Reconfigurable Software Defined Radio in 5G Mobile Communication Systems

An Open Source SDR-Based NOMA System for 5G Networks

Xiong Xiong, Wei Xiang, Kan Zheng, Hengyang Shen, and Xingguang Wei

Abstract

With the rapid advent of various new applications and services, the anticipated use of bandwidth and frequency resources is beyond expectation in future mobile networks. To maximize spectral efficiency, novel radio access techniques need to multiplex users in the most suitable combinations of frequency and radio resources. Non-orthogonal multiple access (NOMA) is one of the candidate radio access techniques for improving spectral efficiency in the 5G mobile network through multiplexing users in the power domain, which has never been explored in past and current communications systems. While the concept of NOMA was proposed several years ago, the performance of NOMA has only been verified in theory but not in practice. In this article, we first introduce the state of the art in open source SDR. Due to the high flexibility and reconfigurability of open source SDR, we choose general-purpose-processor-based SDR to implement our NOMA system, which is based on an open source LTE program. Over-the-air experiments are carried out on the designed NOMA system for the purpose of performance evaluation, and to demonstrate its potential in future 5G mobile networks.

Introduction

To meet the anticipated wireless traffic demands, mobile communications technology is evolving toward the fifth generation (5G) to improve on the performance of existing mobile networks. 5G mobile networks are positioned to provide much greater throughput, much lower latency, ultra-high reliability, much higher connectivity density, and higher mobility range [1]. One of the fundamental objectives of 5G is to achieve massive capacity improvements. There have been various techniques proposed for increasing system capacity in 5G networks, such as millimeter-wave (mmWave) [2], device-to-device (D2D) communications [3], massive multiple-input multiple-output (MIMO) [4], coordinated multipoint (CoMP), three-dimensional MIMO (3D MIMO), and filter-band multicarrier (FBMC) modulation, [5, 6]. Non-orthogonal multiple access (NOMA) is another promising technique for improving spectral efficiency and system capability, which is an intra-cell multi-user multiplexing scheme utilizing a new domain (i.e., the power domain). It is different from the existing multiple access techniques employed in past and current mobile networks, that is, time-division multiple access (TDMA) in 2G, code-division multiple access (CDMA) in 3G, and orthogonal frequency-division multiple access (OFDMA) in 4G systems. In the NOMA scheme, the signals of multiple users are multiplexed in the power domain at the transmitter side, and multi-user signal separation is realized via successive interference cancellation (SIC) at the receiver side. The application of NOMA to the downlink can achieve more than 30 percent gains in system spectral efficiency compared to orthogonal multiple access (OMA) schemes [7].

To further evaluate the performance of practical NOMA systems, software-defined radio (SDR) is resorted to as a flexible and inexpensive approach for rapid prototyping an NOMA design. The concept of SDR is to implement communications modules in software as much as possible in lieu of hardware. Building on open source software development, lots of SDR projects are being developed rapidly in an open source approach with the support of the open source developer community. In an open source SDR project, hardware schematic diagrams and/or software source codes are made openly available to the public. As such, open source SDR provides a flexible and cost-effective means of developing SDR applications, where every component of an SDR application can be tailor made. Thus, NOMA can easily be implemented based on open-source SDR.

To the best of the authors' knowledge, research on NOMA is still at its theoretical stage. There remain a lot of open challenges on practical NOMA implementation, which is the main interest of this article. Herein, we develop a downlink NOMA system using the OpenAirInterface (OAI)[1] program to explore the feasibility of practical NOMA deployment. Benefiting from the OAI program, the NOMA transmitter and receiver are designed and implemented based on the physical layer of the current Long Term

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[1] http://www.openairinterface.org/

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Evolution (LTE) specifications. Based on our developed NOMA prototype, some over-the-air experiments are also conducted to validate the feasibility of deploying NOMA in practical wireless communications systems.

The remainder of this article is organized as follows. We briefly discuss the state of the art in open source SDR techniques. Then we briefly present an application scenario of our proposed NOMA prototype. We elaborate on the system architecture and NOMA implementation in our proposed NOMA prototype system. Simulation and over-the-air experimental results carried out with this prototype are presented. Finally, concluding remarks are drawn.

State of the Art in Open Source SDR

With the rapid development of SDR technology in recent decades, a plethora of SDR systems have been developed by using different hardware: the field programmable gate array (FPGA), digital signal processor (DSP), and general-purpose processor (GPP) [8]. Compared to FPGA and DSP solutions, a GPP-based SDR system becomes appealing recently attributed to its striking advantage in flexibility and reconfigurability. SDR applications are easy to develop and upgrade on a GPP using high-level cross-platform programming languages, rather than hardware description languages. Reconfiguration can be achieved by reloading profiles, or modifying software and recompiling. Furthermore, lots of open source SDR projects are being developed on GPPs with the support of open source libraries, toolkits, and developer communities, which accelerate the development of SDR applications as well as reduce developing costs.

