A 60 GHz Multi-port Receiver with Analog Carrier Recovery for Ultra Wideband Wireless Personal Area Networks

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***Abstract*— A 60 GHz multi-port heterodyne receiver (MPHR) with rapid analog carrier recovery circuit is presented in this paper. The millimeter-wave frequency conversion is performed using a passive circuit, the multi-port interferometer, and related power detectors, avoiding the conventional millimeter-wave active costly mixers. The operating principle of MPHR and the demodulation results of 500Mb/s QPSK signal are presented and discussed in this paper. This receiver is an excellent candidate for the future low-cost, ultra wideband, short range, millimeter-wave Wireless Personal Area Networks.**

I. Introduction

With the rapid evolution of wireless technologies, ubiquitous and always-on wireless systems in homes and enterprises are expected to emerge in the near future. Facilitating these ubiquitous wireless systems is one of the ultimate goals of the next generations' wireless technologies, which are being discussed worldwide today. The coming 60 GHz Wireless Personal Area Networks (WPAN) are focused on short range and high data-rate applications [1]–[4]. These could be high-speed home or office wireless networking and entertainment, such as high definition television (HDTV). The available bandwidth and the efficient reuse of spectrum (due to strong signal attenuation at 60 GHz) make the flexibility, simplicity, and cost, the most critical points.

According to FCC definition, the transmission bandwidth of Ultra Wideband (UWB) signals should be greater than 500 MHz or larger than 20% of the central frequency. This open definition does not specify any air interface or modulation for UWB. In the early stages, time-domain impulse radio (IR) dominated UWB technology and it still plays a crucial role today. However, driven by the standardization activities, conventional modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) or even Single Carrier (SC) have also appeared [3]. The OFDM technique partitions the UWB channel to a group of non-selective narrow-band channels (using a simple modulation technique such as QPSK), making it robust against large delay spreads by preserving orthogonality in the frequency domain. In order to meet at least the "500 MHz requirement" of UWB systems, two approaches can be used: a high number of carriers (16, 32, 64 or 128) with a corresponding relatively low bit-rate/carrier or a small number of carriers (2, 4 or 8) with a corresponding higher bit-rate/carrier. Due to the complexity of the OFDM architecture, in our opinion, only the reduced number of carriers approach is suitable for low-cost 60 GHz UWB WPAN. Efficient carrier recovery techniques must also be developed for several hundreds of Mb/s data rate.

Initial simulations of a 60 GHz high-speed MPHR have been recently published [5]. A bit-rate up to 400 Mb/s has been achieved using a 16 QAM for an intermediary frequency IF of 900 MHz. However, to achieve at least the "500 Mb/s requirement" in a single carrier UWB approach, the IF must also be increased. On the other hand, several Gb/s can be obtained with a small number of carriers using the OFDM approach.

This paper presents a MPHR with a rapid analog carrier recovery technique dedicated to QPSK modulated signals. Transmission range up to 10 m is expected, due to the important free-space loss at 60 GHz band. Considering this reduced input received power and the required output signal to noise ratio, the heterodyne architecture is preferred to the direct conversion, even in the case of low-cost applications [6].

II. Multi-port Architecture

Fig. 1 shows the schematic block diagram of a 60 GHz wireless link using a multi-port architecture. A millimeter-wave direct modulator based on a multi-port circuit can be successfully used in the transmitter module for a low-cost QPSK wireless link implementation. The receiver uses a multi-port heterodyne architecture with rapid analog carrier recovery loop at IF. The main advantage of this architecture is the simplicity of the millimeter-wave I/Q down-conversion circuit using a multi-port module (MPM). This module is composed of a passive UWB multi-port interferometer (MPI) and four power detectors. Basically, the MPM is an additive mixer in which the resulting sum of millimeter-wave signals is nonlinearly processed using millimeter-wave power detectors [5]–[7]. Two IF differential amplifiers (IFDA) will generate quadrature IF signals. This is a low-cost, low-power consumption I/Q mixer, as demonstrated in [8]. A second down-conversion, IF to baseband, is performed using two conventional mixers and the carrier recovery module (CRM).

