SoC for COFDM Wireless Communications: Challenges and Opportunities

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ABSTRACT

Coded Orthogonal Frequency Division Multiplexing (COFDM) technology has been widely accepted in many communication systems due to both bandwidth efficiency and robustness to channel distortion. This opens a great of opportunities for SoC society to deal with design complexity by exploiting benefits of giga-scale integration. In this paper, we'll first review the general design concept of COFDM systems and then highlight several key issues in SoC realization. Then a system-level design flow by taking into account both performance indices and hardware complexity will be introduced. Several core modules related to COFDM system will also be addressed to see how better solutions can be achieved, especially for wireless applications. Finally two case studies on WLAN and OFDM-UWB will be discussed to demonstrate our proposals as well as to provide some directions for further research.

1. INTRODUCTION

Coded orthogonal frequency division multiplexing (COFDM) technique is widely used for high-speed wireless systems such as wireless local area network (WLAN), digital video broadcasting (DVB), and ultra-wide band (UWB) system [1]-[4]. It provides high data rate and high channel capacity; for example 54Mb/s and 480Mb/s data rate can be respectively delivered in 20MHz-bandwidth IEEE 802.11a WLAN and 528MHz-bandwidth UWB. In 54Mb/s WLAN system, BPSK/QPSK/16-QAM/64-QAM constellations are supported and so the wide range of SNR condition and the synchronization sensitivity of 64-QAM are the most focused due to the requirement of high-complexity synchronizer and channel equalizer [1]-[2]. As data rate migrates to 480Mb/s UWB [5], both wide bandwidth and supported QPSK constellation make the system less sensitive to synchronization error. To further enhance system performance, efficient error-control codes are often employed. Convolutional codes and their concatenation with Reed-Solomon codes that have been exploited in communication systems provide a superior error correction capacity while keeping a reasonable coding complexity. Low-density parity-check (LDPC) codes and Convolutional codes, which can reach a capacity approaching performance by iterative decoding algorithm, are undoubtedly the most popular research topics recently. However, the increasing demand of high speed data transmission causes the difficulty in decoder circuit design while considering low power and low cost constraints. Therefore, according to the target systems, we consider different solutions to achieve better performance through system-level optimization and key modules as well. With these solutions, the COFDM baseband transceiver can have opportunities to overcome the challenges of high throughput and low power under system performance requirements.

In this paper we propose a low-complexity design concept for COFDM-based wideband system. First the advantage of wideband system containing higher tolerance to carrier frequency offset (CFO) estimation error is introduced, and hence the synchronizer complexity can be efficiently reduced based on performance consideration. Second the complexity reduction of QPSK-COFDM system is presented, the reduced SNR range and phase-processing can save computations in both symbol timing detection (STD) and channel equalization, leading to a low-cost and acceptable system solution. For low power consideration, we suggest an adaptive decoder based on channel conditions, and many redundant operations can be reduced. To achieve high-throughput, the parallel decoder architectures that are quite area efficient are presented for Viterbi decoders and LDPC decoders. Based on the proposed low-complexity scheme, the power efficiency of COFDM chips, defined as power per Mb/s, can be saved to below 1.2 ~ 2.3mW per Mb/s in 0.18 μ m CMOS process.

The paper is organized as follows. System block diagram of the proposed COFDM SOC are described in section 2. The complexity-saving schemes are described in section 3. System performance and chip summary are respectively shown in sections 4 and 5, followed by the conclusion in section 6.

