# Advances in Cooperative Single-Carrier FDMA Communications: Beyond LTE-Advanced

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***Abstract*—In this treatise, we focus our attention on the cooperative uplink transmissions of systems beyond the LTE-Advanced initiative. We commence a unified treatment of the principle of single-carrier frequency-division multiple-access (FDMA) and the similarities and dissimilarities, advantages and weakness of the localized FDMA, the interleaved FDMA and the orthogonal FDMA systems are compared. Furthermore, the philosophy of both user cooperation and of cooperative single-carrier FDMA is reviewed. They are investigated in the context of diverse topologies, transmission modes, resource allocation and signal processing techniques applied at the relays. Benefits of relaying in LTE-Advanced are also reviewed. Our discussions demonstrate that these advanced techniques optimally exploit the resources in the context of cooperative single-carrier FDMA system, which is a promising enabler for various uplink transmission scenarios.**

***Index Terms*—Cooperative Communications, Diversity, Dynamic Resource Allocation, Frequency-Domain Equalization, LTE-Advanced, MIMO, Opportunistic Relaying, SC-FDMA**

## I. INTRODUCTION

THE worldwide growth in both the number of mobile subscribers and their demand for increased rate mobile broadband services provided further impetus for the mobile telecommunication operators to improve both the capacity and the reliability of cellular networks. Hence, they have been upgraded from the *second generation* (2G) to the *third generation* (3G) globally, namely from the narrowband *time-division multiple-access* (TDMA) based *Global System for Mobile communications* (GSM) to the 3G *code-division multiple-access* (CDMA) based *Universal Mobile Telecommunications Systems* (UMTS). Both the 2G and 3G systems rely on *frequency-division duplexing* (FDD) in Europe and on *time-division duplexing* (TDD) mode in China. Meanwhile, the upgrading of the cellular networks in North America from the *single-carrier* (SC) modulated CDMA to *multi-carrier* (MC) modulated CDMA has also taken place. Recently, further enhancements and extensions of the above-mentioned UMTS systems have been created in the context of the so-called *High Speed Packet Access* (HSPA) techniques and its evolved version HSPA+, for the sake of improving the *uplink* and *downlink* performance at a minimum cost based on the currently operational networks. By contrast, in order to meet the *fourth generation* (4G) requirement, *orthogonal frequency-division multiple-access* (OFDMA) based new air interfaces, such as the *Third Generation Partnership Project's* (3GPP) *Long Term Evolution* (LTE) initiative [1], [2] have also been rolled out in several parts of the globe. In the following sections, we will review both the advantages and disadvantages of SC and MC modulation techniques[1].

TABLE I
ACRONYMS: 2-L

| | |
|---|---|
| 2G | second generation |
| 3G | third generation |
| 3GPP | third Generation Partnership Project |
| 4G | fourth generation |
| AF | amplify-and-forward |
| AWGN | additive white Gaussian noise |
| BER | bit-error ratio |
| BICM | bit-interleaved coded modulation |
| BS | base station |
| CCI | co-channel interference |
| CTF | channel transfer function |
| CDMA | code-division multiple-access |
| CFO | carrier frequency offset |
| CP | cyclic prefix |
| CQI | channel quality information |
| CSI | channel state information |
| CIR | channel impulse response |
| DF | decode-and-forward |
| DFE | decision-feedback equalization |
| DFT | discrete Fourier transform |
| DRA | dynamic resource allocation |
| DRS | dynamic relay selection |
| DSA | dynamic subband allocation |
| DT | direct transmission |
| FD | frequency-domain |
| FDD | frequency-division duplexing |
| FDE | frequency-domain equalization |
| FDMA | frequency-division multiple-access |
| FEC | forward error correction |
| FHQA | first-hop-quality-aware |
| GSM | Global System for Mobile communications |
| HIC | hybrid interference cancellation |
| HSPA | high speed packet access |
| IC | interference cancellation |
| ICI | inter-carrier interference |
| IDFT | inverse discrete Fourier transform |
| IFDMA | interleaved frequency-division multiple-access |
| ISI | inter-symbol interference |
| JDRA | joint dynamic resource allocation |
| JFDEC | joint frequency-domain equalization and combining |
| LE | linear equalization |
| LFDMA | localized frequency-division multiple-access |
| LTE | Long Term Evolution |

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[1] Acronyms (see Tables I and II).

TABLE II
ACRONYMS: M-Z

| | |
|---|---|
| MAP | maximum a-posteriori probability |
| MA-RS | multi-access relay selection |
| MC | multi-carrier |
| MF | matched-filtering |
| MIMO | multiple-input-multiple-output |
| MMSE | minimum mean-square error |
| MT | mobile terminal |
| MU | multi-user |
| MUD | multi-user detection |
| MUI | multi-user interference |
| MU-RS | multi-user relay selection |
| MWR | multi-way relaying |
| OFDM | orthogonal frequency-division multiplexing |
| OFDMA | orthogonal frequency-division multiple-access |
| OR | opportunistic relaying |
| PAPR | peak-to-average power ratio |
| PAM | pulse-amplitude modulation |
| PIC | parallel interference cancellation |
| P/S | parallel-to-serial |
| QAM | quadrature amplitude modulation |
| R-D | relay-to-destination |
| RA | resource allocation |
| RB | resource block |
| RS | relay selection |
| SC | single-carrier |
| S-D | source-to-destination |
| S-R | source-to-relay |
| SDR | single-dedicated-relaying |
| SFBC | space-frequency block code |
| SIC | successive interference cancellation |
| SNR | signal-to-noise ratio |
| SSR | single-shared-relaying |
| STBC | space-time block coding |
| SP | set-partition |
| SU | single-user |
| SU-RS | single-user relay selection |
| TD | time-domain |
| TDD | time-division duplexing |
| TDMA | time-division multiple-access |
| TFD | time-frequency-domain |
| UMTS | Universal Mobile Telecommunications Systems |
| ZF | zero-forcing |
| ZP | zero-padding |

### A. Single-Carrier versus Multi-Carrier Modulation

When communicating over broadband channels imposing frequency-selective fading, conventional SC modulation based systems require high-complexity *time-domain* (TD) equalizers having a large number of taps, in order to suppress the *inter-symbol interference* (ISI) due to time-dispersion. However, this disadvantage can be overcome by the family of MC modulation techniques, such as *orthogonal frequency-division multiplexing* (OFDM), which was originally introduced in [3]. In the context of MC communications, the original *bit stream* is divided into numerous low-rate *substreams* transmitted in parallel, which are mapped to *subcarriers* or *subchannels*. When using a high number of substreams, each subchannel becomes sufficiently narrow compared to the *coherence bandwidth* of the channel. Therefore, the signal transmitted over each non-dispersive subchannel experiences frequency-flat fading. As a result, the ISI of each *frequency-domain* (FD) substream becomes lower and a low-complexity FD equalizer having a single tap may be employed [4]. However, this parallel transmission scheme would potentially require a bank of modulators and demodulators operating in parallel. Fortunately, it was shown in [5] that this problem may be circumvented by employing the DFT and IDFT operations, which carry out the modulation/demodulation in a single step. More explicitly, the implementation complexity of OFDM is significantly lower than that of the parallel banks of modulators and the demodulators/equalizers. A plethora of further OFDM system improvements, such as various combinations of OFDM and CDMA, leading to MC-CDMA systems have been investigated in [6], [7].

The OFDM signaling technique of Fig. 1(a) has the following advantages. Firstly, the ISI can be significantly mitigated with the aid of relatively low signal processing complexity at the receiver. Secondly, in OFDM signaling, using overlapping but orthogonal subcarriers leads to an increased spectral efficiency [4]. Thirdly, the FD channel fluctuations may be accommodated by invoking subband-based adaptive modulation in OFDM, where each subband of parallel subcarriers may be modulated using a FD *channel transfer function* (CTF)-dependent number of bits, depending on the *signal-to-noise ratio* (SNR) of the individual subbands. As a result, the throughput of OFDM systems may be increased with the aid of adaptive modulation.

However, it is a disadvantage that in the absence of channel coding, the OFDM system is incapable of achieving diversity. When channel coding, such as *bit-interleaved coded modulation* (BICM) [8], is applied on an individual subcarrier basis, the system may achieve a certain time-diversity gain as a benefit of channel coding and interleaving, but no frequency-diversity may be attained, unless the same symbol is transmitted several times by mapping it to independently fading subcarriers, which have to reside outside the channel's coherent bandwidth. A better way of achieving frequency-diversity for OFDM is to exploit coding and interleaving applied right across all the subcarriers [9].

Owning to transmitting multiple signals in parallel, OFDM signaling also has some disadvantages. Firstly, due to the superposition of a high number of modulated subcarrier signals, a high *peak-to-average power ratio* (PAPR) may be exhibited [6]. The PAPR problem imposes substantial challenges on the practical design of power amplifiers, which have a limited linear range. In case of non-linear amplification, the resultant high out-of-band harmonic distortion power may contaminate the adjacent channels, when the TD signal evolves from a low-power waveform to a high-power waveform [6]. Diverse techniques of PAPR reduction have been investigated in the literature [10]–[15]. A beneficial low-complexity technique is based on employing a so-called block-coding [16], where some of the subcarriers do not convey useful data - instead, they are simply set to a value, which reduces the peak-power. Secondly, a further impediment of OFDM is that it is very sensitive to both frequency and time offsets [4].

### B. State-of-the-Art of SC-FDMA

Although MC modulation has some advantages over the conventional SC modulation, it suffers from the above-mentioned PAPR problem. Naturally, SC modulation having a significantly lower PAPR is more suitable for uplink transmissions than MC modulation, since the battery-size of *mobile*

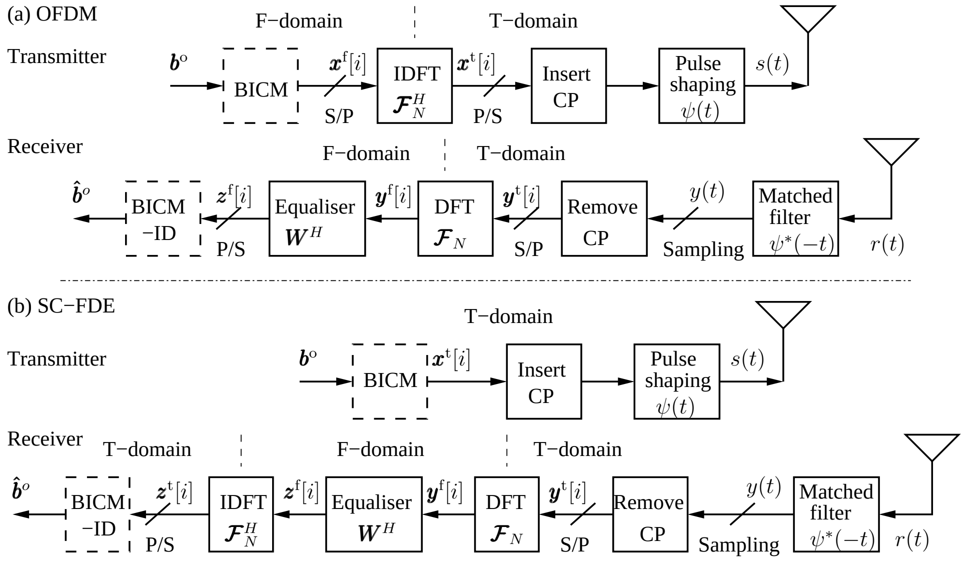


Fig. 1. Block diagram of baseband OFDM and SC-FDE systems: (a) OFDM, (b) SC-FDE

*terminal* (MT) is limited, hence requiring power-efficient nonlinear amplifiers. In order to take advantage of the benefits of both SC and MC modulation, the SC received signal may be transformed to and equalized in the FD with the aid of the IDFT and DFT operations. This arrangement is referred to as SC modulation relying on *frequency-domain equalization* (FDE), which is seen in Fig. 1(b) [17]–[19]. Furthermore, by combining the SC-FDE and FDMA principles, SC-FDMA may rely either on TD or on FD signal generation [20]. The important development mile-stones of SC-FDMA are shown in Tables III and IV. The FD signal generation approach, namely that of DFT-spread OFDMA, has been adopted by the 3GPP-LTE initiative (since Release 8) [21] as well as by its advanced versions (e.g. LTE-Advanced Release 11) [22] for SC-FDMA based uplink transmissions within the 4G wide area cellular broadband wireless systems [1], [2], [23]–[25].

In this treatise, we focus our attention on the cooperative uplink transmissions of systems beyond the LTE-Advanced initiative. Main contributions of this paper can be summarized as follows. A unified treatment of the principle of SC-FDMA is offered. The relationship between the TD and the *time-frequency-domain* (TFD) signal generation of SC-FDMA is detailed, by considering both the *localized* FDMA (LFDMA) [93] and the *interleaved* FDMA (IFDMA) [28] schemes. Finally, the similarities and dissimilarities, advantages and weaknesses of the LFDMA, IFDMA and OFDMA systems are compared. The cooperative SC-FDMA philosophy is reviewed and investigated in the context of diverse uplink topologies, relay resource allocation and signal processing techniques applied at the relays.

The rest of this paper is organized as follows. In Section II, we present a rudimentary introduction to SC-FDMA, commencing by introducing the SC modulation philosophy invoking FDE. Based on the SC-FDE scheme, the conventional signal generation of SC-FDMA and that adopted by the 3GPP-LTE uplink, which is referred to as *discrete Fourier transform* (DFT)-spread OFDMA are compared. Enhanced signal reception and equalization techniques are also conceived for relying on both the linear and iterative approaches. In Section III, we investigate a variety of cooperative relaying schemes designed for the SC-FDMA uplink, when a number of inactive MT as potential relays, which are either geographically distributed or co-located in a cell. Specifically, the resource allocation and signal processing schemes are designed at relays for the sake of power reduction. Finally, we conclude and discuss some open problems set aside for future work in Section IV.

## II. INTRODUCTION TO SINGLE-CARRIER FDMA

In this section, we review the principles of SC-FDE and SC-FDMA. Two types of SC-FDMA schemes are considered as the evolution of SC-FDMA. In the first type, the transmitted signals are only processed in the TD, which is hence referred to as TD processing aided SC-FDMA, or TD SC-FDMA for short. By contrast, in the second type of SC-FDMA, the transmitted signals are processed in both the TD and FD with the aid of the DFT/IDFT. Hence, this type is referred to as TFD SC-FDMA for the sake of distinction.

### *A. Key Modules in OFDM-Style Transceivers*

Let us initially review the key signal processing modules in OFDM-style transceiver structures. Specifically, we consider a *single-user* (SU) OFDM system employing $N$ subcarriers. The block diagrams of the OFDM transmitter/receiver are shown in Fig. 1(a). We describe each module as follows.

- **BICM and BICM-ID:** In the context of BICM in Fig. 1, the bit stream $\boldsymbol{b}^{\mathrm{o}}$ is encoded, interleaved and modulated to generate the *quadrature amplitude modulation* (QAM) based symbol frame in the transmitter. Let the symbols to be transmitted by the $i$-th symbol block be expressed as $\boldsymbol{x}^{\mathrm{f}}[i] = \left[x_0^{\mathrm{f}}[i], x_1^{\mathrm{f}}[i], \cdots, x_{N-1}^{\mathrm{f}}[i]\right]^T$, which is a $N$-length vector for $i = 0, 1, \cdots$. At the

TABLE III
MAJOR CONTRIBUTIONS ON SC-FDE AND SC-FDMA TECHNIQUES

| Year | Authors | Contributions |
|---|---|---|
| 1995 | Sari *et al.* [17] | discussed the OFDM signaling limitations and inherent problems of OFDM emphasized the benefits of SC-FDE for digital TV broadcasting. |
| 1998 | Clark [26] | proposed adaptive FDE and diversity combining. |
| | Sorger *et al.* [27], [28] | proposed the original TD IFDMA signal generation scheme, while the receiver invokes TD equalization. |
| 2002 | Galda *et al.* [29] | proposed the DFT-spreading aided OFDM scheme, which can be combined with FDMA as the TFD signal generation of IFDMA, while the receiver invokes LE and detection in the FD. |
| | Falconer *et al.* [18] | discussed the SC-FDE arrangement using FD LE or TD DFE. The comparison between SC-FDE and OFDM systems and their coexistence were addressed. |
| | Benvenuto *et al.* [30] | proposed the block-wise hybrid DFE structure for SC system by using a FD feedforward filter and a TD feedback filter, and compared it to the OFDM system. |
| 2003 | Gusmão *et al.* [31] | investigated the CP-assisted SC-FDE as well as diversity combining and provided both numerical results and the analytical performance bound. |
| 2004 | Wang [32] | compared OFDM to SC-FDE systems using either ZP or CP over frequency-selective fading channels, and considered the performance versus complexity for both uncoded and coded transmissions. |
| | Dinis *et al.* [33] | proposed a FD SC signal generation scheme, which is equivalent to the OFDM-FDMA using the DFT-spreading of [29]. |
| 2005 | Benvenuto *et al.* [34], [35] | proposed a block-wise DFE, where both the feedforward and the feedback filters were implemented in the FD relying on the MMSE criterion. |
| 2006 | Myung *et al.* [36], [37] | generalized the DFT-spread OFDM scheme of [29] by combining both the IFDMA and LFDMA solutions, PAPR comparisons of IFDMA, LFDMA and of OFDMA signals were provided. |
| | Lim *et al.* [38], [39] | investigated the various types of MU scheduling schemes conceived for SC-FDMA systems. |
| 2007 | Frank *et al.* [40] | reviewed and discussed the IFDMA principle as a combination of OFDMA as well as CDMA and compared IFDMA, LFDMA, OFDMA as well as the SC- or MC-CDMA schemes. |
| 2008 | Myung *et al.* [41] | a book on the topic of SC-FDMA design for LTE uplink combined with beamforming, MU scheduling and PAPR evaluation. |
| | Berardinelli *et al.* [42]–[44] | investigated MU scheduling schemes for SC-FDMA in comparison to OFDMA in LTE-Advanced. |
| 2009 | Adachi *et al.* [45], [46] | overviewed the SC-FDE schemes and that with the aid of IC technique in order to mitigate the residual ISI. Various combinations of SC-FDE with FDMA and CDMA were also investigated. |
| | Lim *et al.* [47] | proposed opportunistic scheduling for SC-FDMA with iterative multi-user detection (MUD). |
| | Dinis *et al.* [48] | proposed a high throughput FD multi-packet detection for SC-FDE systems. |
| | Yang [7] | investigated the subband mapping in SC-FDMA and discussed the trade-off between achieving a frequency diversity gain and mitigating the residual ISI. |
| | Wong *et al.* [49] | investigated optimal resource allocation in uplink SC-FDMA systems. |
| | Yoshida *et al.* [50] | analyzed the compensation of transmitter IQ imbalances in OFDMA and SC-FDMA Systems. |
| | Noune *et al.* [51] | proposed FD implementation of *Tomlinson-Harashima precoding* (THP) and investigate the *bit error rate* (BER) and the PAPR performance for SC-FDMA using THP. |
| 2010 | Al-kamali *et al.* [52] | studied on transceiver scheme for SC-FDMA invoking the wavelet transform and PAPR reduction. |
| | Benvenuto *et al.* [19] | historically reviewed the various non-linear FDE schemes in the context of SC-FDE and SC-FDMA. |
| | Choi *et al.* [53]–[55] | investigated the adaptive multi-level BICM using iterative MUD combined with FDE for *interleaver-division multiplexing* (IDM) aided SC-FDMA. |
| | Ma *et al.* [56], [57] | studied on *inter-carrier interference* (ICI) and MAI suppression and cancellation techniques in SC-FDMA with *carrier frequency offsets* (CFO) due to Doppler effect. |
| | Liu *et al.* [58] | proposed a low-complexity subcarrier-power allocation scheme for both OFDMA and SC-FDMA systems. |
| | Nam *et al.* [59] | investigated the interpolation-based SC-FDMA transmitter with localized resource allocation. |
| | Zhang *et al.* [60], [61] | proposed novel low-complexity FD DFE structures for SC-FDE systems and MU SC-FDMA systems. |
| | Kim *et al.* [62] | investigated inter-subcarrier interference compensation in the frequency-hopped SC-FDMA systems. |

$$\boldsymbol{\mathcal{F}}_N = \frac{1}{\sqrt{N}} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & \exp\left(-j\frac{2\pi}{N}\right) & \cdots & \exp\left(-j\frac{2\pi(N-1)}{N}\right) \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \exp\left(-j\frac{2\pi(N-1)}{N}\right) & \cdots & \exp\left(-j\frac{2\pi(N-1)(N-1)}{N}\right) \end{bmatrix}, \tag{1}$$

$$\boldsymbol{H}^{\mathrm{t}} = \begin{bmatrix} h_0^{\mathrm{t}} & 0 & \cdots & 0 & h_{L-1}^{\mathrm{t}} & h_{L-2}^{\mathrm{t}} & \cdots & h_1^{\mathrm{t}} \\ h_1^{\mathrm{t}} & h_0^{\mathrm{t}} & \cdots & 0 & 0 & h_{L-1}^{\mathrm{t}} & \cdots & h_2^{\mathrm{t}} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{L-2}^{\mathrm{t}} & \cdots & h_1^{\mathrm{t}} & h_0^{\mathrm{t}} & 0 & \cdots & 0 & h_{L-1}^{\mathrm{t}} \\ h_{L-1}^{\mathrm{t}} & \cdots & h_2^{\mathrm{t}} & h_1^{\mathrm{t}} & h_0^{\mathrm{t}} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{L-1}^{\mathrm{t}} & h_{L-2}^{\mathrm{t}} & \cdots & h_1^{\mathrm{t}} & h_0^{\mathrm{t}} \end{bmatrix}, \tag{2}$$

receiver, the BICM decoder carries out the symbol-to-bit demapping, deinterleaving and channel decoding, in

TABLE IV
MAJOR CONTRIBUTIONS ON SC-FDE AND SC-FDMA TECHNIQUES (CONTINUED)

| Year | Authors | Contributions |
|---|---|---|
| 2011 | Yamamoto *et al.* [63] | designed a phase rotation sequence selection method for IFDMA with decision directed channel estimation in fast time-varying fading channel. |
| | Nwamadi *et al.* [64] | investigated dynamic *physical resource block* (PRB) allocation algorithms for LTE uplink SC-FDMA. |
| | Ma *et al.* [65] | proposed optimal orthogonal precoding for power leakage suppression for SC-FDMA systems. |
| | Al-kamali *et al.* [66] | investigated joint equalization and CFO compensation for SC-FDMA uplink. |
| | Gao *et al.* [67] | proposed CP-based orthogonal QAM aided OFDM and its application to SC-FDMA systems. |
| | Song *et al.* [68] | studied on localized and interleaved subband allocation for SC-FDMA in terms of the trade-off between diversity and CFO interference in multi-path channels. |
| | Falconer *et al.* [69] | proposed a power variance-minimizing linear block precoding for OFDMA which requires a slightly lower power back-off than that for DFT precoding adopted in SC-FDMA. |
| | Wylie *et al.* [70] | proposed a *continuous phase modulation* (CPM) aided SC-FDMA transmission for PAPR reduction. |
| | Sanchez *et al.* [71] | analyzed the performance for *zero-forcing* (ZF) FDE based SC-FDMA over Nakagami-m Fading Channels. |
| | Rana *et al.* [72] | investigated *least mean squared* (LMS) based blind channel estimation of SC-FDMA systems using variable step size and phase information. |
| 2012 | Sanchez *et al.* [73] | applied the student's t and behrens-fisher distributions to the analysis of enhanced noise after FDE. |
| | Choi *et al.* [74], [75] | investigated spectral efficient MU techniques with channel-dependent resource allocation for SC-FDMA. |
| | Ochiai [76] | studied on instantaneous power distributions of SC-FDMA signals. |
| | Yaacoub *et al.* [77] | surveyed the uplink resource allocation schemes in OFDMA wireless networks. |
| | Zhang *et al.* [78] | analyzed various turbo FDE receivers in coded SC-FDMA using *extrinsic information transfer* (EXIT) charts. |
| | Geles *et al.* [79] | analyzed performance bounds for *maximum likelihood* (ML) detection of SC-FDMA. |
| | Kim *et al.* [80] | proposed iterative channel estimation with frequency replacement for SC-FDMA systems. |
| | Deng *et al.* [81] | designed a low PAPR transceiver with enhanced link quality for coded SC-FDMA. |
| | Fan *et al.* [82] | jointly optimized user pairing and resource allocation for SC-FDMA LTE uplink. |
| | Yang *et al.* [83] | proposed fast time-varying channel estimation technique for SC-FDMA LTE uplink. |
| | Yuen *et al.* [84] | analyzed optimum precoder for SC-FDMA in order to reduce PAPR. |
| | Azurdia *et al.* [85] | investigated PAPR Reduction in SC-FDMA by pulse shaping using parametric linear combination pulses. |
| | Sridharan *et al.* [86] | analyzed the performance of SC-FDMA in the presence of receiver phase noise and ICI. |
| 2013 | Wen *et al.* [87], [88] | analyzed BER performance of ZF based interleaved SC-FDMA over Nakagami-*m* multi-path fading channel and proposed a general framework for BER analysis of OFDMA and SC-FDMA with arbitrary Nakagami factor *m*. |
| | Zhang *et al.* [89] | investigated an enhanced Greedy algorithm based resource allocation for localized SC-FDMA systems. |
| | Sanchez [90] | analyzed spectral efficiency of SC-FDMA with adaptive modulation and coding over Nakagami-*m* fading channels. |
| | Lei *et al.* [91] | proposed a unified graph labeling algorithm for consecutive-block channel allocation in SC-FDMA transmission. |
| | Cruz *et al.* [92] | investigated SC- and MC- transceivers based on discrete cosine transform in the presence of CFO. |

order to generate the bit stream $\hat{\boldsymbol{b}}^{\rm o}$ from the equalized symbol frame containing the $i$-th equalized symbol vector $\boldsymbol{z}^{\rm f}[i] = \left[z_0^{\rm f}[i], z_1^{\rm f}[i], \cdots, z_{N-1}^{\rm f}[i]\right]^T$ for $i = 0, 1, \cdots$. Additionally, the attainable error correction performance may be improved, when BICM invoking iterative decoding (BICM-ID) is used [8].

