Multipath Measurements for High Data-Rate Wireless Communications

Liam Devlin, Steve Fitz, Jonathon Holmefjord, David Spreadbury
Plextek Communications Technology Consultants
London Road, Great Chesterford, Essex,CB10 1NY
Tel: +44 (0)1799 533200 Fax: +44 (0)1799 533201 Email: lmd@plextek.co.uk

Abstract

There is an increasing demand for high data rate wireless transmission, both for indoor use in office based Wireless LANs and for outdoor use in remote office access systems and multimedia services to the home. The wide bandwidths these high data rate services demand mean that the frequency of operation is generally higher than for cellular and cordless telephony systems. Higher operating frequencies and higher data rates both result in increased multipath problems.

This paper details in-office multipath measurements made at data rates of 50MSymbols/s. The channel sounding equipment, which has been built to perform these measurements, is also described. It is capable of resolving the different multipath propagation routes down to delays approaching 5ns. As long as appropriate transceivers are added, the channel sounding can be performed at any desired frequency. The measurements detailed here were made at 5.25GHz, which is within a U-NII band in the US [1] and within the HIPERLAN band in Europe [2]. Fade rate measurements were also made and example equaliser requirements for data rates of 10Mb/s and 25Mb/s have been developed.

Introduction

Multipath propagation occurs when a transmitted signal reaches the receiver by two or more separate routes, as depicted in Figure 1. The propagation delay and loss for each of these routes is different and the signal, which the receiver observes, is the vector sum of all of the different multipath signals. The effects of the multipath environment are essentially two-fold. As path delays differ by half wavelengths at the carrier frequency, they add destructively or constructively. For an odd number of half wavelength the destructive interference is maximum and the power level of the RF carrier can be reduced to a level where reception is not possible. This is often referred to as frequency selective fading.

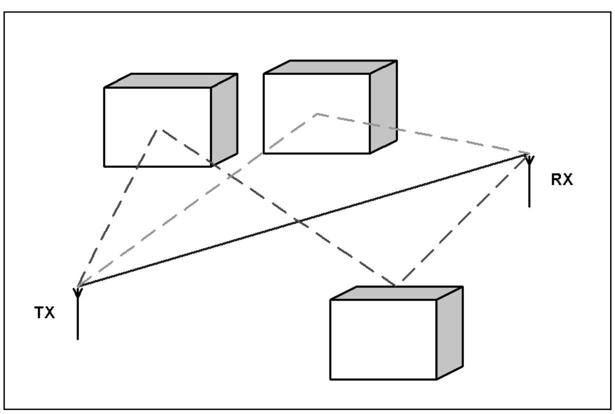

Figure 1. Multipath propagation

With longer delays, in the order of the data symbol length in the case of digital modulation, the multipath signals give rise to Inter-Symbol Interference (ISI). The effect of ISI is that of adding the data stream to time delayed versions of itself. When the relative amplitude of these time delayed versions is significant (greater than around -20dBc in the case of QPSK) this will start to seriously degrade the demodulation process unless appropriate action is taken. Figure 2 shows the eye diagram of the I channel of a received QPSK signal with no ISI, whilst Figure 3 shows the same eye diagram with two multipath signals both at relative amplitudes of -15dBc. Closure of the eye is evident, which will obviously degrade the received Bit Error Rate (BER). In addition to this, clock recovery will also be more difficult, resulting in timing offsets which will further degrade the BER.

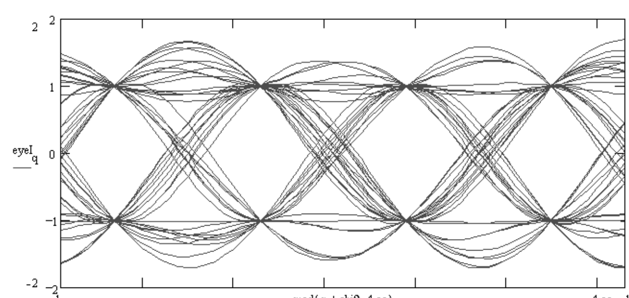

Figure 2. Eye diagram without ISI

It is possible to correct ISI by the use of a suitable equaliser in the digital demodulator. An equaliser is an adaptive filter which iteratively modifies its coefficients in order to generate a transfer function, which is the inverse of the channel [3]. A properly designed equaliser will correct the ISI caused by multipath interference. It is necessary to use an adaptive filter since a wireless channel is both unkown and subject to change, especially in

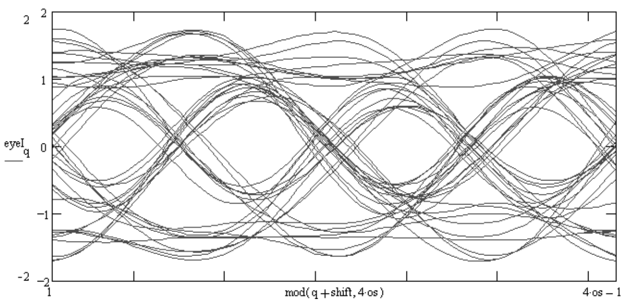

Figure 3. Eye diagram with ISI due to two –15dB multipath signals

the case of a mobile user. A known synchronisation stream is transmitted, normally with each data frame, which is used to "train" the equaliser. The required length and frequency of this training sequence is discussed later in this paper.

