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Adaptive OFDM for Wireless Interconnect in Confined Enclosures

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Abstract

This letter considers and recommends OFDM with adaptive subcarrier modulation as a suitable candidate for wireless UWB communication in computer chassis. A rigorous measurement campaign studies the guaranteed spectral efficiency. It concludes that enhancement of the existing WiMedia OFDM systems with a bandwidth of 528 MHz in order to support adaptive OFDM would enable data-rates above 1 Gbps over short ranges, i.e. the spectral efficiency would be doubled. Moreover, the guaranteed spectral efficiency is shown to increase with bandwidth, i.e. the guaranteed data-rate increases better than linearly with bandwidth.

Index Terms

UWB, Ultrawideband, adaptive OFDM, Wireless Interconnect, Computer chassis

I. Introduction

Wireless interconnect in computer chassis is an emerging field of short range communications. It is expected to replace the wired bus systems [1] - [5]. The benefits are: reduction of latency, chip/printed circuit board area, and electromagnetic interference; simplification of architectures; and increased flexibility of the architecture [1] - [5].

The candidate technologies are Ultrawideband (UWB) [1] - [3], [5], mm-Waves (60 GHz) [1] - [4], sub-THz [2], and THz technologies [2]. mm-Waves, sub-THz, and THz technologies offer significantly higher data-rates and are reported to be more energy efficient than UWB [1], [2], [4], but they have a limited range. Sub-THz and THz links are considered for ranges below 25 mm [2]. SISO 60 GHz links have been considered for ranges below 50 mm [2], [4].

The advantage of UWB communication links, is the fact that they can service links with ranges in the $>$10 cm range even for the NLOS case [1], [5]. Thus for wireless links transferring data between more distant components, e.g. motherboard and the hard-disk unit, UWB, assessed here, seems to be the best alternative. In Section II, the letter discusses the advantages and disadvantages of different architectures for such a system and selects Adaptive OFDM as the most suitable candidate. Sections III and IV then explore the performance of such a system.

II. Implementation of UWB in Computer Chassis

A. Impulse Radio and BPSK

The UWB wireless channels in computer chassis have been studied extensively by numerous authors [5] - [8]. To our best knowledge, the implementation of such a link has only been explored by Intel Corp. e.g. in [1], and by Chen et.al. in [9].

Intel Corporation selected On-Off-Keying (OOK) Impulse radio [1]. The implementation is capable of providing up to 500 Mbps. Despite using 2-tap equalization [10], the performance is limited by the Inter-Symbol-Interference (ISI) in dense multipath environments [10]. For 500 Mbps the system manifests BER $> 10^{-1}$ for ranges $>$ 8 cm [10]. For ranges above 10 cm, the data-rate has to be reduced to 125 Mbps but the system still fails to establish a reliable communication link in more confined areas of the computer chassis [11].

Introduction of a guard interval prevents ISI as discussed e.g. in [12], [13], but such an approach significantly reduces the spectral efficiency of the scheme. Considering the power delay profiles of wireless channels in computer chassis reported in [5] - [8], the guard interval should be at least as long as for indoor systems, i.e. more than 50 ns [5] - [8]. For OOK systems, this means a maximum data-rate of 20 Mbps.

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The direct modulation using BPSK with dynamic shifting of the integral window at the receiver is explored in [11]. The simulated system achieves data-rates of up to 650 Mbps [9], however such data-rates require SNR above 35 dB [9]. Realistic UWB's link budget is 60-65 dB (spanned between thermal noise and UWB radiation limits) [12]. The path loss in computer chassis is 27-30 dB [5] - [8], with fading and the electromagnetic interference the link is likely to fail.

