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A REVIEW OF RADIO CHANNEL SOUNDING TECHNIQUES

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ABSTRACT

This short paper will introduce the key approaches that have been adopted for channel sounding and describe systems that have been reported to date for measuring indoor and outdoor radio channels in the 1-5 GHz range of operating frequencies.

1. INTRODUCTION

The use of multiple antenna techniques for both transmitter and receiver is becoming an increasingly common method being used to exploit channel capacity of radio propagation. In order to evaluate effectiveness of such techniques, a description of the radio environment experienced by such systems is required. This can take the form of a purely theoretical model, a set of measurement data, or something that is a combination of the two. Generally it is accepted that any model requires some form of validation in terms of its applicability to practical environments, hence the requirement to perform channel sounding.

Such soundings can be specific to certain application scenarios, such as the characterising campaign described in [1]. Use of the resulting data can be made either directly as in [2] and [3], or indirectly through the use of models as in [4]. Using models derived from measurement data involves careful, and time-consuming analysis of the data in order to determine the modelling parameters ([5] and [6]).

Although the predominant application of sounders is in describing the radio channel over which other applications will operate, it is also possible to apply sounding technology to identify the environment within which the sounder is operating [7].

This paper will introduce the principles behind channel sounding, and identify design tradeoffs between different sounding strategies as an introduction to this special conference session. Examples of particular implementations will be given, along with key results obtained, and comparisons drawn between techniques.

2. MIMO SOUNDING

Figure 1 illustrates the basic concept of a MIMO channel sounder comprising multiple transmit elements and multiple receive elements. The diagram also illustrates the multiple propagation path nature of the channel which a MIMO system wishes to exploit. It is important to clarify that although the propagation environment can be assumed to be the superposition of a number of propagation paths, the receiver measures only the combined field resulting from all of these paths. A number of techniques may be employed to estimate the propagation paths based upon the received data, with various limitations on their performance. Assuming that there are N transmitters and M receivers, the system is classified as an $M \times N$ MIMO system.

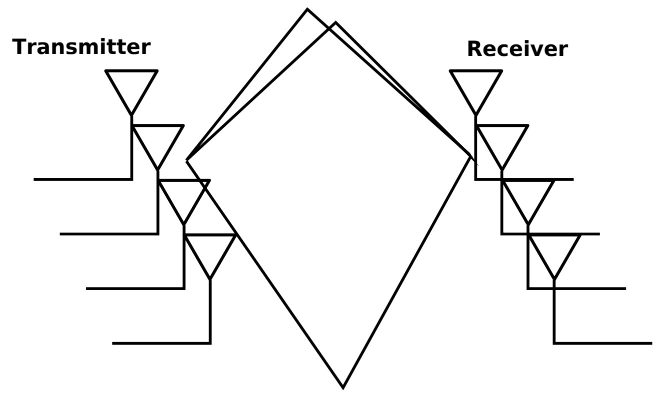

Figure 1: MIMO sounder principles

In essence, the aim of a channel sounder is to characterise the propagation path between each transmitter element and each receiver element, as well as the correlations between these elements. Thus, it is important to be able to distinguish between transmitting elements in order to formulate these relationships.

2.1 Multiplexing techniques

In essence, there are three possible methods by which transmitting antennae may be identified by the receiver:

- by transmitting on only one element at a specific time - that is time division multiplexing (TDM),
- by transmitting at a different frequency, or frequencies, on each element - frequency division multiplexing (FDM),
- or by transmitting a distinguishable codeword on each element - so called code division multiplexing (CDM).

The choice of which multiplexing technique is used is partially constrained by the feasibility of constructing the hardware, as well as the desired resolution of the channel measurements.

3. HARDWARE STRUCTURE

The resolution and capability of the sounder system is dominated by the choice of hardware strategy adopted for the sounder. The most significant element of this choice is in the use of transmitters and receivers. The most straightforward

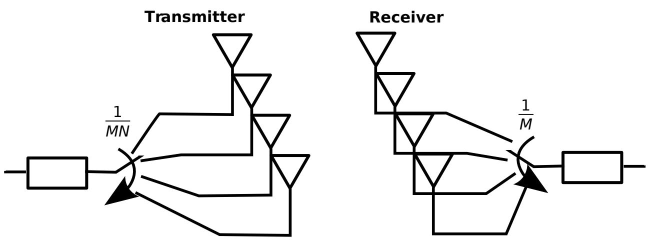

Figure 2: Fully switched MIMO sounder

RF system that can be constructed economically is one with a single transmitter and a single receiver which is switched between the antenna elements [8]. This fully switched system is illustrated in Figure 2.

