FREQUENCY MODULATED CONTINUOUS TECHNOLOGYFOR RADIO CHANNEL MEASUREMENTS IN THE 60 GHZ BAND

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Abstract: The architecture of an UWB multi-band channel sounder is presented. The sounder architecture provides an FMCW source to enable measurements in the frequency range up to 1 GHz (which covers the TV white space / digital dividend), the 2.2 – 2.9 GHz band (ISM and LTE) and the 4.4 – 5.9 GHz band (ISM / WiLAN). Additional frequency converters support operation in the 16 GHz and 60 GHz bands. Here we have configured a 2 by 2 MIMO system in the 60 GHz band specifically targeting channel measurements to support the development of on-body networks and short range backhaul communication networks. Performance results in the 2.4 GHz ISM band demonstrate the resolution of the sounder.

1 INTRODUCTION

The availability of broad blocks of spectrum in the 60 GHz band provides the opportunity to support very high data rate systems. This includes in-flight entertainment content delivery to the seat-back in high capacity passenger aircraft (Garcia, et al., 2009). In addition the 60 GHz band is attractive for on-body networks since antennas can be physically small and the excess absorption assists covert operation of equipment for military applications. Initial on-body measurements (Hall, Hao and Cotton, 2010) at 60 GHz were performed with a 60 GHz SISO channel sounder with ~ 1 GHz of channel width (Feeney and Salous, 2008). These initial measurements stimulated the development of a new system which has 2 by 2 MIMO capability and 6 GHz channel width. The new sounder is also able to support higher sweep repetition rates (more than 2.5 kHz) which provides an unambiguous Doppler measurement to +/- 1.25 kHz. The architecture of the sounder also facilitates the generation of sweep signals which can be used in a broad range of bands which are appropriate for short range wireless applications in cluttered environments.

Additionally the new architecture also addresses the physical size and power limitation of the original sounder which limited operation to either a laboratory environment or within a vehicle (Landrover) that had been specifically adapted to support the operation of the sounder receiver. The new sounder can be operated directly from a 12 V vehicle (or battery pack) supply and is contained within a single 3U rack. Each of the transmitter and receiver consume ~90 W.

2 FMCW CHANNEL SOUNDING

The equipment has been designed to perform channel sounding using the FMCW technique. The FMCW sounder transmitter stimulates the channel with CW signal which is swept across the channel with a constant rate of change of frequency with respect to time. At the receiver a similar sweep provides the local oscillator input to a frequency mixer which is operated as a correlator. The output from the mixer is a beat frequency between the local oscillator and the received signals. Different multipath components produce different beat frequencies. Thus the multipath structure is delineated via spectral analysis using either a

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spectrum analyser for online monitoring or FFT processing following digitisation. A second stage of spectral analysis over a number of frequency sweeps for each time delayed multipath component gives the delay-Doppler function which can be used to estimate the power delay profile and the Doppler spectrum of the channel. Other channel functions such as the time variant frequency function can be also evaluated via a second FFT on each sweep or envelope detection of the received output of the detector.

3 SYSTEM DESCRIPTION

The system block diagram of the 2 by 2 MIMO 60 GHz sounder is shown in Figure 1.

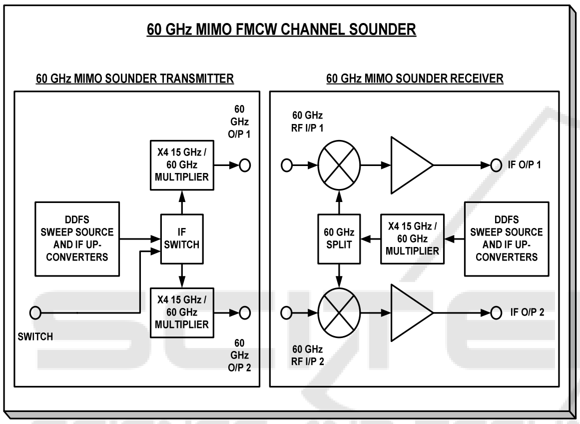

Figure 1: Block diagram of 60 GHz sounder.