2. SYSTEM BLOCK DIAGRAM

FIGURE 1 shows the block diagram of the proposed COFDM baseband transceiver. The upper blocks are transmitter modules to generate the COFDM signal to satisfy the system specification, and the lower blocks are receiver modules to recover the signal and solve the channel distortion. Note that IFFT and FFT can be shared by transmitter and receiver in half-duplex mode. In the receiver, the synchronizer detects the symbol timing and CFO with the signal correlation results. Moreover, the channel equalizer solves the channel frequency response (CFR) and phase error caused by CFO estimation error and sampling clock offset (SCO) with the pilot phase error tracking (PET). The computations of conventional synchronizer and channel equalizer are done with complex divisions and multiplications which dominate the baseband processor complexity. In channel codec, the design is very critical in bit error rate (BER) performance, and channel decoding algorithm is quite computational intensive, especially those approaching Shannon limit. The large amounts of probabilistic message passing also cause enormous memory accesses. In WLAN applications, the low power Viterbi decoder [6] is applied and at most 75% memory accesses in survivor memory can be eliminated. For high speed requirement [5], a high-radix ACS structure [7] is investigated to achieve over 1Gb/s data throughput. On the other hand, a high performance LDPC codec [4],[8] provides better improvement in BER performance and throughput.

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FIGURE 1. SYSTEM BLOCK DIAGRAM OF COFDM BASEBAND TRANSCEIVER

3. KEY COFDM TECHNIQUES

Before addressing the design issues of each module, let's look at the system simulation platform as shown in FIGURE 2. System behavior is constructed by Matlab and C descriptions. Once algorithms are confirmed to system requirements, fixed-point model is set up to provide a link to hardware design. Here both IP and in-house hardware modules can be designed and simulated at HDL level. Finally physical design can be done. With this design platform, it's easy to justify overall system performance and sub-block functionality.

FIGURE 2. PROPOSED SYSTEM-LEVEL INTEGRATION DESIGN FLOW

3.1 Low-Complexity CFO Estimation for Wideband System

In COFDM system the signal is seriously distorted by inter-carrier interference (ICI) caused by CFO, and hence the accurate CFO estimation is required and increases the complexity of synchronizer. However the wider bandwidth can extend the subcarrier spacing to make higher tolerance to CFO estimation error. In 480Mb/s UWB system, the subcarrier spacing is 4.125MHz, equal to 13.2x of that in WLAN. According to Moose's analysis, ICI power is approximately linear to CFO/subcarrier spacing, and the signal-to-ICI ratio (SIR) of UWB is higher than that of WLAN by 13dB. In order to understand the system sensitivity to CFO which causes ICI in COFDM systems, the SNR loss for 8% packet error rate (PER) caused by CFO estimation error is drawn in FIGURE 3.

From FIGURE 3, it's found the tolerant CFO-estimation error of UWB can be higher than that of WLAN in the same SNR-loss constraint. The SNR-loss curves explain the CFO estimation of wider-band system is allowed to be more error tolerant, and the required design complexity can be reduced. Based on this wideband feature, a low-complexity synchronizer such as data-partitioned-

based scheme can be used in UWB system [7], where 75% complex multiplications can be reduced to save 37mW power dissipation with only 0.07dB SNR loss.

FIGURE 3. SNR LOSS FOR 8% PER CAUSED BY CFO ESTIMATION ERROR

3.2 Low-Complexity Schemes for QPSK-COFDM System

In WLAN system with BPSK/QPSK/16-QAM/64-QAM, the design SNR for typical 10% PER ranges in 2.5dB ~ 26.7dB [1], and while in UWB system with only QPSK constellation, the lower bound of SNR range can be increased to about 5dB [4]. In synchronizer, the symbol timing is detected to avoid frame error causing high PER, and hence the frame error rate (FER) should be lower than PER for performance requirement. Compared with WLAN system, the UWB system with higher design SNR can allow higher FER, and hence the complexity of STD in synchronizer can be reduced. A tap-and-register-reduction matched filter is proposed for low-complexity UWB STD, and it can reduce 75% register size to save 28.5mW power with only 0.38dB SNR loss [8]. The wideband and QPSK-only feature can efficiently be exploited to reduce the design complexity of synchronizer. A trade-off between synchronizer complexity and SNR loss for typical 8% PER of UWB system is drawn in FIGURE 4. We can find a synchronizer with reduced 75% complexity can achieve an acceptable SNR loss (~0.3dB).