The rate of switching of the receiver is inversely proportional to the number of receiver elements, whilst the rate of switching of the transmitter is inversely proportional to the product of the number of transmitter elements and receiver elements.

The length of time that is required for each transmitter receiver pair is governed by the maximum delay expected between transmission and reception, which for the indoor environment is of the order of a few ns, but is significantly longer for the outdoor environment, being of the order of tens of μs. This has the effect of dictating the time required to perform an exhaustive combination of switch positions to determine the element to element impulse responses. The limitation imposed by this is that the maximum Doppler frequency that can be accommodated with such a measurement system can fall below that expected to be experienced in the environment. Clearly this problem is exacerbated by the inclusion of more antenna elements.

An additional consideration resulting from the length of time required for sounding is that associated with each measurement there is phase noise in the local oscillators. Since phase noise correlation decreases with time separation, a fully switched architecture, whose soundings taken over a significant length of time, will experience phase noise that is uncorrelated between antenna to antenna channel estimates. Baum and Bölcskei [9] have indicated that in high SNR scenarios, with low rank channels, phase noise can influence capacity estimates to such an extent that they can be in excess of 100% larger than the true channel capacity.

One technique for minimising such problems is to adopt a semi-switched approach where only the transmitter is switched - the receiver comprises multiple radio frequency receiver elements, each attached to a single antenna. Thus there is no need for receiver switching as all of the antennae elements are sampled simultaneously. This has a corresponding increase in the switching rate of the transmitter array system, consequently a shorter duration is required for sampling all impulse responses and a higher maximum Doppler can therefore be accommodated.

The disadvantage of this approach is that the multiple receiver elements require careful matching to ensure that the individual antenna/receiver responses are identical for an identical stimulus.

Both of these approaches lend themselves to TDM at the transmitter as the transmitter is switching between the antenna elements sequentially. The alternative to this approach is to have simultaneous transmission at the separate elements which necessitates separate radio frequency front-ends, with the consequent increase in hardware cost, and difficulties of matching responses. This fully parallel configuration is shown in Figure 3.

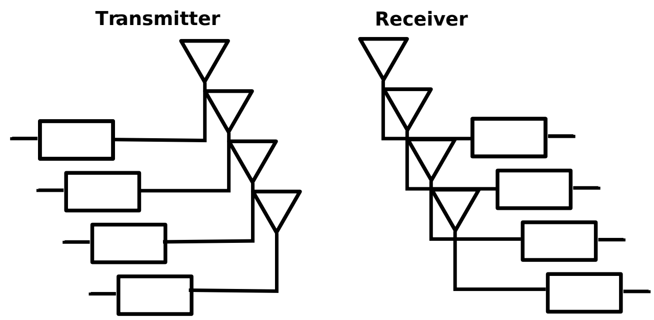

Figure 3: Fully parallel MIMO sounder

The parallel transmission approach supports FDM and CDM, each with different advantages/drawbacks. CDM will give excellent discrimination between antenna elements provided that a low correlation between codes is maintained within the channel being sounded. Unfortunately, as the channel is a multipath one, the cross-correlation between codes at non-zero delays is important. This restricts the dynamic range that can be achieved using this sounding technique. With FDM, a subset of the spanned frequencies are assigned to each antenna, thus they do not all characterise the channel at exactly the same frequencies. [10] details an FDM scheme that subdivides the frequency range into a large number of frequencies spaced by Δf which are then distributed across the antennae such that each antenna transmits a set of tones separated by $N\Delta f$. Provided that $N\Delta f$ is less than the coherence bandwidth of the channel, and $1/\Delta f$ is less than the coherence time of the channel, a good representation will result.

4. PRACTICAL REALISATIONS

In this section, a number of measurement systems will be discussed. Note that it is not intended to detail all of the systems that are currently in use, but rather to illustrate the main techniques used for sounding, and to discuss their strengths and weaknesses in relation to the characterisation that they are able to perform.

4.1 Fully switched systems

In MIMO characterisation, fully switched systems have a certain appeal in that only one set of RF front ends need to be constructed, and therefore need to be characterised. This format may also be popular for a different reason — it is essentially a SISO sounder with a multiplexing switch on the transmitter and one on the receiver elements. Thus preexisting sounders are readily adapted to the more complex antenna configuration.