A typical GPP-based SDR system consists of a single piece of peripheral equipment and a GPP. The former is mainly responsible for frequency conversion and digitization. In [9, 10], various peripheral equipment is introduced in detail, among which the most common open source one is the universal software radio peripheral (USRP) family of devices from Ettus Research.[2] USRP devices can operate at a variety of carrier frequencies with high RF bandwidth, which is versatile for developing all kinds of SDR applications. The GPP is responsible for baseband signal processing. To simplify the development of SDR applications, some software frameworks have been designed and implemented to provide a programming environment for developers [9, 10]. Moreover, an SDR application can be executed more efficiently with the aid of software frameworks. The GNU Radio project[3] is regarded as the most widespread open source real-time signal processing framework, which can operate completely compatibly with USRP. GNU Radio has a set of signal processing tools and provides a library of signal processing functional blocks for streamlining the development of SDR applications.

Many SDR applications have been developed in recent years. For example, a time-division synchronous code-division multiple access (TD-SCDMA)-based SDR system is implemented with USRP and GNU Radio for 4G research [11]. Also, three SDR-based LTE programs are considered as potential platforms for performance assessment of 5G candidate techniques (Amari LTE 100,[4] OpenLTE,[5] and OAI). However, only the OAI program is a full open source implementation of the entire LTE protocol stack from the physical (PHY) layer to the network layer, and comprises all the components of the LTE system, such as the user equipment (UE), evolved Node B (eNB), and enhanced packet core (EPC) [12].

Application Scenario of the NOMA Prototype System

Unlike current OMA schemes, the essential idea behind NOMA is superposition encoding and SIC [13]. The power domain is utilized by NOMA to multiplex multiple UEs. NOMA is considered as a potential radio access technology to improve system capability and spectral efficiency. Moreover, NOMA schemes are very compatible with the current LTE protocols.

In this section, we present the design of an experimental NOMA system using open source SDR, especially the OAI program thanks to its fully implemented PHY layer. The PHY layer of OAI supports many features compatible with the standard LTE specifications, including different system bandwidths, different modulation schemes, all physical channels and transport channels on the downlink (DL) and uplink (UL), and so on. To enhance its real-time performance, the PHY layer of the OAI program is highly optimized using C language with the streaming single instruction multiple data (SIMD) extensions (SSE) instruction sets on a low-latency Linux operation system, which can be used for simulations and/or real-time experimentation in conjunction with some hardware platforms including the USRP.

The proposed NOMA prototype system is deployed in a typical DL two-user paired scenario [13] to operate in the single-input single-output (SISO) mode, as shown in Fig. 1. The process procedures of the NOMA scheme on the eNB and UE are both added to OAI's PHY layer. At the eNB side, the transmit signals of two paired UEs are superimposed and transmitted on the same time and frequency resources. The two paired UEs are multiplexed in conformity with their respective signal powers. At the receiver side, the superimposed signal from the two users can be separated and decoded using SIC techniques. To ensure successful SIC, the signal powers of the two paired UEs should be allocated according to their channel gains [13]. That is, the UE with a higher channel gain is allocated less power, whereas the UE with a lower channel gain is allocated more power. In the following sections, it is assumed that UE1 is located closer to the eNB with a higher channel gain, and UE2 is located further away from the eNB with a lower channel gain, as shown in Fig. 1. Due to the power difference, the signal designated to UE2 can be decoded and reconstituted by the SIC receiver in UE1, and then the received UE1 signal can be decoded by canceling the reconstituted UE2 signal. At the UE2 receiver, the signal designated to UE2 is decoded through treating the UE1 signal as noise.

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[2] http://www.ettus.com/

[3] https://www.gnuradio.org/

[4] http://www.amarisoft.com/

[5] http://sourceforge.net/projects/openlte/

Multitask scheduling is crucial for real-time signal processing. Because a running SDR process may be interrupted by a context switch, it should be given the highest scheduling priority. To attain better real-time performance, GNU/Linux with low-latency patches is required by the OAI program.