B. OFDM

OFDM systems possess higher spectral efficiency [14]. Their drawback is higher complexity associated with higher power consumption per bit. Furthermore, commercial UWB OFDM systems fail to operate in confined environments [15]. The frequency selective fading, which is more severe in confined multipath-rich environments, causes a significant variation in the SNR among OFDM subcarriers. The weakest subcarriers contribute mostly to the overall BER and communication link fails even though the overall energy of the OFDM symbol is well above the system's requirements [15].

C. Adaptive OFDM

It is possible to remedy the OFDM limitations by using OFDM systems which adapt the subcarrier modulation to the specific channel properties. The concept of adaptive OFDM is not new and it has been studied for wideband OFDM systems as well as for UWB OFDM indoor systems [16] - [19]. The contribution of this letter is therefore summarized as follows.

The concept is applied in computer chassis where it has not been considered before. The static environment is suitable for deployment of the adaptive OFDM technique. The wireless channel of the small confined environment is very specific - low path loss but severe frequency selectivity [5] - [8], [15]. Hence, an evaluation using a rigorous channel measurement campaign is necessary.

The main contribution of this letter is quantification of the benefits as a function of bandwidth. This quantification has not been performed before and it enables a) to quantify the minimum bandwidth required for a guaranteed spectral efficiency, i.e. to estimate how much bandwidth is required by a realistic system to guarantee data-rates required by different buses inside the computer, and b) to show how the guaranteed spectral efficiency increases with bandwidth.

III. Channel Measurements

The measurement configuration used for the results reported in this letter was as presented in [5]. It was performed using a Vector Network Analyzer for the frequency range 3-11 GHz in a computer chassis as depicted in Fig. 1. The measurements were performed with the motherboard (incl. network and video cards which are not depicted in Fig. 1) in the chassis.

The antennas were compact bowtie antennas operating in the frequency range 3 - 11 GHz. The receiver was in the proximity of the hard-disk slot and the position of the receiver was varied for two planes perpendicular to the motherboard. In each plane, the receiver was moved into 36 positions (square grid 6x6 positions spaced by 1 cm).

The top plane was at the same level as the receiver antenna, 25 cm above the bottom of the chassis, with a mean TX-RX range of 20 cm. The bottom measurement plane was located 20 cm below the top plane. Both polarizations were explored, providing experimental data for a total of 144 SISO channels.

IV. Adaptive OFDM Evaluation

A. Overview

The performance evaluation of the spectral efficiency of Adaptive OFDM systems is performed as follows. The measured channel transfer functions are applied on the realistic link budget of 60 dB and the SNR of individual subcarriers are calculated.

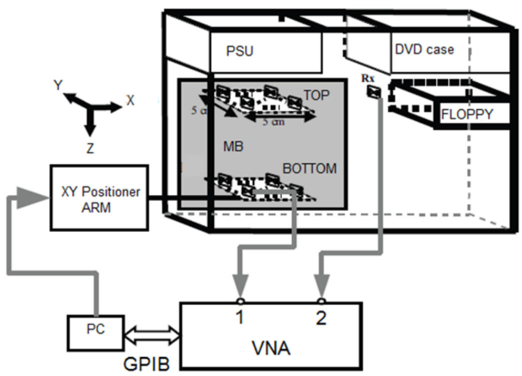

Fig. 1. Measurement setup

These individual SNR levels determine the subcarrier modulation, i.e. the data-rates of individual subcarriers. The total data-rate over all payload subcarriers is calculated. The spectral efficiency is determined as the data-rate over the total bandwidth of the OFDM symbol.

The SNR decision levels for individual subcarrier modulation were selected so that the gross (uncoded) BER of each subcarrier remains below 10^{-2} and are specified below:

SNR $<$ 10.5 dB - none, subcarrier unused
10.5 dB $<$ SNR $<$ 14 dB - QPSK
14 dB $<$ SNR $<$ 17 dB - 8-QAM
17 dB $<$ SNR $<$ 21 dB - 16-QAM
21 dB $<$ SNR $<$ 24 dB - 32-QAM
24 dB $<$ SNR $<$ 27 dB - 64-QAM
27 dB $<$ SNR - 128-QAM

The limit of gross BER below 10^{-2} is chosen as it is the upper limit of the code strength in the WiMedia standard. For gross BER above 10^{-2}, the net BER is such that the PER exceeds 10% [14].