- **S/P and P/S converter:** In Fig. 1(a), the *serial-to-parallel* (S/P) converter converts the serial symbol stream into $N$ parallel symbols hosted in the $i$-th vector. By contrast, the *parallel-to-serial* (P/S) converter converts the $N$ parallel elements in the $i$-th symbol vector into a $N$-times higher-rate serial symbol stream, for $i = 0, 1, \cdots$. The S/P and P/S converters facilitate the processing of serial symbols in parallel by DFT and IDFT.
- **DFT and IDFT:** [2] The $N$-point DFT matrix $\boldsymbol{\mathcal{F}}_N$ is given by Eq. (1), which is an orthogonal matrix, satisfying the property $\boldsymbol{\mathcal{F}}_N \boldsymbol{\mathcal{F}}_N^H = \boldsymbol{\mathcal{F}}_N^H \boldsymbol{\mathcal{F}}_N = \boldsymbol{I}_N$. Furthermore, we have $\boldsymbol{\mathcal{F}}_N^{-1} = \boldsymbol{\mathcal{F}}_N^H$. Multiplying the vector $\boldsymbol{x}^{\rm f}$ by $\boldsymbol{\mathcal{F}}_N^H$ implements the IDFT, as also seen in Fig. 1.
- **Insert and remove cyclic prefix:** In the DFT/IDFT aided multi-carrier system of Fig. 1 experiencing *linear time invariant* (LTI) multi-path fading channels, the linear convolution between the channel's input sequence, i.e. the transmitted signal containing $\boldsymbol{x}^{\rm t}[i]$ for $i = 0, 1, \cdots$ after P/S conversion, and the discrete-time *channel impulse response* (CIR) associated having a finite number of taps $L$, results in ISI between each consecutive serial data sequences $\boldsymbol{x}^{\rm t}[i]$ and $\boldsymbol{x}^{\rm t}[i+1]$ represented in the TD. One solution to this problem is to insert a *cyclic prefix* (CP), which copies the last $L_{\rm CP} \geq L$ samples, i.e. $\{x_{N-L_{\rm CP}}^{\rm t}[i], x_{N-L_{\rm CP}+1}^{\rm t}[i], \cdots, x_{N-1}^{\rm t}[i]\}$, from the end to the beginning of the serial sequence $\boldsymbol{x}^{\rm t}[i]$. This is required, because the inherent assumption facilitating DFT-based demodulation is that the received TD signal is periodic - at least for the duration of the channel's memory. A theoretically less well justified alternative method of mitigating the ISI is known as *zero-padding* (ZP) [4], [94].
- **Pulse shaping and matched filtering:** In order to improve the spectral efficiency of the OFDM modulated signals, typically a pulse shaping technique using a raised-cosine filter is adopted at the transmitter. Let us assume that $\psi(t)$ represents a TD signaling waveform defined over the interval of $[0, T_\psi)$ satisfying the normalization condition of $\int_0^{T_\psi} \psi^2(t){\rm d}t = T_\psi$. Since each DFT block transmits $N$ samples, the duration of each

[2] Let $\{x(0), x(1), \cdots, x(N-1)\}$ be an $N$-length sequence, then the DFT and IDFT are defined as [7]

$$\text{DFT:} \quad X[n'] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] \exp\left(-j\frac{2\pi n' n}{N}\right), n' = 0, 1, \cdots, N-1;$$

$$\text{IDFT:} \quad x[n] = \frac{1}{\sqrt{N}} \sum_{n'=0}^{N-1} X[n'] \exp\left(j\frac{2\pi n' n}{N}\right), n = 0, 1, \cdots, N-1.$$

sample is given by $T_\psi = T/N$, where $T$ denotes the OFDM block duration. Furthermore, the band-limited transmitted pulse $\psi(t)$ is convoluted with the CIR $c(t)$ and the matched filter $\psi^*(-t)$ at the receiver, resulting in the effective received pulse given by the convolution of $\psi(t) * c(t) * \psi^*(-t)$ prior to sampling, as seen in Fig. 1. Naturally, the *Nyquist criterion* [95] must be satisfied by the sampling of effective received pulse for the sake of avoiding ISI between consecutive samples of the received signal.

- **Channel and equalization:** When the above-mentioned CP is employed and when it is sufficiently long, the self-interference of OFDM symbol and the ISI between a pair of consecutive OFDM symbols is mitigated. Let the $L$-tap CIR be expressed as [4]

$$h(t) = \sum_{l=0}^{L-1} h_l^{\mathrm{t}} \delta(t - lT_c), \tag{3}$$

where $h_l^{\mathrm{t}}$ is the gain of the $l$-th resolvable path for $l = 0, 1, \cdots, L-1$. For example, Fig. 2(a) demonstrates a Rayleigh distributed multi-path fading channel represented by $50$ consecutive time-correlated samples of the TD CIR modeled by a *tapped-delay line* (TDL) for $L = 4$ CIR taps associated with a normalized Doppler frequency of $f_{\mathrm{d}} = 0.01$. For the given number of samples, the time-correlation of the CIR taps decreases upon increasing the Doppler spread, which is quantified by the normalized Doppler frequency. Then, after sampling, the channel matrix in the TD may be represented by a $(N \times N)$-element circulant matrix given by Eq. (2) [7], which has the property that $\boldsymbol{H}^{\mathrm{t}} = \boldsymbol{\mathcal{F}}_N^H \boldsymbol{H}^{\mathrm{f}} \boldsymbol{\mathcal{F}}_N$, where $\boldsymbol{H}^{\mathrm{f}} = \mathrm{diag}\{h_0^{\mathrm{f}}, h_1^{\mathrm{f}}, \cdots, h_{N-1}^{\mathrm{f}}\}$. Therefore, after applying the DFT-based detection operation at the receiver and having in mind that IDFT-based modulation was applied at the transmitter, the equivalent FD *channel transfer function* (CTF) can be represented as a $(N \times N)$-element diagonal matrix given by

$$\boldsymbol{H}^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_N \boldsymbol{H}^{\mathrm{t}} \boldsymbol{\mathcal{F}}_N^H \tag{4}$$

For instance, Fig. 2(b) depicts the $L = 4$-path Rayleigh distributed frequency-selective fading channel represented by $50$ consecutive time-correlated samples of the FD CTF over $U = 32$ subcarriers associated with $f_{\mathrm{d}} = 0.01$, corresponding to the TD CIR seen in Fig. 2(a). For the given number of subcarriers, the frequency correlation of the CTF decreases upon increasing the Delay spread, which is quantified in terms of the number of resolvable paths seen in the CIR. Consequently, in OFDM systems, a low-complexity single-tap equalizer is required. As a benefit of the DFT/IDFT operation, the high complexity TD convolution-based equalization may be replaced by the FD *subcarrier-by-subcarrier* based multiplication operation in a linear time-invariant system. Therefore, the computational complexity is significantly reduced.

## B. Transceiver of Time-Domain SC-FDMA

*1) Single-User Version: SC-FDE:* The schematic of SC-FDE system [18], [46] is shown in Fig. 1(b). At the transmitter of Fig. 1(b), let the data symbols be divided into $N$-symbol blocks expressed as $\boldsymbol{x}^{\mathrm{t}}[i] = \left[x_0^{\mathrm{t}}[i], x_1^{\mathrm{t}}[i], \cdots, x_{N-1}^{\mathrm{t}}[i]\right]^T$, $i = 0, 1, \cdots$. Then, each block $\boldsymbol{x}^{\mathrm{t}}[i]$ is transmitted in a conventional serial fashion in the TD within a duration of $T_{\mathrm{v}}$. In order to suppress the ISI between consecutive symbol blocks at the transmitter, as shown in Fig. 1(b), a CP is inserted between a pair of successive symbol blocks. Hence, the duration $T_{\mathrm{v}}$ includes that of CP. At the receiver side, as shown in Fig. 1(b), the TD observations are firstly transformed to FD with the aid of DFT block, where the FDE is invoked. Then, the results are converted to the TD again using the IDFT of Fig. 1(b), where the transmitted symbols are detected. When comparing the OFDM schematic of Fig. 1(a) to Fig. 1(b), we can see that in OFDM transceivers, the transmitter relies on the IDFT-based modulator, while the receiver invokes a DFT-based demodulator. By contrast, in the SC-FDE of Fig. 1(b), both the IDFT and DFT are required at the receiver. More explicitly, given the low PAPR and the low-complexity single-tap FDE of SC-FDMA, we exploit the fact that IDFT/DFT operations facilitate moderate-complexity transformations between the TD and FD.

According to Fig. 1(b), after the CP was removed and following the $N$-point DFT operation, the received FD observation vector may be expressed as

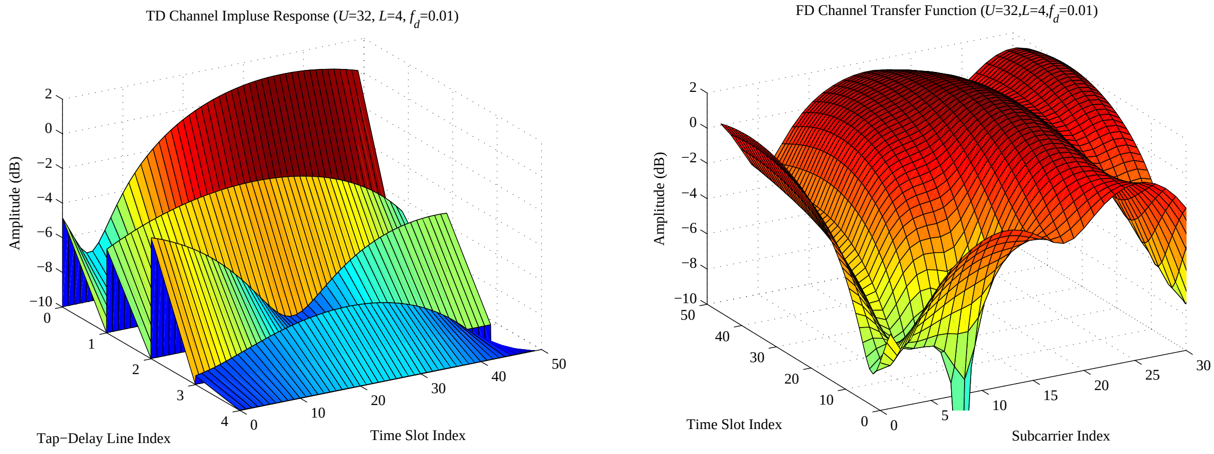
$$\boldsymbol{y}^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_N \boldsymbol{H}^{\mathrm{t}} \boldsymbol{x}^{\mathrm{t}} + \boldsymbol{\mathcal{F}}_N \boldsymbol{n}^{\mathrm{t}}, \tag{5}$$

where $\boldsymbol{n}^{\mathrm{t}} = \left[n_0^{\mathrm{t}}, n_1^{\mathrm{t}}, \cdots, n_{N-1}^{\mathrm{t}}\right]^T$ represents the $N$-length complex-valued *additive white Gaussian noise* (AWGN) vector having a zero mean and a variance of $\sigma_{\mathrm{N}}^2$ at each element, denoted by $\mathcal{CN}(0, \sigma_{\mathrm{N}}^2)$. Since the channel matrix obeys the circulant property of $\boldsymbol{H}^{\mathrm{t}} = \boldsymbol{\mathcal{F}}_N^H \boldsymbol{H}^{\mathrm{f}} \boldsymbol{\mathcal{F}}_N$, Eq. (5) may be rewritten as $\boldsymbol{y}^{\mathrm{f}} = \boldsymbol{H}^{\mathrm{f}} \boldsymbol{x}^{\mathrm{f}} + \boldsymbol{n}^{\mathrm{f}}$, where $\boldsymbol{H}^{\mathrm{f}}$ represents an $(N \times N)$-element diagonal FD channel matrix, while $\boldsymbol{x}^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_N \boldsymbol{x}^{\mathrm{t}}$ and $\boldsymbol{n}^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_N \boldsymbol{n}^{\mathrm{t}}$. The corresponding FD CTF associated with frequency-selective fading will be further discussed in the context of Fig. 9(c). Similar to OFDM, a single-tap FD equalizer may be employed in each subband. Finally, the resultant FD equalized symbol vector $\boldsymbol{z}^{\mathrm{f}}$ is transformed by the $N$-point IDFT to the estimated TD decision variable vector representing the $N$ transmitted symbols, which may be expressed as

$$\boldsymbol{z}^{\mathrm{t}} = \boldsymbol{\mathcal{F}}^H \boldsymbol{W}^H \boldsymbol{H}^{\mathrm{f}} \boldsymbol{x}^{\mathrm{f}} + \boldsymbol{\mathcal{F}}^H \boldsymbol{W}^H \boldsymbol{n}^{\mathrm{f}}. \tag{6}$$

Finally, the *iterative detection* aided BICM (BICM-ID) decoder of Fig. 1(b) is invoked for channel decoding. Note that in Eq. (6) the FDE weight-matrix $\boldsymbol{W}$ is a diagonal matrix, since $\boldsymbol{H}^{\mathrm{f}}$ is diagonal.

Again, we assume that the perfect knowledge of the FD CTF $\boldsymbol{H}^{\mathrm{f}}$ is available at the BS's receiver. In the SC-FDE, various FDE approaches may be employed based on diverse criteria. When the *matched-filtering* (MF), *zero-forcing* (ZF) or the *minimum mean-square-error* (MMSE) criterion is employed, the equalizer-weight matrix $\boldsymbol{W}$ may be expressed as [7], [45],



(a) TD CIR Tap-Delay Line (b) FD CTF in Subcarriers

Fig. 2. An example of multi-path fading for in the context of our OFDM/SC-FDE system versus both the time-slots, and the TDL index in (a) and versus the subcarriers index in (b), respectively. The example characterizes the fading channel within $50$ consecutive time-slots associated with $L = 4$ taps and a total system bandwidth of $U = 32$ subcarriers. These $50$ samples of the TD fading envelope are time-correlated in conjunction with a normalized Doppler frequency of $f_d = 0.01$.

[46].

$$\boldsymbol{W} = \begin{cases} \boldsymbol{H}^{\mathrm{f}}, & \text{MF-FDE} \\ (\boldsymbol{H}^{\mathrm{f}})^{-1}, & \text{ZF-FDE} \\ \left[\boldsymbol{H}^{\mathrm{f}}(\boldsymbol{H}^{\mathrm{f}})^{H} + \frac{1}{\bar{\gamma}}\boldsymbol{I}_N\right]^{-1}\boldsymbol{H}^{\mathrm{f}}, & \text{MMSE-FDE} \end{cases}, \quad (7)$$

where $\bar{\gamma} = P/\sigma_{\mathrm{N}}^2$ denotes the average SNR. It can be seen from Eq. (6) and Eq. (7) that the symbols within $\boldsymbol{x}^{\mathrm{t}}$ interfere with each other, when invoking the MF- and MMSE-based FDE (MF-FDE, MMSE-FDE) schemes, which results in a residual ISI. By contrast, the residual ISI is completely eliminated by the ZF based FDE (ZF-FDE), but as a price, the noise may be amplified by a factor of $1/h_n^{\mathrm{f}}$, when a deep FD fade is encountered in the $n$-th subband, for example. As a benefit, the MMSE-FDE strikes a trade-off between the *residual* ISI suppression and noise enhancement imposed on $\boldsymbol{z}^{\mathrm{t}}$ [7], [45]. In Fig. 9(d) a snapshot of the FD weight values using both the MF as well as the ZF and MMSE algorithms for SC-FDE is captured, when communicating over frequency-selective fading channels associated with $L = 4$ CIR taps. The ISI mitigation effects may be observed in Fig. 9(e) and Fig. 9(f) by comparing $y$ and $z$, which represent the signal waveform or spectrum both before and after FDE in the TD or FD, respectively.

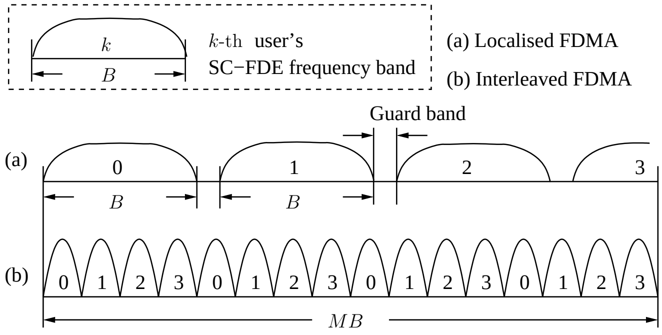


Fig. 3. An example of band-conversion and bandwidth-expansion for the TD SC-FDMA systems using (a) LFDMA and (b) IFDMA, respectively. Both the systems have a total bandwidth of $MB = 4B$, with a symbol rate of $B$ for supporting $K \leq M = 4$ users.

The differences between OFDM and SC-FDE transceiver structures lead to different features during signal transmissions. For example, the data detection of the SC-FDE receiver depends on the FD CTF of all the subbands, hence any deep fade of a specific subband may be mitigated. By contrast, in OFDM, individually applying data detection on a per subcarrier basis may result in decision errors for the subcarrier symbols suffering from deep FD fading. Furthermore, the SC-FDE signal cannot readily invoke adaptive bit- and power-loading depending on the subchannel qualities. By contrast, adaptive bit- and power-loading is feasible in OFDM, since the bit-to-symbol mapping may be carried out on a per-subcarrier basis after S/P conversion at the transmitter. In summary, we compare the features of OFDM and SC-FDE in Table V [41].

*2) Multi-User Version: TD SC-FDMA:* Above the SC-FDE scheme has only been considered in the context of SU transmission. Let us now focus our attention on *multi-user* (MU) FDMA scenarios. In order to support $K$ users in the uplink, two TD signaling schemes using SC-FDE have been considered by the 3GPP-LTE standardization body [96], [97], namely the *localized* FDMA (LFDMA) and the *interleaved* FDMA (IFDMA) schemes. Let us assume that the symbol duration is $T_{\mathrm{s}}$. Then, the duration of a SC-FDE block is $T_{\mathrm{v}} = NT_{\mathrm{s}}$, when each SC-FDE block contains $N$ symbols. As shown in Fig. 3, we assume that the symbol rate is $B = 1/T_{\mathrm{s}}$. Hence, if the total system bandwidth is $MB$, the maximum number of users supported becomes $K = M$. Let us now detail the operational principles of the LFDMA and IFDMA schemes using SC-FDE.

- *TD localized FDMA* [93], [96]: The transmitter schematic of the TD LFDMA is shown in Fig. 4(a), which is

TABLE V
COMPARISON OF OFDM AND SC-FDE SYSTEMS

| | OFDM | SC-FDE |
|---|---|---|
| Implementation | Similar, DFT/IDFT-aided, SC-FDE transmitter is simpler. | |
| ISI | Similar, non ISI by using CP | |
| Complexity | Similar, lower than that of the TD equalizer | |
| Modulation | MC | SC |
| Transmission | Parallel | Serial |
| Symbol duration | $N$ times per subcarrier | Unchanged |
| Bandwidth | $1/N$ per subcarrier | $1/N$ per subband at receiver |
| Frequency offset | Sensitive | Less sensitive |
| Against deep FD fading | Weak | Robust |
| Bit/power loading | Frequency-selective adaptation | Not applicable |

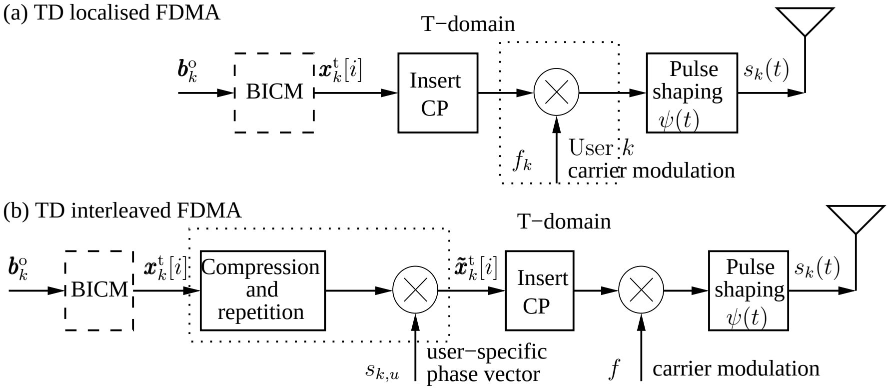
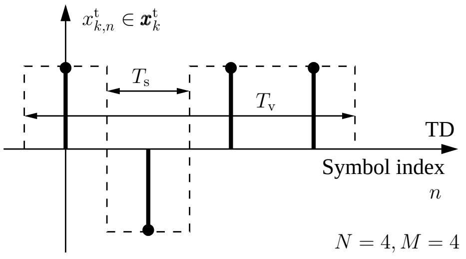
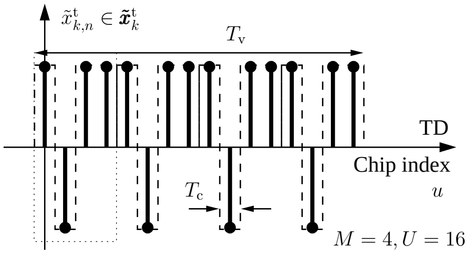


Fig. 4. Transmitter schematic of the TD SC-FDMA signaling scheme. The corresponding waveforms are seen in Fig. 5.



