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Implementation of a 6 GHz band TDD RF transceiver for the next generation mobile communication system

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Abstract: The development of a high performance wideband radio frequency (RF) transceiver used in the next generation mobile communication system is presented. The developed RF transceiver operates in the 6 to 6.3 GHz band and the channel bandwidth is up to 100 MHz. It operates in the time division duplex (TDD) mode and supports the multiple-input multiple-output (MIMO) technique for the international mobile telecommunications (IMT)-advanced systems. The classical superheterodyne scheme is employed to achieve optimal performance. Design issues of the essential components such as low noise amplifier, power amplifier and local oscillators are described in detail. Measurement results show that the maximum linear output power of the RF transceiver is above 23 dBm, and the gain and noise figure of the low noise amplifier is around 24 dB and below 1 dB, respectively. Furthermore, the error vector magnitude (EVM) measurement shows that the performance of the developed RF transceiver is well beyond the requirements of the long term evolution (LTE)-advanced system. With up to 8 × 8 MIMO configuration, the RF transceiver supports more than a 1 Gbit/s data rate in field tests.

Key words: radio frequency (RF) transceiver; orthogonal frequency division multiplexing (OFDM); IMT-advanced system; phase noise; low noise amplifier; power amplifier; LTE-advanced system

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The successes of 3G mobile communication systems around the world as well as the popularity of data hungry applications such as personal video online-sharing, brighten the prospects of 4G systems in the future which can provide much more data bandwidths to end users. Today the so-called 4G mobile communication system (or the next generation mobile communication system) usually refers to the international mobile telecommunications (IMT)-advanced system proposed by the International Telecommunication Union (ITU). An IMT-advanced system is expected to provide users robust and high speed data services which support more than 1 Gbit/s in low mobility[1]. To achieve the required data rate, one method is to allocate more spectrum resources which is difficult in frequency bands below 2 GHz where so many applications are overcrowded. Fortunately it is easier to find more spectrum resources in higher frequency band and some systems have been designed to meet the requirements of the IMT-advanced system in 3.5 GHz band[2-3]. In the field of wireless LAN, IEEE 802.11ac in the 5 GHz band and applications in the unlicensed 60 GHz band have been popular recently[4]. The RF transceiver reported in this paper is designed for an experimental wireless network aiming to seek the probability of establishing an IMT-advanced system in the 6 GHz band with a channel bandwidth up to 100 MHz. According to the knowledge of the authors, this is the first attempt in this frequency band.

Instead of the incredible user experiences brought by the next generation technologies, they do bring great challenges to engineers. As an important part of the system, the new air interface evolving from the beyond 3G systems such as 3GPP long term evolution (LTE) needs to be carefully studied to gain better performance at a reasonable cost. In addition to the required bandwidth which is much wider in an IMT-advanced system, the most significant change in the new air interface is the utilization of orthogonal frequency division multiplexing (OFDM) and its nature makes the system more sensitive to frequency offset and phase noise[5-6]. Moreover the high peak-to-average power ratio (PAPR) of the OFDM signal makes it difficult to realize a power amplifier with high efficiency and high linearity. Other RF impairments such as carrier leakage and I/Q image which are common to other single carrier systems should also be addressed in the design process of a high performance RF transceiver.

In this paper, the design of a high performance RF transceiver is reported, which operates in the 6 to 6.3 GHz band with a channel bandwidth up to 100 MHz. The system scheme as well as design issues and measurement results of the essential components are introduced in detail. Because the LTE-advanced system has been considered as a candidate for the IMT-advanced system, the simulations and measurements in this paper all refer to

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3GPP Release 10. The measurement results indicate that the performance of the realized RF transceiver is well beyond the requirements of the LTE-advanced system.