Two evaluations are performed. Firstly it is shown that even though the WiMedia devices are not suitable for operation in an enclosed environment, a small modification of the system using the channel estimation already present in the standard enables to achieve data-rates above 1 Gbps. Secondly, the achieved spectral efficiency was explored as a function of bandwidth (number of data subcarriers) in order to quantify what bandwidth is required for an adaptive OFDM system to provide a wireless replacement for a specific bus.

B. Discussion about the assumptions

The performance evaluation as discussed in the preceding section is based on two assumptions - the properties of the channel transfer function are known, and the channel is static at least for the duration between two channel estimations. In this section it is shown that the WiMedia OFDM system satisfies both conditions. Thus the consideration of Adaptive OFDM represents only a minor change to the scheme.

The packets in the Wimedia Standard, described in detail in [14], have the following structure. The packet consists of a preamble, header and the payload. The header carries information for the PHY and MAC layer. The preamble consists of synchronization sequences followed by six pilot symbols for channel estimation essential for channel equalization. With the received signal strength intensity and received signal quality indexes also foreseen by the standard, the receiver can determine the instantaneous SNR [20] of individual subcarriers.

The first condition is therefore satisfied when the reciprocity of the wireless channel is assumed, or if a feedback-channel transferring the channel-state-information is implemented. Since the feed-back channel for sharing channel state-information is being routinely implemented in other systems such as the IEEE 802.11n systems [21]. It is contended here that such a change to the system is a worthwhile endeavor considering the performance improvement quantified in sections IV.C and IV.D.

In terms of channel stationarity, the maximum length of the packet in the WiMedia standard is 656 OFDM symbols, i.e. its duration is 205 μs [14]. This duration was selected with the stationarity of the indoor wireless channel in mind. In other words, the channel estimation determined by the preamble is sufficiently precise for all OFDM symbols in the same packet in a dynamic indoor environment. The computer chassis is a significantly more static environment than the indoor channel [5] - [8]. Most of the electromagnetic interference occurs outside the UWB band [1]. Hence, it is concluded that even the second condition is satisfied.

Since the environment is more static than indoor or outdoor channels, the system can additionally benefit from slow resource allocation algorithms with low requirement of computational resources such as [22], [23].

As a final note before the performance evaluation, it is noted that not all subcarriers in an OFDM symbol transmit data. In the WiMedia OFDM symbol, only 100 subcarriers represent payload, the remaining 28 are pilots or guard subcarriers. The role of the pilot subcarriers is to improve the equalization [14]. This is comparable to the IEEE802.11a standard with 48 data subcarriers out of 64 [21].

In the first evaluation, 100 payload subcarriers spaced as in the WiMedia standard are assumed. In the second evaluation with variable bandwidth, it is assumed that the payload represents 80% of the bandwidth of the OFDM symbol.

C. Results - Fixed bandwidth

The performance of the WiMedia-like system with fixed bandwidth is presented in Fig. 2 which compares the spectral efficiency of a WiMedia-like system considering the measured channels for the 14 center frequencies as specified by the WiMedia standard [14].

The following can be concluded based on Fig. 2. Firstly, the performance is slightly inferior for higher frequencies. This is due to the fact that the path-loss increases with range (higher at the bottom level) and with frequency.

Secondly, the spread is lower for lower frequencies the maximum data-rate is limited by the maximum modulation level, i.e. some subcarriers could support modulations higher than 128-QAM which would increase the spread towards higher values. 128-QAM was selected as the highest modulation order bearing the system complexity in mind.