(a) Localized FDMA



(b) Interleaved FDMA

Fig. 5. An example of transmitted signal waveforms of the TD SC-FDMA signaling systems using (a) LFDMA and (b) IFDMA, respectively. Both the systems have a block duration of $T_{\mathrm{v}}$, with a symbol duration of $T_{\mathrm{s}}$ and the chip duration of IFDMA is $T_{\mathrm{c}} = T_{\mathrm{s}}/M = T_{\mathrm{s}}/4$. The system may support $K \leq M = 4$ users. The corresponding spectrum are seen in Fig. 3.

the conventional FDMA-based SC-FDE. The transmitted TD signal waveform of LFDMA is shown in Fig. 5(a). The signals of different users are transmitted in different frequency bands associated with different carriers. Specifically, the $k$-th user's signal is conveyed by the $k$-th subband with a bandwidth of $B$ Hz, as shown in Fig. 4(a). As shown in Fig. 3(a), in order to guarantee the orthogonality between the different users' signals, a guard band is inserted between two adjacent bands.

- *TD interleaved FDMA* [27], [28]: The corresponding transmitter schematic is shown in Fig. 4(b). In contrast to the above-mentioned TD LFDMA signaling, which allocates localized frequency bands to each of the users, the idea behind the TD IFDMA scheme is to disperse each user's signal equidistantly to $N$ distributed subbands, each having a bandwidth of $B/N$ Hz, which are equally distributed across the entire system bandwidth of $MB$ Hz, as shown in Fig. 3(b). Therefore, each user still occupies $B$ Hz and the system is capable of supporting a maximum of $K = M$ users. Observe in the TD IFDMA transmitter of Fig. 4(b) that the original $N$ symbols of user $k$ having a symbol duration $T_{\mathrm{s}}$ are first compressed into $N$ chips with a chip duration of $T_{\mathrm{s}}/M$. Then, the $k$-th user's resultant $N$-chip segment is repeated $M$ times, while being subjected to the user-specific phase rotation factor of $k/T_{\mathrm{v}}$ for $k = 0, 1, \cdots, K-1$. As shown in Fig. 5(b), the resultant symbol vector having a duration of $T_{\mathrm{v}}$ is denoted as $\tilde{\boldsymbol{x}}_k^{\mathrm{t}}[i]$, which contains $U = MN$ chips, namely $N$ chips from each of the $K$ users. Finally, the

$u$-th, $u = 0, 1, \cdots, U-1$, chip in $\tilde{\boldsymbol{x}}^{\mathrm{t}}_k[i]$ is expressed as

$$\tilde{x}^{\mathrm{t}}_{k,u}[i] = \frac{1}{\sqrt{M}} \exp\left[j\frac{2\pi(mN+n)k}{U}\right] x^{\mathrm{t}}_{k,n}[i], \tag{8}$$

if $u = mN + n$; otherwise $\tilde{x}^{\mathrm{t}}_{k,u}[i] = 0$, for $m = 0, 1, \cdots, M-1$ and $n = 0, 1, \cdots, N-1$, where $x^{\mathrm{t}}_{k,n}[i]$ represents the $n$-th symbol of the $i$-th symbol vector $\boldsymbol{x}^{\mathrm{t}}_k[i]$ of user $k$. Finally, the different users' signals can be transmitted orthogonally using the same carrier frequency. It can be shown that if each of the $K$ users transmits its signals in the form of Eq. (8), the received signal vector will be de-spread with the aid of the user-specific phase de-rotation vector [28]. Hence, applying the DFT to transform the TD signal to the FD, it may be expressed in the form of Eq. (5), which is beneficial, because it is capable of employing FDE.

Both the TD LFDMA and IFDMA schemes characterized in Fig. 5 have their advantages and disadvantages. The main advantage of TD LFDMA which is explicitly shown in Fig. 5(a) is that the different MTs map each user's signals to different carrier frequencies using different timing, hence synchronization is not necessary, which facilitates asynchronous uplink communications. However, using guard bands reduces the spectral efficiency of the LFDMA. Additionally, the LFDMA system may not achieve frequency-diversity, if each user's signal is a narrow-band signal. By contrast, the TD IFDMA system characterized in Fig. 5(b) transmits the different users' signals at the same carrier frequency in conjunction with user-specific phase rotation. However, accurate timing should be guaranteed. Hence, it requires tight synchronization in the uplink, which constitutes a challenge for MTs roaming at different distances and at a high speed. However, as a benefit, the IFDMA system does not require a guard band between the adjacent subbands. Therefore, the bandwidth efficiency of the IFDMA scheme may be higher than that of the LFDMA scheme. On the down-side again, when the MTs of the IFDMA system roam at a high velocity, the frequency offset due to the Doppler frequency shift may significantly degrade the performance of IFDMA systems.

### *C. Transmitter of Time-Frequency-Domain SC-FDMA*

The transmitter schematic of TFD SC-FDMA is shown in Fig. 6(a). In comparison to the OFDM scheme of Fig. 1(a) and to the TD SC-FDMA arrangement of Fig. 4, which requires no DFT/IDFT at the transmitter, the transmitter of the TFD SC-FDMA necessitates both the DFT and the IDFT. The DFT operation of the TFD SC-FDMA scheme is referred to as DFT-based spreading [29], [36], which transforms and spreads each TD symbol to the FD as a feature of DFT, yielding a modulated signal in the form of the OFDM modulated signal. Then, as shown in Fig. 7, the subcarrier signals are mapped to different subbands according to the matrix $\boldsymbol{P}_k$ of Fig. 6(a). Following mapping to the subbands, the results are transformed back to the TD by the IDFT, where the signals are transmitted following the principles of OFDM, after inserting the CP and pulse-shaping, as seen in Fig. 6(a). Let us now describe some of the components portrayed in Fig. 6(a) in more detail.

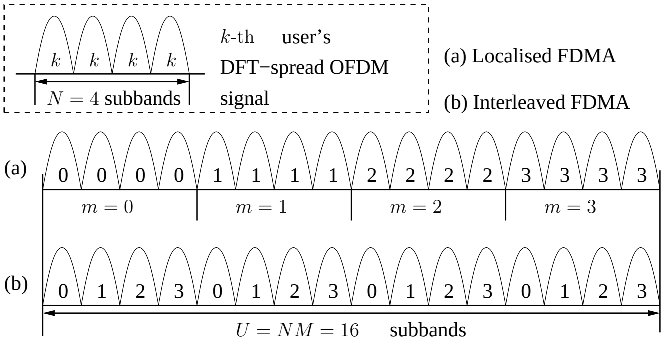


Fig. 7. An example to illustrate the bandwidth expansion and subband mapping in the TFD SC-FDMA system of Fig. 6 using a total of $U = 16$ subbands, and $N = 4$ subbands per user. The system can support $K \leq M = 4$ users.

Let us assume that the TFD SC-FDMA system employs $U = MN$ subbands to support $K \leq M$ uplink users, where each user occupies $N$ subbands. According to [7], after S/P conversion, the $k$-th user's $N$ symbols may be expressed in the TD as

$$\boldsymbol{x}^{\mathrm{t}}_k = [x^{\mathrm{t}}_{k,0}, x^{\mathrm{t}}_{k,1}, \cdots, x^{\mathrm{t}}_{k,(N-1)}]^T, \quad k = 0, 1, \cdots, K-1, \tag{9}$$

where the superscript t refers to the TD. Each element in $\boldsymbol{x}^{\mathrm{t}}_k$ is independent and identically-distributed (i.i.d.) with a normalized transmission power $P$. Following the $N$-point DFT-spreading using the DFT matrix $\boldsymbol{\mathcal{F}}_N$ of Fig. 6(b), $\boldsymbol{x}^{\mathrm{t}}_k$ is transformed to the FD, yielding

$$\boldsymbol{x}^{\mathrm{f}}_k = [x^{\mathrm{f}}_{k,0}, x^{\mathrm{f}}_{k,1}, \cdots, x^{\mathrm{f}}_{k,(N-1)}]^T = \boldsymbol{\mathcal{F}}_N \boldsymbol{x}^{\mathrm{t}}_k, \tag{10}$$

where the superscript f refers to the FD. Note that a conventional OFDMA system may be formed, when $\boldsymbol{\mathcal{F}}_N$ is replaced by the identity matrix $\boldsymbol{I}_N$.

As shown in Fig. 6(b), following the DFT operation, the $k$-th user's FD symbols in $\boldsymbol{x}^{\mathrm{f}}_k$ are mapped to the most appropriate $N$ subbands, which are selected from the $U = (M \times N)$ subbands of the SC-FDMA system with the aid of the subband mapping matrix $\boldsymbol{\mathcal{P}}_k$ of user $k$. Following subband mapping, the $U$-length FD symbol vector may be expressed as

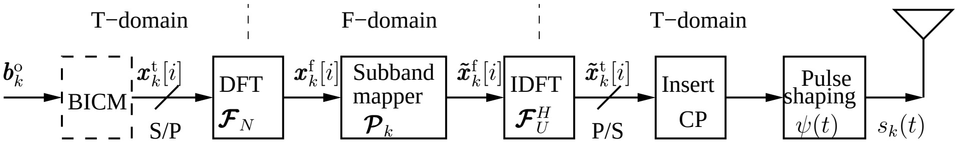
$$\tilde{\boldsymbol{x}}^{\mathrm{f}}_k = [\tilde{x}^{\mathrm{f}}_{k0}, \tilde{x}^{\mathrm{f}}_{k1}, \cdots, \tilde{x}^{\mathrm{f}}_{k(U-1)}]^T = \boldsymbol{\mathcal{P}}_k \boldsymbol{x}^{\mathrm{f}}_k. \tag{11}$$

Again, in the context of SC-FDMA typically two subband mapping schemes are used, namely the localized mapping and distributed mapping schemes shown in Fig. 7.

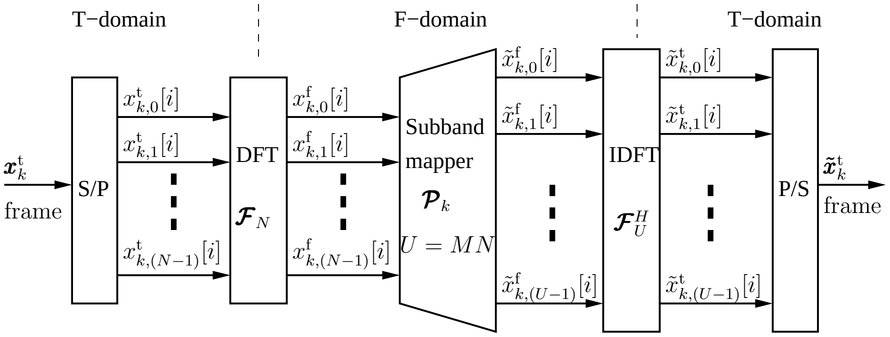
- *Localized subband mapping*: As shown in Fig. 7(a), the localized mapping allows each user's $N$ symbols to be transmitted on $N$ consecutive subbands of the $U$ subbands. It can be shown that the entries of $\boldsymbol{\mathcal{P}}_k$ seen in Fig. 6 are defined as

  $$\mathcal{P}_{k,(u,n)} = \begin{cases} 1, & \text{if } u = kN + n \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

  for $n = 0, 1, \cdots, N-1$ and $u = 0, 1, \cdots, U-1$.
- *Distributed subband mapping*: When the distributed mapping of Fig. 7(b) is employed, the $N$ symbols of a user are spread across the entire bandwidth of $U$ subbands. A



(a) Transmitter block diagram



(b) Baseband signal processing in the transmitter

Fig. 6. Transmitter structure of the TFD SC-FDMA signaling adopting the principle of DFT-spread OFDMA. In contrast to the pure TD LFDMA/IFDMA schemes of Fig. 4, in the TFD SC-FDMA we have the additional DFT - subband mapper - IDFT processing chain, which facilitates the flexible mapping of the symbols to subbands.

typical distributed symbol-to-subband mapping scheme is the so-called *interleaved subband mapping* proposed in [29], [33], which allocates the $N$ symbols of a user to equidistant subbands, where the entries of the mapping matrix $\boldsymbol{\mathcal{P}}_k$ are defined as

$$\mathcal{P}_{k,(u,n)} = \begin{cases} 1, & \text{for } u = nM + k \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

for $n = 0, 1, \cdots, N-1$ and $u = 0, 1, \cdots, U-1$.

In the context of TFD SC-FDMA scheme, the system invoking localized subband mapping is referred to as the LFDMA arrangement of Fig. 4(a), which has now been adopted by the 3GPP-LTE and LTE-Advanced standards [1], [2], [21], [22]. By contrast, the TFD SC-FDMA system using the interleaved subband mapping is referred to as the TD IFDMA arrangement of Fig. 4(b). In TFD SC-FDMA, the DFT-spread OFDMA structure allows the user signals to be transmitted with a high flexibility. For example, the length of transmitter's DFT/IDFT may be adaptively reconfigured for the sake of accommodating diverse time-varying channel environments in order to achieve frequency diversity. The length of DFT/IDFT can also be adjusted, in order to support variable-rate services. When comparing the IDFMA scheme to LFDMA, it becomes plausible that the IFDMA system is capable of achieving the maximum attainable frequency diversity in dispersive multipath fading channels, since each symbol of a user carried by $N$ subcarriers is distributed evenly across the entire transmission band. By contrast, owing to experiencing correlated fading, the LFDMA system can only achieve frequency diversity, when using either *dynamic subband allocation* [98] or *MU scheduling* [41].

As seen in Fig. 6(b), following the symbol-to-subband mapping, the $U$-point IDFT is invoked to transform the symbols of $\tilde{\boldsymbol{x}}_k^{\mathrm{f}}$ from the FD to TD, yielding

$$\tilde{\boldsymbol{x}}_k^{\mathrm{t}} = [\tilde{x}_{k0}^{\mathrm{t}}, \tilde{x}_{k1}^{\mathrm{t}}, \cdots, \tilde{x}_{k(U-1)}^{\mathrm{t}}]^T = \boldsymbol{\mathcal{F}}_U^H \tilde{\boldsymbol{x}}_k^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_U^H \boldsymbol{\mathcal{P}}_k \boldsymbol{\mathcal{F}}_N \boldsymbol{x}_k^{\mathrm{t}}. \tag{14}$$

Specifically, when considering TFD LFDMA and substituting Eq. (12) into Eq. (14), it can be shown in Fig. 9(b) that the $u$-th element of $\tilde{\boldsymbol{x}}_k^{\mathrm{f}}$ becomes zero, provided that we have $u \neq kN+n$, while the $u'$-th, $u' = 0, 1, \cdots, U-1$, element of $\tilde{\boldsymbol{x}}_k^{\mathrm{t}}$ can be expressed as [7]

$$\tilde{x}_{k,u'}^{\mathrm{t}} = \frac{1}{\sqrt{M}} \exp\left(j\frac{2\pi u' k}{M}\right) x_{k,n}^{\mathrm{t}}, \tag{15a}$$

if $u' = nM$, and

$$\begin{aligned} \tilde{x}_{k,u'}^{\mathrm{t}} = {} & \frac{1}{\sqrt{M}} \exp\left(j\frac{2\pi u' k}{M}\right) \\ & \times \left[1 - \exp\left(j\frac{2\pi u'}{M}\right)\right] \\ & \times \frac{1}{N} \sum_{n'=0}^{N-1} \frac{x_{k,n}^{\mathrm{t}}}{1 - \exp(j2\pi u'/U)\exp(-j2\pi n'/N)}, \end{aligned} \tag{15b}$$

otherwise. Observe in Eq. (15a), Eq. (15b) as well as Fig. 9(a), that the $N$ symbols of $x_{k,0}^{\mathrm{t}}, x_{k,1}^{\mathrm{t}}, \cdots, x_{k,(N-1)}^{\mathrm{t}}$ are transmitted as the chips $\tilde{x}_{k,u'}^{\mathrm{t}}$ of Fig. 9(a) within the chip durations of $u' = 0, M, \cdots, (N-1)M$, respectively, at the same subcarrier frequency $kN/T_{\mathrm{v}}$, which corresponds to $ku'/M$ in both Eq. (15a) and in Fig. 9(a), when we have $u' = nM$. Otherwise, when $u' \neq nM$, the original symbols in $\boldsymbol{x}_k^{\mathrm{t}}$ are transmitted by three subcarriers at the frequencies $kN/T_{\mathrm{v}}$, $N/T_{\mathrm{v}}$ and $1/T_{\mathrm{v}}$, corresponding to $ku'/M$, $u'/M$ and $u'/U$, as seen both in Eq. (15b) and in Fig. 9(a). Therefore, the spectrum of the TFD LFDMA signal is similar to that of the conventional TD LFDMA signal, as shown in Fig. 4(a). However, in the TFD LFDMA the guard band between the adjacent MU channels

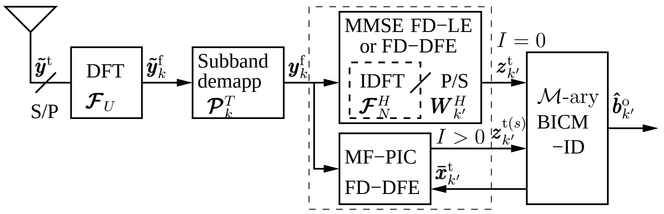


Fig. 10. PIC or HIC aided turbo FD-DFE receiver for SC-FDMA

that used in the conventional TD LFDMA is not necessary. Hence, the bandwidth efficiency of TFD LFDMA may be enhanced. Since the TFD LFDMA scheme only transmits three subcarriers regardless of the value of $N$ and $U$, TFD LFDMA is capable of attaining a much lower PAPR, in comparison to OFDMA.

By contrast, in the context of TFD IFDMA, when substituting Eq. (13) into Eq. (14), we find that the $u$-th element of $\tilde{\boldsymbol{x}}^{\rm f}_k$ is zero for any $u \neq nM + k$ as shown in Fig. 9(a), while we have [7]

$$\tilde{x}^{\rm t}_{k,u'} = \frac{1}{\sqrt{M}} \exp\left[j\frac{2\pi(mN+n)k}{U}\right] x^{\rm t}_{k,n}, \qquad (16)$$

when $u' = mN + n$, for $m = 0, 1, \cdots, M-1$ and $n = 0, 1, \cdots, N-1$. Observe from Eq. (16) that for the $k$-th user only a single subcarrier located at the frequency of $k/T_{\rm v}$ is activated to convey each of $N$ symbols in $\boldsymbol{x}^{\rm t}_k$ which is transmitted repeatedly $M$ times within a TD segment duration of $T_{\rm v}$. Hence, it can be shown that the transmitted signal's spectrum in the TFD IFDMA of Fig. 9(b) is equivalent to that of the TD IFDMA signal, as seen in Fig. 3(b). Since TFD IFDMA only transmits a single carrier at any time, it does not impose any of the severe PAPR problems of OFDM.

Finally, as seen in Fig. 6(b), the TFD SC-FDMA (LFDMA, IFDMA) signals are transmitted after P/S conversion, CP concatenation and chip waveform filtering. Let us now consider the receiver.

### *D. Receiver of Time-Frequency-Domain SC-FDMA*

The receiver schematic of TFD SC-FDMA is shown in Fig. 8(a). More details are illustrated in Fig. 8(b). Explicitly, the receiver typically carries out the inverse operations of the transmitter. Since the symbols are transmitted in blocks within TFD SC-FDMA systems, they are also detected on a block-by-block basis. Following the matched-filtering operation, the CP is removed. Then, $U$-point DFT is carried out to transform the TD observations to the FD, where subband demapping and FDE are invoked. Specifically for user $k'$, $k' = 0, 1, \cdots, K-1$, we exploit the property of [7]

$$\boldsymbol{\mathcal{P}}^T_{k'}\boldsymbol{\mathcal{P}}_k = \begin{cases} \boldsymbol{I}_N, & \text{for } k = k', \\ \boldsymbol{0}_N, & \text{for } k \neq k', \end{cases} \qquad (17)$$

Finally, following the $N$-point IDFT, which transforms the equalized FD signals to the TD, the decision variables can be formed for the $N$ transmitted symbols of a specific user. Additionally, channel decoding using BICM-ID may be carried out.

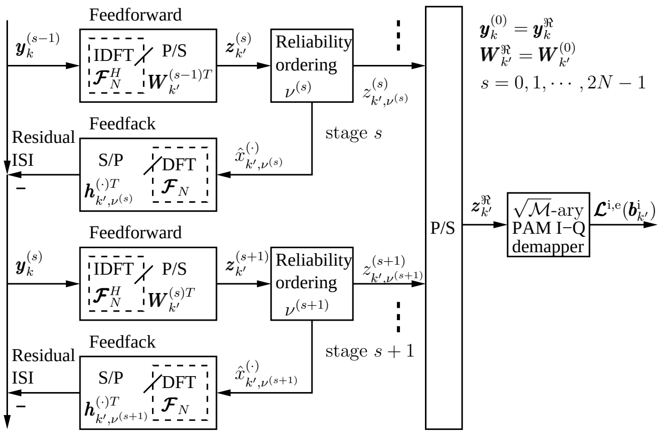


Fig. 11. Schematic of the reliability-aided real-valued MMSE-SIC relying on soft-outputs. This arrangement involves a similar procedure to that used for detection in the classic CDMA and SDMA systems [99]. The real and imaginary parts of $x^{\rm t}_{k',n}$ are allowed to be equalized separately, on the basis of SIC during a total of $2N$ consecutive stages, where each stage equalizes half a symbol $x^{(\cdot)}_{k',n}$ which is the most reliable one of those that have not as yet been detected.