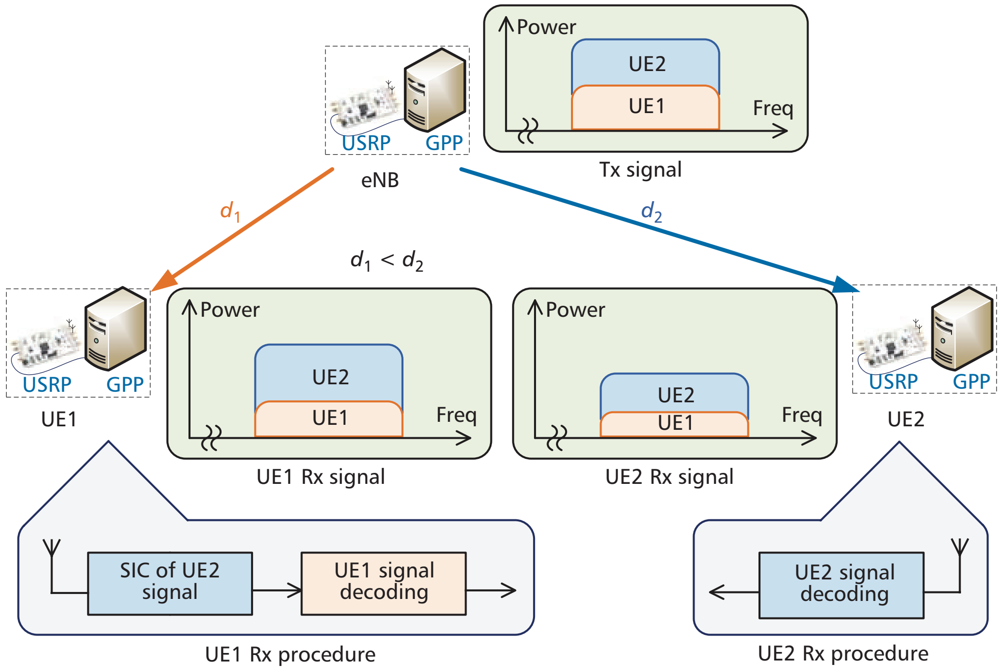

Figure 1. The deployment scenario of two-UE NOMA in downlink.

Implementation of an Open Source SDR-Based NOMA System

System Architecture

The system architecture of the proposed NOMA prototype system is illustrated in Fig. 2a. In what follows, we elaborate on the two aspects of this NOMA architecture (i.e., hardware and software).

Hardware: The system hardware is composed of a USRP and a GPP. To maintain backward compatibility with the LTE system, the USRP B200 is selected as the peripheral equipment due to its 61.44 MHz sampling rate, which is a multiplier of all the sampling rates defined in Third Generation Partnership Project (3GPP) LTE specifications. This helps reduce the complexity of baseband signal processing in the GPP. Moreover, the USPR B200 can operate on all LTE frequency bands and is fully supported by OAI.

The USRP B200 consists of four key components, as illustrated in Fig. 2a: the RF front-end, the analog-to-digital converter (ADC)/digital-to-analog converter (DAC), the FPGA module, and the interface. The RF front-end is mainly responsible for frequency conversion and RF band selection, and operates in the analog domain. On the receive path, the RF signal received from the antenna is selected by a band-pass filter and amplified by a low-noise amplifier (LNA). It is then down converted to the baseband using a mixer and a local oscillator (LO). Then the ADC digitizes the baseband signal, and passes the digital baseband signal to the FPGA module for further processing. Since only a discrete set of frequencies can be generated by the LO synthesizer, the baseband signal cannot be precisely tuned to zero frequency at the previous mixing stage in the RF front-end. Thus, a second mixing stage is necessary and realized with the FPGA module using a digital down converter (DDC), which removes any residual frequency offset and shifts of the digital signal. Moreover, decimation is carried out in the DDC to reduce the sampling rate without violating the Nyquist criterion, reducing the complexity of further processing in the GPP. Finally, the digital baseband signal is transferred to the GPP via a USB 3.0 interface.

On the other hand, the transmit path operates in reverse to the receive path. The SDR application generates the digital baseband signal in the GPP, which is then transferred to the USRP via the interface. After digital frequency conversion and interpolation using a digital up converter (DUC), the digital signal is converted to an analog one by the DAC, and then up converted to the target RF frequency.

Software: All baseband signal processing of the NOMA system is realized in software. The essential software component of the GPP is the operation system (OS). The OS provides a basic programming environment for developing SDR applications, which provides system functions such as interrupts handling, memory management, and multitask scheduling. Multitask scheduling is crucial for real-time signal processing. Because a running SDR process may be interrupted by a context switch, it should be given the highest scheduling priority. To attain better real-time performance, GNU/Linux with low-latency patches is required by the OAI program.

Building on the OS, a large variety of open source software libraries and toolkits can be utilized for developing SDR applications. Among them, the USRP hardware driver (UHD)[6] is an indispensable software component. The UHD is a hardware driver for all USRP devices, pro-