1 System Architecture

To boost the performance of the 6 GHz band RF transceiver, the classical superheterodyne scheme is employed and the block diagram is illustrated in Fig. 1. One of the most important procedures to realize a qualified superheterodyne transceiver is careful frequency planning which can lessen the requirement of the filters and make the system realizable and robust to interferences. Considering the channel bandwidth of 100 MHz and the working frequencies above 6 GHz, there are some restrictions on the selection of the intermediate frequency (IF). First, the design of a high selectivity and low distortion IF filter usually requires a reasonable relative bandwidth, so the IF should be above 1 GHz. Secondly, due to the complexity and cost of realizing a high performance local oscillator (LO) at a higher frequency, a low side LO is chosen which is different from the cases in some low frequency designs. The above restrictions make the spurs crowd around the working frequency band. Among these spurs, more attention should be paid to some low order intermodulation (IM) products, because these low order spurs locate near the pass-band of the IF filters in the receiver or the RF filter in the transmitter, while the levels of them are relatively large. There are some useful tools to assist the engineers in the frequency planning process such as a classical spurs chart and its extension[7], distances chart[8] and some EDA tools. It should be aware that the prediction of spurs levels in these tools is based on the mixer spurs tables provided by the manufacturers. These spurs tables are usually measured at a low IF, for example below 100 MHz, so it is necessary to obtain the new spurs tables of a high IF from measurements in the design process, at least the levels of the low order spurs should be identified. Eventually the IF is set at 1.85 GHz.

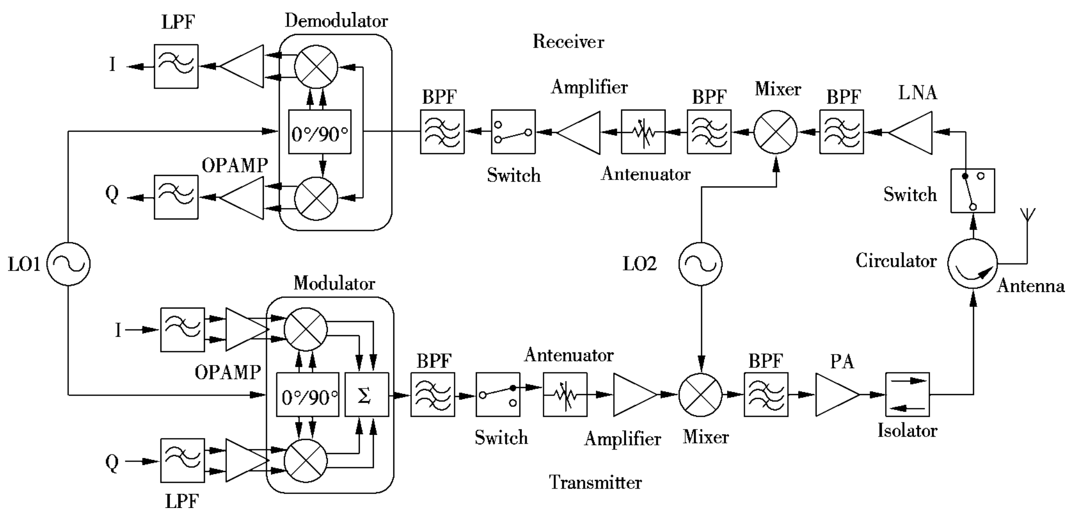

Fig. 1 System block diagram of the reported RF transceiver

The input and output of the reported RF transceiver are analog baseband I/Q signals. In the transmitter part, the unbalanced I/Q signals are converted to differential ones and fed to the quadrature modulator by a differential operational amplifier for the benefits of better common mode rejection and the minimization of the transmitter carrier leakage as well as the even order harmonics of the modulator. After the band-pass filter, an RF switch is utilized to improve the power-off transient response and minimize the power-off power transmitted. The power control is implemented in the IF block using digital control attenuators which provide a sufficient dynamic range. After upconversion by the passive mixer, the image signal and other unwanted spurs are filtered by a band-pass filter. Then the power is boosted by the succeeding power amplifiers, and the resulting RF signal is circulated to the antenna and transmitted.

Along the receiver path, the RF signal received is fed to the switch through the circulator. The switch together with the circulator can provide enough isolation between the transmitter and the receiver. After being amplified by the LNA, the RF signal is filtered by a band-pass filter. Thus the RF image and other interferences out of the band are reduced, and the spurs radiation level of the receiver is minimized as well. The channel selectivity is guaranteed by two IF DR (dielectric-resonator) band-pass filters, the first of which is placed right after the passive mixer to suppress the LO leakage and other IM products. The automatic gain control (AGC) is implemented using two digital control attenuators, each of which provides more than a 30 dB control range with a 0.5 dB step. Finally, the IF signal is demodulated and the resulting differential I/Q analog baseband signals are buffered and converted to single-ended I/Q outputs.

2 Design of the Transceiver

To achieve the high end performance requirements of the IMT-advanced system, the reported RF transceiver utilizes multiple-input multiple-output (MIMO) technique and supports up to an 8 × 8 MIMO configuration. The design issues of the receiver and the transmitter in each channel of the RF transceiver are presented as follows.