Thirdly, even though the communication range is larger for the bottom level, the results do not suggest that either of the positions is better. This is a positive result as it suggests that the achievable data-rates are independent of the transceiver's position to the motherboard.

Finally, in terms of result quantification, it can be concluded that for center frequencies below 6 GHz, for all bands the measured efficiency was above 3 bit/(s·Hz) which corresponds to data-rates above 1.5 Gbps. With the exception of the top level position for the highest center frequency, all of the measurements provided the data-rate with spectral efficiency above 2 bit/(sHz) which corresponds to gross data-rates above 1 Gbps.

In comparison, the WiMedia system has gross data-rate of 640 Mbps, which corresponds to 1.21 bit/(s·Hz), but as shown experimentally in [15] even with the lower spectral efficiency the WiMedia systems fail to establish a data-link due to severe multipath fading in confined environments.

D. Results - Variable bandwidth

Fig. 3 then compares spectral efficiencies achieved in the measured channels with variable bandwidth for five center frequencies (5, 6, 7, 8, and 9 GHz). The number of subcarrier was varied from 2 to 950 corresponding to OFDM symbol bandwidth from 8.5 MHz to 4 GHz. The duration of the OFDM symbol was kept 312.5 ns as in the WiMedia systems. As mentioned n IV.B it is assumed that only 80% of the subcarriers carry data payload.

In Fig. 3, it can be observed that the median spectral efficiency remains constant, independent of the bandwidth. However, the spread of the spectral efficiencies between different positions decreases, due to the ability of the adaptive OFDM system to mitigate the impact of frequency fading, i.e. strong subcarriers compensate for weak ones.

For bandwidths below 50 MHz, the system cannot guarantee spectral efficiencies above 1 bit/(s·Hz). To guarantee efficiencies above 2 bit/(s·Hz) the adaptive OFDM system in a computer chassis should have a minimum bandwidth of 200 MHz.

For UWB bandwidths of 500 MHz and 2 GHz, none of 720 measurements (144 positions for 5 frequencies) yielded in spectral efficiency below 2.3 bit/(s·Hz) and 2.7 bit/(s·Hz), respectively. These measured values suggest the spectral efficiencies

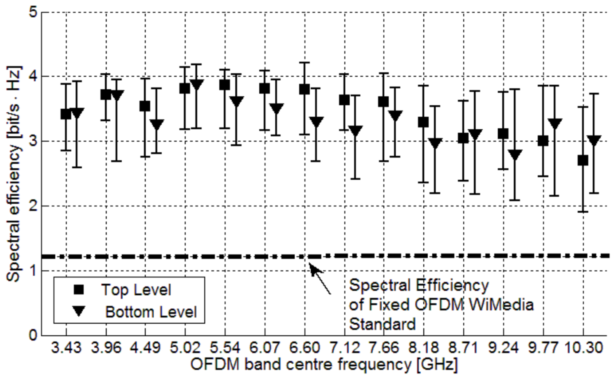

Fig. 2. Spectral efficiency of an adaptive OFDM system with bandwidth 528 MHz as a function of center frequency. The error-bars represent the minimum/maximum measured spectral efficiency over 72 measurements.

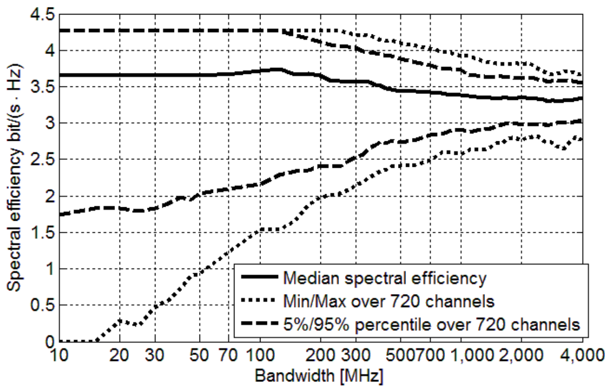

Fig. 3. The spectral efficiency of adaptive OFDM for various total OFDM symbol bandwidths

are guaranteed for more than 99% of the cases.