[6] http://ettus-apps.sourcerepo.com/redmine/ettus/projects/uhd/wiki

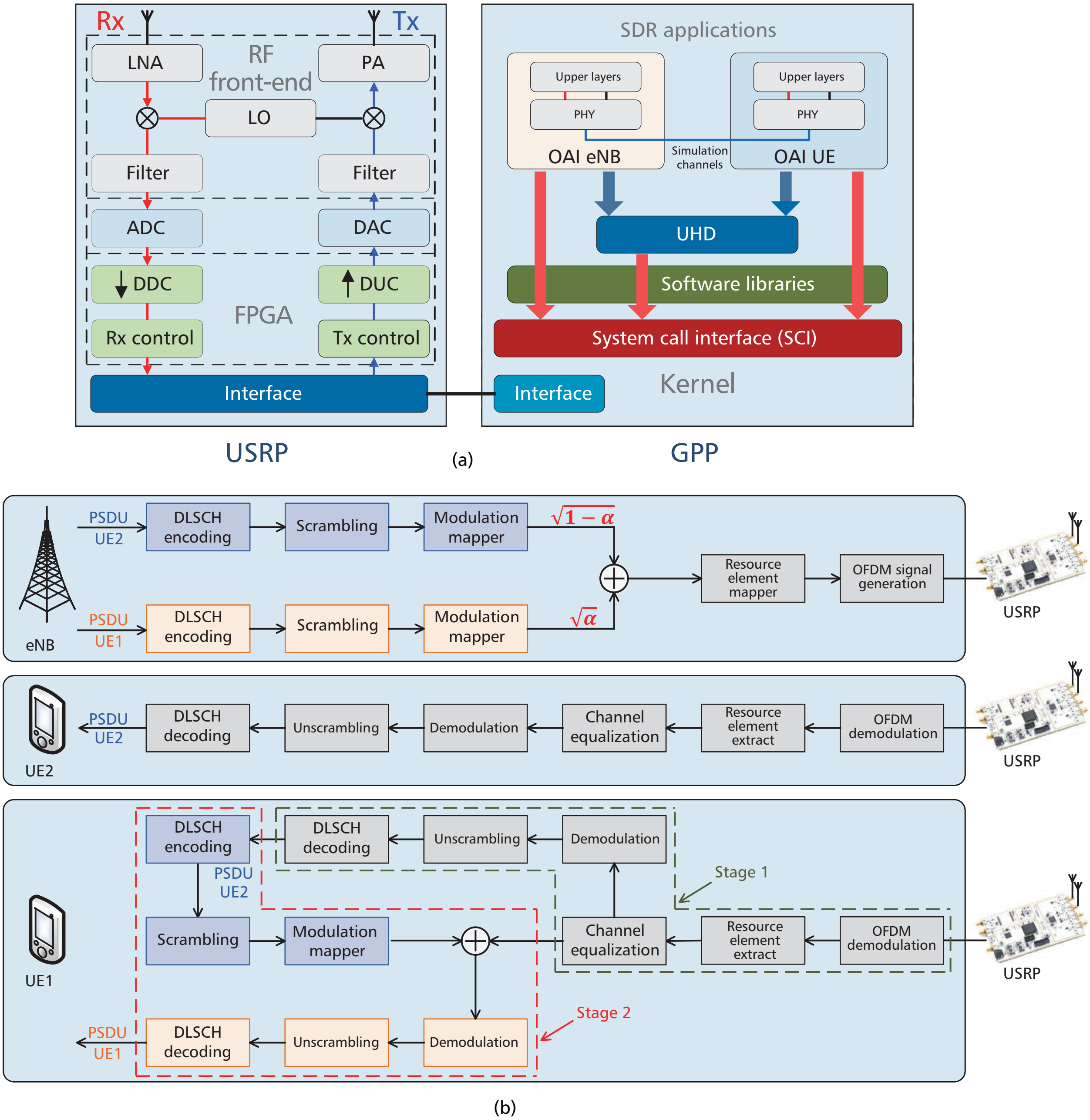

Figure 2. NOMA implementation based on open source SDR: a) open source SDR-based NOMA system architecture; b) process diagrams of the NOMA transmitter at the eNB side and the NOMA receiver at the UE side.

viding a series of application program interfaces (APIs) for SDR developers to control USRPs. These APIs offer numerous functions, such as frequency tuning, RF bandwidth setting, and data transmit/receive. This demonstrates the flexibile and reconfigurable capabilities of SDR technology.

With the support of the OS, UHD, and other software libraries, the OAI program can be compiled and executed as the eNB or UE with different configuration parameters. Although OAI provides a full implementation of the LTE stack, only the PHY layers at the eNB and UE sides are utilized in our NOMA implementation. Currently, three process threads are employed in the UE software architecture for all the procedures of the PHY layer. One thread is responsible for the DL procedures of the PHY layer, and another one processes the UL procedures. The third process thread is responsible for synchronization and data exchange with the USRP and scheduling the other two threads every subframe (i.e., 1 ms). Thus, the DL procedures at the UE must be completed within 1 ms or the next subframe cannot be processed. This poses a big challenge to the real-time implementation of the NOMA receiver due to the serial processing of SIC. On the other hand, the superposition encoding at the eNB does not cause a significant increase in complexity, which can be realized with the current eNB software architecture.

	Item	Value
Hardware	USRP	Ettus Research USRP B200
	CPU	Intel(R) Xeon(R) CPU E5-1620 v2 @ 3.70 GHz
Software	OS	64-bit Ubuntu 14.04 LTS with low-latency kernel 3.17.0
	UHD	Version 3.8.0
	OAI	Version trunk 7528
Parameter	Duplex mode	FDD
	Transmission mode SISO	System bandwidth 5 MHz
	Carrier frequency	DL 2.66 GHz (band 7)
	Power allocation factor α	0.25, 0.15
	Modulation scheme	UE1: QPSK, 16-QAM, 64-QAM UE2: QPSK
	Channel estimation	Least square (LS) estimation
	Channel coding/decoding	Turbo coding/Max-Log-MAP decoding (four iterations)
	DCI format	Format 1

Table 1. System configuration.

NOMA Implementation

To simplify the NOMA implementation, two UEs are paired manually and assigned the same radio network temporary identity (RNTI), which is used for CRC attachment of downlink control information (DCI) coding processing in the physical downlink control channel (PDCCH). Therefore, the two paired UEs can decode the same DCI and extract the resource block (RB) assignment information, which indicates the RBs bearing the physical downlink shared channel (PDSCH). Then the superimposed traffic data transmitted over the PDSCH can be decoded by each UE seperately. The baseband signal processing of the NOMA system is mainly implemented on the downlink shared channel (DLSCH) and PDSCH at both the eNB and UE sides, as illustrated in Fig. 2b.

