Asymmetric Dual-Band UWB / 60 GHz Demonstrator

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Abstract—This paper describes a pragmatic approach on the up-conversion of WiMedia compliant UWB signals into the 60 GHz band. This dual band concept is based on propagation measurements at [3.1-10.6] and 60 GHz. Due to stringent frequency regulation, UWB systems operating in the 3.1 to 10.6 GHz bands are both bandwidth limited and power limited. Therefore, many potential users hesitate to deploy this technology. Up-conversion to the 60 GHz band and enhanced baseband parameters can make UWB technology more reliable and hence, more attractive. An experimental system based on a commercially available UWB development kit and IHP’s 60 GHz chip-set has been developed. The system architecture is described. Measurement results indicate that this combination may be interesting for many applications.

Keywords—UWB; OFDM; 60 GHz; millimeter wave; WPAN

I. INTRODUCTION

This paper addresses Ultra Wide Band (UWB) air interfaces for short range radio transmissions supporting data rates ranging from 53 Mbps to 480 Mbps [1]. We consider two interesting RF bands: the [3.1-10.6] GHz band and the [57-66] GHz band. These bands have been selected for their equivalent spectrum availability. Both bands are used for Wireless Personal Area Network (WPAN) applications. The appropriate RF band can be selected depending on spectrum occupancy, desired data rates and radio coverage requirements. This use of multiple RF bands can also be seen as an extension of Frequency Division Duplex (FDD) access modes.

The targeted system features highly spectrum efficient OFDM modes, common baseband processing, as well as advanced interleaving and sub-carrier mapping schemes [2][3]. In this paper, experimental channel propagation characteristics in the [57-66] GHz and [3.1-10.6] GHz bands are analyzed to justify common baseband algorithms for WPANs operating in those frequency bands [4]. WiMedia and 60 GHz up-converted WiMedia systems are implemented at the uplink and downlink respectively. This dual band operation would enable the support of asymmetric data rates and introduce diversity on the radio link. The concept of multiple RF bands using both 5 GHz and 60 GHz for WLAN applications has been first introduced within the IST Broadway project [5]. In this project, backward compatibility between Hiperlan2/ IEEE802.11a and the mm-Wave Broadway system was ensured considering a sub-channel size of multiples of 20 or 40 MHz and a sub-carrier spacing of multiples of the IEEE802.11a sub-carrier spacing. Increased subcarrier spacing was chosen to mitigate the effect of increased phase noise at 60 GHz. The Broadway system offers data rates up to 360 Mbps to ensure a high capacity multi-user transmission.

For future WPAN applications based on MultiGigabit Wireless Systems (MGWS), we introduced the concept of an UWB-OFDM PHY layer using multiple RF bands with a common baseband processor [2][3][4]. The proposed bandwidths are multiples of the WiMedia bandwidth. Within the IST-MAGNET project, multiple WPAN air interfaces depending on the desired data rate have been designed. The considered systems included UWB-FM transmissions for low data rates (100-300 kbps), Multi-Carrier Spread Spectrum (MC-SS) techniques for high data rates up to 150 Mbps, and the WiMedia system [6][7]. The deployment of new license free RF-bands is motivated by a data rate increase by a factor of 10 in the past ten years, and the progressive introduction of High-Definition (HD) content into various services. Recent IEEE802.15.3c usage models [8] show the relevance of MGWS for short range applications.

In the future, we intend to implement multiple air interfaces using the [3.1-10.6] GHz and the 60 GHz bands, including the WiMedia specification [1], an enhanced WiMedia system up-converted to 60 GHz, as well as optimized UWB-OFDM systems [2][3].

In this paper, we demonstrate dual band UWB WiMedia system capabilities and extend this concept to higher data rates considering link level simulations. Section II describes future MGWS applications. Section III demonstrates the dual band concept, provides link level performance data and enhanced features for the system. Sections IV and V describe the dual band WiMedia system front end and provide experimental results. The last section is dedicated to conclusions and future issues for the UWB dual band prototype.
II. MULTI GIGABIT WPAN APPLICATIONS

A. Motivations and Dual Band Architectures

The MGWS concept will be investigated within the ICT-FP7 project OMEGA [9]. This project is aimed at designing and building a home network, enabling 1 Gbps data rates and low latency over heterogeneous technologies. Radio technologies are a natural candidate for the end connectivity of this home network. WPAN systems are particularly attractive since they offer very high data rates. Indeed, WiMedia technologies are becoming commercially available, and promise a maximum throughput of 480 Mbps. Higher, multi-Gigabit throughput will be possible with millimeter-wave technologies based on IEEE802.15.3c WPAN proposals [19], FTR&D UWB-OFDM PHY layer design [2][3] or enhanced 60 GHz up-converted WiMedia-like systems.