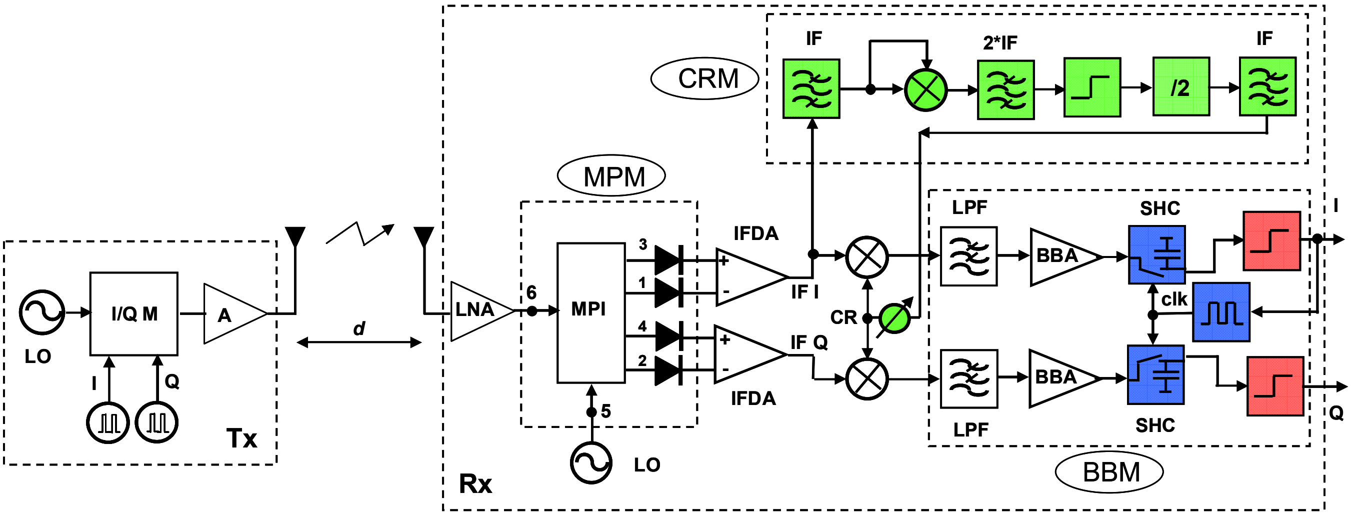

Fig. 1 Schematic block diagram of 60 GHz wireless link using a multi-port heterodyne architecture with carrier recovery loop at IF

This CRM generates the IF coherent signal. A rapid analog carrier recovery loop was chosen for synchronous demodulation [9], in order to follow the inherent frequency/phase shift of the millimeter-wave frequency local oscillator (LO) and the eventual Doppler shift due to relative movements between transmitter and receiver.

After low pass filtering (LPF) and baseband amplification (BBA), the quadrature baseband demodulated signals are obtained at the outputs of the sample and hold circuits (SHC). A clock recovery circuit generates an in-phase clock at the symbol rate using one of the outputs. The use of two limiters improves the demodulated QPSK signals at the baseband module (BBM) output.

III. Simulation Results

The wireless link simulation block diagram using the ADS software follows the schematic block diagram of Fig. 1.

Simulations are performed using a 60 GHz carrier frequency and a pseudorandom signal which drives the direct millimeter-wave QPSK modulator. The bit-rate is chosen at 500 Mb/s with a corresponding symbol rate of 250 MHz. The transmitter power is set at 10 dBm, and the antenna gains are 10 dBi. A loss-link model based on the Friis equation is used to simulate the signal propagation over the distance *d* of 10 m.

According to UWB requirements, the IF of the heterodyne receiver has been chosen at 2.45 GHz. The MPM computer model is the same as presented in [5]. The band-pass and low-pass filters are modeled using the ADS Chebyshev analog filter models with 1 dB ripple and 30 dB attenuation in the stop band. The gain of low noise amplifier (LNA), of IFDA and BBA are set at 20 dB, 20 dB, and 30 dB, respectively.