Along the transmit path of the eNB, the physical service data units (PSDUs) of the two paired UEs are processed separately in three sections: DLSCH encoding, scrambling, and the modulation mapper. In the DLSCH encoding section, the PSDUs are processed by code block segmentation, turbo encoding, and rate matching in sequence. After the modulation mapper section, the scrambled bits are mapped into a constellation. Then, transmit powers are allocated for the two UEs with two different power allocation factors, i.e., α for UE1, and 1 – α for UE2. The modulated signal of each UE is multiplied by the square root of its respective power allocation factor. According to the UE location assumption mentioned earlier, UE1 should be allocated less power, and the power allocation factor α ranges from 0 to 0.5. After power allocation, the symbols of the two UEs are superimposed and mapped to the same RBs according to the indication of the DCI transmitted on the PDCCH. Finally, the superimposed signal is modulated to OFDM symbols and then transmitted by the USRP.

Based on our power allocation assumption, the PDSCH process procedures in the receive path of the two UEs are different. The UE2 receiver directly decodes the received superimposed signal as the original OAI UE receiver, which treats the interference from the signal designated for UE1 as noise. Different from the UE2 receiver, a codeword-level SIC receiver is implemented in the UE1 receive path due to its better performance than symbol-level SIC [14, 15]. At first, the UE1 receiver decodes the received superimposed signal the same as the UE2 receiver. With an appropriate selection of α, the PSDU of UE2 can be decoded successfully. Then the decoded PSDU of UE2 is encoded and modulated into symbols again through the same processes as in the transmit path of UE2 at the eNB side (i.e., DLSCH encoding, scrambling, and the modulation mapper). Thus, the UE2 signal is reconstituted and then canceled from the received signal after channel equalization. After interference cancellation, the receiver can demodulate and decode the signal intended for UE1.

Experimental Results and Discussions

System Configuration

The proposed NOMA system is implemented in a general-purpose computer in conjunction with Ettus Research USRP B200. The CPU model of the general purpose computer is Intel Xeon CPU E5-1620 v2, which has four physical cores supporting hyper-threading, and operates at a maximum clock frequency of 3.7 GHz. It is considered to be capable of providing sufficient computational power for our NOMA implementation. As for the OS, 64-bit Ubuntu 14.04 patched with a low-latency kernel is used, which can provide preemptive scheduling.

In our experiments, the NOMA system operates in the frequency-division duplexing (FDD) duplex mode and the SISO transmission mode. The DL carrier frequency is 2.66 GHz (band 7), and the system bandwidth is 5 MHz. UE2 only employs quadrature phase shift keying (QPSK) modulation, while QPSK, 16-quadrature amplitude modulation (QAM), and 64-QAM modulation schemes are employed in UE1. The other common system parameters used in our experiments are summarized in Table 1.

Experimental Results

Both simulations and experiments are carried out to evaluate the performance and feasibility of the proposed NOMA system.

Simulation: NOMA is first implemented on a unitary link-level simulator of the OAI program for the DLSCH and PDSCH at the PHY layer, which is conducted in a computer without the

USRP. Most system parameters are configured as shown in Table 1. Besides, two channel models are used in the simulation: additive white Gaussian noise (AWGN) and Rayleigh. The block error rate (BLER) of UE1 is chosen as the metric to evaluate the performance of NOMA. The signal-to-noise ratio (SNR) ranges from 0 to 40 dB, and the simulation terminates when the BLER is below 1 percent or 1000 frames are completed. Figure 3 plots the simulation results of two power allocation schemes in the NOMA implementation, where the power allocation factor α is set to 0.25 and 0.15.

As can be seen from the simulation results, there is around 2 dB difference between the two power allocation schemes. This is because the two power allocation factors give rise to different inter-user interference, which impacts on the performance of the SIC receiver at UE1. Besides, the performance of the UE1 receiver is also affected by the adopted modulation scheme, since a higher order modulation scheme is less susceptible to interference and noise. To employ NOMA in a practical network, the power allocation factor and the modulation scheme should be selected in accordance with the channel quality. One possible solution is to add some additional signaling to the adaptive modulation and coding (AMC) procedure of the current LTE specifications. For example, the eNB may distribute the transmit power of different UEs dynamically based on their channel quality indicator (CQI). Then the power allocation factor can be transmitted to the UEs in a new format of DCI on the PDCCH.

Offline Experimentation: Since our current NOMA implementation has not been sufficiently opti. mized, UE1 cannot operate with all the modulation schemes in real time for the SIC process. Thus, an offline experiment is considered as a compromised method for evaluating the over-the-air performance of NOMA.

In the offline experiment, two pairs of computers and USPRs are utilized to act as the eNB and UE1, respectively. At first, the NOMA simulator generates the superimposed symbols of UE1 and UE2, which are then dumped to a file. The superimposed symbols are read from the file at the eNB and transmitted over the air with the aid of the USRP. Next, the UE1 receives the DL RF signal transmitted from the eNB. After channel equalization, UE1 dumps both the equalized signal and the channel information into files, which are further utilized and decoded in the receive path of the NOMA simulation program. Therefore, the performance of NOMA can be evaluated in a real channel instead of the theoretical AWGN and Rayleigh channels.