Spectrum represents a scarce resource, especially at the lower frequency bands. Due to the large available bandwidth, and the limited range, WPAN systems at 60 GHz have a significant advantage regarding interference and security.

B. Regulation Issues


The FCC defines UWB signals as having a fractional bandwidth greater than 0.20 or an absolute bandwidth greater than 500 MHz. Fractional bandwidth denotes the ratio between signal bandwidth and carrier frequency. In the {3.1-10.6} GHz band, the radiated power per frequency unit is limited to -41.3 dBm/MHz and the maximum peak EIRP to 0dBm in 50 MHz transmission bandwidth. For the WiMedia OFDM system, the {3.1-10.6} GHz band is split into 5 band-groups composed of 3 logical sub-channels each. Initially, the ECC limits the UWB radiations to the {6-8.5} GHz band. For the First Generation of UWB (1G), the ECC defined a ‘phased approach’ allowing UWB devices to operate in the {4.2-4.8} GHz band with -41.3 dBm/MHz until 2010. After 2010, (1G) UWB would be enhanced towards (2G) which is improved with different mitigation techniques in this band. The actual spectrum mask in USA (FCC) and Europe (ECC) is illustrated in Fig. 1.

Regulation for the {57-66} GHz band allowing license exempted use, are specified in FCC 15.255 in USA, and CEPT Recommendation in Europe. The ETSI document TR 22-03 [12] and ECC Report 114 ETSI DTR/ERM [13] detail regulation issues in Europe where the {59-63} GHz band is mainly assigned to WPAN applications. In Fig. 2, the EIRP numbers represent maximum values including a particular antenna gain. In some countries the total radiated power is also limited and denoted as the ‘Max’ value.

In Europe, the band {63-64} GHz is reserved for Intelligent Transportation Systems (ITS). Frequency regulation for {57-66} GHz in Europe is not finalized yet. The Millimeter Wave band Frequency Study Group (MWFSG) in Korea allocated the {57-64} GHz spectrum to indoor WPANs with a maximum transmit power of 10 dBm. In Japan, the band is defined at {59-66} GHz with similar power limits. Fig. 2 shows the allocation of the unlicensed 60 GHz band for Europe, Australia, Japan, Korea, Canada, and USA.

III. DUAL BAND UWB PHY LAYER SYSTEM AND LINK LEVEL PERFORMANCE

A. UWB Propagation Modeling

This section provides UWB propagation characteristics of the channel, derived from France Telecom R&D measurements carried out in the MAGNET project [6] at 60 GHz and Pagani’s thesis work [14] in the {3.1-10.6} GHz. The comparison between these two RF bands is performed considering RMS delay spread (DS) and RMS power spread (p). Measurements are filtered with the WiMedia OFDM spectrum. Under dual band considerations, similar filtering is performed upon 60 GHz and {3.1-10.6} GHz measurements. Channel sounding techniques using a Vector Network Analyzer (VNA) are based on a frequency sweeping mode and transfer function assessments [6][14]. A specific channel model, the ‘Canal Enregistré de Propagation Déterministe’ (Recorded Deterministic Propagation Channel - CEPD) was developed [6][15]. The input files of the CEPD model describe dedicated propagation scenarios and antenna designs. CEPD output realizations provide appropriate FIR filter coefficients associated with a particular scenario for a specific PHY layer. The advantage of the model is that it is based on experimental results without stochastic assumptions on Doppler variations, the cluster number and power delay.
profile shaping. Wideband selectivity parameters are summarized in Table I and Table II. For the {3.1-10.6} GHz band, parameters have been derived for each WiMedia band group (see Section II.B). We can observe that in the LOS case, the RMS delay spread is smaller in the 60 GHz band with respect to the {3.1-10.6} GHz band. In the NLOS case, the RMS delay spread is similar in both bands for comparable Tx-Rx distance. This validates the choice of a common baseband processing in these two frequency bands: a system designed for the {3.1-10.6} GHz band will be well adapted for transmission at 60 GHz.

| TABLE I. RMS DELAY SPREAD AND RMS POWER IN {3.1-10.6} GHz |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|
| Centre frequency                | Band#1           | Band#2           | Band#3           | Band#4           | Band#5           |
| Distance (m)                    | 4                | 4                | 4                | 4                | 4                |
| RMS Delay spread σ_DS (ns)      | 7.9              | 8.25             | 7.55             | 7.71             | 7.19             |
| RMS power σ_P                   | 0.96             | 1.13             | 1.26             | 1.80             | 2.02             |