Initial envelope simulations (an efficient simulation technique for the complex digitally modulated RF signals) are performed supposing a stable millimeter-wave LO and no Doppler effect, using a step of 17 ps. Fig. 2 shows a typical IF spectrum (IF I) and the carrier recovered one (CR). As seen, due to the high efficiency of the CRM, the recovered spectrum, centered at 2.45 GHz, is extremely narrow.

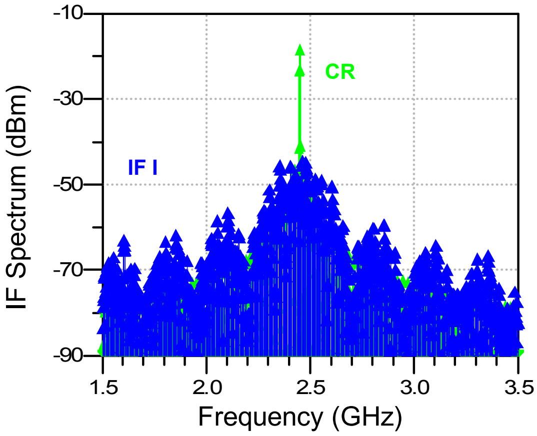

Fig. 2 IF spectrum of a the modulated and carried recovery signals

A 150 ns pseudorandom demodulated bit sequence is shown in Fig. 3. Both I/Q outputs are practically similar. Demodulated signals at the SHC input/output and at the limiter output are plotted versus the time.

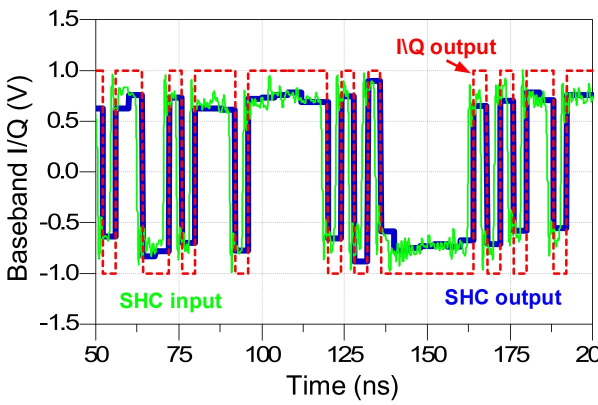

Fig. 3 Demodulated pseudorandom baseband I/Q signals supposing a stable millimeter-wave LO and no Doppler effect

The limiters connected at the end of the BBM dramatically improve the QPSK demodulated signal shape. As a result, the demodulated output signals have exactly the same bit sequence and the same shape as those generated by the transmitter.

The demodulated constellation can also be visualized in XY format (similar to an XY oscilloscope view in practice). Figs. 4 and 5 show the QPSK demodulated constellation supposing a stable millimeter-wave LO and no Doppler effect. The use of SHC eliminates transitions between clusters, as seen in Fig. 5. In addition, limiters concentrate each cluster in one single point, generating a perfect QPSK demodulated constellation.