The wideband channel sounder developed at Helsinki University of Technology (HUT) [11] falls into this category, operating at frequencies of 2.154 GHz and 5.3 GHz. This sounder uses a pseudo-random noise sequence for wideband excitation, and in its MIMO configuration, employs rapid microwave switches at the transmitter and at the receiver. The switches are capable of switching up to 32 elements, allowing for a significant MIMO complexity to be exercised. The sampling rate is 120 MHz for both I and Q channels, with a chip rate of 60 MHz. The full matrix can be measured in 8.7 ms, which corresponds to a maximum Doppler frequency of 115 Hz. Thus, the resulting maximum speed of movement of any object in the environment of under 12 km/h. This illustrates the main consequence of a fully switched system, since as the time required to perform one full measurement cycle dictates the maximum rate of change of the environment, the product of the number of antenna elements can severely restrict the environments in which a sounder can be employed. Of course, if fewer elements are required in the MIMO system, then a higher Doppler frequency can be supported.

One commercial system that uses the fully switched configuration is the MEDAV RUSK channel sounder [12]. This system operates at a frequencies UMTS (1.8–2.5 GHz) and WLAN (5–6 GHz) with a sounding bandwidth of up to 240 MHz. It uses switches at both transmitter and receiver to switch the periodic multi-tone transmitted signal between the transmitter elements once per set of soundings made by the receiver switching between all of the received elements. The shortest impulse response length that can be used with the sounder is 6.4 μs, which dictates the length of time required to estimate a single channel between one transmitter element and one receiver element. The result is that the maximum Doppler frequency that can be sustained is roughly equivalent to the Finnish sounder [11].

A side effect of this is that with such a short impulse response length, only channels that have such a short response can be correctly measured. For channels, such as outdoor ones, where channels can be of the order of up to 40 μs, a longer sampling period is required, and hence an even longer time to sample all channels, and consequently lower Doppler frequency sustainable.

One other issue that becomes apparent with fully switched systems is the volume of data that needs to be stored in a very short space of time. The MEDAV RUSK, for example, quotes a data storage rate of 320 Mb/s during the sounding period. Given this quantity of data, it is not surprising that this can become the bottleneck in the process when large arrays are considered.

4.2 Semi-switched systems

The University of Durham have constructed a semi-switched system with parallel receiver channels and a switched transmitter [13]. As the receivers operate in parallel, this has the advantage that the sounding period required to exercise all of the channels is limited to the time to switch between the transmitting antennae, and not the product of the transmitting and receiving antennae. Thus a better compromise between a higher Doppler frequency and time delay spread can be made. The sounder system, as detailed in [13], is set-up to have a 60 MHz bandwidth, a 40 μs time delay window and a waveform repetition rate of between 100 Hz and 250 Hz.

In this system, instead of a pseudo-random code, a chirp waveform of 60 MHz bandwidth is used, as is common in many radar applications. In this system, the transmitted waveform is chirped, and at the receiver demodulated with an identical chirp waveform. The resulting beat frequencies are isolated by a filter, sampled, and then stored. The significant advantage of this approach is that the sampling rate is relatively low. [14] gives a description of the underlying

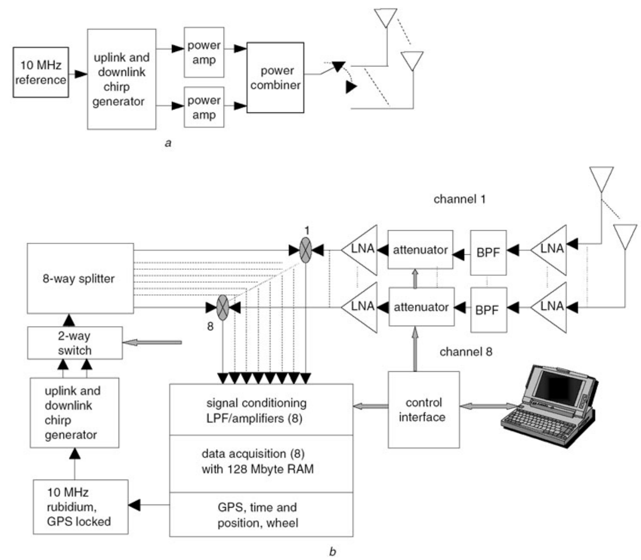

Figure 4: Channel sounder block diagram, reproduced from [13]

process and the practicalities involved in achieving an accurate representation of the environment.

It will be noted that in Figure 4 that reference is made to an uplink and a downlink chirp at both the transmitter and the receiver. The sounder is capable of performing simultaneous measurement of two frequencies corresponding to the uplink and downlink of a paired spectrum system, such as UMTS. Clearly with a sounder system, measurements are performed at only one end of the link, and reciprocity is assumed. As the receiver hardware is duplicated, as opposed to being shared between multiple antennae elements, it is possible to connect two receiver blocks to one antenna element, and thus have the capability of measuring both uplink and downlink simultaneously [15].