<table>
<thead>
<tr>
<th>NLOS</th>
<th>Band#1</th>
<th>Band#2</th>
<th>Band#3</th>
<th>Band#4</th>
<th>Band#5</th>
</tr>
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<tr>
<td>Distance (m)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>RMS Delay spread σ_DS (ns)</td>
<td>14.3</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>13.3</td>
</tr>
<tr>
<td>RMS power σ_P</td>
<td>1.73</td>
<td>1.43</td>
<td>1.76</td>
<td>1.81</td>
<td>1.58</td>
</tr>
</tbody>
</table>

| TABLE II. RMS DELAY SPREAD AND RMS POWER AT 60 GHz |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|
| CEPD scenario                  | LOS channel      | Moderate NLOS channel | Selective NLOS channel |
| Distance (m)                    | 7.61              | 8.36             | 12.11             |
| RMS Delay spread σ_DS (ns)      | 2.73              | 7.38             | 12.75             |
| RMS power σ_P                   | 0.66              | 1.97             | 0.8              |

B. WiMedia PHY Layer Design

The WiMedia PHY [1] uses OFDM transmission together with time-frequency hopping denoted MultiBand (MB) processing. UWB-OFDM is performed using a FFT length of 128 over 528 MHz logical sub-channels [1].

WiMedia supports data rates ranging from 53.3 Mb/s to 480 Mb/s by applying different coding rates and spreading techniques.

For the MB processing, the {3.1-10.6} GHz spectrum is split into 5 band-groups, each composed of 3 sub-channels of 528 MHz. Time-Frequency hopping is introduced through Time-Frequency Codes realized by a Time-Frequency Interleaver (TFI). A TFI provides RF sub-channel allocation patterns attributed to a single user during a period of 6-OFDM symbols. MB processing with different TFI patterns allows several devices operating in the same area using different RF sub-channels. This limits collisions and introduces frequency diversity for each user.

Spreading techniques are intended to support FEC convolutional coding and enhance performance. Frequency Domain Spreading (FDS) is done by mapping symbols in the OFDM spectrum according to a Hermitian symmetry in order to generate a real signal in the time domain. Time domain spreading consists in transmitting simultaneously the same OFDM signal using two separate RF sub-channels connected to a band-group and select the best one. Information bits are first encoded with a convolutional code of 1/3 mother code rate, and a constraint length of 7. Encoded bits are punctured, interleaved using a three stage interleaver and mapped to data symbols. OFDM modulation is performed with a zero-forcing suffix to cope with ISI and RF sub-channel switching latency.

A binary interleaving process completes the MB processing. Block interleaving is performed thanks to a three stage interleaver applied upon six consecutive OFDM symbols allocated to three RF bands.

![Figure 3. WiMedia PHY Layer with MB process.](image)

The first stage performs binary spreading over 6 consecutive OFDM symbols based on a matrix interleaver composed of \( N_c = N_{CBPS} \) rows (\( N_{CBPS} \) is the number of coded bits per OFDM symbol) and \( N_c = 6/N_{TDS} \) columns.

The second step is intra-symbol tone interleaving that permutes the bits on different subcarriers within one OFDM symbol. This interleaver is also a matrix interleaver with an interleaving depth \( K' = N_{CBPS} \) where \( N_{CBPS} \) is the number of encoded bits per OFDM symbol (\( N_{CBPS} = N_{TINT} \times 10 \)).

The third step is a cyclic shifter that cyclically shifts bits within the span of the symbol interleaver (6 OFDM symbols), with different cyclic shifts within each block of \( N_{CBPS} \). The cyclic shift parameter is \( N_{cyc} = N_{CBPS}/6 \).

This allows exploiting frequency diversity, both for time-domain spreading and fixed-frequency-interleaved (FFI) codes. In simulations, we replace the guard sub-carriers with data-sub-carriers in order to enhance the data rate. Therefore, \( N_{cyc} \) is then adjusted to \( N_{cyc} = 36 \) and the second stage implements 11 columns in the matrix interleaver \( N_{TINT} = N_{CBPS}/11 \).