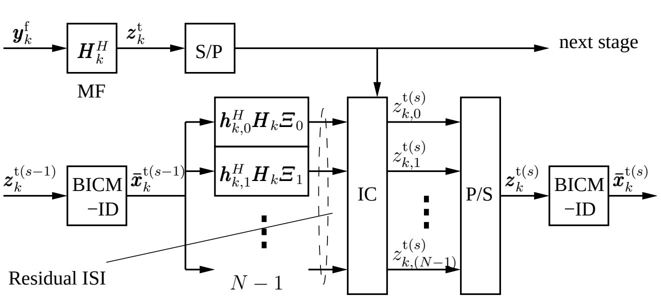
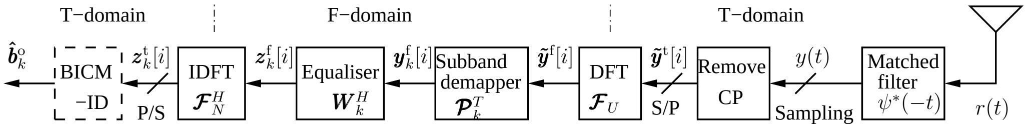


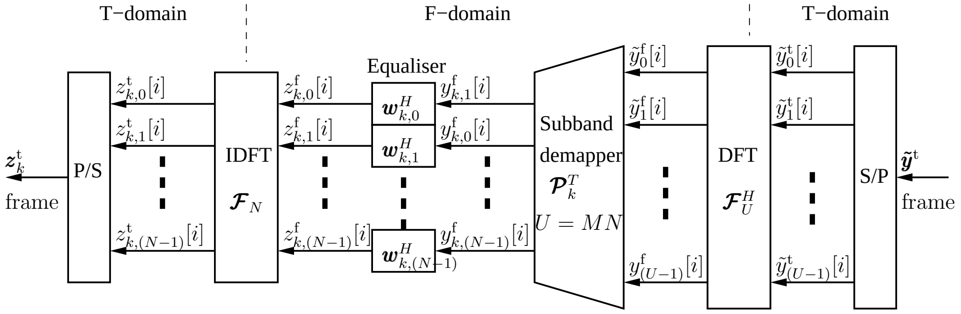
Fig. 12. Schematic diagram of the iterative MF-PIC.

Apart form the above-mentioned linear equalization (LE) schemes as discussed in Section II-B, non-linear equalization methods, such as decision-feedback equalization (DFE) may also be considered for the SC-FDMA systems [19]. The MMSE based *successive interference cancellation* (SIC) style FD-DFE (MMSE-SIC FD-DFE) of [78], [98] relys on the reliability-aided real-valued MMSE-SIC philosophy of Fig. 11 [99], [100], which determines the SIC-ordering based on the maximum *a posteriori* probability (MAP) criterion. It unlikes the conventional MMSE-SIC, which quantifies the reliabilities of the detected symbols in terms of the SINR. Therefore, the impact of both the fading and that of random noise is taken into account during the SIC process. Performance results of in [78], [98] show that the reliability-aided MMSE-SIC FD-DFE is capable of suppressing the residual ISI and hence significantly outperforms the single-tap MMSE FDE benchmark for both the uncoded and channel coded SC-FDMA system for transmission over frequency-selective fading channels, respectively.

For the sake of further improving the achievable performance, joint equalization and decoding has been invoked for designing FEC coded SC-FDMA systems [54], [101], where either hard- or soft-decisions may be fed back to the equalizer by FEC decoder. Most recently, three different types of turbo



(a) Block diagram



(b) Baseband signal processing

Fig. 8. Receiver structure of the TFD SC-FDMA scheme. The corresponding transmitter was shown in Fig. 6, while the associated waveforms and spectrum in Fig. 9.

FDEs were designed for BICM-aided SC-FDMA in [78].

The first type is the soft-MMSE based turbo FD-LE relying on exchanging extrinsic information in a number of consecutive iterations between the MMSE FD-LE and the FEC decoder [102]. Hence the MMSE weight matrix is updated based on the *a-priori* information gleaned during each iteration. This regime further reduces the residual ISI imposed on the estimated symbols.

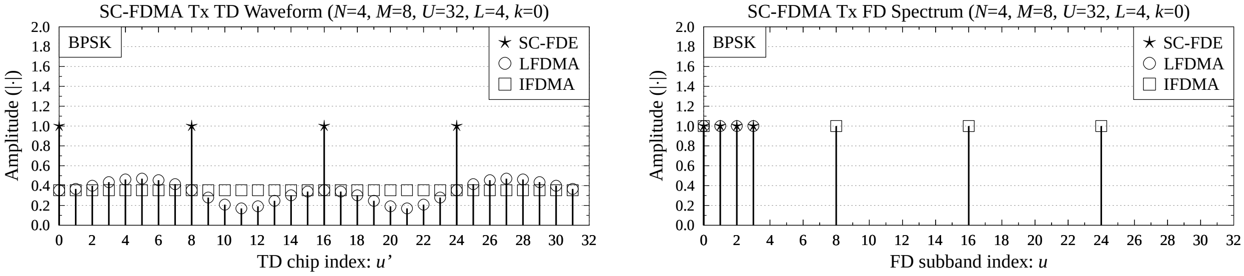
The second type is referred to as the *parallel interference cancellation* (PIC)-assisted turbo FD-DFE, which combines iterative PIC with FEC decoding. Specifically, the PIC aided turbo FD-DFE of Fig. 10 may employ a LE based on the MMSE principle, invoked for the initial filtering of the received signal in the FD, before FEC decoding takes place. Then, this PIC aided turbo FD-DFE carries out the MF based PIC (MF-PIC) operation as shown in Fig. 12 on a block-by-block basis using the FEC decoded bit stream during each iteration.

Additionally, the third type referred to as the hybrid IC (HIC)-assisted turbo FD-DFE of Fig. 10 invokes the MMSE-SIC FD-DFE of Fig. 11 to suppress the ISI as its first stage. Then the PIC-aided turbo FD-DFE of Fig. 12 becomes active, in order to further improve the attainable performance. In other words, as shown in Fig. 10, the PIC turbo FD-DFE scheme becomes a HIC turbo FD-DFE, when the MMSE-SIC FD-DFE replaces the MMSE FD-LE in PIC turbo FD-DFE of Fig. 10. The MF-PIC operation invoked in the turbo FD-DFE may be carried out by using *soft*-decisions, where the number of iterations carried out in the PIC turbo FD-DFE may be varied, based upon the extrinsic information improvement of consecutive iterations between the demodulator and the decoder. The results of [78] show that the soft-MMSE turbo FD-LE is capable of providing a better performance than the PIC- and HIC-aided turbo FD-DFE schemes, while all the IC techniques considered strike an attractive trade-off between the *bit-error ratio* (BER) achieved and the complexity imposed.

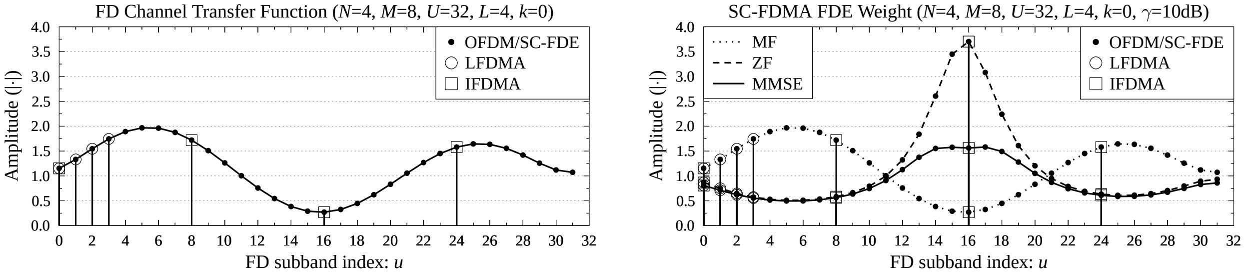
### *E. Comparison of OFDMA and SC-FDMA*

In Table VI, the major differences of OFDMA and the TFD SC-FDMA schemes are summarized, where both the LFDMA and IFDMA schemes are considered. Let us elaborate on the table in a little more detail [7], [40], [41], [44].

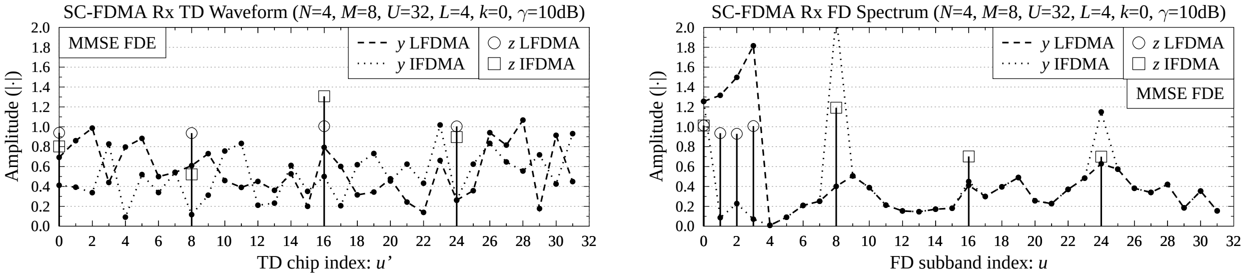
1) Both OFDMA and SC-FDMA adopt the IDFT/DFT for MC modulation/demodulation at the transmitter/receiver, respectively. However, in SC-FDMA, the DFT-based spreading operation seen in the transmitter of Fig. 6 results in SC transmission for SC-FDMA. By contrast, the OFDMA scheme simultaneously transmits all the subcarriers in parallel.
2) Both the OFDMA and SC-FDMA schemes are free from *MU interference* (MUI), owing to the orthogonal subcarrier/subband mapping scheme of the users supported.
3) The CP-based technique is employed by both OFDMA and SC-FDMA transmissions in order to suppress the effects of ISI.
4) Symbols within one data block do not interfere with each other in the OFDMA system. However, due to the IDFT operation used at the receiver of Fig. 8, the symbols in one block may interfere with each other in the SC-FDMA systems, when the channel's fading becomes frequency selective.
5) As seen in Fig. 13, both the LFDMA and IFDMA schemes may achieve a certain diversity gain in the presence of frequency-selective fading. Nevertheless, this frequency-diversity gain is only achievable, when the residual ISI is efficiently mitigated, for example with the aid of the MMSE based FDE schemes of Fig. 8 and Fig. 11. By contrast, frequency-diversity is not inherent in the OFDM(A) as shown in Fig. 13, unless the same symbols are mapped to several independently fading subcarriers, which reduces the throughput. Similar to OFDM, a frequency diversity gain may be also achieved, when OFDMA is combined with channel coding/interleaving



(a) Transmitted TD Waveform (b) Transmitted FD Spectrum



(c) FD Channel Transfer Function (d) FD Equalization Weight



(e) Received TD Waveform (f) Received FD Spectrum

Fig. 9. Examples of the $k = 0$-th user's transmitted and received signal waveforms and spectrums of the TFD SC-FDMA signaling systems using either LFDMA or IFDMA in comparison to SC-FDE, respectively. Snapshots of the FD CTF and FDE weight values at a single block of the OFDM or SC-FDE, LFDMA and IFDMA transmissions over frequency-selective fading channels subject to a SNR of 10dB, respectively. All the systems involve $U = 32$-point DFT and IDFT having an equivalent FD CTF over a total of $32$ subcarriers/subbands. Both the systems have a block duration of $T_{\rm v}$ with a symbol duration of $T_{\rm s}$ and the chip duration is $T_{\rm c} = T_{\rm s}/M = T_{\rm s}/4$, regarding a system bandwidth of $MB$ a subband bandwidth of $B/N$. The system may support $K \leq M = 8$ users. The corresponding subband mapping are seen in Fig. 7.

TABLE VI
COMPARISON OF OFDMA, TFD SC-FDMA (LFDMA AND IFDMA) SCHEMES

| | OFDMA | LFDMA | IFDMA |
|---|---|---|---|
| Transmitter | IDFT | DFT, IDFT | |
| Receiver | DFT | DFT, IDFT | |
| Complexity | Similar | | |
| MUI | Non | | |
| ISI | Non-ISI between two OFDMA/SC-FDMA symbols by using CP | | |
| Residual ISI | Absence | Presence, unless using ZF-FDE | |
| Transmission | Parallel | Serial | |
| Carrier modulation | MC | SC | |
| Involved subcarriers | $U$ subcarriers | 1 or 3 subcarriers | 1 subcarrier |
| PAPR | Highest | Very low | Lowest |
| Symbol duration | $NT_{\rm s} = T_{\rm v}$ | $T_{\rm s}$ ($M$ chip duration) | $T_{\rm s}/M$ (1 chip duration) |
| Symbol bandwidth | $B/N$ (compressed) | $B$ (localized) | $MB$ (distributed) |
| Frequency diversity gain | Non, unless FEC | Limited | Significant |
| Multiuser scheduling gain | Significant | Sufficient | Limited |
| Mobility scenario (speed) | Depends (scheduling) | Low (scheduling) | High |
| Channel estimation | Depends (subc. mapp.) | Low overhead | High overhead |

[6] or MU scheduling [103].

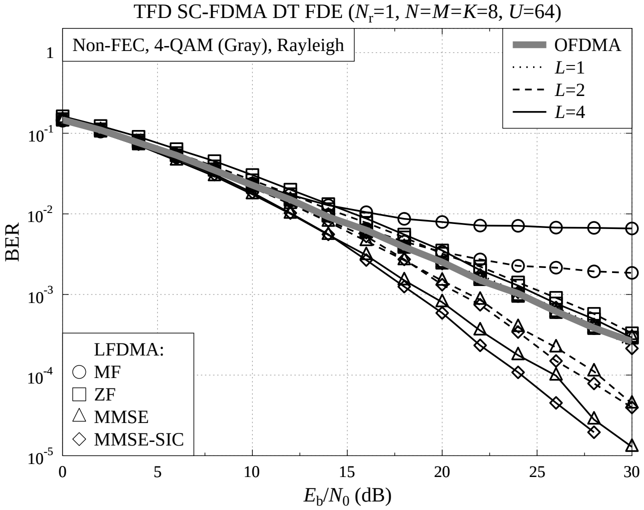
6) In the IFDMA scheme, each user's symbols are evenly distributed over the entire frequency band of the system, while in LFDMA, the symbols of a user are conveyed by a set of consecutive subbands. Therefore, the achievable frequency-diversity gain of the IFDMA system is typically higher than that of the LFDMA system as seen in Fig. 13. By contrast, MU scheduling can be efficiently carried out in the context of the LFDMA system, since the co-located subbands may be allocated to the most appropriate frequency bands associated with a high channel gain. Additionally, similar to OFDMA, MU scheduling may be invoked by the LFDMA scheme in order to attain a higher *MU diversity* gain than that of the IFDMA system.
7) MU scheduling may be carried out, when communicating over slowly fading correlated channels corresponding to a relatively low Doppler frequency. Otherwise, the overhead imposed by the reference symbols or pilots, which are required for channel estimation will be increased in order to obtain an accurate *channel state information* (CSI) estimate. As a result, the spectral efficiency of the LFDMA or OFDMA system may degrade, when the MTs travel at a higher speed.
8) In order to carry out the FDE operation of Fig. 8, channel estimation is required. It can be shown that in a given mobility scenario associated with a specific multi-path power delay profile, the LFDMA system may require a lower channel estimation overhead than IFDMA, since the co-located subbands of LFDMA experience correlated fading, while the distributed subbands of IFDMA may experience independent fading.
9) In the OFDMA system all the subcarriers are transmitted simultaneously, leading to a high PAPR. In comparison to OFDMA, the PAPR of LFDMA is substantially decreased, since either one or three subcarriers are transmitted, as seen in Fig. 9(a) in the context of Eq. (15a) and Eq. (15a). Among the three schemes, IFDMA guarantees the lowest PAPR, since according to Eq. (16) only one subcarrier is transmitted at any time as shown in Fig. 9(a). The PAPR of the OFDMA, IFDMA and the LFDMA schemes was quantified in [41].
10) As a benefit of its diversity gain, SC-FDMA - especially the IFDMA scheme - outperforms the OFDMA scheme in terms of its achievable BER performance [7], when no other BER enhancement techniques are invoked. The IFDMA arrangement outperforms LFDMA in terms of its BER performance, when operating without the assistance of other techniques [104].

“

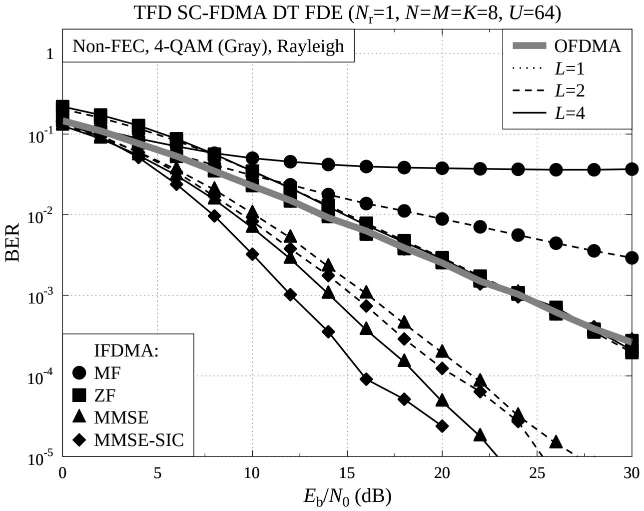
## III. COOPERATIVE COMMUNICATIONS FOR SC-FDMA

### A. Multiple-Input Multiple-Output Techniques

Since the pioneering work of Shannon [105] in 1948, researchers have endeavored to improve the capacity, the integrity as well as the *quality-of-service* (QoS) of wireless communications. However, the channel capacity of conventional *single-input single-output* systems is severely limited by the logarithmic low of $C = B\log_2(1 + SNR)$. As a remedy, multiple-antenna aided systems have been conceived [106], [107]. The *single-input multiple-output* (SIMO) architecture employs a single transmit antenna and multiple receive antennas for uplink transmission, while the *multiple-input single-output* (MISO) architecture invokes multiple transmit antennas and a single receive antenna for downlink transmission. Upon combining the SIMO and MISO architectures, we arrive at the *multiple-input multiple-output* (MIMO) concept relying on diverse multi-antenna aided systems [108]–[115].



(a) LFDMA



(b) IFDMA

Fig. 13. BER performance versus $E_b/N_0$ of TFD SC-FDMA systems for $N = M = 8$ supporting $K = 8$ users over a total of $U = 64$ subbands, when the BS invokes various FDE receivers, i.e. MF, ZF, MMSE and MMSE-SIC [7], in comparison with OFDMA. The system experiences frequency-selective Rayleigh fading associated with $L = 1, 2$ and $4$ paths, respectively.

MIMO techniques are capable of achieving diversity gains without increasing the transmission power. Specifically, a *transmit diversity* gain is achieved by MISO transmissions with the aid of *space-time coding* (STC) techniques, while a receive diversity gain is achieved by SIMO reception relying on *maximum ratio combining* (MRC) at the receiver [106], [110], [111], [113], [116], [117]. Multi-antenna aided techniques have also been employed at the transmitter of OFDM-based systems, namely *space-frequency coding* (SFC) for the sake of achieving a transmit diversity gain [114], [118]–[122]. Previous studies on extending the context of STC/SFC schemes to SC-FDE and to SC-FDMA systems are listed in Table VII.

Nevertheless, the most valuable bandwidth used for mobile communications lies in the range of 700 MHz to 3.8 GHz [123]. In order to guarantee the independent fading of the physical wireless channels at multiple antennas, a sufficiently high minimum distance has to be maintained between the adjacent antennas, which is not practically feasible, given the limited size of the MT. However, most of the benefits of MIMO techniques relying on multiple co-located antennas potentially erode in the context of compact, shirt-pocket-sized MTs, owning to the correlation of signal received by the insufficiently widely spaced antennas. Fortunately, the single-antenna-aided MTs can cooperate by sharing their antennas in order to form a virtual MIMO system, where the MTs are carefully selected by the resource allocation algorithm to avoid their correlation.

### *B. Relay-Assisted Transmission and Cooperation*

The conventional relaying technique known from the classic telegraph simply repeats a weak signal received at the end of a long wire-section in order to extend the coverage. Similarly, the relay of a wireless back-haul is capable of amplifying a weak signal in order to compensate for the path-loss effects during radio propagation. The philosophy of three-terminal communication channel model was introduced by van der Meulen *et al.* in 1970's [124], [125]. Forty years later, this concept of relay-assisted transmission has been adopted by the *3GPP-LTE Advanced* standard for commercial employment [126]–[128].

With the aid of relaying, the so-called '*user cooperation*' concept relying on 'antenna sharing' and relaying was proposed by Sendonaris *et al.* in 1998 [129], which was then further developed by Laneman and Wornell in 2000 [130]. The basic idea in the context of cellular systems is that a MT may be assigned by the BS to assist another MT as a cooperating partner, where the cooperating MT may relay the source information and additionally it may also transmit its own information to the destination [131], [132]. Note that the source and the destination might be the BS or another MT, depending on whether uplink or downlink transmissions are considered.

Furthermore, user cooperation allows the collaborative MTs to be distributed across the terrain and may be able to achieve a power reduction by reducing the path-loss. Furthermore, it is capable of eliminating the spatial correlation of shadow fading, since the cooperative MTs are typically selected to be at geographically separated locations. Ultimately, user cooperation is capable of achieving substantial gains by providing the following benefits [131], [132]:

1) achieving an improved energy/power efficiency;
2) increasing the attainable system throughput;
3) improving the cell-edge coverage;
4) guaranteeing a given QoS, etc.

Recently, the cooperative concepts have been introduced into OFDM-based systems associated with appropriate *dynamic resource allocation* (DRA) for exploiting the benefits of frequency-selective fading [133]–[138]. Although the majority of the signal processing in OFDM and OFDMA systems is carried out in the FD, no frequency-selection diversity gain can be achieved without FD spreading or subcarrier-repetition when experiencing frequency-selective fading. By contrast, TFD SC-FDMA is capable of exploiting the benefits of frequency-selection diversity with the aid of DFT-spreading, which spreads the TD symbols right across the FD before OFDM modulation. This DFT-spreading principle is similar to the effect of MC-CDMA experienced in broadband channels, where the FD spreading sequence spreads each subcarrier's symbol across the entire bandwidth. Furthermore, SC-FDMA attains a similar overall performance as OFDMA, but it is more suitable for uplink transmission due to its lower PAPR, which is typically high in MC systems. Moreover, in comparison to TD SC-FDMA and SC-DS-CDMA using FDE, the TFD SC-FDMA scheme can be adaptively reconfigured in order to mitigate the effects of time-dispersive channels. Therefore, by invoking relays, the cooperative SC-FDMA system also benefits from cooperative communications. The cooperative relaying designs conceived for the SC-FDMA uplink are listed in Table VII.