2.1 Design of the receiver

2.1.1 Low noise amplifier

It is well known that the overall noise figure (NF) of the receiver is determined by the LNA which is usually employed at the front of the RF block to amplify the received weak signal and introduces less noise than other amplifiers. In the reported RF transceiver, the LNA is designed to provide a power gain of more than 20 dB in two stages and each stage employs a high electron mobility transistor (HEMT) which has such advantages as noise and gain especially in high frequency[9]. Simulations are carried out to optimize the design of the impedance matching network and to ensure the stability of the LNA. The fabricated LNA in the transceiver is shown in Fig. 2 and the measured results are shown in Fig. 3. The measurement results indicate that the NF of the LNA is below 1 dB and the gain is around 24 dB with a ripple of 0.3 dB across the desired frequency range. To support the TDD operation, a circulator and a switch are placed right before the LNA, and thus the noise figure of the whole receiver is increased slightly.

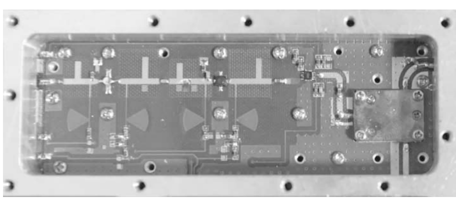

Fig. 2 Photo of the fabricated LNA

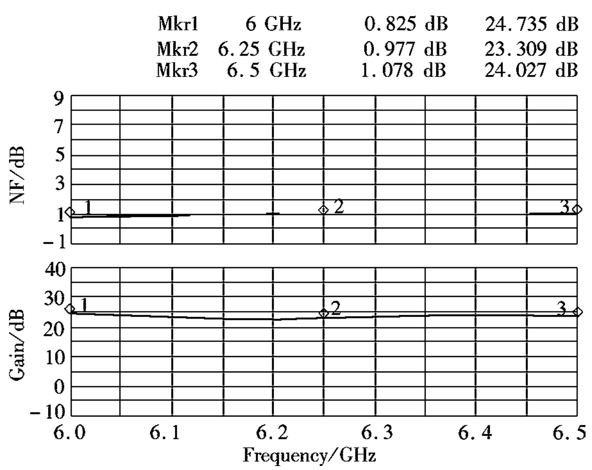

Fig. 3 Measured NF and gain of the LNA

2.1.2 Link budget of the receiver

The output level of the receiver is required to be around1 V (peak to peak). Then the optimum level of the IF signal fed into the demodulator is determined because the gain of the demodulator and the baseband circuits are all fixed in our design. Based on the optimum level of the IF signal before the demodulator, the link budget of the receiver is simulated and optimized. The final gain distributions of the RF and IF blocks are shown in Tab. 1.

Tab. 1 The link budget of the receiver

Key component	NF/dB	Gain/dB	IIP3/dBm
Circulator	0.5	-1	50
Switch	1	-1	45
LNA	1	24	5
RF filter	2	-2	>50
Mixer	7	-7	25
IF filter 1	2	-2	>50
IF VGA	4	-3 to 60	24
IF filter 2	2	-2	>50
Total	3.4	6 to 69	>5.7

2.2 Design of the transmitter

The gain of the baseband circuit in the transmitter is fixed, and then the average output power of the modulator is supposed to be -9 dBm when stimulated by the I/Q signal with a PAPR of 8 dB from the baseband unit. The maximum output power required by the system specification is 23 dBm and the minimum output power is required to be below -40 dBm. Thus the total gain of the transmitter is supposed to be above 32 dB with a control range of more than 63 dB.

Due to the high PAPR of the baseband signal in the OFDM system, power backoff is considered in the design of the power amplifier to assure the modulation performance and the adjacent channel leakage ratio (ACLR) of the transmitter to meet the system specifications[10-11]. The ACLR measurement results of the power amplifier is shown in Fig. 4. The total insertion loss of the attenuator and cables used in the test is about 28 dB. The test signal of the measurement is a standard downlink signal of the LTE-advanced system. The signal bandwidth is 20 MHz with 1 200 subcarriers, and 100 resource blocks (RB) are allocated. The modulation of the data channel is QAM64. The result shows that the ACLR of the power amplifier in 6 GHz band is below -42 dBc when the output power achieves 23 dBm.