The main system parameters are configured as shown in Table 1. Besides, the transmit power of the eNB is fixed to around 10 dBm, limited primarily by the RF capability of the USRP. UE1 is located about 2 m away from the eNB in an indoor environment. The power allocation factor is set to only 0.25. Figure 4 shows the constellation of the received signal at different positions in the UE1 receive path with various modulation schemes.

When QPSK modulation is employed by UE1,

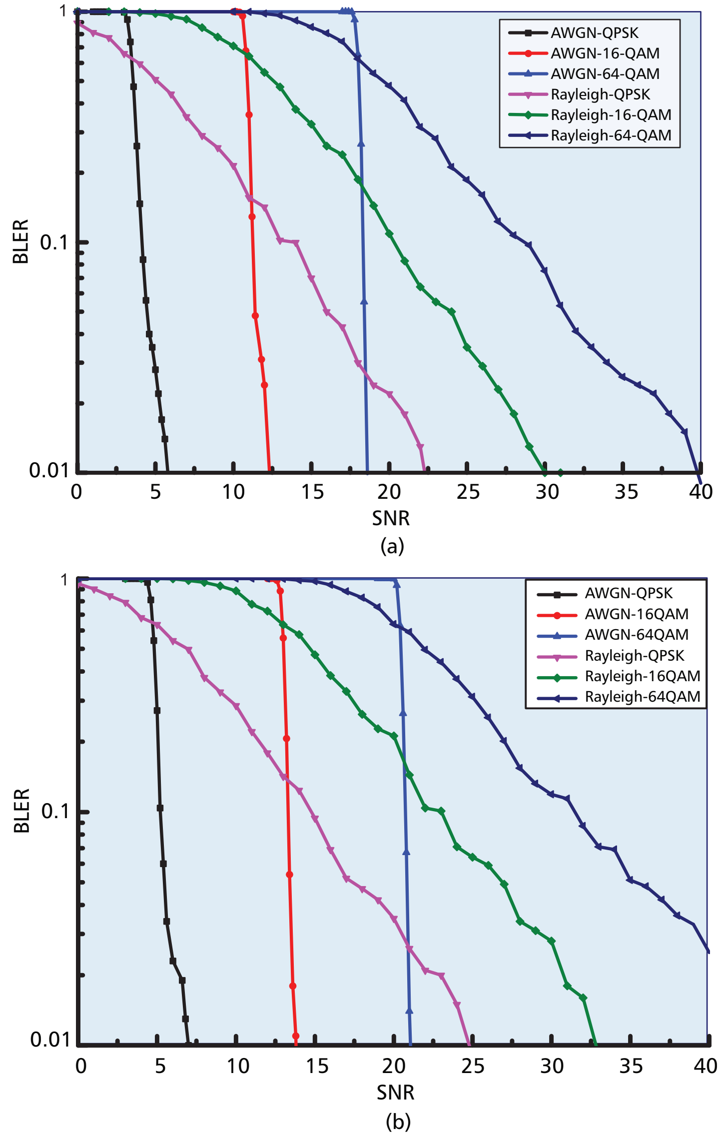

Figure 3. BLERs of UE1 with two different power allocation factors and modulation schemes under the AWGN and Rayleigh channels: a) power allocation factor α = 0.25; b) power allocation factor α = 0.15.

the constellation of the superimposed signal after channel equalization is shown in Fig. 4a, which is similar to the 16-QAM constellation. Then the remaining SIC procedures decode the equalized superimposed signal and reconstruct the UE2 signal successfully. Figure 4b plots a QPSK signal constellation after interference cancellation. Thus, the signal intended for UE1 can be further decoded through the following processes in the receiver. The SIC receiver can also decode the PSDU intended for UE1 correctly when using 16-QAM modulation, and the constellation diagrams after channel equalization and interference cancellation are shown in Figs. 4c and 4d, respectively. When UE1 employs 64-QAM modulation, Fig. 4e shows the constellation of the superimposed signal after channel equalization, while Fig. 4f shows the constellation after interference cancellation. Although these two constellation diagrams seem scattered, the SIC receiver can decode the PSDU intended for UE2 and reconstitute the UE2 signal. However, the remaining procedures after interference cancellation cannot finally decode the UE1 PSDU.

The offline experimental results demonstrate the feasibility of deploying NOMA in a practical wireless environment. Moreover, the performance of the SIC receiver degrades with an increasing modulation order employed by UE1 under almost the same wireless environment, which is in conformity with the simulation results.