At the transmitter and receiver identical sweep generation systems are used as shown in Figure 2.

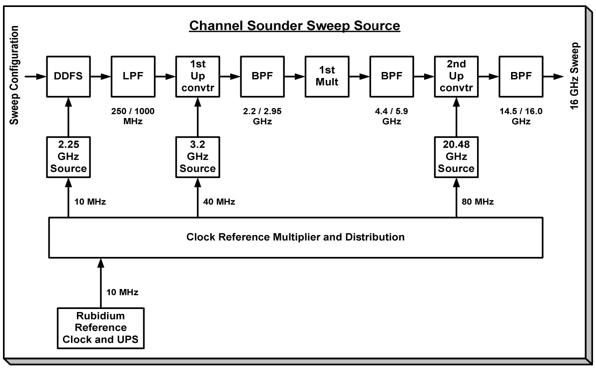

Figure 2: Sweep Generator Block Diagram.

The sweep generator contains three sub-modules: reference unit, sweep source and auxiliary converter. These modules are housed in 3U 19" rack cases and can be operated from mains or 12 V battery power.

The reference unit contains a Rubidium disciplined OCXO with an uninterruptable supply with internal battery back-up (~1 hour). This enables continuous operation of the Rubidium standard should the system be temporarily moved from the mains supply as for example to be set up in a vehicle or moved to location. The reference module also includes a distribution module which provides multiplication and buffering of the 10 MHz internal standard. Outputs are provided at 10 MHz, 20 MHz, 40 MHz and 80 MHz. These signals are used as references for the various phase locked loops in the sweep generator, for system synchronisation and for clock for the analogue to digital converter in the data acquisition unit. Figure 3 shows the UPS and the reference multiplier and distribution boards located on the underside of the reference module.

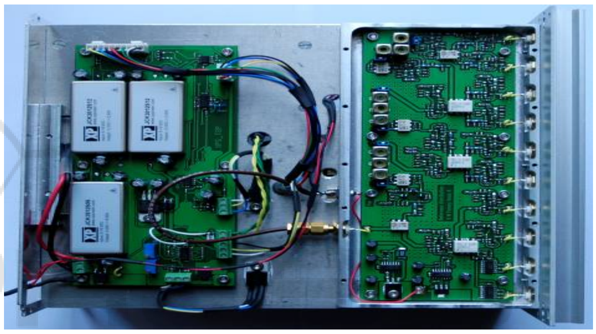

Figure 3: Reference module internal view.

The sweep source module consists of several stages of up-conversion to cover the various frequency bands. At baseband, a Direct Digital Frequency Synthesiser, DDFS which is configured via a USB interface uses a 2.25 GHz PLL clock source (f_{ck}) derived from the 10 MHz reference. This enables the generation of frequency sweeps up to 1 GHz. The DDFS has a frequency update rate equal to $f_{ck}/32$ which enables the generation of short duration sweeps or equivalently high waveform repetition rates for high Doppler coverage. The DDFS has the capability of either to free run or to be synchronised to an external trigger signal. An additional marker signal is available to confirm the start of the sweep which can be used to synchronise the data acquisition unit or to trigger other DDFS units. The DDFS output is band-limited to eliminate alias signals using a 15 pole low-pass filter which has been fabricated as a distributed design on a Rogers 4003 substrate. The filter and its measured response are displayed in Figure 4. Taking the output of the DDFS directly, measurements in the Digital dividend band around 800 MHz and the VHF band can be performed using suitable RF front ends at the transmitter and at the receiver.