V. Conclusion

This letter has studied adaptive OFDM as a suitable candidate for wireless UWB communication in computer chassis. Results from an extensive measurement campaign have led to two main conclusions:

1) If existing WiMedia systems were enhanced to support adaptive OFDM, a system with a bandwidth of 528 MHz would enable data-rates above 1 Gbps across the entire UWB band and above 1.5 Gbps for the lowest 6 WiMedia Bands. Our measurement suggests that this measure should at least double the spectral efficiency of WiMedia system, it is also expected to improve its energy consumption per bit.

2) The guaranteed (99% of cases) spectral efficiency of a UWB OFDM system with adaptive subcarrier modulation increases with bandwidth. Efficiency >2 bit/(s·Hz) is guaranteed for bandwidths above 200 MHz. The practical importance of this result is that the guaranteed data-rate for such a system increases more than linearly with bandwidth. Our results suggest that bandwidths of 500 MHz and 1 GHz guarantee data-rates of 1.2 and 2.6 Gbps, respectively.

The disadvantage of this technique is that the transmitted waveform is tailored for the specific frequency selectivity of the channel between the transmitter and the receiver. This frequency selectivity is a location-specific fingerprint of the amplitudes and delays of the multipath rays. Hence, the adaptive OFDM system can only be used for point-to-point data-links, not for complex information dissemination in multi-node networks as e.g. in [24].

In summary, despite the location-specific drawback the adaptive OFDM for wireless interconnects in computer chassis or other confined environments it is believed to be a power efficient, high-data-rate competitor to existing wired connections for ranges above 10 cm.

References

[1] P. Chiang, S. Woracheewan, C. Hu, L. Guo, R. Khanna, J. Nejedlo, and H. Liu, "Short-range, wireless interconnect within a computing chassis: Design challenges," *Design Test of Computers, IEEE*, vol. 27, no. 4, pp. 32–43, 2010.

[2] S. Deb, A. Ganguly, P. Pande, B. Belzer, and D. Heo, "Wireless noc as interconnection backbone for multicore chips: Promises and challenges," *Emerging and Selected Topics in Circuits and Systems, IEEE Journal on*, vol. 2, no. 2, pp. 228–239, 2012.

[3] B. Jung and C. Yue, "Trends and outlook of wireless i/o's for short-range connectivity and beyond," in *Radio-Frequency Integration Technology (RFIT), 2011 IEEE International Symposium on*, 2011, pp. 33–36.

[4] D. DiTomaso, S. Laha, S. Kaya, D. Matolak, and A. Kodi, "Energy efficient modulation for a wireless network-on-chip architecture," in *New Circuits and Systems Conference (NEWCAS), 2012 IEEE 10th International*, 2012, pp. 489–492.

[5] J. Gelabert, D. Edwards, and C. Stevens, "Experimental evaluation of uwb wireless communication within pc case," *Electronics Letters*, vol. 47, no. 13, pp. 773–775, 2011.

[6] Z. M. Chen and Y.-P. Zhang, "Inter-chip wireless communication channel: Measurement, characterization, and modeling," *Antennas and Propagation, IEEE Transactions on*, vol. 55, no. 3, pp. 978–986, 2007.

[7] J. Karedal, A. Singh, F. Tufvesson, and A. Molisch, "Characterization of a computer board-to-board ultra-wideband channel," *Communications Letters, IEEE*, vol. 11, no. 6, pp. 468–470, 2007.

[8] S. Redfield, S. Woracheewan, H. Liu, P. Chiang, J. Nejedlo, and R. Khanna, "Understanding the ultrawideband channel characteristics within a computer chassis," *Antennas and Wireless Propagation Letters, IEEE*, vol. 10, pp. 191–194, 2011.