Real-time Experimentation — One of the most crucial challenges for implementing a practical NOMA system is the complexity of the SIC receiver. All processes in the SIC receiver are carried out in sequence without proper parallelism, resulting in increased processing time. Thus, an experiment

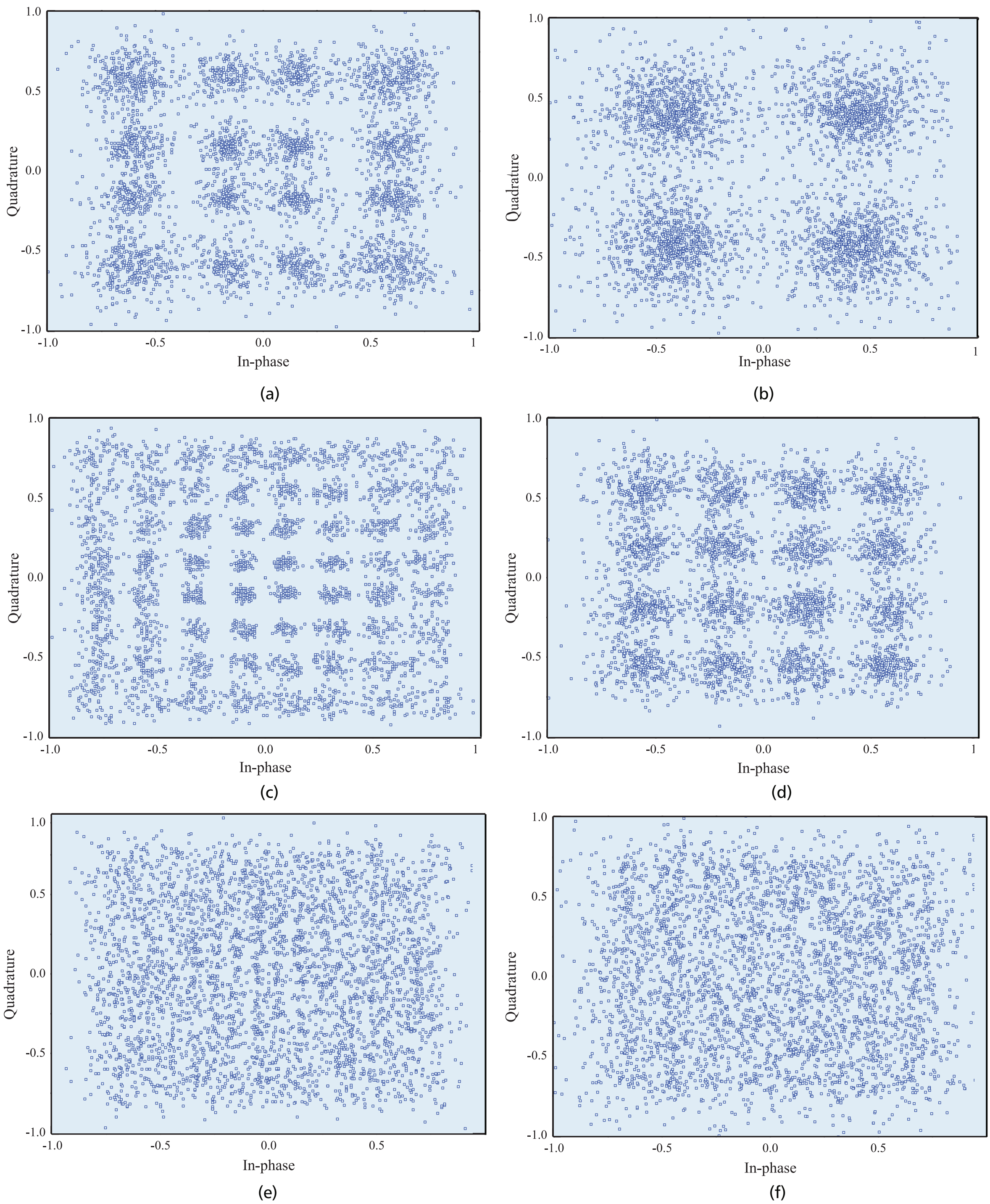

Figure 4. Signal constellation diagrams after channel equalization and interference cancellation with various modulation schemes: a) after channel equalization with QPSK; b) after interference cancellation with QPSK; c) after channel equalization with 16-QAM; d) after interference cancellation with 16-QAM; e) after channel equalization with 64-QAM; f) after interference cancellation with 64-QAM.

is conducted to evaluate the real-time performance of the SIC receiver.

In this experiment, the NOMA system is deployed in the same scenario as that of the former offline experiment with the same system configuration. Different from the offline experiment, the eNB superim.poses the transmit signals of two paired UEs without reading the dump file generated from the NOMA simulation program, while UE1 employs the SIC receiver and calculates the time consumption of each processing stage in the SIC receiver. Moreover, the experiment also evaluates the real-time performance of the NOMA system under different system bandwidths (i.e., 5 MHz, 10 MHz, and 20 MHz). The experiment results are shown in Table 2.

The time consumption of the SIC receiver is composed of three parts: the time for stage 1, the time for stage 2, and the grand total. The two stages are depicted in Fig. 2b. Stage 1 operates the same as the UE receiver in the original OAI program, while some additional processes are carried out in stage 2, such as UE2 signal reconstruction, interference cancellation, and UE1 decoding. As can be observed from the third column of Table 2, stage 1 consumes more time with the increase of the system bandwidth and modulation order. Notwithstanding, the time consumption of stage 1 is no more than 0.554 ms (less than 1 ms), which indicates that the original OAI UE receiver is capable of operating in real time. However, the total time consumption of the SIC receiver is several times more than that of stage 1 due to the additional procedures of stage 2. When UE1 operates at 10 MHz with 64-QAM or 20 MHz with any modulation scheme, the total time consumption is more than 1 ms, as shown in the fifth column of Table 2. Under these system configurations, the SIC receiver in UE1 is unable to execute in real time. Thus, the implementation of our NOMA system needs to be further optimized to enhance its real-time performance.