TABLE VIII
ILLUSTRATION OF TDD RELAYING PROTOCOLS FOR THE THREE-TERMINAL FADING RELAY CHANNEL [181]

| | Protocol I | Protocol II | Protocol III |
|---|---|---|---|
| TS-1: broadcast phase | S→R, D | S→R, D | S→R |
| TS-2: relay/coop. phase | S→D, R→D | R→D | S→D, R→D |
| Equivalent model | MIMO | SIMO | MISO |

### *C. Cooperative Relaying Protocols*

As mentioned in Section III-A, user cooperation may be regarded as a specific manifestation of a *virtual* or *distributed* MIMO scenario, where the cooperating single-antenna-aided MTs may be treated as the external antennas of cooperating partners [181], [182]. Therefore, user cooperation is capable of providing a *cooperative diversity* gain in the form of *spatial diversity*, since the destination may receive the replicas of signal via both the direct- and relay-aided links. According to [181], the classic three-terminal fading relay channels may be converted into equivalent MIMO, SIMO and MISO channel models with the aid of the different *time-division-*

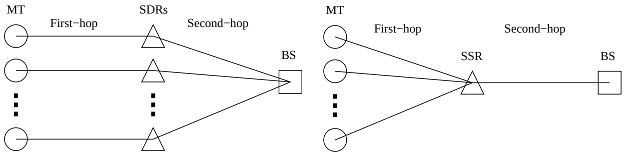
TABLE VII
MAJOR CONTRIBUTIONS ON TRANSMIT/COOPERATIVE DIVERSITY AIDED SC-FDE AND SC-FDMA TECHNIQUES

| Year | Authors | Contributions |
|---|---|---|
| 2001 | Al-Dhahir *et al.* [139] | investigated SC-FDE with STBC system over frequency-selective fading channels. |
| 2004 | Zhu *et al.* [140]–[142] | proposed layered linear, adaptive and semi-blind space-frequency equalization for MIMO aided SC block transmissions. |
| 2005 | Zhu *et al.* [143] | studied SC-FDE with decision-feedback processing for time-reversal STBC system. |
| | Coon *et al.* [144] | proposed adaptive FDE for STBC aided SC transmissions over dispersive channel. |
| 2006 | Jang *et al.* [145] | investigated CP-based SC transmissions with SFBC over mobile fading channel. |
| 2007 | Mheidat *et al.* [146] | proposed SC-FDE techniques for distributed STBC with AF relaying. |
| | Seol *et al.* [147]–[151] | proposed spectral efficient cooperative diversity schemes for SC-FDMA uplink and analyzed their performance over fading relay channels. |
| 2008 | Yune *et al.* [152]–[154] | proposed iterative MUD for both the SFBC aided SC transmission and spectral efficient relay aided SC-FDE. |
| | Li *et al.* [155] | proposed SFBC SC systems with turbo FDE receiver. |
| | Li *et al.* [156] | designed block adaptive equalization and diversity combining for STBC-aided SC transmission. |
| 2009 | Zhang *et al.* [157] | proposed subband-based AF relaying schemes for SC-FDMA uplink in MU scenario. |
| | Ciochina *et al.* [158] | proposed a PAPR-preserving mapping methods for SC-FDMA with SFBC. |
| 2010 | Zhang *et al.* [159], [160] | proposed power-Efficient opportunistic AF-relaying schemes for MU SC-FDMA uplink. |
| | Kim *et al.* [161] | investigated decision-directed channel estimation for SC-FDE in AF relaying networks. |
| | Woo *et al.* [162] | proposed an efficient receive-diversity-combining technique for SC-FDMA-based cooperative relays. |
| | Chen *et al.* [163] | studied precoding-based blind channel estimation for STBC aided SC-FDE system. |
| | Zhang *et al.* [164] | proposed joint estimation and suppression of phase noise and CFO for SFBC-aided SC-FDMA . |
| 2011 | Eghbali *et al.* [165], [166] | proposed a novel receiver for SC-FDE with the aid of AF relaying using distributed STBC and studied on relay selection and resource allocation in the distributed STBC-aided multi-relay network. |
| 2012 | Zhang *et al.* [98], [167] | investigated energy-efficient dynamic resource allocation for opportunistic relaying assisted SC-FDMA using turbo equalizer aided soft DF. |
| | Nakada *et al.* [168] | proposed power allocation schemes for direct/cooperative AF relay switched SC-FDMA. |
| | Tao *et al.* [169] | overview the cooperative techniques for LTE/LTE-Advanced downlink transmission, such as relay, *distributed antennas systems* (DAS), multi-cell processing (MCP), coordinated multiple point transmission and reception (CoMP), and proposed several joint processing schemes for CoMP. |
| | Wu *et al.* [170] | investigated cooperative FD beamforming for SC-FDE systems with aid of single- or multiple relays. |
| | Hassan *et al.* [171] | proposed energy-efficient hybrid opportunistic cooperative protocol for SC-FDMA. |
| | Kuchi *et al.* [172] | proposed MMSE-prewhitened ML equalizer for MIMO DFT-recoded OFDMA. |
| | Luo *et al.* [173] | combined STBC and spatial multiplexing with quadrature OFDM structure using ZF and MMSE FDE schemes for OFDMA/SC-FDMA systems. |
| 2013 | Kadir *et al.* [174] | proposed *space-time shift keying* (STSK) for OFDMA and SC-FDMA in dispersive fading channels. |
| | Adachi *et al.* [175] | proposed joint cooperative-transmit/receive FDE with IR for broadband SC transmission under the source-relay total and individual transmit power constraint. |
| | Kha *et al.* [176], [177] | proposed joint optimization of source power allocation and cooperative beamforming for MU SC-FDMA in multi-relay networks. |
| | Rajashekar *et al.* [178] | consider SBTC based spatial modulation operating in a frequency-selective ZP-aided SC transmission scenario. |
| | Guvensen *et al.* [179] | proposed a general framework for optimum iterative blockwise equalization of MIMO SC transmission and analyzed its asymptotic performance. |
| | Li *et al.* [180] | proposed a high-throughput adaptive modulation and coding scheme for cooperative SC-FDMA transmissions. |

*duplex* (TDD) *relaying protocols* of Table VIII[3], respectively.

Moreover, when multiple source nodes exchange their information and then act as relays for assisting each other, a beneficial cooperative diversity gain may be achieved by the cooperative/distributed STC schemes studied in [146], [154], [165], [183]–[190].

The diversity versus multiplexing trade-off is an important issue in the context of cooperative relaying [191]. Naturally, relaying requires two-hop or multi-hop transmissions, hence its achievable throughput is lower than that of direct transmission (DT). In order to improve the the achievable throughput of cooperative relaying, a range of advanced schemes have been proposed. For example, the near-capacity space-time coded cooperation schemes of [116], [187] employs the irregular channel coded space-time diversity schemes for cooperative nodes, while successive relaying [188] allows two or more relays to alternately receive the signal transmitted from the source node, which does not pause its transmissions as in the conventional half-duplex mode. The network-coded two-way relaying of [192], [193], as well as the linear dispersive coding aided cooperation of [117], [174], etc.



(a) Single-dedicated-relaying (b) Single-shared-relaying

Fig. 14. Topologies for single-relay aided MU SC-FDMA uplink transmissions.

## D. Cooperative Relaying Topologies

Let us elaborate on the cooperative relaying topologies designed in the context of the SC-FDMA uplink a little further. In [157], the authors conceived two single-relay assisted

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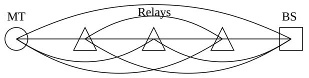
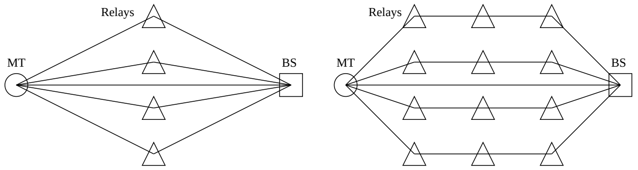
[3] Illustration of TDD relaying protocols for the three-terminal fading relay channel of [181] over two time-slots (TSs), namely *broadcast* phase and *relay/cooperation* phase, constituted by the source (S), relay (R) and destination (D), each of which employs a single antenna. The notation 'A→B' denotes the signals transmitted from terminal A to terminal B.



(a) Serial multi-relaying



(b) Parallel multi-relaying (c) Generalized multi-relaying

Fig. 15. Topologies of multi-relay aided cooperative networks for SU uplink transmissions

topologies for the sake of exploiting the achievable cooperative diversity, as shown in Fig. 14. Explicitly, in *single-dedicated-relaying* (SDR) each relay is dedicated to a single user, while in *single-shared-relaying* (SSR) a single relay assists multiple users.

By contrast, when multiple relays are invoked, the resultant cooperative relaying topologies may be classified follows.

- **Serial multi-relaying**: As shown in Fig. 15(a), the source's signals were forwarded with the aid of *multi-hop relaying/cooperation*, depending on the absence or presence of cooperative diversity combining at each hop [194], [195].
- **Parallel multi-relaying**: While in Fig. 15(b), the signals are forwarded with the aid of *multi-branch cooperation* for the sake of maximizing the achievable diversity order [196], [197].
- **Generalized multi-relaying**: Observe in Fig. 15(c), a combination of both multi-hop relaying and multi-branch cooperation was examined in [198] aiming for both relaying-aided path-loss reduction and for diversity gain.

Considering the network deployment, the serial multi-relay network is suitable for further extending the cellular coverage, albeit this is achieved at the expense of increasing the delay and decreasing the throughput. By contrast, the parallel multi-relay network may be use to beneficially increase the network capacity without coverage extension. Although the generalized multi-relay network inherits the advantages of both above two, the architecture design is complicated.

### *E. Transmission Modes at the Relay*

There are two main transmission modes operated at the relays, namely the *amplify-and-forward* (AF) mode and the *decode-and-forward* (DF) mode [199]. The AF relays simply normalize and amplify the signals received from the source prior it is transmission to the destination. In parallel, the DF relays firstly detect, demodulate and decode the source's signals; after hard- or soft-decision the bit stream is then encoded and re-transmitted [200]. Other types of relaying, such as the so-called *compress-and-forward* [201], *detect-and-forward* or *demodulate-and-forward* [202] techniques may be regarded as modified transmission modes of the AF and DF modes.

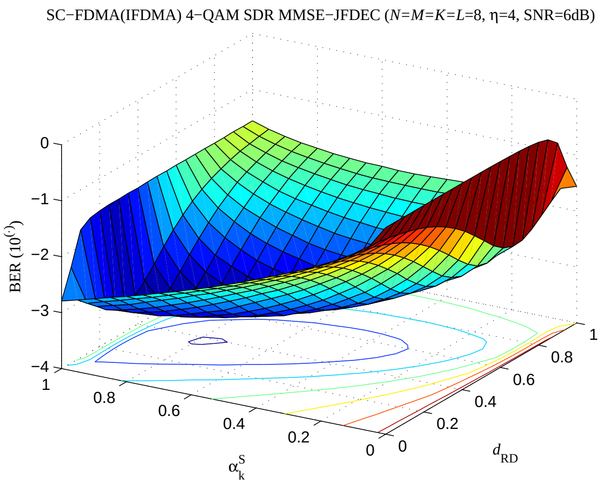


Fig. 16. BER performance versus both the normalized transmit power $(\alpha_k^{\mathrm{S}}$ at the source MT and versus the normalized R-D distance $\delta_k^{\mathrm{RD}}$ of subband-based AF SDR aided SC-FDMA (IFDMA) systems for $N = M = 8$ supporting $K = 8$ users over a total of $U = 64$ subbands, when the BS invokes an MMSE JFDEC receiver [160], [215]. The system experiences frequency-selective Rayleigh fading associated with $L = 8$ paths and a path-loss exponent of $\eta = 4$ in the absence of shadowing, when $E_{\mathrm{b}}/N_0 = 6$ dB.

Generally, the AF relays jointly increase both the signal power and the noise power. By contrast, DF relays are capable of eliminating the effects of noise, provided that the source's signals are decoded without error. However, at low SNR, they often result in decoding error propagation, which degrades the *bit-error rate* (BER) performance at the destination. Hence, for the sake of achieving an improved link reliability, it is suggested to appoint AF relay(s) roaming close to the destination, as shown in Fig. 16. By contrast, it is beneficial to employ DF relay(s) near to the source for the sake of reducing the decoding error propagation [160], [167], [203]–[205]. In order to mitigate the effects of error propagation, the DF relays are also capable of carrying out soft-decisions rather than hard-decisions, where the soft-information is forwarded [206]. A more sophisticated solution is constituted by *coded-cooperation* [207]–[209] as a form of enhanced DF relaying, which allows the joint design of *forward-error-correction* (FEC) coding of both the source's and the relay's information [210], [211]. In this scenario, the presence of the direct link in the distributed coding aided cooperative network may provide additional gains by improving the error-correction capability for the sake of near capacity operation [187], [188], [212], [213]. Another extension of DF mode, referred to *incremental relaying* (IR), is to invoke the *automatic repeat-request* (ARQ), namely hybrid-ARQ, during transmissions for the sake of increasing the redundancy [175], [199], [214].

### *F. Relay-Assisted Dynamic Resource Allocation*

The OFDM-based LTE air-interface, such as the OFDMA downlink scheme and the SC-FDMA uplink, conveniently facilitate near-instantaneous adaptive *multi-user scheduling* and *subcarrier allocation*, depending on the CSI of the subcarriers, when communicating over frequency-selective fading channels [103], [216]–[220]. Compared to classic single-hop transmissions, optimizing radio resource allocation for relay-assisted dual-hop transmissions involves more substantial technical challenges, especially, when considering both multiple users and multiple relays sharing the resource in terms of *time*, *frequency*, *space* and *power*, leading to the cross-layer operation problems [221]–[223].

*1) Relay Selection:* In the topologies mentioned in Section III-D, the assignment of relays is assumed to be fixed. However, the availability of inactive mobiles as candidate relays has the potential of mitigating the effects of fading. The activation of multiple relays results in *cooperative* or *selection diversity* in the *spatial-domain*, which transforms the *relay selection* (RS) problem into a *multi-relay scheduling* scenario reminiscent of *multi-user scheduling*. RS may be carried out in numerous ways.

- **Static RS** assigns the relays for the entire duration of a session, hence the achievable gains depend on the velocity of cooperating nodes[4]. Besides, other RS schemes as follows may be regarded as *dynamic relay selection* (DRS).
- **Random RS** appoints the relays stochastically without relying on any channel knowledge, but in this case only a limited gain may be attained.
- **Distance-dependent RS** is capable of maximising the relaying-aided path-loss reduction by appointing relays in the optimum locations [203], [204].
- **Channel-dependent RS** monitors the instantaneous channel conditions, including the associated path-loss, shadowing and multi-path fading effects. Therefore, both relaying-aided path-loss reduction and a diversity gain may be achieved. When the S-D direct link is unavailable, this kind of relaying scheme is referred to as *opportunistic relaying* (OR) [167], [224]–[227]; when the S-D direct link is available, the corresponding cooperative relaying scheme is known as *opportunistic cooperation* (OC) [160].

Therefore, in terms of the locations of relays in a cluster, the cooperative relaying topologies may be investigated in both geographically distributed and co-located scenarios.

*a) Geographically Distributed Relays:* In the geographically distributed OR-assisted uplink, multiple relays are considered in three typical scenarios, namely when we have a sufficiently high number of relays, a moderate number of relays and an insufficient number of relays. The corresponding RS schemes, namely the *single-user relay selection* (SU-RS), *multi-user relay selection* (MU-RS) and *multiple-access relay selection* (MA-RS) regimes are shown in Fig. 17 of [160]. The BS is assumed to be capable of acquiring both the CSI at the receiver and the SNR of all the cooperative links based on pilot-assisted channel estimation. The power allocation and RS operations are carried out with the objective of maximising the average received instantaneous SINR of each user at the BS for both the direct and relaying branches. Additionally, it is assumed that the transmissions of the *source-to-destination* (S-D), *source-to-relay* (S-R) and *relay-to-destination* (R-D) links are orthogonal and hence they do not impose an increased MUI.

Let us elaborate on the cooperative diversity oriented RS schemes proposed in [160] a little further. By invoking SU-RS in Fig. 17(a), the BS allocates a beneficial relay to each source MT based on the instantaneous SNRs of the links via the $J/K$ candidate relays within a user-specific cluster. Accordingly, the RS of each source user is different. By contrast, in the MU-RS of Fig. 17(b), the BS allows multiple source MTs to access upto $J$ candidate relays. Hence, the instantaneous SNRs are evaluated at the BS in order to find for each source a single desired relay from the shared cluster of $J$ candidate relays with the aid of user-pairing techniques. However, the BS employs the MA-RS of Fig. 17(c) by selecting a single shared relay for cooperation with all source users based on the instantaneous SNRs of the links from each of the $J$ relays to the BS within a cluster.

By comparing the various RS schemes for the same $J$ as a fairness, the cooperative and selection diversity gain may be observed in Fig. 18. Specifically, in comparison to the RRS, the fixed relay having an optimal location offers a relaying gain, while SU-RS provides a selection diversity gain from each user-specific relay cluster. Moreover, MU-RS provides an additional multi-user diversity gain over and above that of SU-RS, which is an explicit benefit of the RS procedure that avoids the effects of deep shadow fading. Additionally, the MA-RS scheme provides a useful selection diversity gain with the aid of the second hop as it only requires a single R-D link. However, by invoking all the $(K\times J)$ possible S-R links for supporting all $K$ source MTs via a single target relay, the selection diversity gain glean by the first-hop of MA-RS does not improve the link-level reliability in the presence of deep shadow fading.

*b) Geographically Co-located Relays:* By contrast, Fig. 19 illustrates the geographically co-located OR-assisted uplink of [167], where the $K$ uplink users of a traffic cell are considered. The idle terminals located in each other's vicinity may act as members of a relay cluster. These relays are assumed to be located midway between the source MT and the destination BS. In other words, it is a generalized case of the RS schemes of Fig. 17, while the multiple relays of Fig. 19 are assumed to be capable of exchanging the pilot-based *channel quality information* (CQI) of all the users, facilitating cooperation at the relays in order to carry out *dynamic resource allocation* (DRA). The original MU information exchange scheme operating with the aid of a single relay was referred to as *multi-way relaying* (MWR), which is shown in Fig. 19(b). [5] However, the multiple relays participating in the MWR procedure aim for CQI exchange, rather than for payload exchange.

*2) Resource Allocation at the Opportunistic Relays:* The selection diversity may be achieved also in the FD with the aid of beneficial *subcarrier allocation* and *power allocation*

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[4] The relays having higher velocity communicate over the fading channel with lower time-correlation. In this case, the SRS within a session benefits from time-diversity gain over a high correlated fading channel but it may also suffer from poor channel quality over a low correlated fading.

[5] This terminology is reminiscent of the process used in [228] for describing the data-exchange that takes place amongst multiple data-source and destinations, but again, we only assume the employment of MWR for CQI exchange.

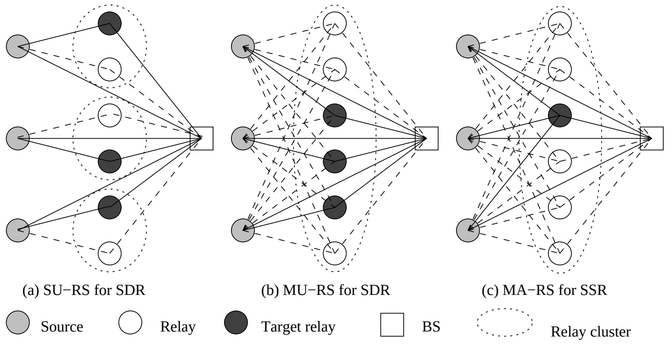


Fig. 17. The snapshot of topologies for OC-aided SC-FDMA uplink invoking various RS schemes [160]. We consider a fair comparison using $K = 3$ users and a total of $J = 6$ relays for all the RS schemes in subfigures (a), (b) and (c). When the specific relays are selected depending on the instantaneous SINR, the solid lines in (a), (b) and (c) characterize the corresponding SDR and SSR topologies portrayed in Fig. 14, while the dashed lines indicate the other opportunistic cooperation via SDR/SSR links. The relays roam between the source and destination, while satisfying the normalized distances of the S-R and R-D links with $d_{\rm SR}+d_{\rm RD} = 1$. The source/relay power constraints are given by $d_{\rm SR} + d_{\rm RD} = 1$ and the source/relay power constraints are $\alpha_k^{\rm S} + \alpha_k^{\rm R} = 1$ for SDR, while we have $\alpha_{\rm R} = \sum_{k=0}^{K-1} \alpha_k^{\rm R} = 1$ for SSR.

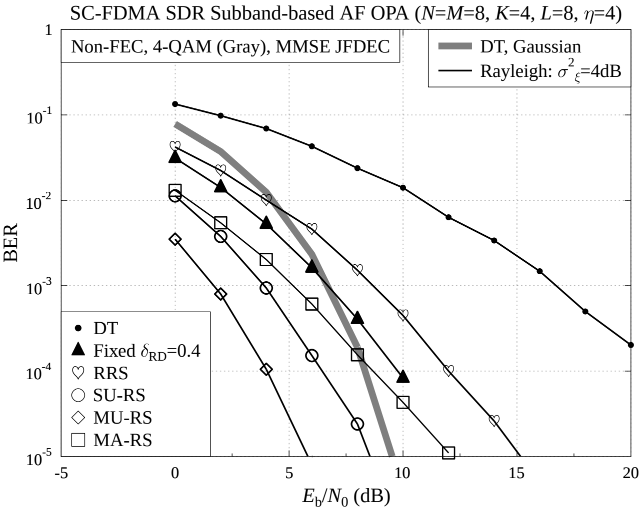
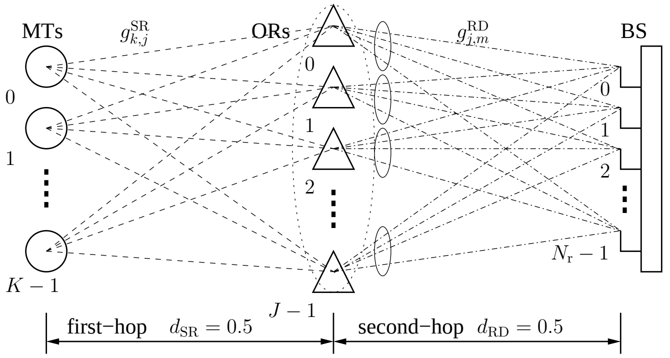
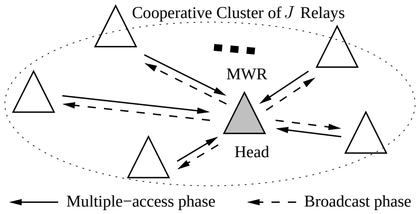


Fig. 18. Performance of various RS schemes for subband-based AF aided OC uncoded SC-FDMA (IFDMA) uplink for $N = M = 8$, $K = 4$ users and $J = 16$ relays, when the BS invokes the MMSE JFDEC receiver [160]. The systems communicate over frequency-selective Rayleigh fading channels associated with $L = 8$, when the path-loss exponent is $\eta = 4$ with a shadowing variance $\sigma_\xi^2 = 4$dB for all the S-D, S-R and R-D links [160].



(a) Opportunistically relayed SC−FDMA uplink



(b) Pilot−aided CQI exchange in a cooperative relay cluster by assuming multi−way relaying (MWR)

Fig. 19. The topology of OR-based MU SC-FDMA Uplink with the aid of CQI exchange [167]. Compared to Fig. 17, the basic differences in Fig. 19(a) rely on that (1) the direct transmission (DT) link is unavailable; (2) cooperating relays geographically localized in a cluster are capable of exchanging CQI; (3) the BS's receiver employs multiple antennas.

schemes. The optimization cost-function, may be the channel gain, the SNR, the spectral efficiency, etc.