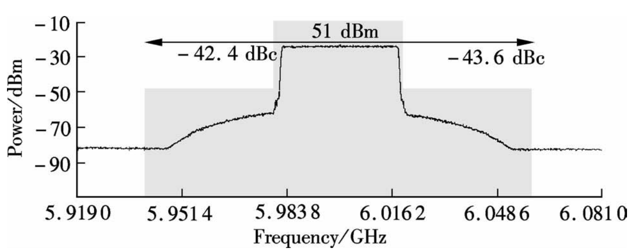

Fig. 4 ACLR measurement of the power amplifier

The final gain distributions assigned to the IF and RF blocks of the transmitter are listed in Tab. 2.

Tab. 2 Gain distribution of the transmitter

Key component	Gain/dB	OIP3/dBm
IF filter	−2	>50
Switch	−1	48
IF amplifier	10	36
Mixer	−7	32
RF filter	−2	>50
RF amplifier	11	24
PA	28	43
Isolator	−1	>50
Circulator	−1	>50
Total	35	40

2.3 Phase noise requirement of the local oscillator

It has been well studied that OFDM systems are very sensitive to phase noise of the local oscillators. Many methods have been proposed to alleviate the performance degradation in the digital domain[12−15]. As to the RF designer, a qualified local oscillator should be designed to lessen the burden of the baseband processing.

It has been investigated that the signal-to-noise ratio (SNR) degradation in the OFDM system due to phase noise is closely related to the subcarrier spacing and the phase noise power spectrum of the local oscillator. Then simulations are carried out to evaluate the required phase noise performance to fulfill the specifications of the LTE-advanced system. Eventually the local oscillators are realized using phase lock loop (PLL) and the test result of the 4 GHz band local oscillator is shown in Fig. 5.

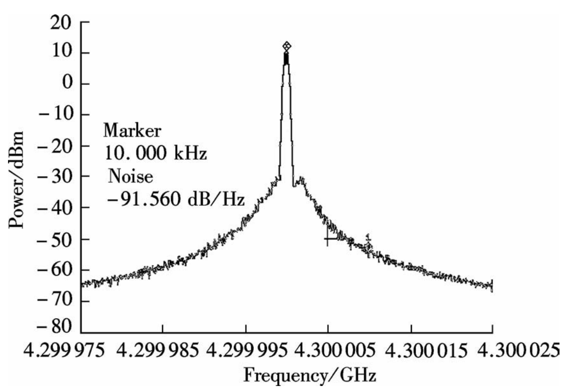

Fig. 5 Phase noise of the 4GHz band local oscillator

3 Measurement Results

The RF transceiver reported in this paper is realized using a standard PCB process and one channel of it is illustrated in Fig. 6. The whole 8 × 8 MIMO RF transceiver consists of eight individual channels sharing the same 10 MHz reference source as well as one control channel which acts as an interface to the baseband serial control signals, and one power supply board providing the DC-DC conversion from 48 to 6 V and 12 V used by the transceiver. The 8 × 8 MIMO RF transceiver is shown in Fig. 7.

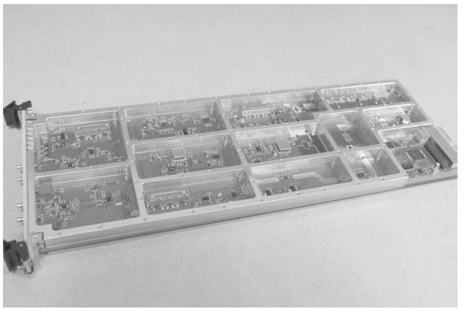

Fig. 6 Photo of one channel in the RF transceiver

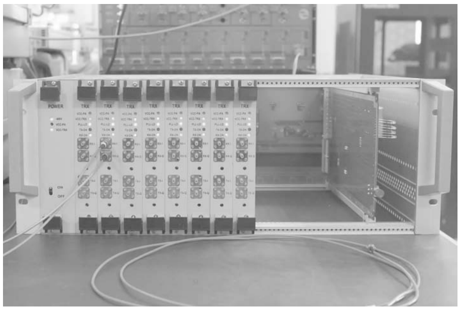

Fig. 7 Photo of the RF transceiver with 8 × 8 MIMO configuration

Measurement results of the key RF parameters of the transceiver such as gain, NF, phase noise and so on are summarized in Tab. 3.