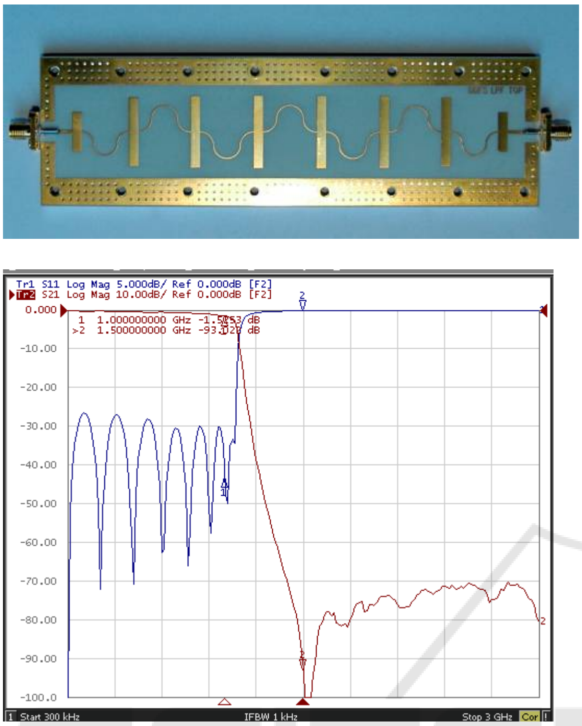

Figure 4: DDFS low pass filter and its frequency response.

To cover the LTE band and ISM bands the frequency range 2.2-2.95 GHz was chosen as the first intermediate frequency (IF) following the DDFS output. This gives an overall 750 MHz instantaneous bandwidth when the DDFS is programmed to sweep from 250 MHz up to 1 GHz. This IF is realised by up-converting the DDFS output using a heterodyne converter which uses a high-side local oscillator at 3.2 GHz derived from a 40 MHz reference. The lower sideband output of the heterodyne converter is selected using a nine pole band-pass filter. This filter provides more than 50 dB of attenuation to the upper sideband and local oscillator residual response.

The 3.2 GHz PLL in the up-converter and the 2.25 GHz PPL used as a clock to the DDFS have a similar PCB design as shown in Figure 5 where the frequency band is selected via appropriate choice of the VCO and the loop filter parameters. This provides an efficient design and fabrication advantage for reproducibility of the sounder. The first heterodyne up-converter is shown in Figure 6.

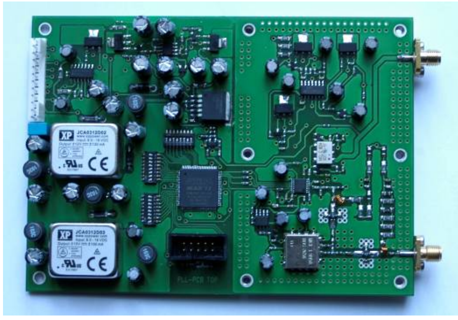

Figure 5: 2.25 and 3.2 GHz sources.

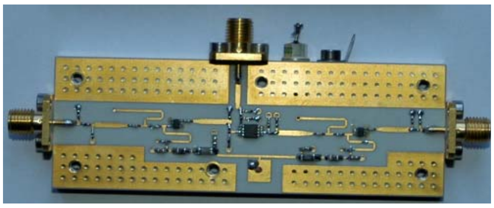

Figure 6: First heterodyne up-converter.

The second IF frequency is generated by doubling the frequency output of the first heterodyne up-converter. When swept across the 2.2-2.95 GHz band, this generates a 1.5 GHz frequency sweep from 4.4-5.9 GHz which provides high resolution of multipath. This frequency range also covers the second ISM band and the C band at 5.2 GHz. The realised frequency doubler consists of an amplifier and then a MMIC balanced doubler as shown in Figure 7. A band-pass filter provides attenuation of the fundamental and other harmonic outputs from the doubler. The 5 GHz band-pass filter is shown in Figure 8.

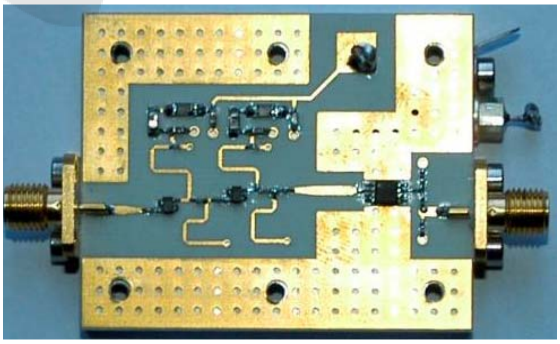

Figure 7: Frequency doubler to 4.4-5.9 GHz.

