization problem.

5.2 Realistic Channel Modeling

In most existing papers of relay assisted OFDM-IM, due to the analytical simplicity, Rayleigh fading model is adopted in most cases and an ideal environment is taken into account, where there is not interference and correlation in all domains. To be more realistic, other fading models, for example Rician, Nakagami, and Weibull fading models shall be investigated depending on the signal propagation environment. Meanwhile, without proper measures, a variety of interference would exist and should be modeled as random variables. Even through frequency correlation can be eliminated by interleaved grouping (Xiao et al. (2014)), correlation in the spatial domain is also possible when relays are close to each other and/or move at a high speed, which will lead to sophisticated multi-hop channel modeling.

5.3 Synchronization and Coordination

Synchronization and coordination among multiple relays are always indispensable in order to fully exploit the advantages of relay assisted OFDM. Both regulate the relays by when and how to collaborate so as to optimize one or several performance gains. However, in all existing papers, they are simply assumed to be perfectly arranged, which might not be the case in realistic environments. Further research activities considering both issues are worthwhile.

5.4 Multi-User Scenarios and Resource Allocations

Most existing papers consider a single user pair. More generally, it would be interesting to extend the relay assisted OFDM-IM to multi-user scenarios. As a consequence, the resultant resource allocation problems have at least three dimensions: relay, subcarrier and power, that is, which user pairs should activate which subcarriers to transmit via which relays by how much amount of transmit power. Consequently, this extension could bring relay assisted OFDM-IM to a new realm and is therefore worth studying.

5.5 Relay Assisted OFDM-IM with Advanced OFDM-IM Schemes

Apart from the original OFDM-IM scheme relying on the look-up table method and the combinatorial method proposed by Basar et al. (2013), there are also a plenty of advanced and derivative OFDM-IM schemes, for example OFDM with generalized IM (OFDM-GIM), OFDM with precoded IM (OFDM-PIM), enhanced OFDM-IM (E-OFDM-IM), vector OFDM-IM (V-OFDM-IM), Differential OFDM-IM (D-OFDM-IM), multiple-mode OFDM-IM (MM-OFDM-IM), and so on (Basar et al. (2017)). Because they are not conflict with the cooperative multi-hop architecture in essence, cooperative relaying would also be incorporated with these novel OFDM-IM schemes, so as to achieve better performance.

5.6 System-Level Implementation and Verification

Although analysis and numerical results generated by simulations have proved the feasibility and superiority of relay assisted OFDM-IM in a number of application scenarios. In order to fully capture the characteristics of relay assisted OFDM-IM and testify its values in practical wireless communication systems, relevant system-level experiments on laboratory testbeds are required, but have not been done yet.

6 CONCLUSION

In this paper, we first introduced the basics of relay assisted OFDM-IM applied over three major cooperative structures. Following the basics, we summarized the state-of-the-art achievements associated with this new paradigm in recent years via a brief literature review. Following the literature review, the advantages and disadvantages of relay assisted OFDM-IM have been summarized and demonstrated by a series of comprehensive simulations. Finally, to promote relay assisted OFDM-IM and accelerate the related research activities, we outlined the existing challenges and revealed potential research directions for future work. Overall, we aim to present a full picture and insightful information for the practical implementation of this new paradigm in next generation networks. Through the results obtained and illustrated in this paper, relayed OFDM-IM is able to enhance the SE and EE for 5G and 5G+ communication networks.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Basem Shihada and Mohamed-Slim Alouini conceived the work and suggested the outline of the paper. Shuping Dang and Jiusi Zhou carried out investigations and wrote the paper.

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FIGURE CAPTIONS

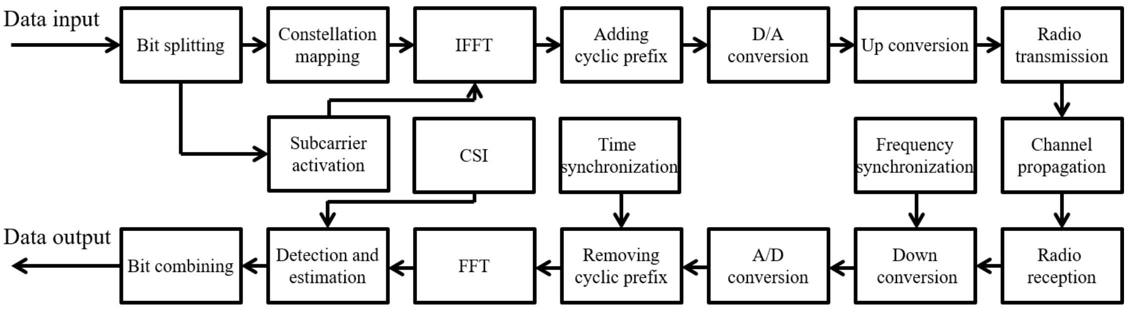

Figure 1. System diagram of a typical DF relay assisted OFDM-IM system.