Tab. 3 Measurement results of the key RF parameters of the transceiver

Key component	Parameter	Value
First LO (1.85 GHz)	Phase noise	−93 dBc/Hz@10 kHz; −118 dBc/Hz@100 kHz
Second LO (4.2 to 4.3 GHz)	Phase noise	−90 dBc/Hz@10 kHz; −111 dBc/Hz@100 kHz
Transmitter	Maximum output power/dBm	23
	ACLR/dBc	<−42
	Carrier leakage suppression/dBc	>50 (in the entire power range)
	I/Q image rejection/dBc	>35 (across the 100 MHz bandwidth)
Receiver	Noise figure/dB	<4.1
	Maximum gain/dB	>72
	I/Q image rejection/dBc	> 35 (across 100 MHz bandwidth)

The error vector magnitude (EVM) measurement is used to evaluate the overall performance of the RF transceiver. The downlink signal of the TDD LTE-advanced system generated by the Agilent Signal Studio is used in the measurement. The signal bandwidth is 20 MHz, meanwhile 100 RBs are allocated and the modulation of the data channel is QAM64. Because the system is very sensitive to frequency offset, the instruments used in the measurement and the RF transceiver under test are all synchronized together to obtain accurate results.

The EVM measurement results of the transmitter at its maximum output power are shown in Fig. 8, which indicate that the average EVM of 3.0% in one frame is achieved. The measured results of the receiver are shown in Fig. 9, from which it is observed that the average EVM of 2.1% in one frame is obtained. According to the specifications of the LTE-advanced system, the maximum EVM required is 8% when QAM64 is employed. It is obvious that the performance of the realized transceiver is well beyond the requirements of the LTE-advanced system.

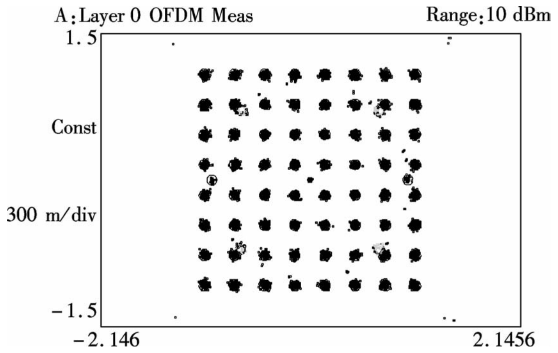

Fig. 8 Measured constellation of the transmitter with maximum output power

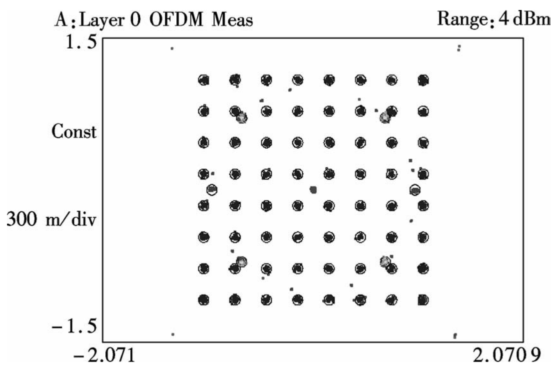

Fig. 9 Measured constellation of the receiver

4 Conclusion

In this paper, the design of a high performance TDD MIMO RF transceiver in the 6 GHz band is presented. The measurement results show that the developed RF transceiver has excellent performance. The developed RF transceiver has been successfully used in the IMT-advanced trial network in the high frequency band.

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用于下一代移动通信系统的6 GHz 频段时分双工射频收发信机的设计

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摘要：介绍了一种应用于下一代移动通信系统的高性能宽带射频收发信机的实现. 本射频收发信机工作在6～6.3 GHz 频段，信道带宽达到100 MHz，工作在时分双工模式并支持IMT-advanced 系统采用的多输入多输出(MIMO)技术. 为了获得最佳的性能，采用了经典的超外差结构. 详细介绍了系统关键部件如低噪声放大器、功率放大器以及本地振荡器的设计问题. 测试结果表明，射频收发信机的最大线性输出功率大于23 dBm，低噪声放大器的增益和噪声系数分别为大约24 dB 和小于1 dB. 此外，误差矢量幅度(EVM)的测试结果表明实现的射频收发信机的性能远超过LTE-advanced 系统的要求. 采用最大8×8 的MIMO 配置，本射频收发信机在现场试验中支持超过1 Gbit/s 的数据传输率.

关键词：射频收发信机；正交频分复用；IMT-advanced 系统；相位噪声；低噪声放大器；功率放大器；LTE-advanced 系统

中图分类号：TN92