- **Subcarrier allocation** allows the different users' signals to be assigned to the most appropriate subcarriers or to a subcarrier-group in the LTE system [49], [64], [229]–[231]. In the context of relay-assisted OFDM systems, the joint optimization of the subcarrier allocation of all hops is desirable, namely that of the S-R link, of the S-R link and of the R-D link in the dual-hop scenario. This was also referred to as *subcarrier pairing* in [136], [232]–[237].
- **Power allocation** determines the total transmit power of the individual users' signals shared by the source and the multiple relays subject to the total power constraint [133], [238], [239]. In [136], [233], [234], the power allocation was also jointly optimized with the subcarrier allocation subject to a specific maximum power constraint at the individual nodes, while striking a trade-off between the cost, the complexity and the achievable performance. Fig. 16 illustrates that an improved performance may be achieved by an AF relay aided SC-FDMA system, when the source node is allocated a higher fraction of power than the relay node, which is roaming close to the destination [160].

In the OR-channel considered in Fig. 19(a) [167], both the spatial- and spectral-domain resources offered by the multiple relays may be explored for the sake of power reduction. In order to achieve a selection diversity gain, the DRS allows each user to benefit from exploring both $J$ different S-R channels and $J$ R-D channels. The corresponding complex-valued fading envelope may be deemed to be independent and identically distributed (i.i.d) for each of these links of the resultant virtual MIMO scheme created from the single antennas of the MTs. Furthermore, the *dynamic subband allocation* (DSA) beneficially rearranges the MU signals for transmission over the most appropriate subband groups for second-hop relaying. Moreover, experiencing frequency-selective fading in the DRA assisted OR scheme may provide an additional MU diversity gain for the system.

Although the conventional combination of DRS and DSA achieves a diversity gain with the aid of beneficial subband allocation and RS, the grade-of-freedom associated with beneficially allocating the MU signals across the entire set of $(M \times J)$ subband groups of the $J$ relays has not been fully exploited. Unless near-error-free decoding is possible at the DF relays, the MU signals received and forwarded by the AF or DF relays may result in error-propagation at the BS, due to the first-hop transmissions in terms of the S-R CQI.

Therefore, the so-called *First-Hop-Quality-Aware* (FHQA) *joint dynamic resource allocation* (JDRA) schemes were conceived for OR-assisted SC-FDMA in [167] as the solution of the above-mentioned issues. By assuming that these cooperating relays are capable of exchanging their CQIs as mentioned in Section III-F1a, the $(J-1)$ relays of Fig. 19(b) transmit their CQI to an appropriately selected relay that acts as a *cluster-head*, which then broadcasts the CQI back to the $(J-1)$ relays. Two JDRA schemes were designed in [167], [215], where the relevant decision are made at the relay rather than at the BS. This implies that the BS's receiver does not require the CQI of the first hop.

As described in [167], [215], both FHQA JDRA schemes have three main functions, namely the relay selection, subband allocation and user assignment. Explicitly, the subband allocation of both JDRA schemes is based on the second-hop quality, while the user assignment depends on the first-hop quality. The RS of JDRA-1 is based on the second-hop quality, while that of JDRA-2 relies on the first-hop quality. Therefore, the JDRA-1 method predominantly relies on the second-hop quality, while JDRA-2 on the first-hop quality. As a result, the attainable performance of both JDRA-1 and JDRA-2 is limited by the quality of its dominant channels.

Naturally, the diversity gain of a multi-antenna assisted BS reduces the fading variation $g_{j,m}^{\mathrm{RD}}$ with the aid of an increased number of $N_\mathrm{r}$ independent channel attentions, which are averaged over the $m$-th subband group of a frequency-selective fading channel between the $j$-th relay and the BS. Hence, the achievable selection diversity gain of using $J$ R-D channels is reduced in the absence of shadowing. As observed in Fig. 20, the FHQA JDRA methods applied to subband-based AF OR in uncoded SC-FDMA are capable of achieving an additional gain by rearranging the resources of ORs by appropriately exploiting the S-R link quality. The first-hop quality becomes a particularly dominant factor for JDRA-2 in determining the achievable performance benefits of exchanging CQI between the cooperating relays. By contrast, observe in Fig. 21, the selection diversity gain of JDRA-2 exceeds that of the multi-antenna assisted Rayleigh fading benchmarker in the context of soft-decision based DF aided OR invoked in the BICM SC-FDMA uplink relying on an MMSE turbo FD-LE.

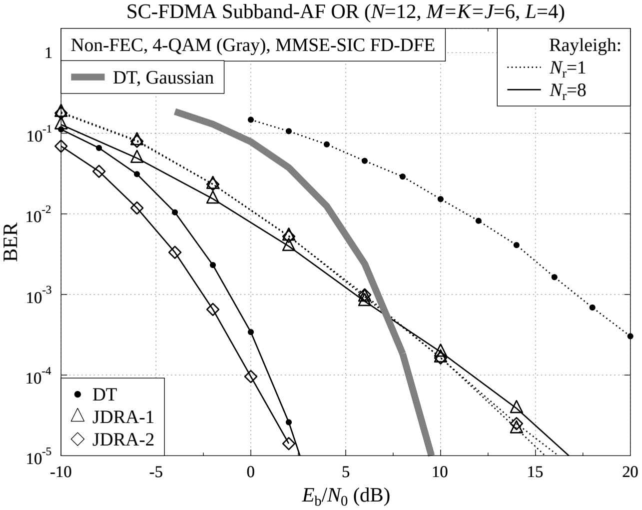


Fig. 20. Performance of various DRA schemes for subband-based AF aided uncoded OR SC-FDMA (LFDMA) uplink where the BS's receiver employs either a single- or multiple antennas for $N_\mathrm{r} = 1$ and $8$, when invoking the MMSE-SIC FD-DFE of Fig. 11 [98].

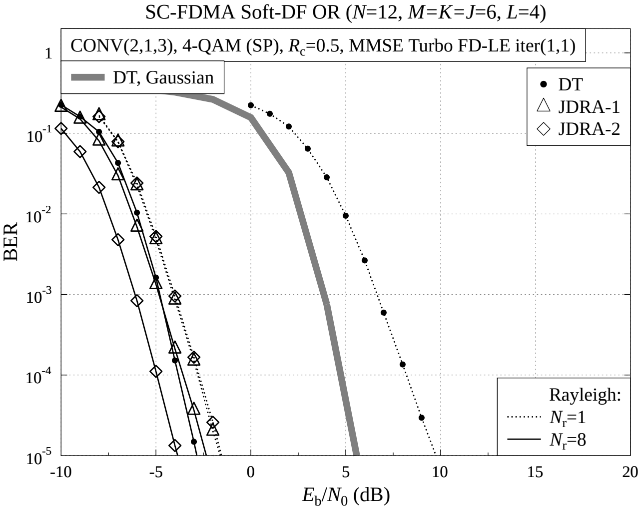


Fig. 21. Performance of various DRA schemes for soft-decision based DF aided OR SC-FDMA (LFDMA) invoking BICM and turbo FDE, when the relay channels experience uncorrelated fading. Both the BS's and the relay's receivers invoke the MMSE turbo FD-LE ($I_\mathrm{D} = 1$) of Fig. 10 [167].

## *G. Signal Processing at the Relays*

In order to eliminate both the MUI and for the sake of mitigating the noise inflicted upon the other users' subbands imposed by AF relaying in the MU uplink, an efficient subband-based AF scheme combined with subband demapping and remapping was proposed in [157]. Furthermore, a joint FDE and diversity-combining scheme (JFDEC) was proposed in [160], which combines the signals received from both the direct and relaying links for the sake of increasing the achievable cooperative diversity gain. Moreover, joint cooperative transmit/receive FDE was conceived for cooperative relaying in broadband SC systems in [175], which satisfied both the total and the individual transmit power constraints at the source and the relays. Hence joint transmit power allocation may be carried out in the MMSE sense in the FD and in the maximal ratio transmission (MRT) sense in the spatial domain.

### H. Relay Technology in LTE-Advanced Standards

Relaying was proposed for improving the LTE-Advanced standard in [240] and the relay architectures proposed for LTE-Advanced were defined in the LTE Release-9 [241].

The relays of the LTE-Advanced system complying with its Release-10 [23], [126] are operated in the relay transmission modes discussed in Section III-E [242]. Specifically, the so-called Layer-1 relays are simply operated as repeaters in AF mode, while the Layer-2 relays rely on the DF mode. Finally, the Layer-3 relays perform DF relaying relying on full user data regeneration.

Meanwhile, the relays may be operated in two different access types [243], [244]. Specifically, the so-called Type-I relays, which possess their own cell identifier, are capable of supporting the MTs with the aid of similar functions to those of the BS in order to improve the cell-edge coverage, when the direct link between the BS and MTs is of low quality. By contrast, the Type-II relays do not have their own cell identifier and hence do not offer BS-like functions. Their main function is that of creating cooperative relaying links between the BS and MTs for the sake of achieving cooperative diversity. In [128], [245], [246], the relay operation techniques were investigated both from a physical layer and a MAC layer perspective.

Both types relays obeying the LTE-Advanced standards [247] were designed to form an inherent part of the fixed infrastructure, hence they are stationary. However, the an improved performance may be achieved by mobile relays. Hence, in [248], [249], the networking architecture of mobile relay was investigated with a view to include them in future LTE-Advanced releases. For more details on relay and on the standardization of LTE-Advanced, please refer to [250] and [127], [128], [241], [246], [247], [249], [251], respectively.

## IV. CONCLUSIONS

### A. Summary

In this paper, we have reviewed the principles of SC-FDMA techniques and investigated a variety of cooperative relaying schemes designed for the SC-FDMA uplink, when communicating over broadband wireless channels, for the sake of increasing the achievable power-reduction. A number of inactive MTs are assumed to act as potential relays, which have either fixed or time-variant positions in a cell. We focused on the optimum exploitation of the resources, when considering relay selection, power allocation and subband allocation, as well as novel signal processing algorithms at the relays. Our investigation demonstrated that reliability and power-reduction of the cooperative SC-FDMA systems can be significantly improved.

### B. Design Guideline

1) The SC-FDMA arrangement benefits from the flexibility of transceiver reconfiguration in the form of either IFDMA or LFDMA, both of which may achieve some diversity gain in the presence of frequency-selective fading when the residual ISI was efficiently mitigated. In this case, IFDMA is capable of achieving much higher attainable frequency-diversity gain than LFDMA, when the LFDMA scheme does not invoke intelligent resource allocation schemes.
2) The IFDMA signaling scheme is capable of providing a significant frequency diversity gain in cooperative systems, where cooperative diversity may be achieved in a multi-path environment. The subband-based AF scheme exploiting the benefit of the noise suppression capability of the relay is capable of achieving a multi-user performance, which is better than that of the conventional SU AF protocol.
3) The cooperative networks may rely on either serial or parallel multi-relay assisted regimes, as well as on a generalized model combining both of them. The AF relays benefit from low-complexity implementation, while the DF relays are capable of achieving higher power reduction with the aid of FEC coding.
4) The optimal location of the AF relay is close to the BS and the AF relay requires a lower transmit power than the source MT. When the relays are dynamically distributed, the proposed SU-RS, MU-RS and MA-RS schemes benefit from substantial selection diversity gains in diverse shadowing scenarios.
5) The resource allocation schemes for the relays may be invoked in cooperative SC-FDMA system for the sake of achieving a selection diversity gain in both the frequency- and spatial-domains as well as for reducing the transmitted power. Specifically, the dynamic approaches of relay selection, power allocation and subband allocation require the knowledge of instantaneous CSI.
6) The FHQA aided JDRA-1 and JDRA-2 schemes were activated depending on whether the second-hop or the first-hop channel quality dominates the attainable performance. By employing a multi-antenna BS, the JDRA schemes are capable of achieving a superior performance in comparison to the DT benchmark, while its counterparts consume significantly more power.
7) The channel coded OR systems were found to be capable of reducing the transmit power as a benefit of its spatial interleaving gain owing to increasing the number of relays, when communicating over highly correlated fading channels. Hence, for the sake of decreasing the buffering delay and increasing the power-reduction, the interleaver depth of the proposed systems may be shortened, when the relays invoke the soft-DF protocol.

### C. Suggestions for Future Work

In this paper, we mainly considered the user cooperation in a *single-cell* scenario. However, in a *multi-cell* network [252], substantial *Co-channel interference* (CCI) may be imposed on the received signals at the MT, at the BS as well as at the relays [253]. In [254], [255], various architectures of stationary relay deployment have been designed for LTE-Advanced systems by taking into account the MT location, BS sectoring and frequency-reuse in interference-limited scenarios as well as *coordinated multi-point* (CoMP) transmission and reception schemes. In order to mitigate the CCI and reduce the energy per bit, a trade-off has to be struck between the energy-efficiency and spectral-efficiency.

For the prospective of fifth generation (5G) mobile communications, MIMO and cooperative communications are key techniques which are adopted within various technology directions, such as large-scale antenna systems, cognitive radio networks, device-to-device (D2D) communications, etc [256]–[258].

Owning to the beneficial diversity gain by employing a large the number of antennas in MIMO systems, large-scale antenna systems, which is now well known as massive MIMO, have been proposed and investigated [259], [260]. In order to realistically apply massive MIMO for LTE-Advanced based cellular systems, challenges rely on several issues including channel estimation, system architecture, smart antenna, and channel modeling, etc [258]. Various approaches such as full-dimension MIMO and elevation beamforming techniques have been studied and implemented in various aspects [261]–[263]. In [264], [265], the authors quantified the number of massive antennas employed for cellular system and discussed its relations to small-cell and heterogeneous network solutions.

Meanwhile, the rapid growth of wireless communications faces the increased critical issues of spectrum utilization, particularly for transmissions in the licensed bands. Therefore, with the aid of intelligent cooperation and opportunistic transmissions, cognitive radio becomes emerging technology in wireless networks [266]–[270]. However, in order to meeting the requirements and limitations for the practical cognitive radio based heterogeneous networks in beyond LTE-Advanced cellular systems, many challenges and design trade-offs are being explored [271]–[277].

## REFERENCES

[1] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution: from theory to practice*. Wiley, 2011.

[2] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-Advanced for Mobile Broadband*. Elsevier, 2011.

[3] R. W. Chang, "Synthesis of band-limited orthogonal signals for multichannel data transmission," *Bell System Technical Journal*, vol. 46, pp. 1775–1796, Dec. 1966.

[4] A. J. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[5] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete fourier transform," *IEEE Trans. Commun. Technol.*, vol. 19, no. 5, pp. 628–634, Oct. 1971.

[6] L. Hanzo, M. Münster, B.-J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*. Wiley, 2003.

[7] L.-L. Yang, *Multicarrier Communications*. Wiley, 2009.

[8] L. Hanzo, T. Liew, B. Yeap, R. Tee, and S. X. Ng, *Turbo Coding, Turbo Equalisation and Space-Time Coding (EXIT-Chart-Aided Near-Capacity Designs for Wireless Channels)*. Wiley (IEEE Press), 2011.

[9] D. Huang, K. B. Letaief, and J. Lu, "Bit-interleaved time-frequency coded modulation for OFDM systems over time-varying channels," *IEEE Trans. Commun.*, vol. 53, no. 7, pp. 1191–1199, Jul. 2005.

[10] X. Li and J. Cimini, L. J., "Effects of clipping and filtering on the performance of OFDM," *IEEE Commun. Lett.*, vol. 2, no. 5, pp. 131–133, may 1998.

[11] J. Cimini, L. J. and N. R. Sollenberger, "Peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences," *IEEE Commun. Lett.*, vol. 4, no. 3, pp. 86–88, Mar. 2000.

[12] A. D. S. Jayalath and C. R. N. Athaudage, "On the PAR reduction of OFDM signals using multiple signal representation," *IEEE Commun. Lett.*, vol. 8, no. 7, pp. 425–427, Jul. 2004.

[13] X. Huang, J. Lu, J. Zheng, K. B. Letaief, and J. Gu, "Companding transform for reduction in peak-to-average power ratio of OFDM signals," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 2030–2039, Nov. 2004.

[14] T. Jiang and G. Zhu, "Complement block coding for reduction in peak-to-average power ratio of OFDM signals," *IEEE Commun. Mag.*, vol. 43, no. 9, pp. S17–S22, Sep. 2005.

[15] M. Sharif, V. Tarokh, and B. Hassibi, "Peak power reduction of OFDM signals with sign adjustment," *IEEE Trans. Commun.*, vol. 57, no. 7, pp. 2160–2166, Jul. 2009.

[16] A. E. Jones, T. A. Wilkinson, and S. K. Barton, "Block coding scheme for reduction of peak to mean envelope power ratio of multicarrier transmission schemes," *Elect. Lett.*, vol. 30, no. 25, pp. 2098–2099, Dec. 1994.

[17] H. Sari, G. Karam, and I. Jeanclaude, "Transmission techniques for digital terrestrial TV broadcasting," *IEEE Commun. Mag.*, vol. 33, no. 2, pp. 100–109, Feb. 1995.

[18] D. D. Falconer, S. L. Ariyavisitakul, A. Benyamin-Seeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," *IEEE Commun. Mag.*, vol. 40, no. 4, pp. 58–66, Apr. 2002, white paper.

[19] N. Benvenuto, R. Dinis, D. D. Falconer, and S. Tomasin, "Single carrier modulation with nonlinear frequency domain equalization: An idea whose time has come-again," *Proc. IEEE*, vol. 98, no. 1, pp. 69–96, Jan. 2010.

[20] Ericsson, "Some aspects of single-carrier transmission for E-UTRA, (TSG-RAN WG1 #42)," 3GPP, London, UK, Tech. Rep. R1-050765, Aug. 2005.

[21] *E-UTRA: Physical channels and modulation (Release-8)*, 3GPP Std. TS 36.211 (V8.5.0), 2008.

[22] *E-UTRA: Physical channels and modulation (Release-11)*, 3GPP Std. TS 36.211 (V11.0.0), 2012.

[23] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-advanced: next-generation wireless broadband technology," *IEEE Wireless Commun. Mag.*, vol. 17, no. 3, pp. 10–22, Jun. 2010.

[24] M. Baker, "From LTE-Advanced to the future," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 116–120, Feb. 2012.

[25] D. Bai, C. Park, J. Lee, H. Nguyen, J. Singh, A. Gupta, Z. Pi, T. Kim, C. Lim, M.-G. Kim, and I. Kang, "LTE-advanced modem design: challenges and perspectives," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 178–186, Feb. 2012.

[26] M. V. Clark, "Adaptive frequency-domain equalization and diversity combining for broadband wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1385–1395, Oct. 1998.

[27] U. Sorger, I. De Broeck, and M. Schnell, "Interleaved FDMA- A new spread-spectrum multiple-access scheme," in *Proc. IEEE ICC 1998*, vol. 2, Jun. 1998, pp. 1013–1017 vol.2.

[28] M. Schnell, I. D. Broeck, and U. Sorger, "A promising new wideband multiple-access scheme for future mobile communications systems," *European Trans. Telecommun.*, vol. 10, no. 4, pp. 417–427, Jul. 1999.

[29] D. Galda and H. Rohling, "A low complexity transmitter structure for OFDM-FDMA uplink systems," in *Proc. IEEE VTC 2002 Spring*, vol. 4, 2002, pp. 1737–1741.

[30] N. Benvenuto and S. Tomasin, "On the comparison between OFDM and single carrier modulation with a DFE using a frequency-domain feedforward filter," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 947–955, Jun. 2002.

[31] A. Gusmao, R. Dinis, and N. Esteves, "On frequency-domain equalization and diversity combining for broadband wireless communications," *IEEE Trans. Commun.*, vol. 51, no. 7, pp. 1029–1033, Jul. 2003.

[32] Z. Wang, X. Ma, and G. B. Giannakis, "OFDM or single-carrier block transmissions?" *IEEE Trans. Commun.*, vol. 52, no. 3, pp. 380–394, Mar. 2004.

[33] R. Dinis, D. D. Falconer, C. T. Lam, and M. Sabbaghian, "A multiple access scheme for the uplink of broadband wireless systems," in *Proc. IEEE GLOBECOM 2004*, vol. 6, Nov. 2004, pp. 3808–3812.

[34] N. Benvenuto and S. Tomasin, "Block iterative DFE for single carrier modulation," *Elect. Lett.*, vol. 38, no. 19, pp. 1144– 1145, Sep. 2002.

[35] ——, "Iterative design and detection of a DFE in the frequency domain," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1867– 1875, Nov. 2005.

[36] H. G. Myung, J. Lim, and D. J. Goodman, "Single carrier FDMA for uplink wireless transmission," *IEEE Veh. Technol. Mag.*, pp. 30–38, Sep. 2006.

[37] ——, “Peak-to-average power ratio of single carrier FDMA signals with pulse shaping,” in *Proc. IEEE PIMRC 2006*, Sep. 2006, pp. 1–5.

[38] J. Lim, H. G. Myung, K. Oh, and D. J. Goodman, “Proportional fair scheduling of uplink single-carrier FDMA systems,” in *Proc. IEEE PIMRC 2006*, Sep. 2006, pp. 1–6.

[39] ——, “Channel-dependent scheduling of uplink single carrier FDMA systems,” in *Proc. IEEE VTC2006-Fall*, Sep. 2006, pp. 1–5.

[40] T. Frank, A. Klein, and E. Costa, “IFDMA: A scheme combining the advantages of OFDMA and CDMA,” *IEEE Wireless Commun.*, pp. 9–10, Jun. 2007.

[41] H. G. Myung and D. J. Goodman, *Single Carrier FDMA: A New Air Interface for Long Term Evolution*. Wiley, 2008.

[42] G. Berardinelli, B. Priyanto, T. B. Sorensen, and P. Mogensen, “Improving SC-FDMA performance by turbo equalization in utra lte uplink,” in *Proc. IEEE VTC-2008-Spring*, May 2008, pp. 2557–2561.

[43] L. Ruiz de Temino, G. Berardinelli, S. Frattasi, and P. Mogensen, “Channel-aware scheduling algorithms for SC-FDMA in LTE uplink,” in *Proc. IEEE PIMRC 2008*, Sep. 2008, pp. 1–6.

[44] G. Berardinelli, L. Ruiz de Temino, S. Frattasi, M. Rahman, and P. Mogensen, “OFDMA vs. SC-FDMA: Performance comparison in local area IMT-A scenarios,” *IEEE Wireless Commun. Mag.*, vol. 15, no. 5, pp. 64–72, Oct. 2008.

[45] F. Adachi, K. Takeda, and H. Tomeba, “Frequency-domain equalization for boradband single-carrier multiple access,” *IEICE Trans. Commun.*, vol. E92-B, no. 5, pp. 1441–1456, May 2009.

[46] ——, “Introduction of frequency-domain signal processing to boradband single-carrier transmissions in a wireless channel,” *IEICE Trans. Commun.*, vol. E92-B, no. 9, pp. 2789–2808, Sep. 2009.