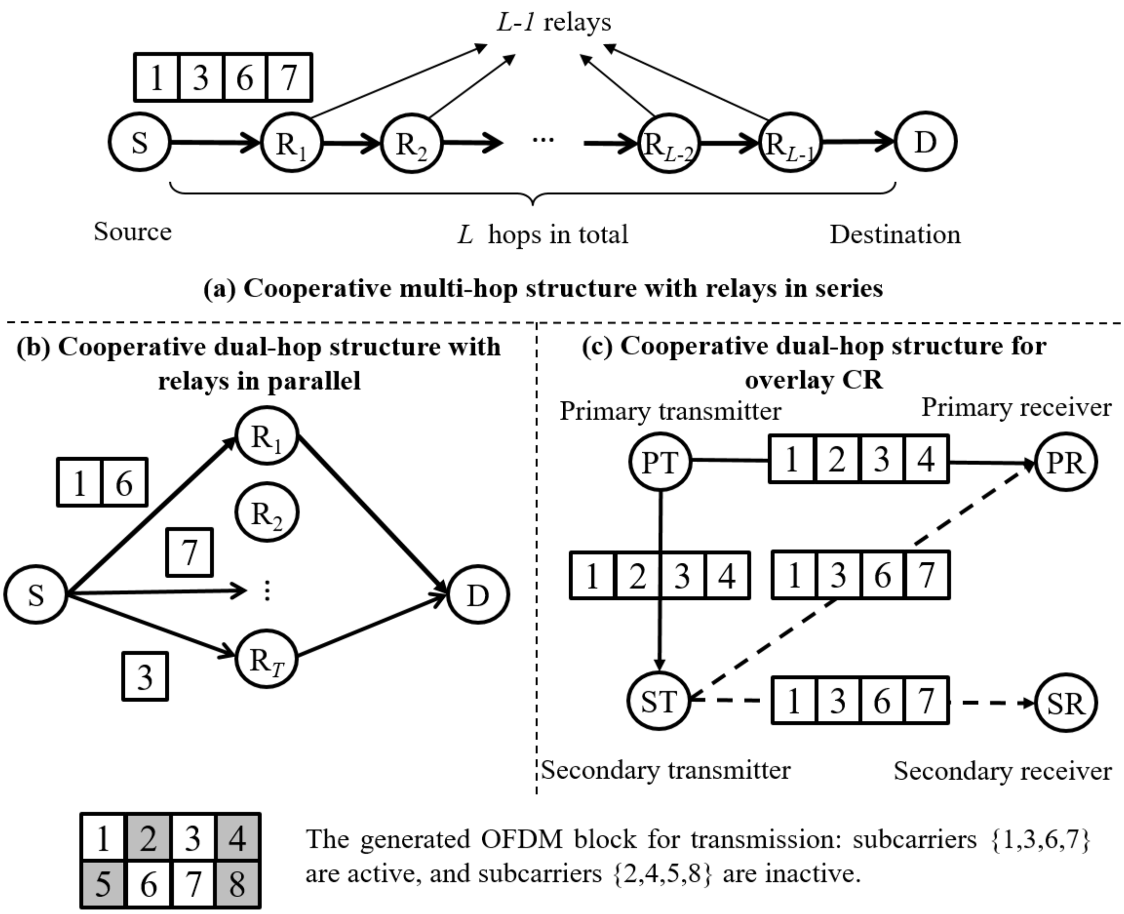

Figure 2. Three major cooperative multi-hop structures for relay assisted OFDM-IM.