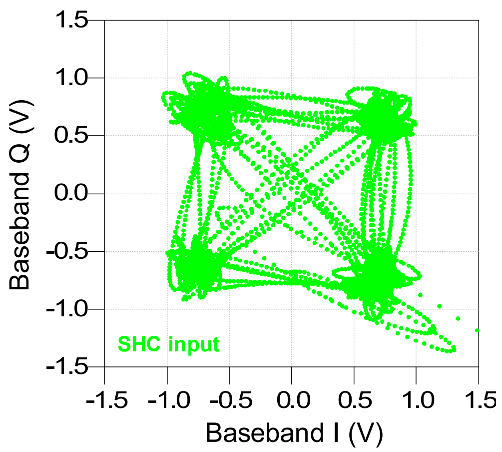

Fig. 4 Demodulated constellation at the SHC input without Doppler shift

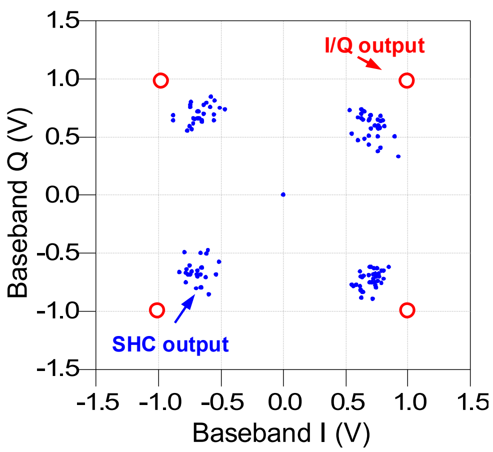

Fig. 5 Demodulated constellation at the SHC output and I/Q output without Doppler shift

As known, a millimeter-wave oscillator does not have excellent frequency stability and is difficult to control. In addition, movements of the portable stations, as well as movement of objects in the environment cause relatively severe Doppler effects at 60 GHz, because they are proportional with the carrier frequency. For example, if a person moves at a walking speed of 1.5 m/s, the Doppler spread is 1200 Hz. The demodulated constellation turns clockwise or anti-clockwise, depending on the sign of this frequency difference [10]. Therefore, the analog carrier recovery loop of Fig. 1 must generate a coherent IF signal to stabilize the demodulated constellation.

The Doppler shift is implemented into the ADS envelope simulation platform using corresponding phase shift equations in the propagation path (it can include both movement effects and inherent millimeter-wave LO frequency shifts). The simulation result of the baseband demodulated signals, corresponding to a 200 KHz Doppler shift, is shown in Fig. 6. The demodulated constellation, in XY format, is presented in Fig. 7.

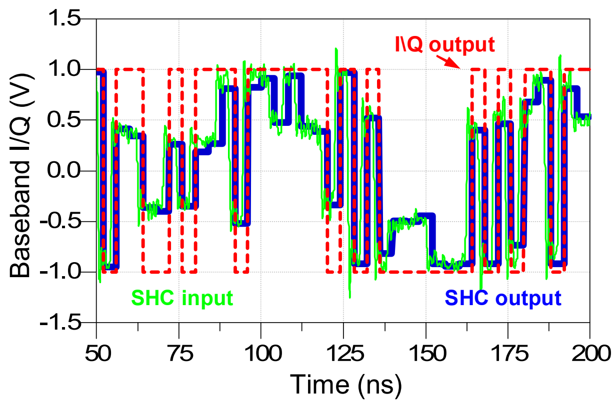

Fig. 6 Demodulated pseudorandom baseband I/Q signals for 200 KHz Doppler shift

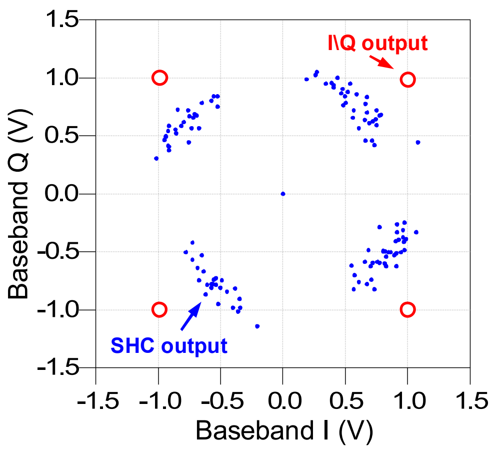

Fig. 7 Demodulated constellation at the SHC output and I/Q output for 200 KHz Doppler shift

These demodulated signals at the SHC input/output, and at the I/Q limiter output are presented for the same 150 ns pseudorandom bit sequence, as in the initial case, without the Doppler shift (see Fig.3). As seen in Fig. 6, the demodulated output signals using limiters have an identical bit sequence, demonstrating the robustness of the QPSK demodulation. Therefore, the carrier recovery loop generates a very good IF signal for coherent demodulation. However, the inherent phase errors of the recovered carrier, determinate a spread of the demodulated clusters, as seen in Fig.7. The baseband signal at the SHC output is clearly a multi-level signal and only the use of limiters insures an optimal QPSK demodulation.