Table III provides WiMedia data rates and coding schemes and Table IV provides time related parameters.
### Table III. Data Rates, Modulation and Coding Schemes

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Modulation</th>
<th>Coding Rate $R$</th>
<th>FDS</th>
<th>TDS</th>
<th>Data bits per 6 OFDM symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.3</td>
<td>QPSK</td>
<td>1/3</td>
<td>YES</td>
<td>YES</td>
<td>420</td>
</tr>
<tr>
<td>80</td>
<td>QPSK</td>
<td>1/2</td>
<td>YES</td>
<td>YES</td>
<td>560</td>
</tr>
<tr>
<td>106.7</td>
<td>QPSK</td>
<td>1/3</td>
<td>NO</td>
<td>YES</td>
<td>840</td>
</tr>
<tr>
<td>160</td>
<td>QPSK</td>
<td>5/8</td>
<td>NO</td>
<td>YES</td>
<td>1120</td>
</tr>
<tr>
<td>200</td>
<td>QPSK</td>
<td>1/2</td>
<td>NO</td>
<td>YES</td>
<td>1680</td>
</tr>
<tr>
<td>320</td>
<td>DCM/QPSK$^1$</td>
<td>1/2</td>
<td>NO</td>
<td>NO</td>
<td>2240</td>
</tr>
<tr>
<td>400</td>
<td>DCM/QPSK$^1$</td>
<td>5/8</td>
<td>NO</td>
<td>NO</td>
<td>2800</td>
</tr>
<tr>
<td>480</td>
<td>DCM/QPSK$^1$</td>
<td>3/4</td>
<td>NO</td>
<td>NO</td>
<td>3360</td>
</tr>
</tbody>
</table>

$^1$: Modulation performed in link level simulations

### Table IV. Time Related Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td># of data subcarriers $N_{SD}$</td>
<td>100/110$^1$</td>
<td>Cyclic prefix duration $T_{cyc}$</td>
<td>70 ns</td>
</tr>
<tr>
<td># of pilot carriers $N_{PC}$</td>
<td>12</td>
<td>IFFT/FFT period $T_{FFT}$</td>
<td>242.42 ns</td>
</tr>
<tr>
<td># of DC carriers $N_{DC}$</td>
<td>1</td>
<td>Symbol interval $T_{sym}$</td>
<td>312.42 ns</td>
</tr>
<tr>
<td># of guard carriers $N_{GC}$</td>
<td>10/0$^1$</td>
<td>FFT size $N_{FFT}$</td>
<td>128</td>
</tr>
<tr>
<td>Channel bandwidth $B_{FFT}$</td>
<td>528 MHz</td>
<td>FEC generator polynomials</td>
<td>(133, 165, 171)</td>
</tr>
</tbody>
</table>

C. Link Level Performance

For the experiments in Sections IV and V, we make the assumption that the power delay profile is equivalent within the {3.1-10.6} GHz band and the 60 GHz band. Therefore, we used for our simulations the same CEPD propagation channel model to assess link level performance. Link level results for LOS and selective NLOS channels are presented in Fig. 4 and Fig. 5 respectively. BER results exhibit high sensitivity to FEC code rates. This effect is increasing with multipath selectivity of the channel as illustrated in Fig. 5 where 8 dB degradation is observed between code rates ½ and ¾ for a selective channel. For LOS channels (Fig. 4), this degradation is limited to 3 dB.
B. UWB Combination with 60 GHz Front-end

Initially a complete 60 GHz OFDM demonstrator was developed. The channel bandwidth of this demonstrator is 500 MHz. The analog front-end is based on a superheterodyne architecture with an intermediate frequency of 5 GHz. This allowed the re-use of circuit blocks which were developed for 5 GHz WLAN systems earlier. The OFDM baseband processor is implemented on an FPGA board and allows data rates up to 1.08 Gbit/s \[18][19].

On the basis of this solution, we developed a combined UWB/60 GHz prototype. This prototype consists of a commercially available WiMedia compliant UWB development system, extended with our 60 GHz radio front-end. The UWB system uses the frequency band from \{3.1-5\} GHz. The three centre frequencies of the UWB-OFDM transmission are: \(f_1 = 3.432\) GHz, \(f_2 = 3.96\) GHz and \(f_3 = 4.488\) GHz. This is equivalent to band group#1 in Table I. These centre frequencies are relatively close to the 5 GHz IF of our 60 GHz up- and down-converters. Hence, it appeared conceivable to simply upconvert the UWB signal from the 3-to-5-GHz band to the 60 GHz band using our existing up-converter. Empirical experiments showed that it is possible to directly connect the 60 GHz up- and down-converters to the antenna output or input of the UWB development system. To show that the same OFDM signal can be transmitted both in the 3-to-5-GHz band as well as in the 60 GHz band, we decided to use the 60 GHz band for the downlink and 3-to-5-GHz (UWB) for the uplink. For this purpose, the frequency hopping was switched off. The architecture of our system is shown in Fig. 7. For each of the two transceivers, a TX/RX switch is needed. The switches are controlled with a suitable signal derived from the UWB development board.