FIGURE 4. TRADE-OFF OF UWB SYNCHRONIZER

On the other hand, the QPSK constellation also implies the complexity reduction of channel equalizer. In conventional channel equalizer both divider and multiplier occupy about 60% hardware cost. Since the QPSK signal can be de-mapped with just the phase information, a divider-and-multiplier-free channel equalizer can be

exploited [4]. In this low-complexity equalizer scheme, the phase information can be used instead of complex signals. As a result both complex divider and multiplier can be replaced by real-number adders. Furthermore the storage space storing channel information can be reduced by 50%. This divider-and-multiplier-free equalizer scheme can save 61.8mW power dissipation with only 0.3dB SNR loss for 8% PER.

3.3 Low-Power Viterbi Decoder for WLAN and UWB System

Low-power Viterbi decoders for WLAN system in [1] and [6] have 30%~ 40% reductions as compared to conventional designs. The modified compare-select-add (CSA) architecture lowers down hardware complexity as well as power dissipation. With the aid of path merging and prediction features, the traceback length dynamically changes according to channel conditions, and the memory accesses is reduced more than 70% on the average. Moreover, the power consumption is improved due to the reduced memory accesses. A 0.18- μ m test chip also shows that the power efficiency reaches 0.75mW per Mb/s at 6Mb/s and 1.26mW per Mb/s at 54Mb/s as specified in IEEE 802.11a.

A high-speed Viterbi decoder is proposed in [7]. It applies the 2-D add-compare-select (ACS) structure and the retiming mechanism. The proposed 2-D architecture provides an area efficient solution for high-radix trellis decoding, resulting in a high-level parallel decoding. Besides, the retiming techniques (RT) can be used to reduce the critical path delay of ACS for further high-speed applications. A Viterbi decoder for the UWB system [5] is implemented with the proposed ACS-4x4 approach, and experimental results indicate a 60% area reduction in contrast to radix-16 ACS based decoders. It has a considerable improvement in throughput when the retiming process is employed. Measurement of a 0.18- μ m test chip shows that over 500Mb/s data rate is accomplished at 1.8V supply. Furthermore, with the retiming technique, the proposed decoder can achieve 731Mb/s data rate under the worst case corner. TABLE 1 also presents the Viterbi decoder for the UWB system [5] and highlights the effect of retiming techniques.

TABLE 1. DESIGNS OF VITERBI DECODER FOR UWB SYSTEM

Design	ACS-4x4	ACS-4x4 with RT
Technology	0.13- μ m	0.13- μ m
Data Throughput	900Mb/s	1100Mb/s
Chip Area	1.28mm ²	1.96mm ²
Gate count	239K	358K
Chip Density	96%	94%

3.4 High-Rate LDPC Decoder for Gb/s Wireless System

The difficulty in realizing a parallel LDPC decoder is the signal routing congestion problem due to the randomness of parity-check matrix and large amount of message passing. In [4], the routing issue is resolved with pipelined datapaths which have smaller signal transmission delay. In the (1200,720) decoder of [8], the message memory (MMU) architecture allows parallel decoding of two codewords and minimizes the routing congestion issues with the register exchange approach. The message memory is divided into four blocks, and an additional temporal block (TMP) is included to simplify the data switch. Additionally, the data rescheduling minimizes the signal routing between datapaths and memory units as shown in FIGURE 5. Consequently, the chip becomes smaller due to the increased chip density. From simulation results, the 0.13- μ m chip reaches the maximum 5.92Gb/s data rate with 13.5mm² area and 268mW power consumption; the chip density is about 75%.