4.3 Fully parallel system

The system of Takada *et al.* [16] demonstrates an interesting technique for exercising the full frequency range of interest across all antenna elements, yet using frequency separation to distinguish between transmitting elements. The technique relies on dividing the frequency range being sounded, B, into M sub-bands, which are further divided into N frequencies assigned in a cyclic fashion to each transmitting element. The frequency spacing of tones in a given transmitting element is $\Delta_F = B/M$, and the maximum frequency difference between antenna elements is $\Delta_f = \Delta_F/N$, although in practice a smaller shift was employed to avoid the effects of a DC offset. This scheme is shown diagrammatically in Figure 5

Using this technique, the maximum time delay spread that can be measured is specified by $1/\Delta_F$, however the duration of sounding for a single snapshot of the channel is dictated by $1/\Delta_f$. The demultiplexing at the receiver is carried out by a discrete Fourier transform (DFT) operation which produces multiple interleaved channel transfer functions averaged over a period of $1/\Delta_f$. In effect, therefore, the length of time required to perform a measurement is not substantially different from that required by a semi-switched system, and has the disadvantage of requiring multiple RF transmit-

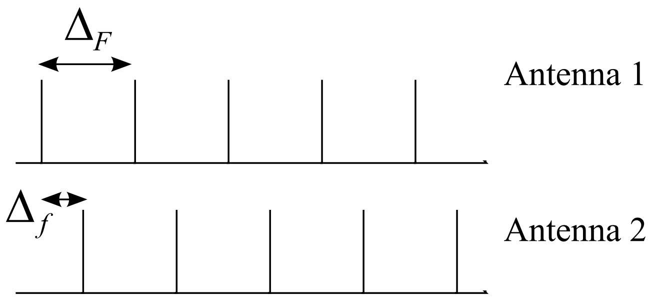

Figure 5: Frequencies allocated to antenna elements

ters.

4.4 Hybrid systems

Of course it is possible to combine schemes such as the semi-switched approach and the fully parallel approach into a hybrid scheme. [17] describes such a system for measuring the transfer functions for a 16×32 element wideband MIMO sounder.

In this sounder, the 16 transmitters are fully parallel, and it is the receiver elements that are switched in banks of 4 simultaneous measurements. The transmitting antennae are arranged in a 4×4 grid, and the receiving antennae in an 8×4 grid, with dummy antenna elements arranged to minimise the effects of mutual coupling at the grid edges.

In this system, unlike [16] which also employs parallel transmission, CDM is used to identify different transmitter elements. The transmitter elements are assigned different m-sequences of length 1023 so that the receiver can identify the different impulse responses. The receiver stores the IF signal to disk, extracting the impulse responses off-line. One set of measurements across the whole array of sensors takes 572 μs. In order to deal with the high volume of data produced by this process the receiver system uses multiple disks, one per receiver.

5. DISCUSSION

The channel sounders described above all involve a tradeoff between complexity and speed. With the fully switched system it is clear that the snapshot time is significantly longer than with a fully parallel, or even the hybrid scheme described by [17]. This limits the use of such sounders to environments that are not changing rapidly, otherwise the coherence time of the channel will be shorter than the measurement duration, and any correlation information between channels will be inaccurate. Attempts to decrease the sampling time for a fully switched system are only effective when it is known that the time delay spread is smaller than the maximum impulse response time that can be measured.

Moving to a semi-parallel or a parallel system dramatically reduces the time required to perform a sampling of the channel, thus the sounder can be successfully used in more environments. Clearly, the more elements that are used, the greater the requirement to use parallelism within the system. The issue that becomes significant with such systems is the not insubstantial cost of constructing, tuning and characterising the multiple radio systems within the sounder.

A second issue, which is particularly exacerbated by MIMO systems, is the amount of data that needs to be logged by the sounder. Where PN sequences are being stored, the storage process becomes a significant factor in sounder performance. This, presumably, is the reason that [17] uses parallel disks to store separate antenna data. Sounders, such as [13], that perform the channel impulse response or channel transfer function in hardware, or on-board processors, have significantly lower storage requirements than this, although the quantity of data obtained is still relatively large.

6. CONCLUSIONS

This paper has reviewed architectures for channel sounders and, with reference to current implementations, has discussed their strengths and weaknesses. It is clear that sounder construction is a tradeoff between cost and performance - the determining factor being the environments that are targeted, and the type of information being sought from the measurements.

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