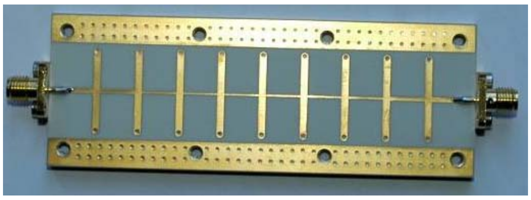

Figure 8: 4.4-5.9 GHz Band Pass Filter.

The second heterodyne stage up-converts the 4.4-5.9 GHz to 14.5-16 GHz using a high side local oscillator (LO) injection at 20.48 GHz. The LO signal is derived from a 5.12 GHz PLL with 80 MHz reference followed by two doubler stages. The output signal is available at the front panel at a nominal level of +17 dBm and is connected via external cables to the final stage of up-conversion to the 60 GHz band. This approach avoids the use of cables at 60 GHz with associated high loss and reduced dynamic range. This is particularly crucial for on-body networks where it is necessary to have the 60 GHz units on the user when performing measurements.

The 60 GHz transmitter module shown in figure 9 takes the 14.5-16.0 GHz signal and routes it to two separate times four (X4) multiplier modules via a two way PIN switch. This approach avoids the use of a 60 GHz switch which would provide limited isolation and incur losses at 60 GHz. This approach has demonstrated very high (more than 100 dB) of channel isolation at the transmitter. Each transmitter channel provides an active output power of nominally +7 dBm (5 mW).

Figure 9: Two channel 60 GHz transmitter module.

The receiver uses a single X4 multiplier to produce the reference signal for the correlator signal in the 60 GHz band. The output of the multiplier is routed to two separate mixers via a 3 dB multi-hole directional coupler. Each down-converter mixer/correlator has a signal-conditioning pre-amplifier on the mixer output. The directivity of the directional coupler in addition to the LO / RF isolation provided within the fundamental mode balance mixers provides a measured channel isolation of more than 50 dB. The pre-amplifier has a noise figure of ~5 dB, the mixer conversion loss is ~7 dB and including image noise the total receiver noise figure is ~15 dB.

4 SWEEP OUTPUT

The measured sweep output from the DDFS (after low-pass filtering) is shown in Figure 10 where the slope due to the sin*x*/*x* response of the DDFS can be observed. Although the DDFS does not have a compensation circuit for the sin*x*/*x* function, the slope does not impact on the compression of the received signal. However, if frequency variations across the swept bandwidth are of interest, then the output can be compensated for in processing. The plot in Figure 10 demonstrates excellent attenuation of the DDFS clock (2.25 GHz) and the primary alias response (1.25-2 GHz).

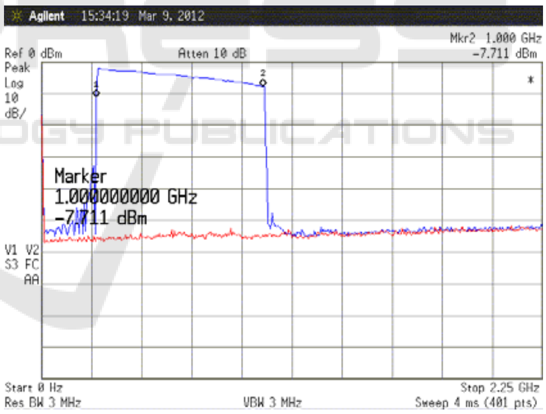

Figure 10: Output of DDFS after LPF.

The output from the sweep generator in the 14.5 GHz to 16 GHz band is shown in Figure 11 which demonstrates a substantially flat signal. This has been achieved through driving the amplifier close to compression. This approach can be used at any stage of the sweep generator if desired. However, in general the main sources of distortion for the compression of the chirp signal are phase non-linearity, and amplitude ripple in the pass band. Phase non-linearity reduces the resolution by broadening the width of the compressed pulse and amplitude ripple produces sidebands in the compressed signal which reduce the dynamic range of the measured impulse response of the channel.