Bit error rate (BER) analysis is also performed using an appropriated length pseudorandom bit stream and various Doppler shifts. Fig. 8 shows the BER results versus the energy per bit to the spectral noise density (Eb/No), in the case of an ideal QPSK demodulator, of a Doppler shift up to 200 KHz, and of a Doppler shift of 600 KHz.

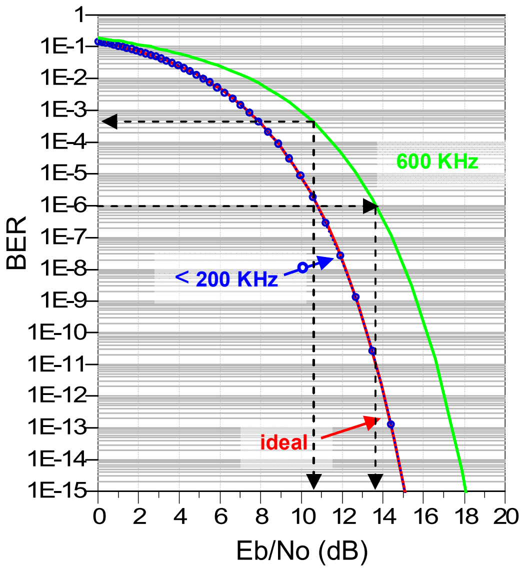

Fig. 8 BER simulation results for various Doppler shifts

The simulation results show a very good performance of the proposed wireless link: the BER is 10^{-6} for an Eb/No ratio of 10.4 dB, similar to the ideal demodulator, if the Doppler shift is less than 200 KHz (circles on the BER diagram). For a Doppler shift of 600 KHz, corresponding to a millimeter-wave LO frequency stability of 10^{-5}, the BER is less than 10^{-6} for an Eb/No ratio of around 13.5 dB. Therefore, the Eb/No ratio of the received 600 KHz Doppler shift signal must increase with 3 dB for similar results, as in the ideal case. The BER value deteriorates from 10^{-6} to around 10^{-3} for the Eb/No ratio of 10.4, remaining at a reasonable level.

Transmission on range up to 10 m, as required for UWB short range WPAN, has been demonstrated using previous simulations. The efficient 500 Mb/s QPSK signal demodulation demonstrates the validity of the MPHR architecture including rapid analog carrier recovery loop. As known, the free-space loss at 60 GHz is significant and is evaluated at 88 dB, according to the Friis equation. This equation shows that, for equal antenna gains, path loss increases with the square of the carrier frequency. Therefore, 60 GHz communications have an additional 22 dB of path loss when compared to an equivalent 5 GHz system. However, 60 GHz antennas have a smaller form factor than 5 GHz antennas, as antenna dimensions are inversely proportional to carrier frequency. Therefore, more antennas can be placed within a fixed area and the resultant antenna array can increase the antenna gain. The directive antenna pattern of a beam forming antenna array improves the channel multipath profile by limiting the spatial extent of the transmitting and receiving antenna patterns to the dominant transmission path. This aspect opens up new opportunities for system and baseband design [6]. In fact, future high data-rate WPAN will be certainly realized using smart antennas to reduce at the same time power consumption, link budget, and multipath effects.

IV. Conclusions

The proposed architecture enables the design of compact and low-cost wireless millimeter-wave communication receivers for future UWB WPAN.

Even if the MPHR demodulates arbitrary QAM/MPSK signals, the use of this specific carrier recovery technique and limiters at I/Q output proposes this architecture to BPSK/QPSK modulated signals only. Very good demodulation results are demonstrated for a 500 Mb/s QPSK wireless link in presence of an important Doppler frequency shift using a rapid analog carrier recovery technique.

Acknowledgment

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