[47] H.-J. Lim, T.-W. Yune, and G.-H. Im, “QoS-constrained opportunistic scheduling for SC-FDMA with iterative multiuser detection,” *IEEE Commun. Lett.*, vol. 13, no. 1, pp. 4–6, Jan. 2009.

[48] R. Dinis, P. Montezuma, L. Bernardo, R. Oliveira, M. Pereira, and P. Pinto, “Frequency-domain multipacket detection: a high throughput technique for SC-FDE systems,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3798–3807, Jul. 2009.

[49] I. C. Wong, O. Oteri, and W. Mccoy, “Optimal resource allocation in uplink SC-FDMA systems,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2161–2165, May 2009.

[50] Y. Yoshida, K. Hayashi, H. Sakai, and W. Bocquet, “Analysis and compensation of transmitter IQ imbalances in OFDMA and SC-FDMA systems,” *IEEE Trans. Signal Process.*, vol. 57, no. 8, pp. 3119–3129, Aug. 2009.

[51] M. Noune and A. Nix, “Frequency-domain precoding for single carrier frequency-division multiple access,” *IEEE Commun. Mag.*, vol. 47, no. 6, pp. 68–74, Jun. 2009.

[52] F. Al-kamali, M. Dessouky, B. Sallam, F. Shawki, and F. El-Samie, “Transceiver scheme for single-carrier frequency division multiple access implementing the wavelet transform and peak-to-average-power ratio reduction methods,” *IET Commun.*, vol. 4, no. 1, pp. 69–79, Jan. 2010.

[53] C.-H. Choi and G.-H. Im, “Bit-interleaved coded multilevel modulation for single-carrier frequency-domain equalization,” *IEEE Commun. Lett.*, vol. 14, no. 3, pp. 193–195, Mar. 2010.

[54] T.-W. Yune, C.-H. Choi, G.-H. Im, J.-B. Lim, E.-S. Kim, Y.-C. Cheong, and K.-H. Kim, “SC-FDMA with iterative multiuser detection: improvements on power/spectral efficiency,” *IEEE Commun. Mag.*, vol. 48, no. 3, pp. 164–171, Mar. 2010.

[55] T.-K. Kim, C.-H. Choi, H.-J. Lim, and G.-H. Im, “User scheduling and adaptive multilevel modulation for SC-FDMA with iterative multiuser detection,” *IEEE Commun. Lett.*, vol. 15, no. 9, pp. 919–921, Sep. 2011.

[56] X. Zhang and H.-G. Ryu, “Suppression of ICI and MAI in sc-fdma communication system with carrier frequency offsets,” *IEEE Trans. Consum. Electron.*, vol. 56, no. 2, pp. 359–365, May 2010.

[57] M. Ma, X. Huang, and Y. Guo, “An interference self-cancellation technique for SC-FDMA systems,” *IEEE Commun. Lett.*, vol. 14, no. 6, pp. 512–514, Jun. 2010.

[58] T. Liu, C. Yang, and L.-L. Yang, “A low-complexity subcarrier-power allocation scheme for frequency-division multiple-access systems,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1564–1570, May 2010.

[59] H. Nam, “Interpolation-based sc-fdma transmitter with localized resource allocation,” *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 948–950, Oct. 2010.

[60] C. Zhang, Z. Wang, Z. Yang, J. Wang, and J. Song, “Frequency domain decision feedback equalization for uplink SC-FDMA,” *IEEE Trans. Broadcast.*, vol. 56, no. 2, pp. 253–257, Jun. 2010.

[61] C. Zhang, Z. Wang, C. Pan, S. Chen, and L. Hanzo, “Low-complexity iterative frequency domain decision feedback equalization,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 3, pp. 1295–1301, Mar. 2011.

[62] J. Kim and H.-G. Ryu, “Inter-subcarrier interference compensation in the frequency-hopped single-carrier frequency division multiple access communication system,” *IET Commun.*, vol. 4, no. 12, pp. 1443–1451, Aug. 2010.

[63] K. Yamamoto, K. Adachi, and T. Ohtsuki, “Phase rotation sequence selection method for IFDMA with DDCE,” in *Proc. IEEE VTC 2011-Spring*, May 2011, pp. 1–5.

[64] O. Nwamadi, X. Zhu, and A. K. Nandi, “Dynamic physical resource block allocation algorithms for uplink Long Term Evolution,” *IET Commun.*, vol. 5, no. 7, pp. 1020–1027, May 2011.

[65] M. Ma, X. Huang, B. Jiao, and Y. Guo, “Optimal orthogonal precoding for power leakage suppression in DFT-based systems,” *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 844–853, Mar. 2011.

[66] F. Al-kamali, M. Dessouky, B. Sallam, F. Shawki, and F. Abd El-Samie, “Uplink single-carrier frequency division multiple access system with joint equalisation and carrier frequency offsets compensation,” *IET Commun.*, vol. 5, no. 4, pp. 425–433, Mar. 2011.

[67] X. Gao, W. Wang, X.-G. Xia, E. Au, and X. You, “Cyclic prefixed OQAM-OFDM and its application to single-carrier fdma,” *Communications, IEEE Transactions on*, vol. 59, no. 5, pp. 1467–1480, May 2011.

[68] S. Song, G. Chen, and K. Letaief, “Localized or interleaved? a tradeoff between diversity and CFO interference in multipath channels,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 2829–2834, September 2011.

[69] D. Falconer, “Linear precoding of ofdma signals to minimize their instantaneous power variance,” *IEEE Trans. Commun.*, vol. 59, no. 4, pp. 1154–1162, Apr. 2011.

[70] M. P. Wylie-Green, E. Perrins, and T. Svensson, “Introduction to CPM-SC-FDMA: A novel multiple-access power-efficient transmission scheme,” *IEEE Trans. Commun.*, vol. 59, no. 7, pp. 1904–1915, Jul. 2011.

[71] J. Sanchez-Sanchez, M. Aguayo-Torres, and U. Fernandez-Plazaola, “BER analysis for zero-forcing SC-FDMA over nakagami-m fading channels,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 4077–4081, Oct. 2011.

[72] M. Rana and J. Kim, “LMS based blind channel estimation of SC-FDMA systems using variable step size and phase information,” *Elect. Lett.*, vol. 47, no. 5, pp. 346–348, Mar. 2011.

[73] J. Sanchez-Sanchez, C. del Castillo-Vazquez, M. Aguayo-Torres, and U. Fernandez-Plazaola, “Application of student’s t and behrens-fisher distributions to the analysis of enhanced noise after zero-forcing frequency domain equalisation,” *IET Commun.*, vol. 6, no. 1, pp. 55–61, Jan. 2012.

[74] C.-H. Choi, H.-J. Lim, T.-K. Kim, G.-H. Im, and V. Lawrence, “Spectral efficient multiuser technique with channel-dependent resource allocation schemes,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 990–999, Mar. 2012.

[75] Y.-S. Cho, D. Kim, T.-K. Kim, and G.-H. Im, “Improved channel-dependent user selection for an SC-FDMA system,” *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1608–1611, Oct. 2012.

[76] H. Ochiai, “On instantaneous power distributions of single-carrier FDMA signals,” *IEEE Wireless Commun. Lett.*, vol. 1, no. 2, pp. 73–76, Apr. 2012.

[77] E. Yaacoub and Z. Dawy, “A survey on uplink resource allocation in OFDMA wireless networks,” *IEEE Commun. Surveys Tuts.*, vol. 14, no. 2, pp. 322–337, 2nd 2012.

[78] J. Zhang, L.-L. Yang, and L. Hanzo, “Frequency-domain turbo equalisation in coded SC-FDMA systems: EXIT chart analysis and performance,” in *Proc. IEEE VTC 2012-Fall*, Sep. 2012, pp. 1–5.

[79] M. Geles, A. Averbuch, O. Amrani, and D. Ezri, “Performance bounds for maximum likelihood detection of single carrier FDMA,” *IEEE Trans. Commun.*, vol. 60, no. 7, pp. 1945–1952, Jul. 2012.

[80] D. Kim, H.-M. Kim, and G.-H. Im, “Iterative channel estimation with frequency replacement for SC-FDMA systems,” *IEEE Trans. Commun.*, vol. 60, no. 7, pp. 1877–1888, Jul. 2012.

[81] J.-H. Deng, S.-M. Liao, and S.-Y. Huang, “Design of low peak-to-average power ratio transceiver with enhanced link quality for coded single-carrier frequency division multiple access system,” *IET Commun.*, vol. 6, no. 15, pp. 2432–2441, Oct. 2012.

[82] J. Fan, G. Li, Q. Yin, B. Peng, and X. Zhu, “Joint user pairing and resource allocation for LTE uplink transmission,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2838–2847, Aug. 2012.

[83] L. Yang, G. Ren, B. Yang, and Z. Qiu, “Fast time-varying channel estimation technique for LTE uplink in HST environment,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 9, pp. 4009–4019, Nov 2012.

[84] C. Yuen and B. Farhang-Boroujeny, “Analysis of the optimum precoder in sc-fdma,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 4096–4107, Nov. 2012.

[85] C. Azurdia-Meza, K. Lee, and K. Lee, “Papr reduction in sc-fdma by pulse shaping using parametric linear combination pulses,” *IEEE Commun. Lett.*, vol. 16, no. 12, pp. 2008–2011, Dec. 2012.

[86] G. Sridharan and T. J. Lim, “Performance analysis of SC-FDMA in the presence of receiver phase noise,” *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3876–3885, Dec. 2012.

[87] M. Wen, X. Cheng, M. Wang, B. Ai, and B. Jiao, “Error probability analysis of interleaved SC-FDMA systems over nakagami-m frequency-selective fading channels,” *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 2, pp. 748–761, Feb. 2013.

[88] M. Wen, X. Cheng, X. Yin, L. Yang, and B. Jiao, “A general framework for ber analysis of OFDMA and zero-forcing interleaved SC-FDMA over nakagami-m fading channels with arbitrary m,” *IEEE Wireless Commun. Lett.*, vol. 2, no. 4, pp. 395–398, Aug. 2013.

[89] M. Zhang and Y. Zhu, “An enhanced greedy resource allocation algorithm for localized SC-FDMA systems,” *IEEE Commun. Lett.*, vol. 17, no. 7, pp. 1479–1482, Jul. 2013.

[90] J. Sanchez-Sanchez, M. Aguayo-Torres, and U. Fernandez-Plazaola, “Spectral efficiency of interleaved SC-FDMA with adaptive modulation and coding over nakagami-m fading channels,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3663–3670, Oct. 2013.

[91] L. Lei, D. Yuan, C. K. Ho, and S. Sun, “A unified graph labeling algorithm for consecutive-block channel allocation in SC-FDMA,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, pp. 5767–5779, Nov. 2013.

[92] F. Cruz-Roldan, M. Dominguez-Jimenez, G. Sansigre Vidal, J. Pineiro-Ave, and M. Blanco-Velasco, “Single-carrier and multicarrier transceivers based on discrete cosine transform type-IV,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, pp. 6454–6463, Dec. 2013.

[93] R. Dinis, D. Falconer, T. Matsumoto, M. Ran, A. Springer, and P. Zhu, “A mixed OFDM plus single-carrier mode air interface, (WG4 white paper),” WWRF, Ottawa, Canada, Tech. Rep., Aug. 2003.

[94] B. Muquet, Z. Wang, G. B. Giannakis, M. de Courville, and P. Duhamel, “Cyclic prefixing or zero padding for wireless multicarrier transmissions?” *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 2136–2148, Dec. 2002.

[95] R. Steele and L. Hanzo, *Mobile Radio Communications, 2th Edition*. IEEE Press and John Wiley, 1999.

[96] Nokia, “Uplink considerations for UTRAN LTE, (TSG-RAN WG1 #40bis),” 3GPP, Beijing, China, Tech. Rep. R1-050251, Mar. 2005.

[97] Motorola, “Uplink multiple access for E-UTRA, (TSG-RAN WG1 #40bis),” 3GPP, Beijing, China, Tech. Rep. R1-050245, Apr. 2005.

[98] J. Zhang, L.-L. Yang, and L. Hanzo, “First-hop-quality-aware dynamic resource allocation for amplify-and-forward opportunistic relaying assisted SC-FDMA,” in *Proc. IEEE ICC 2012*, Jun. 2012, pp. 1–5.

[99] L.-L. Yang, “Receiver multiuser diversity aided multi-stage MMSE multiuser detection for DS-CDMA and SDMA systems employing I-Q modulation,” in *Proc. IEEE VTC2010-Fall*, Sep. 2010, pp. 1–5.

[100] ——, “Receiver multiuser diversity aided multi-stage minimum mean-square error detection for heavily loaded DS-CDMA and SDMA systems,” *IEEE Trans. Commun.*, vol. 58, no. 12, pp. 3397–3404, Dec. 2010.

[101] B. Ng, C.-T. Lam, and D. D. Falconer, “Turbo frequency domain equalization for single-carrier broadband wireless systems,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 759–767, Feb. 2007.

[102] M. Tüchler and A. C. Singer, “Turbo equalization: An overview,” *IEEE Trans. Inf. Theory*, vol. 57, no. 2, pp. 920–952, Feb. 2011.

[103] K. B. Letaief and Y. J. Zhang, “Dynamic multiuser resource allocation and adaptation for wireless systems,” *IEEE Wireless Commun. Mag.*, vol. 13, no. 4, pp. 38–47, Aug. 2006.

[104] L. Electronics, “Performance of localised and distributed SC-FDMA, (TSG-RAN WG1 #44),” 3GPP, Denver, USA, Tech. Rep. R1-060540, Feb. 2006.

[105] C. E. Shannon, “A mathematical theory of communication,” *Bell System Technical Journal*, vol. 27, pp. 379–423, 623–656, Jul. 1948.

[106] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge University Press, 2003.

[107] D. N. C. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge University Press, 2005.

[108] A. Wittneben, “A new bandwidth efficient transmit antenna modulation diversity scheme for linear digital modulation,” in *Proc. IEEE ICC 1993*, May 1993, pp. 1630–1634.

[109] G. J. Foschini, “Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas,” *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 41–59, Aut. 1996.

[110] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[111] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[112] P. Vandenameele, L. Van Der Perre, M. G. E. Engels, B. Gyselinckx, and H. J. De Man, “A combined OFDM/SDMA approach,” *IEEE J. Sel. Areas Commun.*, vol. 18, no. 11, pp. 2312–2321, Nov. 2000.

[113] B. Hassibi and B. M. Hochwald, “High-rate codes that are linear in space and time,” *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1804–1824, Jul. 2002.

[114] W. Su, Z. Safar, M. Olfat, and K. J. R. Liu, “Obtaining full-diversity space-frequency codes from space-time codes via mapping,” *IEEE Trans. Signal Process.*, vol. 51, no. 11, pp. 2905–2916, Nov. 2003.

[115] L. Hanzo, O. Alamri, M. El-Hajjar, and N. Wu, *Near-capacity Multi-functional MIMO Systems: Sphere-packing, Iterative Detection and Cooperation*. Wiley, 2009.

[116] N. Wu and L. Hanzo, “Near-capacity irregular-convolutional-coding-aided irregular precoded linear dispersion codes,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 6, pp. 2863–2871, Jul. 2009.

[117] N. Wu, S. Sugiura, and L. Hanzo, “Coherent versus noncoherent,” *IEEE Veh. Technol. Mag.*, vol. 6, no. 4, pp. 38–48, Dec 2011.

[118] H. Bolcskei, M. Borgmann, and A. Paulraj, “Impact of the propagation environment on the performance of space-frequency coded MIMO-OFDM,” *IEEE J. Sel. Areas Commun.*, vol. 21, no. 3, pp. 427–439, Apr 2003.

[119] G. Bauch, “Space-time block codes versus space-frequency block codes,” in *IEEE VTC2003-Spring*, vol. 1, Apr. 2003, pp. 567–571.

[120] W. Zhang, X.-G. Xia, and K. Ben Letaief, “Space-time/frequency coding for MIMO-OFDM in next generation broadband wireless systems,” *IEEE Wireless Commun. Mag.*, vol. 14, no. 3, pp. 32–43, Jun. 2007.

[121] L. Hanzo, Y. Akhtman, L. Wang, and M. Jiang, *MIMO-OFDM for LTE, WIFI and WIMAX: Coherent Versus Non-Coherent and Cooperative Turbo-Transceivers*. Wiley (IEEE Press), Oct. 2010.

[122] J. Zhang, H. Gharavi, and B. Hu, “Performance of space-time/frequency transmit diversity aided MIMO-OFDM transmissions over time-/frequency-selective fading channels,” in *NIST Internal Report*, Apr. 2014, pp. 1–5.

[123] *E-UTRA: UE radio transmission and reception (Release-10)*, 3GPP Std. TS 36.101 (V10.2.1), 2011.

[124] E. C. van der Meulen, “Three-terminal communication channels,” *Advances in Applied Probability*, vol. 3, no. 1, pp. 120–154, 1971.

[125] ——, “A survey of multi-way channels in information theory: 1961-1976,” *IEEE Trans. Inf. Theory*, vol. 23, no. 1, pp. 1–37, Jan. 1977.

[126] *E-UTRA: LTE physical layer; General description (Release-10)*, 3GPP Std. TS 36.201 (V10.0.0), 2011.

[127] *E-UTRA: Physical layer for relaying operation (Release-10)*, 3GPP Std. TS 36.216 (V10.2.1), 2011.

[128] *E-UTRA: Physical layer for relaying operation (Release-11)*, 3GPP Std. TS 36.216 (V11.0.0), 2012.

[129] A. Sendonaris, E. Erkip, and B. Aazhang, “Increasing uplink capacity via user cooperation diversity,” in *Proc. IEEE ISIT 1998*, Aug. 1998, p. 156.

[130] J. N. Laneman and G. W. Wornell, “Energy-efficient antenna sharing and relaying for wireless networks,” in *Proc. IEEE WCNC 2000*, vol. 1, Sep. 2000, pp. 7–12.

[131] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity-Part I: System description,” *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[132] ——, “User cooperation diversity- Part II: Implementation aspects and performance analysis,” *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[133] Y. Li, B. Vucetic, Z. Zhou, and M. Dohler, “Distributed adaptive power allocation for wireless relay networks,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 948–958, Mar. 2007.

[134] M. Kaneko, K. Hayashi, P. Popovski, K. Ikeda, H. Sakai, and R. Prasad, “Amplify-and-forward cooperative diversity schemes for multi-carrier systems,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1845–1850, May 2008.

[135] J. Huang, V. Subramanian, R. Agrawal, and R. Berry, "Joint scheduling and resource allocation in uplink OFDM systems for broadband wireless access networks," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 2, pp. 226–234, Feb. 2009.

[136] W. Dang, M. Tao, H. Mu, and J. Huang, "Subcarrier-pair based resource allocation for cooperative multi-relay OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1640–1649, May 2010.

[137] S. Ren and M. Van Der Schaar, "Distributed power allocation in multi-user multi-channel cellular relay networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 6, pp. 1952–1964, Jun. 2010.

[138] B.-G. Kim and J.-W. Lee, "Joint opportunistic subchannel and power scheduling for relay-based OFDMA networks with scheduling at relay stations," *IEEE Trans. Veh. Technol.*, vol. 59, no. 5, pp. 2138–2148, Jun. 2010.

[139] N. Al-Dhahir, "Single-carrier frequency-domain equalization for space-time block-coded transmissions over frequency-selective fading channels," *IEEE Commun. Lett.*, vol. 5, no. 7, pp. 304–306, Jul. 2001.

[140] X. Zhu and R. Murch, "Layered space-frequency equalization in a single-carrier MIMO system for frequency-selective channels," *IEEE Trans. Wireless Commun.*, vol. 3, no. 3, pp. 701–708, May 2004.

[141] L. Sarperi, X. Zhu, and A. Nandi, "Semi-blind layered space-frequency equalization for single-carrier MIMO systems with block transmission," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1203–1207, Apr. 2008.

[142] Y. Wu, X. Zhu, and A. Nandi, "Low complexity adaptive turbo frequency-domain channel estimation for single-carrier multi-user detection," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4094–4099, Nov. 2008.

[143] Y. Zhu and K. Letaief, "Single-carrier frequency-domain equalization with decision-feedback processing for time-reversal space-time block-coded systems," *IEEE Trans. Commun.*, vol. 53, no. 7, pp. 1127–1131, Jul. 2005.

[144] J. Coon, S. Armour, M. Beach, and J. McGeehan, "Adaptive frequency-domain equalization for single-carrier multiple-input multiple-output wireless transmissions," *IEEE Trans. Signal Process.*, vol. 53, no. 8, pp. 3247–3256, Aug 2005.

[145] J.-H. Jang, H.-C. Won, and G.-H. Im, "Cyclic prefixed single carrier transmission with SFBC over mobile wireless channels," *IEEE Signal Process. Lett.*, vol. 13, no. 5, pp. 261–264, May 2006.

[146] H. Mheidat, M. Uysal, and N. Al-Dhahir, "Equalization techniques for distributed space-time block codes with amplify-and-forward relaying," *IEEE Trans. Signal Process.*, vol. 55, pp. 1839–1852, May 2007.

[147] H.-J. Kwon, J.-S. Baek, and J.-S. Seo, "Weighted block adaptive channel estimation for STBC SC-FDE over frequency-selective fading channels," *Elect. Lett.*, vol. 43, no. 15, pp. 840–841, July 2007.

[148] D.-Y. Seol, U.-K. Kwon, G.-H. Im, and E.-S. Kim, "Relay-based single carrier transmission with SFBC in uplink fast fading channels," *IEEE Commun. Lett.*, vol. 11, no. 12, pp. 928–930, Dec. 2007.

[149] D.-Y. Seol, U.-K. Kwon, and G.-H. Im, "Performance of single carrier transmission with cooperative diversity over fast fading channels," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2799–2807, Sep. 2009.

[150] U.-K. Kwon, C.-H. Choi, and G.-H. Im, "Full-rate cooperative communications with spatial diversity for half-duplex uplink relay channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 11, pp. 5449–5454, Nov. 2009.

[151] U.-K. Kwon, D.-Y. Seol, and G.-H. Im, "Spectral efficient transmit diversity techniques without cyclic prefix for fading relay channels," *IEEE Trans. Commun.*, vol. 58, no. 2, pp. 568–577, Feb. 2010.

[152] T.-W. Yune, J.-B. Lim, Y.-C. Cheong, and G.-H. Im, "Iterative multiuser detection with spectral efficient protocol for relay-assisted SC-FDE," *IEEE Commun. Lett.*, vol. 12, no. 3, pp. 182–184, Mar. 2008.

[153] J.-B. Lim, C.-H. Choi, H.-J. Lim, and G.-H. Im, "Iterative multiuser detection for single-carrier transmission with SFBC," *IEEE Signal Process. Lett.*, vol. 15, pp. 525–528, 2008.

[154] T.-W. Yune, J.-B. Lim, and G.-H. Im, "Iterative multiuser detection with spectral efficient relaying protocols for single-carrier transmission," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3789–3797, July 2009.