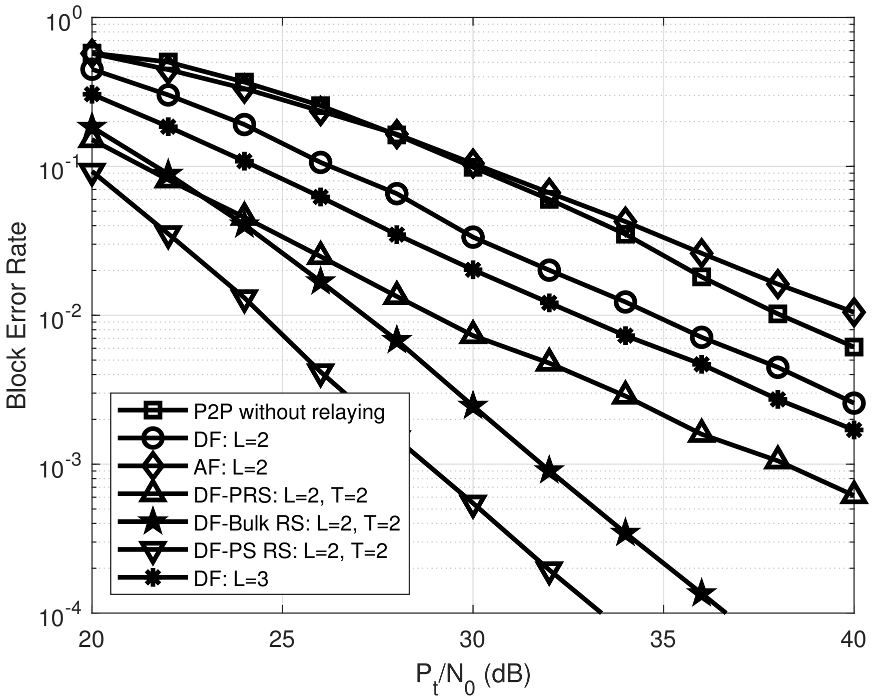

Figure 3. BLER comparison among point-to-point plain OFDM-IM system and various relay assisted OFDM-IM systems with different system configurations.

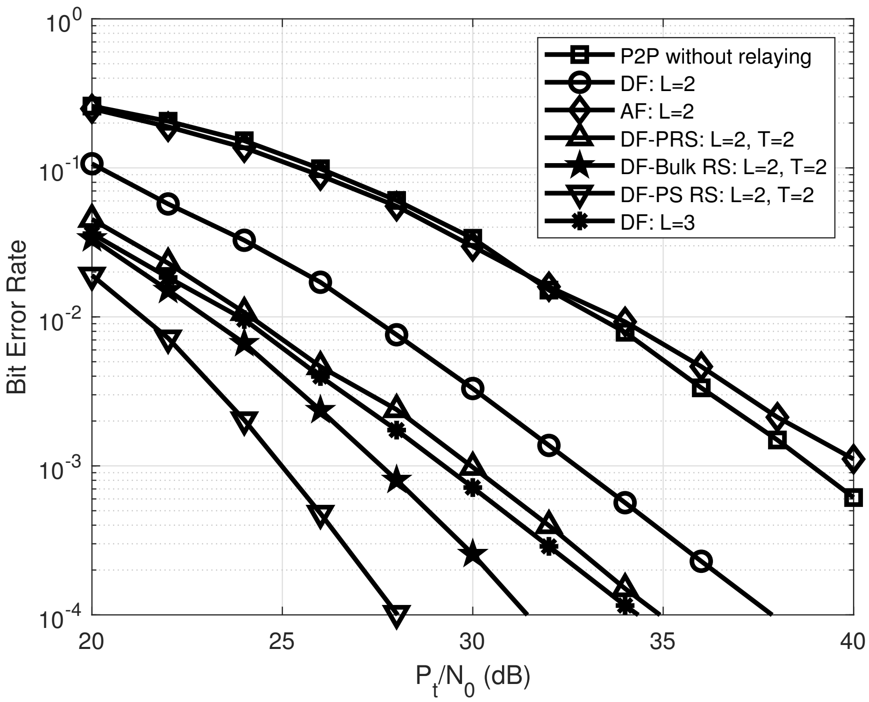

Figure 4. BER comparison among point-to-point plain OFDM-IM system and various relay assisted OFDM-IM systems with different system configurations.