[9] Z. Chen, Y. P. Zhang, A. Q. Hu, and T.-S. Ng, "Bit-error-rate analysis of uwb radio using bpsk modulation over inter-chip radio channels for wireless chip area networks," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 5, pp. 2379–2387, 2009.

[10] C. Hu, R. Khanna, J. Nejedlo, K. Hu, H. Liu, and P. Chiang, "A 90 nm-cmos, 500 mbps, 3-5 ghz fully-integrated ir-uwb transceiver with multipath equalization using pulse injection-locking for receiver phase synchronization," *Solid-State Circuits, IEEE Journal of*, vol. 46, no. 5, pp. 1076–1088, 2011.

[11] S. Woracheewan, C. Hu, R. Khanna, J. Nejedlo, H. Liu, and P. Chiang, "Measurement and characterization of ultra-wideband wireless interconnects within active computing systems," in *VLSI Design, Automation and Test (VLSI-DAT), 2011 International Symposium on*, 2011, pp. 1–4.

[12] V. Sipal, B. Allen, D. Edwards, and B. Honary, "Twenty years of ultrawideband: Opportunities and challenges," *Communications, IET*, vol. 6, no. 10, pp. 1147–1162, 2012.

[13] V. Sipal, B. Allen, and D. Edwards, "Multi-tone frequency shift keying for ultrawideband wireless communications," *Communications, IET*, vol. 6, no. 10, pp. 1170–1178, 2012.

[14] G. Heidari, *WiMedia UWB - technology choice for wireless USB and Bluetooth*. John Wiley & Sons, 2008.

[15] V. Sipal, J. Gelabert, C. Stevens, B. Allen, and D. Edwards, "Impact of confined environments on wimedia uwb systems," in *Antennas and Propagation Conference (LAPC), 2011 Loughborough*, 2011, pp. 1–4.

[16] L. Zeng, S. McGrath, and E. Cano, "Rate maximization for multiband ofdm ultra wideband systems using adaptive power and bit loading algorithm," in *Telecommunications, 2009. AICT '09. Fifth Advanced International Conference on*, 2009, pp. 369–374.

[17] L. Jie and W. Yiwen, "Adaptive resource allocation algorithm based on sequence strategy of modulated mimo-ofdm for uwb communication system," in *Measuring Technology and Mechatronics Automation (ICMTMA), 2010 Int. Conf.*, vol. 1, 2010, pp. 424–427.

[18] M.-S. Baek and S. H.-K., "Performance evaluation of adaptive uwb system with multiple antennas," *rogress In Electromagnetics Research C*, vol. 5, pp. 1–12, 2008.

[19] M. Magani, L. Guo, and X. Chen, "Improved ber performance on mb-ofdm uwb system using adaptive bit loading," in *Ultra-Wideband (ICUWB), 2010 IEEE Int. Conf.*, vol. 1, 2010, pp. 1–4.

[20] L. Toni and A. Conti, "Does fast adaptive modulation always outperform slow adaptive modulation?" *Wireless Communications, IEEE Transactions on*, vol. 10, no. 5, pp. 1504–1513, 2011.

[21] IEEE, "Ieee802.11-2012," IEEE, Tech. Rep., 2012.

[22] A. Conti, M. Win, and M. Chiani, "Slow adaptive m -qam with diversity in fast fading and shadowing," *Communications, IEEE Transactions on*, vol. 55, no. 5, pp. 895–905, 2007.

[23] W.-L. Li, Y. Zhang, A.-C. So, and M. Win, "Slow adaptive ofdma systems through chance constrained programming," *Signal Processing, IEEE Transactions on*, vol. 58, no. 7, pp. 3858–3869, 2010.

[24] A. Conti, M. Guerra, D. Dardari, N. Decarli, and M. Win, "Network experimentation for cooperative localization," *Selected Areas in Communications, IEEE Journal on*, vol. 30, no. 2, pp. 467–475, 2012.