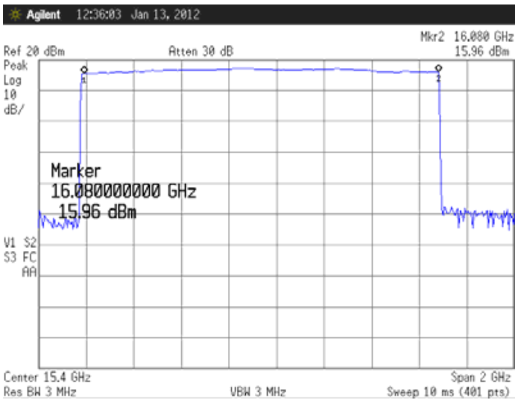

Figure 11: Frequency sweep after upconversion to the 14.5-16 GHz band.

5 MIMO ISOLATION

The measured isolation between the transmit channels and the receive channels is shown in Figure 12. The primary response between the active transmitter and the active receiver is shown in the blue trace. The green trace indicates the residual response from the non-active receiver channel. This demonstrates more than 50 dB of receiver channel isolation.

The red trace indicates the output from the receiver channel when the transmitter output channels are switched. This demonstrates ~100 dB of transmitter isolation.

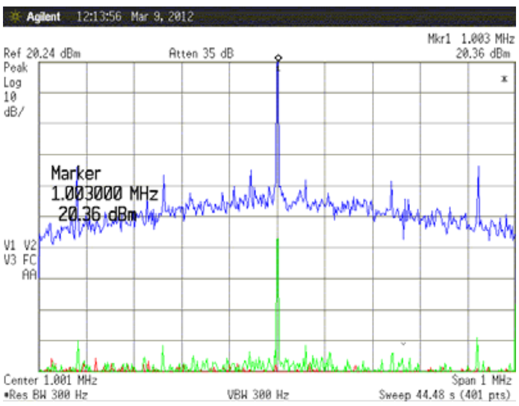

Figure 12: Measured MIMO isolation.

6 PHASE NOISE

The instantaneous dynamic range for an FMCW sounder is determined by the close to carrier phase noise of the sweep signals. Close in phase noise broadens the skirts of the compressed pulse and thus limits the resolution of multipath components. In addition close synchronisation between the transmitter and receiver sweeps is required to support Doppler discrimination. A time drift between the transmitter and receiver sources reduces the time interval over which Doppler analysis can be carried out which is particularly crucial for high resolution sounders.

This system uses 10 MHz Rubidium standards. The synthesisers within the equipment use digital phase / frequency comparators. This type of device has a phase noise floor which is proportional to frequency. The phase noise degradation due to division within the PLL is proportional to the frequency squared. Subject to the actual noise floor of the 10 MHz reference and the noise performance of the PLL digital devices the net phase noise degradation can be minimised by exploiting multiplication of the reference. Multiplication of the reference reduces the available range of PLL frequencies which can be realised. Here we have been able to exploit this technique at 3.2 GHz (40 MHz reference) and 5.12 GHz (80 MHz). The net improvement in the phase noise at 3.2 GHz is ~6 dB and ~8 dB at 5.12 GHz.

The PLLs use relatively wide closed loop bandwidths (~100 kHz) with high phase margin (~75˚). This approach minimises “noise bumps” in the phase noise response and is highly tolerant of loop parameter changes.

The DDFS sources were replaced with synthesised signal generators at 650 MHz and 650.125 MHz to produce a constant beat note at the output of the receiver at 1 MHz. This response is shown in Figure 13. Data have been recorded using 300 Hz resolution bandwidth to provide comparison with the prior 60 GHz system. The total system signal to noise ratio due to phase noise is ~52 dB at 300 Hz bandwidth. This represents an improvement of ~7 dB to the prior system (Feeney and Salous, 2008).

With 2.5 k sweeps / second this should provide more than 40 dB instantaneous dynamic range with an effective system bandwidth of 3 kHz (2.5 kHz FFT bin-width).