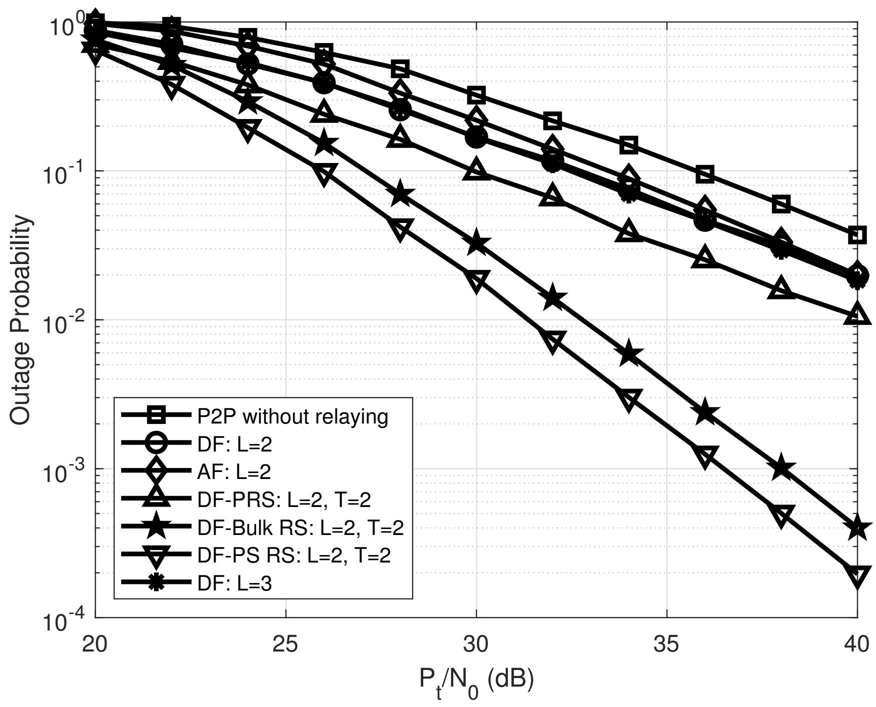

Figure 5. Outage probability comparison among point-to-point plain OFDM-IM system and various relay assisted OFDM-IM systems with different system configurations.

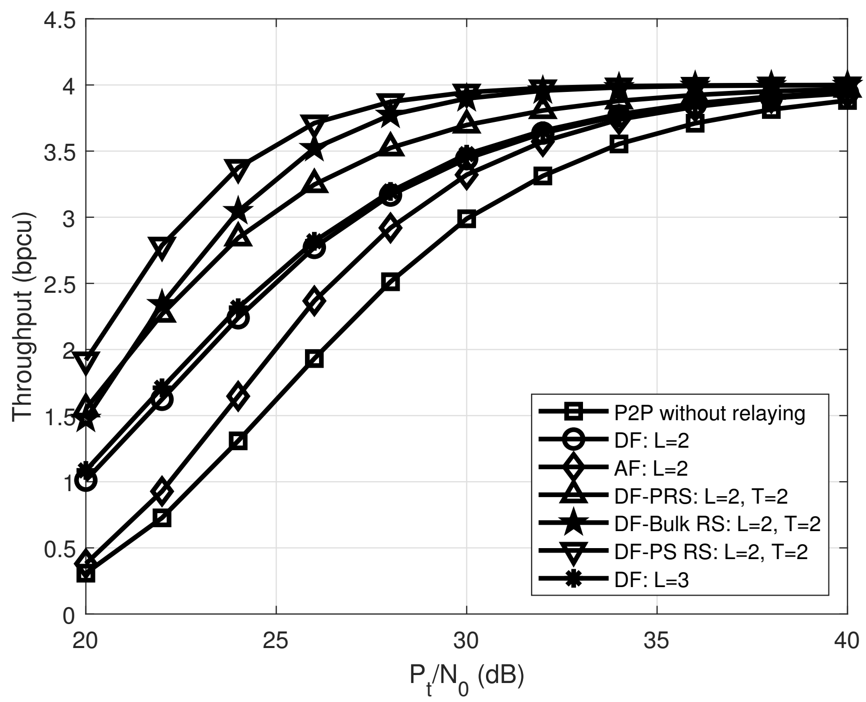

Figure 6. Throughput comparison among point-to-point plain OFDM-IM system and various relay assisted OFDM-IM systems with different system configurations.

Table 1. Qualitative Comparisons among plain OFDM, classic OFDM-IM and relay-assisted OFDM-IM.

Key measures	Plain OFDM	Classic OFDM-IM	Relay assisted OFDM-IM
Reliability	Moderate	Moderate	High
Throughput	Low	Moderate	Moderate
Spectral efficiency	Moderate	Moderate	High
Energy efficiency	Low	Moderate	High
System complexity	Low	Moderate	High
Signaling overhead	Low	Low	Moderate
Transmission delay	Low	Low	High