FIGURE 5. HIGH-SPEED (1200,720) LDPC DECODER

TABLE 2. SUMMARY OF (1200,720) LDPC DECODER CHIPS

Technology	0.13- μ m 1P8M	0.18- μ m 1P6M
Data Throughput	5.92Gb/s	3.33Gb/s
Power	268mW@1.2V	644mW @1.8V
Chip Area	13.5 mm ²	25mm ²
Gate Count	1.15M	1.15M
Chip Density	75.4%	71.2%

TABLE 2 summarizes the (1200,720) LDPC decoder in 0.13- μ m 1P8M and 0.18- μ m 1P6M technologies. The data throughput is estimated with eight decoding iterations, which is sufficient for the UWB system. Note that more metal layers lead to higher chip density and better timing, but fabrication cost will be increased too.

4. SYSTEM PERFORMANCE

System performances of the proposed COFDM systems are listed in TABLE 3 and TABLE 4. The design SNR for typical 10% PER of the WLAN system can be lower than the system constraint as listed in TABLE 3 [1]. When system migrates to UWB, the low-complexity schemes are used, and the transmission distances of the UWB system can be still longer than the system requirement as listed in TABLE 4. The transmission distances listed in TABLE 4 are derived from the system link-budget listed in [5] and SNR. conditions

5. CHIP SUMMARY

The chip micro-photo of COFDM baseband transceivers for WLAN [1] and UWB [4] are shown in FIGURE 6. From the chip summary listed in TABLE 5, we can find the 54Mb/s WLAN and 480Mb/s UWB baseband chips consume 123.5mW and 575mW, resulting in power efficiency of 2.3mW and 1.2mW per Mb/s. Based on the proposed low-complexity schemes, the power can be efficiently saved when system migrates from WLAN to UWB. In addition, a new version with dynamic sampling and I/Q mismatch compensation is proposed for the 480Mb/s multi-band (MB)-OFDM UWB chip in 0.13 μ m CMOS process. It consumes only 31.2mW for the MODEM part, resulting in power efficiency of 0.065mW per Mb/s [11].

6. CONCLUSION

In this paper, we have addressed the SoC design flow for COFDM wireless communications systems. At system level, a trade-off between performance and computational complexity is done through a system simulation platform. Then all core modules are designed under target system architecture to reach better performance indices, especially in low-power issue. Research results with two test vehicles on WLAN and COFDM-UWB show that our proposal can

reach better power efficiency while maintaining acceptable system transmission performance. In addition, core modules also reach better design efficiency by taking into system behavior. Currently a memory-based system architecture is explored to provide COFDM-SoC solutions to solve multi-standard and multi-channel applications.

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TABLE 3. SNR FOR 10% PER OF COFDM-BASED WLAN SYSTEMS

Data Rate (Mb/s)	6	9	12	18	24	36	48	54
Design SNR (dB)	2.5	4.0	5.2	7.4	10.1	14.2	18.6	20.3
System Constraint (dB)	9.7	10.7	12.7	14.7	17.7	21.7	25.7	26.7

TABLE 4. TRANSMISSION DISTANCE FOR 8% PER OF COFDM-BASED UWB SYSTEMS

	LDPC-COFDM System [4]			MB-OFDM System [5]		
Data Rate (Mb/s)	120	240	480	110	200	480
Transmission Distance in AWGN Channel (meters)	14.4	11.5	8.5	19.1	13.8	9.0
Transmission Distance in Multipath Channel (meters)	11.7	9.4	6.8	11.0	4.2	2.4
System Requirement (meters)	10	4	2	10	4	2

(a) COFDM-based WLAN

(b) COFDM-based UWB

FIGURE 6. CHIP MICROPHOTO OF COFDM BASEBAND TRANSCEIVERS

TABLE 5. CHIP SUMMARY OF COFDM BASEBAND TRANSCEIVER

Technology	Standard 0.18 μ m CMOS, 1.8V Core, 3.3V I/O	
Function	WLAN Baseband Transceiver	UWB Baseband Transceiver
Die Size	4.8 $\times$ 4.8 mm ²	6.5 $\times$ 6.5 mm ²
Equivalent Gate-Count	525K	1065K
Maximum Data Rate (Mb/s)	54	480
RX Core Power (mW)	123.5	575
Power Efficiency (mW per Mb/s)	2.3	1.2

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