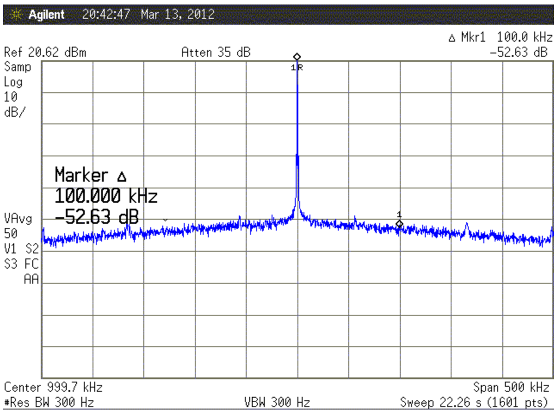

Figure 13: Complete system phase noise.

7 PERFORMANCE RESULTS IN THE ISM BAND

The sounder was tested from back to back measurements and in an indoor environment to verify its performance. Figure 14 shows the impulse response of the sounder in the 2.2-2.95 GHz band with both the overall 750 MHz swept bandwidth and for 375 MHz obtained by dividing the sweep into two 375 MHz sections. The figure shows that a dynamic range of about 60 dB is achieved with minimum distortion to the impulse response.

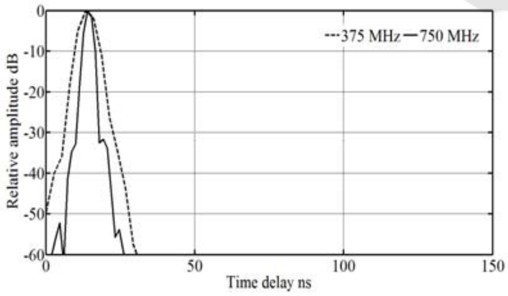

Figure 14: Back to back performance of channel sounder in the ISM band.

The sounder performance was also tested on the air in an indoor environment and Figure 15 shows the corresponding power delay profile obtained across 750 MHz bandwidth and across 375 MHz bandwidth. Although the reduced time delay resolution is evident in the lower bandwidth, the overall shape of the power delay profile shows a similar trend.

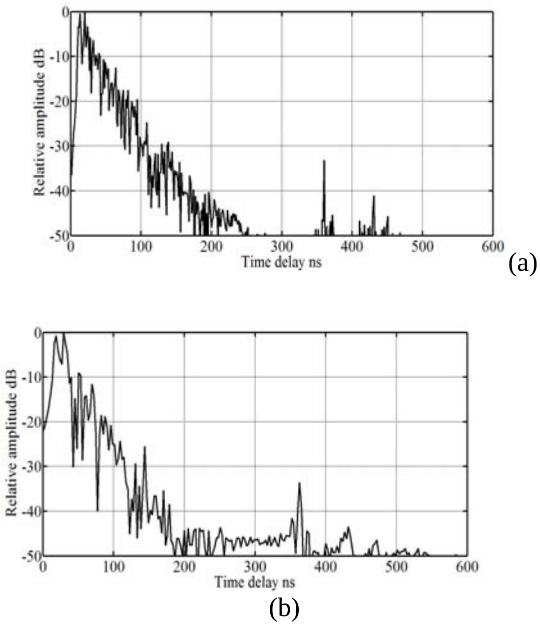

Figure 15: Indoor measurement in the ISM band with (a) 750 MHz swept bandwidth, (b) 375 MHz swept bandwidth.

8 CONCLUSIONS AND FURTHER WORK

A new compact FMCW sweep generator platform to support measurements in multiple frequency bands has been developed. The sounder has programmable bandwidth which at baseband can extend up to 1 GHz. With various stages of up-converters it can generate signals with bandwidths up to 750 MHz in the 2.2-2.95 GHz, and 1.5 GHz bandwidth in the 4.4-5.9 GHz band. Additional equipment to provide 2 by 2 MIMO capability within the 58-64 GHz band has been produced. Enhanced phase noise and excellent MIMO channel isolation has been demonstrated. Integration to the data acquisition system to complete the system is under way along with multiple transmitters and multiple receivers to enable simultaneous measurements in the two ISM bands in addition to the 60 GHz band. The sounder will be used in various indoor environments representative of test-beds in the CREW consortium to generate a typical channel model and to study the benefits of cooperative sensing. Other applications of the sounder include studies such as on-body network and car to car communication.

ACKNOWLEDGEMENTS

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