[155] B. Li, X. Zhang, and D. Yang, "Sfbc single-carrier systems with turbo frequency domain equalisation," *Elect. Lett.*, vol. 44, no. 13, pp. 812–813, Jun. 2008.

[156] J.-S. Baek and J.-S. Seo, "Efficient design of block adaptive equalization and diversity combining for space-time block-coded single-carrier systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2603–2611, Jul. 2008.

[157] J. Zhang, L.-L. Yang, and L. Hanzo, "Multi-user performance of the amplify-and-forward single-relay assisted SC-FDMA uplink," in *Proc. IEEE VTC 2009-Fall*, Sep. 2009, pp. 1–5.

[158] C. Ciochina, D. Castelain, D. Mottier, and H. Sari, "New PAPR-preserving mapping methods for single-carrier FDMA with space-frequency block codes," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5176–5186, Oct. 2009.

[159] J. Zhang, L.-L. Yang, and L. Hanzo, "Power-efficient opportunistic amplify-and-forward single-relay aided multi-user SC-FDMA uplink," in *Proc. IEEE VTC 2010-Spring*, May 2010, pp. 1–5.

[160] ——, "Energy-efficient channel-dependent cooperative relaying for the multiuser SC-FDMA uplink," *IEEE Trans. Veh. Technol.*, vol. 60, no. 3, pp. 992–1004, Mar. 2011.

[161] H.-M. Kim, T.-W. Yune, D. Kim, and G.-H. Im, "Decision-directed channel estimation for SC-FDE in amplify-and-forward relaying networks," *IEEE Commun. Lett.*, vol. 14, no. 3, pp. 211–213, Mar. 2010.

[162] K. S. Woo, H. Yim, Y. J. Kim, H. I. Yoo, and Y. S. Cho, "An efficient receive-diversity-combining technique for SC-FDMA-based cooperative relays," *IEEE Trans. Veh. Technol.*, vol. 59, no. 8, pp. 4187–4191, Oct. 2010.

[163] Y.-S. Chen, "A simple precoding-based blind channel estimation for space-time block-coded single-carrier with frequency-domain equalization systems," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5430–5437, Oct 2010.

[164] X. Zhang and H.-G. Ryu, "Joint estimation and suppression of phase noise and carrier frequency offset in multiple-input multiple-output single carrier frequency division multiple access with single-carrier space frequency block coding," *IET Commun.*, vol. 4, no. 16, pp. 1998–2007, Nov. 2010.

[165] H. Eghbali, S. Muhaidat, and N. Al-Dhahir, "A novel receiver design for single-carrier frequency domain equalization in broadband wireless networks with amplify-and-forward relaying," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 721–727, Mar. 2011.

[166] H. Eghbali, S. Muhaidat, S. Hejazi, and Y. Ding, "Relay selection strategies for single-carrier frequency-domain equalization multi-relay cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2034–2045, May 2013.

[167] J. Zhang, L.-L. Yang, and L. Hanzo, "Energy-efficient dynamic resource allocation for opportunistic relaying assisted SC-FDMA using turbo equaliser aided soft decode-and-forward," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 235–246, Jan. 2013.

[168] M. Nakada, T. Obara, T. Yamamoto, and F. Adachi, "Power allocation for direct/cooperative af relay switched SC-FDMA," in *Proc. IEEE VTC 2012-Spring*, May 2012, pp. 1–5.

[169] X. Tao, X. Xu, and Q. Cui, "An overview of cooperative communications," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 65–71, June 2012.

[170] P. Wu and R. Schober, "Cooperative beamforming for single-carrier frequency-domain equalization systems with multiple relays," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2276–2286, Jun. 2012.

[171] E. S. Hassan, "Energy-efficient hybrid opportunistic cooperative protocol for single-carrier frequency division multiple access-based networks," *IET Commun.*, vol. 6, no. 16, pp. 2602–2612, 6 2012.

[172] K. Kuchi, "MMSE-prewhitened-MLD equalizer for MIMO DFT-precoded-OFDMA," *IEEE Wireless Commun. Lett.*, vol. 1, no. 4, pp. 328–331, Aug. 2012.

[173] L. Luo, J. Zhang, and L. Davis, "Space-time block code and spatial multiplexing design for quadrature-OFDMA systems," *IEEE Trans. Commun.*, vol. 60, no. 10, pp. 3133–3142, Oct. 2012.

[174] M. Kadir, S. Sugiura, J. Zhang, S. Chen, and L. Hanzo, "OFDMA/SC-FDMA aided space-time shift keying for dispersive multiuser scenarios," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 408–414, Jan 2013.

[175] K. Adachi, K. Takeda, S. Sun, and F. Adachi, "Joint cooperative-transmit and receive FDE for single-carrier incremental relaying," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 1–13, Jan. 2013.

[176] H. H. Kha, H. D. Tuan, H. Nguyen, and T. Pham, "Optimization of cooperative beamforming for SC-FDMA multi-user multi-relay networks by tractable D.C. programming," *IEEE Trans. Signal Process.*, vol. 61, no. 2, pp. 467–479, Jan. 2013.

[177] H. Kha, H. Tuan, and H. Nguyen, "Joint optimization of source power allocation and cooperative beamforming for SC-FDMA multi-user multi-relay networks," *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2248–2259, Jun. 2013.

[178] R. Rajashekar, K. Hari, and L. Hanzo, "Spatial modulation aided zero-padded single carrier transmission for dispersive channels," *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2318–2329, June 2013.

[179] G. Guvensen and A. Yilmaz, "A general framework for optimum iterative blockwise equalization of single carrier MIMO systems and

asymptotic performance analysis," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 609–619, February 2013.

[180] Y. Li, C. Wu, D. Sun, J. Xia, and H.-G. Ryu, "A new physical layer transmission scheme for lpi and high throughput in the cooperative sc-fdma system," *J. Commun. Netw.*, vol. 15, no. 5, pp. 457–463, Oct 2013.

[181] R. U. Nabar, H. Bölcskei, and F. W. Kneubühler, "Fading relay channels: Performance limits and space-time signal design," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1099–1109, Aug. 2004.

[182] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[183] A. Ribeiro, R. Wang, and G. Giannakis, "Multi-source cooperation with full-diversity spectral-efficiency and controllable-complexity," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 415–425, Feb. 2007.

[184] B. Hu and H. Gharavi, "Directional routing protocols for ad-hoc networks," *IET Commun.*, vol. 2, no. 5, pp. 650–657, May 2008.

[185] R. Zhang and L. Hanzo, "Interleaved random space-time coding for multisource cooperation," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 2120–2125, May 2009.

[186] N. Wu and H. Gharavi, "Asynchronous cooperative MIMO systems using a linear dispersion structure," *IEEE Trans. Veh. Technol.*, vol. 59, no. 2, pp. 779–787, Feb. 2010.

[187] L. Kong, S. X. Ng, R. G. Maunder, and L. Hanzo, "Maximum-throughput irregular distributed space-time code for near-capacity cooperative communications," *IEEE Trans. Veh. Technol.*, vol. 59, no. 3, pp. 1511–1517, Mar. 2010.

[188] ——, "Near-capacity cooperative space-time coding employing irregular design and successive relaying," *IEEE Trans. Commun.*, vol. 58, no. 8, pp. 2232–2241, Aug. 2010.

[189] C. Xu and H. Gharavi, "A low-complexity solution to decode diversity-oriented block codes in MIMO systems with inter-symbol interference," *IEEE Trans. Wireless Commun.*, vol. 11, no. 10, pp. 3574–3587, Oct. 2012.

[190] H. Gharavi and B. Hu, "Cooperative diversity routing and transmission for wireless sensor networks," *IET Wireless Sens. Syst.*, vol. 3, no. 4, pp. 277–288, Dec. 2013.

[191] K. Azarian, H. El-Gamal, and P. Schniter, "On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 12, pp. 4152–4172, Dec. 2005.

[192] K. C. Lee and L. Hanzo, "MIMO-assisted hard versus soft decoding-and-forwarding for network coding aided relaying systems," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 376–385, Jan. 2009.

[193] Q. You, Z. Chen, and Y. Li, "A multihop transmission scheme with detect-and-forward protocol and network coding in two-way relay fading channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 433–438, Jan. 2012.

[194] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. Commun.*, vol. 52, no. 10, pp. 1820–1830, Oct. 2004.

[195] D. Chen, L.-L. Yang, and L. Hanzo, "Multi-hop diversity aided multi-hop communications: A cumulative distribution function aware approach," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4486–4499, Nov. 2013.

[196] P. A. Anghel and M. Kaveh, "Exact symbol error probability of a cooperative network in a Rayleigh-fading environment," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1416–1421, Sep. 2004.

[197] L.-L. Yang and H.-H. Chen, "Error probability of digital communications using relay diversity over Nakagami-m fading channels," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1806–1811, May 2008.

[198] A. Ribeiro, X. Cai, and G. B. Giannakis, "Symbol error probabilities for general cooperative links," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1264–1273, May 2005.

[199] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[200] T. Liu, C. Yang, and L.-L. Yang, "A unified analysis of spectral efficiency for two-hop relay systems with different resource configurations," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3137–3148, Sep. 2013.

[201] S. Simoens, O. Muoz-Medina, J. Vidal, and A. Del Coso, "Compress-and-forward cooperative MIMO relaying with full channel state information," *IEEE Trans. Signal Process.*, vol. 58, no. 2, pp. 781–791, Feb. 2010.

[202] J. Yuan, Y. Li, and L. Chu, "Differential modulation and relay selection with detect-and-forward cooperative relaying," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 261–268, Jan. 2010.

[203] W. Fang, L.-L. Yang, and L. Hanzo, "Single-user performance of direct-sequence code-division multiple-access using relay diversity and power allocation," *IET Commun.*, vol. 2, no. 3, pp. 462–472, Mar. 2008.

[204] L. Wang and L. Hanzo, "The resource-optimized differentially modulated hybrid AF/DF cooperative cellular uplink using multiple-symbol differential sphere detection," *IEEE Signal Process. Lett.*, vol. 16, no. 11, pp. 965–968, Nov. 2009.

[205] ——, "Dispensing with channel estimation: Differentially modulated cooperative wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 836–857, 3rd 2012.

[206] Y. Li, B. Vucetic, T. F. Wong, and M. Dohler, "Distributed turbo coding with soft information relaying in multihop relay networks," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 11, pp. 2040–2050, Nov. 2006.

[207] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[208] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[209] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 283–289, Feb. 2006.

[210] Y. Li, "Distributed coding for cooperative wireless networks: An overview and recent advances," *IEEE Commun. Mag.*, vol. 47, no. 8, pp. 71–77, Aug. 2009.

[211] M. F. U. Butt, S. X. Ng, and L. Hanzo, "Self-concatenated code design and its application in power-efficient cooperative communications," *Communications Surveys Tutorials, IEEE*, vol. 14, no. 3, pp. 858–883, 3rd 2012.

[212] L. Wang, L. Kong, S. X. Ng, and L. Hanzo, "Code-rate-optimized differentially modulated near-capacity cooperation," *IEEE Trans. Commun.*, vol. 59, no. 8, pp. 2185–2195, Aug. 2011.

[213] D. Liang, S. X. Ng, and L. Hanzo, "Near-capacity turbo coded soft-decision aided DAPSK/star-QAM for amplify-and-forward based cooperative communications," *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 1080–1087, Mar. 2013.

[214] H. A. Ngo and L. Hanzo, "Hybrid automatic-repeat-request systems for cooperative wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 25–45, 1st 2014.

[215] J. Zhang, "Energy-efficient cooperative single-carrier frequency-division multiple-access," Ph.D. dissertation, University of Southampton, 2012.

[216] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit and power allocation," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 10, pp. 1747–1758, Oct. 1999.

[217] T. Keller and L. Hanzo, "Adaptive multicarrier modulation: a convenient framework for time-frequency processing in wireless communications," *Proc. IEEE*, vol. 88, no. 5, pp. 611–640, May 2000.

[218] X. Wang, G. B. Giannakis, and A. G. Marques, "A unified approach to qos-guaranteed scheduling for channel-adaptive wireless networks," *Proc. IEEE*, vol. 95, no. 12, pp. 2410–2431, Dec. 2007.

[219] H. Zhu and J. Wang, "Chunk-based resource allocation in OFDMA systems - Part I: chunk allocation," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2734–2744, Sep. 2009.

[220] ——, "Chunk-based resource allocation in OFDMA systems - Part II: Joint chunk, power and bit allocation," *IEEE Trans. Commun.*, vol. 60, no. 2, pp. 499–509, Feb. 2012.

[221] G. Song and G. Y. Li, "Cross-layer optimization for OFDM wireless networks- Part I: Theoretical framework," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 614– 624, Mar. 2005.

[222] ——, "Cross-layer optimization for OFDM wireless networks- Part II: Algorithm development," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 625– 634, Mar. 2005.

[223] G. Miao, N. Himayat, G. Y. Li, and A. Swami, "Cross-layer optimization for energy-efficient wireless communications: a survey," *Wireless Communications and Mobile Computing*, vol. 9, no. 4, p. 529542, Apr. 2009.

[224] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[225] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wireless Commun.*, vol. 6, no. 9, pp. 3450–3460, Sep. 2007.

[226] R. Madan, N. Mehta, A. Molisch, and J. Zhang, "Energy-efficient cooperative relaying over fading channels with simple relay selection," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3013–3025, Aug. 2008.

[227] Y. Jing and H. Jafarkhani, “Single and multiple relay selection schemes and their achievable diversity orders,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1414–1423, Mar. 2009.

[228] D. Gunduz, A. Yener, A. J. Goldsmith, and H. V. Poor, “The multi-way relay channel,” in *Proc. IEEE ISIT 2009*, Jul. 2009, pp. 339–343.

[229] Y. Peng, S. Armour, and J. McGeehan, “An investigation of dynamic subcarrier allocation in MIMO-OFDMA systems,” *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2990–3005, Sep. 2007.

[230] Y.-F. Chen and J.-W. Chen, “A fast subcarrier, bit, and power allocation algorithm for multiuser OFDM-based systems,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 873–881, Mar. 2008.

[231] W.-C. Pao and Y.-F. Chen, “Reduced complexity subcarrier allocation schemes for DFT-precoded OFDMA uplink systems,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, pp. 2701–2706, Sep. 2010.

[232] 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.

[233] O. Duval, Z. Hasan, E. Hossain, F. Gagnon, and V. Bhargava, “Subcarrier selection and power allocation for amplify-and-forward relaying over OFDM links,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 4, pp. 1293–1297, Apr. 2010.

[234] C.-N. Hsu, H.-J. Su, and P.-H. Lin, “Joint subcarrier pairing and power allocation for OFDM transmission with decode-and-forward relaying,” *IEEE Trans. Signal Process.*, vol. 59, no. 1, pp. 399–414, Jan. 2011.

[235] H. Boostanimehr and V. K. Bhargava, “Selective subcarrier pairing and power allocation for DF OFDM relay systems with perfect and partial CSI,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 4057 –4067, Dec. 2011.

[236] Y. Liu and M. Tao, “Optimal channel and relay assignment in OFDM-based multi-relay multi-pair two-way communication networks,” *IEEE Trans. Commun.*, vol. 60, no. 2, pp. 317–321, Feb. 2012.

[237] H. Zhang, Y. Liu, and M. Tao, “Resource allocation with subcarrier pairing in OFDMA two-way relay networks,” *IEEE Wireless Commun. Lett.*, vol. 1, no. 2, pp. 61–64, Apr. 2012.

[238] Y. Zhao, R. Adve, and T. J. Lim, “Improving amplify-and-forward relay networks: Optimal power allocation versus selection,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 3114–3123, Aug. 2007.

[239] K. Bakanoglu, S. Tomasin, and E. Erkip, “Resource allocation for the parallel relay channel with multiple relays,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 792–802, Mar. 2011.

[240] *E-UTRA: Further advancements for E-UTRA physical layer aspects (Release 9)*, 3GPP Std. TR 36.814 (V9.0.0), Mar. 2010.

[241] *E-UTRA: Relay architectures for E-UTRA (LTE-Advanced) (Release-9)*, 3GPP Std. TR 36.806 (V9.0.0), 2010.

[242] M. Iwamura, H. Takahashi, and S. Nagata, “Relay technology in LTE-advanced,” *NTT DoCoMo Technical J.*, vol. 12, no. 2, pp. 29–36, 2010.

[243] Huawei, “Understanding on Type 1 and Type 2 relay, (TSG-RAN WG1 #57bis),” 3GPP, Los Angeles, USA, Tech. Rep. R1-092370, 2009.

[244] Y. Yang, H. Hu, J. Xu, and G. Mao, “Relay technologies for WiMax and LTE-advanced mobile systems,” *IEEE Commun. Mag.*, vol. 47, no. 10, pp. 100–105, Oct. 2009.

[245] C. Hoymann, W. Chen, J. Montojo, A. Golitschek, C. Koutsimanis, and X. Shen, “Relaying operation in 3GPP LTE: challenges and solutions,” *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 156–162, Feb. 2012.

[246] *E-UTRA: Relay radio transmission and reception (Release-11)*, 3GPP Std. TR 36.826 (V11.3.0), 2013.

[247] *E-UTRA: Relay radio transmission and reception (Release-11)*, 3GPP Std. TS 36.116 (V11.3.0), 2013.

[248] L. Chen, Y. Huang, F. Xie, Y. Gao, L. Chu, H. He, Y. Li, F. Liang, and Y. Yuan, “Mobile relay in LTE-advanced systems,” *IEEE Commun. Mag.*, vol. 51, no. 11, pp. 144–151, Nov. 2013.

[249] *Study on Mobile Relay for Evolved Universal Terrestrial Radio Access (E-UTRA) (Release-12)*, 3GPP Std. TR 36.836 (V2.0.2), 2013.

[250] Y. Yuan, *LTE-Advanced Relay Technology and Standardization*. Springer, 2013.

[251] *E-UTRA: Relay conformance testing (Release-11)*, 3GPP Std. TS 36.117 (V11.1.0), 2013.

[252] R. Zhang and L. Hanzo, “Wireless cellular networks,” *IEEE Veh. Technol. Mag.*, vol. 5, no. 4, pp. 31–39, Dec. 2010.

[253] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, “Interference coordination and cancellation for 4G networks,” *IEEE Commun. Mag.*, vol. 47, no. 4, pp. 74–81, Apr. 2009.

[254] S. W. Peters, A. Y. Panah, K. T. Truong, and R. W. Heath, “Relay architectures for 3GPP LTE-advanced,” *EURASIP J. Wireless Commun. Netw.*, vol. 2009, pp. 1–14, Mar. 2009. [Online]. Available: http://dx.doi.org/10.1155/2009/618787

[255] Q. Li, R. Hu, Y. Qian, and G. Wu, “Cooperative communications for wireless networks: techniques and applications in LTE-advanced systems,” *IEEE Wireless Commun. Mag.*, vol. 19, no. 2, pp. –, Apr. 2012.

[256] F. Boccardi, R. Heath, A. Lozano, T. Marzetta, and P. Popovski, “Five disruptive technology directions for 5G,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[257] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, and *et al.*, “Cellular architecture and key technologies for 5G wireless communication networks,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[258] J. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. Soong, and J. Zhang, “What will 5G be?” *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[259] T. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[260] F. Rusek, D. Persson, B. K. Lau, E. Larsson, T. Marzetta, O. Edfors, and F. Tufvesson, “Scaling up MIMO: Opportunities and challenges with very large arrays,” *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.

[261] Y. Pan, Q. Luo, G. Li, Y. Zhao, and Z. Xiong, “Performance evaluation of 3D MIMO LTE-Advanced system,” in *IEEE VTC2013 Fall*, Sep. 2013, pp. 1–5.

[262] Y.-H. Nam, B. L. Ng, K. Sayana, Y. Li, J. Zhang, Y. Kim, and J. Lee, “Full-dimension MIMO (FD-MIMO) for next generation cellular technology,” *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 172–179, June 2013.

[263] M. Wu, B. Yin, G. Wang, C. Dick, J. Cavallaro, and C. Studer, “Large-scale MIMO detection for 3GPP LTE: Algorithm and FPGA implementation,” *IEEE J. Sel. Topics Signal Process.*, vol. PP, no. 99, pp. 1–1, 2014.

[264] J. Hoydis, S. ten Brink, and M. Debbah, “Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 160–171, Feb. 2013.

[265] E. Larsson, O. Edfors, F. Tufvesson, and T. Marzetta, “Massive MIMO for next generation wireless systems,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[266] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[267] Z. Quan, S. Cui, H. Poor, and A. Sayed, “Collaborative wideband sensing for cognitive radios,” *IEEE Signal Process. Mag.*, vol. 25, no. 6, pp. 60–73, Nov. 2008.

[268] K. Letaief and W. Zhang, “Cooperative communications for cognitive radio networks,” *Proc. IEEE*, vol. 97, no. 5, pp. 878–893, May 2009.

[269] Y. Zou, Y.-D. Yao, and B. Zheng, “Cooperative relay techniques for cognitive radio systems: Spectrum sensing and secondary user transmissions,” *IEEE Commun. Mag.*, vol. 50, no. 4, pp. 98–103, Apr. 2012.

[270] X. Chen, H. Chen, and W. Meng, “Cooperative communications for cognitive radio networks: From theory to applications,” *IEEE Commun. Surveys Tuts.*, vol. PP, no. 99, pp. 1–13, 2014.

[271] J. Wang, M. Ghosh, and K. Challapali, “Emerging cognitive radio applications: A survey,” *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 74–81, Mar. 2011.

[272] M. Haddad, S. Elayoubi, E. Altman, and Z. Altman, “A hybrid approach for radio resource management in heterogeneous cognitive networks,” *IEEE J. Sel. Areas Commun.*, vol. 29, no. 4, pp. 831–842, Apr. 2011.

[273] J. Huang and V. Krishnamurthy, “Cognitive base stations in LTE/3GPP femtocells: A correlated equilibrium game-theoretic approach,” *IEEE Trans. Commun.*, vol. 59, no. 12, pp. 3485–3493, Dec. 2011.

[274] A. Attar, V. Krishnamurthy, and O. Gharehshiran, “Interference management using cognitive base-stations for UMTS LTE,” *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 152–159, Aug. 2011.

[275] J. Xiao, R. Hu, Y. Qian, L. Gong, and B. Wang, “Expanding LTE network spectrum with cognitive radios: From concept to implementation,” *IEEE Wireless Commun. Mag.*, vol. 20, no. 2, pp. 12–19, Apr. 2013.

[276] M. Matinmikko, M. Palola, H. Saarnisaari, and *et al.*, “Cognitive radio trial environment: First live authorized shared access-based spectrum-sharing demonstration,” *IEEE Veh. Technol. Mag.*, vol. 8, no. 3, pp. 30–37, Sep. 2013.

[277] S.-Y. Lien, K.-C. Chen, Y.-C. Liang, and Y. Lin, “Cognitive radio resource management for future cellular networks,” *IEEE Wireless Commun. Mag.*, vol. 21, no. 1, pp. 70–79, Feb. 2014.

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