System bandwidth	Modulation scheme of UE1	Stage 1 (ms)	Stage 2 (ms)	Total time (ms)
5 MHz	QPSK	0.152	0.198	0.35
	16-QAM	0.15	0.305	0.455
	64-QAM	0.15	0.468	0.618
10 MHz	QPSK	0.298	0.388	0.686
	16-QAM	0.291	0.609	0.9
	64-QAM	0.298	0.73	1.028
20 MHz	QPSK	0.556	0.791	1.347
	16-QAM	0.563	1.252	1.815
	64-QAM	0.554	1.311	1.865

Table 2. Time consumption of the SIC receiver.

Conclusions and Outlook

NOMA is a candidate radio access technique for improving spectral efficiency and system capability in future 5G mobile networks, which multiplexes UEs in the power domain, which has never been exploited in current mobile networks. Based on existing open source SDR-based LTE platforms, NOMA systems can easily be implemented due to the flexibility and reusability of open source SDR. We first introduce the state of the art in open source SDR, followed by the design and implementation of our NOMA system based on the OAI software. Then the results of several experiments carried out with our developed NOMA system to evaluate the performance of NOMA in a practical environment are presented. Our link-level simulations show that the power allocation factor and the modulation scheme for UEs significantly affect the performance of the SIC procedure in the UE receive path, which should be distributed dynamically according to channel quality. Furthermore, our offline experiments validate the feasibility of applying NOMA in a practical wireless environment.

For future work, the implementation of our NOMA system will be optimized to enhance its real-time performance. Moreover, we will design a new power allocation scheme at the eNB based on the CQI reports from UEs, and also design a new DCI format compatible with the AMC procedure in current LTE networks. Toward this end, more tests need to be conducted to further validate the real-time performance of the developed NOMA system with dynamic power allocation in practical wireless environments.

Acknowledgment

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References

[1] METIS, "Scenarios, Requirements and KPIs for 5G Mobile and Wireless System (deliverable D1.1)," May 2013.

[2] K. Zheng *et al.*, "10 Gb/s HetSNets with Millimeter-Wave Communications: Access and Networking — Challenges and Protocols," *IEEE Commun. Mag.*, vol. 53, no. 1, Jan. 2015, pp. 222–31.

[3] L. Lei *et al.*, "Performance Analysis of Device-to-Device Communications with Dynamic Interference Using Stochastic Petri Nets," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, Dec. 2013, pp. 6121–41.

[4] K. Zheng *et al.*, "Survey of Large-Scale MIMO Systems," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 3, 3rd qtr. 2015, pp. 1738–60.

[5] Z. Su *et al.*, "A Novel Design for Content Delivery Over Software Defined Mobile Social Networks," *IEEE Network*, vol. 29, no. 4, July 2015, pp. 62–67.

[6] M. Chen *et al.*, "EMC: Emotion-Aware Mobile Cloud Computing in 5G," *IEEE Network*, vol. 29, no. 2, Mar./Apr. 2015, pp. 32–38.

[7] Y. Saito *et al.*, "System-Level Performance Evaluation of Downlink Non-Orthogonal Multiple Access (NOMA)," *Proc. IEEE Annual Symp. Personal, Indoor and Mobile Radio Communications*, London, U.K., Sept. 2013, pp. 1–5.

[8] T. Ulversoy, "Software Defined Radio: Challenges and Opportunities," *IEEE Commun. Surveys & Tutorials*, vol. 12, no. 4, 4th qtr. 2010, pp. 531–50.

[9] M. Dardaillon *et al.*, "Cognitive Radio Programming: Existing Solutions and Open Issues," Inria Research Report, Sept. 2013, pp. 27–51.
[10] P. Pawelczak *et al.*, "Cognitive Radio: Ten Years of Experimentation and Development," *IEEE Commun. Mag.*, vol. 49, no. 3, Mar. 2011, pp. 90–100.
[11] K. Zheng *et al.*, "Beyond 3G Evolution," *IEEE Vehic. Tech. Mag.*, vol. 3, no. 2, June 2008, pp. 30–36.
[12] N. Nikaein *et al.*, "OpenAirInterface: A Flexible Platform for 5G Research," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 44, no. 5, Oct. 2014, pp. 33–38.
[13] Y. Saito *et al.*, "Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access," *IEEE VTC-Spring*, Dresden, Germany, June 2013, pp. 1–5.
[14] K. Saito *et al.*, "Link-Level Performance of Downlink NOMA with SIC Receiver Considering Error Vector Magnitude," *IEEE VTC-Spring*, Glasgow, Scotland, May 2015, pp. 1–5.
[15] C. Yan *et al.*, "Receiver Design for Downlink Non-Orthogonal Multiple Access (NOMA)," *IEEE VTC-Spring*, Glasgow, Scotland, May 2015, pp. 1–6.

Biographies

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