After up-conversion, the transmit signal is band-filtered and directly fed to a Vivaldi antenna. The up-converter contains an integrated power amplifier which delivers about 3 dBm average output power.

The receiver reciprocates the architecture of the transmitter. Here, the signal received by a Vivaldi antenna is fed directly to the receiver chip. It contains an integrated LNA and the complete down-converter to the 5 GHz/UWB band. The resulting IF signal is used as an input to the UWB development board. This demonstrator allows a transparent asymmetric TCP/IP link. The UWB development boards have to be configured as master and slave as indicated in Fig. 7. A photo of the master transceiver is shown in Fig. 8. Here the transmit signal is upconverted to the 60 GHz band whereas the receiver uses the UWB frequency band. Please note that the observed link performance is determined both, by the 60 GHz and UWB transmission.

Figure 8. Photo of experimental UWB / 60 GHz communication system (Master transceiver only).

V. MEASUREMENT RESULTS

The test system consists of commercially available UWB boards with a 100 Mbit/s Ethernet. An USB interface is used to control and setup the UWB baseband and MAC parameters and to get statistical information about the wireless link quality of the system.

The pure UWB system works in bidirectional mode. For our test scenario we use the Tx/Rx antenna switch signal of the UWB system to split the bidirectional mode in a 60 GHz downlink and an UWB uplink. A small Rx/Tx board with a 5 GHz antenna switch is inserted between the UWB frontend and the UWB antenna (see Fig. 7). The 60 GHz transmission in one direction and the \{3.1-10.6\} GHz transmission in the other direction allows maintaining a transparent TCP/IP connection. To test the link quality of such hybrid system, we used the statistical information from the UWB baseband and monitored the quality of a transmitted video.

Since we have no access to the internal operation of the UWB-OFDM baseband processor, we were only able to do some symptomatic measurements. In particular, the distance of communication is an interesting parameter. Having connected the system, we were pleased to observe that the communication was generally quite stable. The maximum distance for line-of-sight communication was 8 m. In this case, the data rate was 53 Mbit/s. For higher data rates, the maximum distance was reduced as can be seen in Fig. 9. For very high data rates of 400 Mbit/s and 480 Mbit/s also the minimum distance was increased. The maximum data rate of 480 Mbit/s can only be achieved within a range of 40 cm to 1 m. The reasons for the increased value of the minimum distance are obviously saturation effects and associated nonlinearities in the receiver. It has not yet been investigated whether these limitations are due to the UWB or the 60 GHz link.

Another interesting observation was made with the demonstrator in a desktop scenario. We found some unstable operation when transmitter and receiver were directly placed on one table with about 30 to 60 cm distance, whereby the height of the antennae above the table was about 2 cm. After some investigations it was discovered that the unstable operation is a result of interference due to the 1st Fresnel
zone. A simple solution of the problem is increasing the height of the demonstrator (i.e. the height of the 60 GHz antennae) above the table surface to about 15 cm or more.

With our hybrid 60 GHz – WiMedia UWB test system, we could verify the compatibility of these two different wireless technologies. This could be an interesting solution to enhance the advantage of high data rate communication in the 60 GHz band with the robustness of the transmission in the UWB frequency range.

VI. CONCLUSIONS

This paper investigates the potential of upconverting a WiMedia UWB system to the 60 GHz band. The combination of mm-Wave and usual UWB bands is motivated by spectrum availability and the targeted common WPAN applications. The dual band concept can also be considered as a frequency diversity and coverage enhancement technique. Within the context of UWB, this concept is also considered as an extension to the multiband processing [2]. A propagation analysis of the channel has been performed proving that common baseband processing can be considered for frequency ranges {3.1-10.6} GHz and 60 GHz RF bands. Link level performance figures are obtained considering multipath 60 GHz UWB channel models using the generic CE PD model [15] and appropriate 60 GHz Channel Impulse Responses issued from WPAN measurements carried out within the framework of MAGNET [6]. Simulation results exhibit a high sensitivity to FEC code rate values. The difference between simulations and experimental results, come from selectivity variations of the channel with a higher frequency selectivity in simulations associated with typical LOS CEPD realizations for a distance of 7 m and receiver/transmitter antenna aperture close to 70° (Table I).

With our dual-band 60 GHz/WiMedia UWB test system, we could verify the compatibility of these two different wireless technologies. This could be an interesting solution to combine the advantage of high data rate communication in the 60 GHz band with the robustness of the transmission in the UWB frequency range.

Further work planned in the OMEGA project [9] will focus on making the combined UWB / 60 GHz radio technologies widely available for future application in a home scenario.

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