In the case of frequency-selective fading, the signal level of the RF carrier has just faded and once it has faded to a level below the threshold, which the receiver is capable of detecting, the data will be lost. The way to combat frequency-selective fading is with diversity. There are three basic forms of diversity: space, time and frequency. With space diversity, two (or more) receiving antennas are used, which are spatially separated. It is unlikely that both antennas will be simultaneously experiencing frequency selective fading and one technique would be to just use a simple Received Signal Strength Indicator (RSSI) to select the most appropriate. Spatial diversity is used in DECT base stations. Time diversity techniques, as used in GSM, work by interleaving the data over a number of frames. If a single frame of data is lost, the bits which are lost are not all consecutive and it is possible that the error correction algorithms can reconstruct the data. Frequency diversity is inherent in direct sequence CDMA systems. Again the data is interleaved, and it is also spread in frequency using a pseudo-random spreading code. Because the fading is frequency selective, only a portion of the spread signal is lost, and because the data bits were interleaved, a large number of consecutive bits are not lost. Once again, it is possible that the error correction algorithms can reconstruct the data.

Propagation measurements have been made which look at the multipath environment for the transmission of high data rate, digitally modulated signals at a carrier frequency of 5.25GHz. In addition to this, the fade rate of the frequency selective fading has also been measured.

Channel Sounder Design

A purpose-built channel sounder has been designed and fabricated to allow the measurement of multipath signals to a high resolution (short time delay). The channel sounder transmitter generates a Pseudo Random Binary Sequence (PRBS) using a ten bit shift register configured to produce a maximal length binary sequence [4]. A useful property of maximal length sequences is that the correlation between it and delayed versions of itself is minimal, even for delays of a single bit. The data rate of the PRBS is 100MB/s and the length is 1023 bits (2N-1).

Adjacent pairs of bits are then used to generate a QPSK modulated carrier at a 100MHz IF in the digital domain. An extra bit is forced into the PRBS of 1023 bits, to generate a sequence of 512 symbols in length. A Digital to Analogue Converter (DAC) is then used to convert the signal to a 100MHz carrier, QPSK modulated at a symbol rate of 50MS/s. A dual conversion upconverter is used to translate the modulated signal up to the required transmission frequency, in this case 5.25GHz. A simplified block diagram of the transmitter is shown in Figure 4.

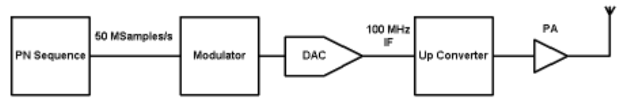

Figure 4. Simplified block diagram of channel sounder transmitter

The receiver consists of a dual conversion downconverter to convert the RF signal from 5.25GHz back down to 100MHz. A high speed Analogue to Digital Converter (ADC) samples the IF at a rate of 400MS/s, 8 bits of data per sample are generated and sent to a buffer. A PC is then used to compare the data from the buffer with the transmitted data and to output the correlation of the received data to the transmitted, versus time. The sampling provides 4 complex samples per symbol, which means the resolution of the correlation can approach 5ns. The noise floor of the correlation is around –30dBc, so only multipath signals above this level are discernible. A simplified block diagram of the receiver is shown in Figure 5.

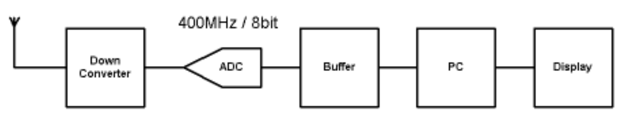

Figure 5. Simplified block diagram of channel sounder receiver

The Office Environment

In order to design a good communications system it is vital that the propagation environment is well understood. The modern office can represent a harsh propagation environment, metal filing cabinets and other office furniture can prove to be good reflectors and blockers of RF signals. The measurements presented here were made at Plextek's offices in the UK, which are typical of modern, open plan office areas. A photograph of the office area is shown in Figure 6.

A number of locations were chosen around the office area and measurements were made between different pairs of sites. Figure 7 shows a plan view of the office with the different, numbered sites identified

Figure 6. Photograph of Plextek office area

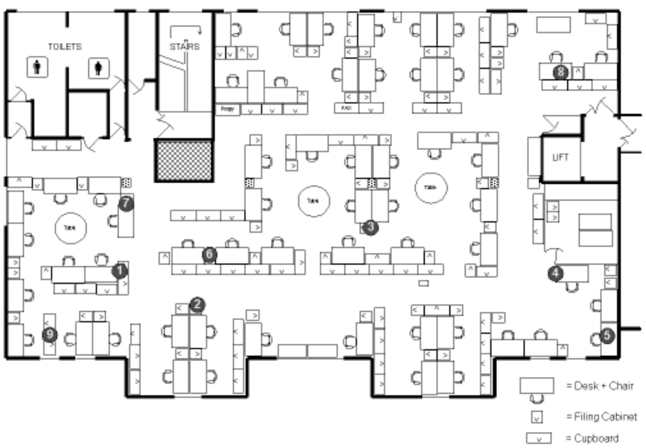

Figure 7. Plan view of office area

Measured Multipath

Numerous measured results were taken and those presented here represent a typical selection. Measurements were made with two types of antennae the first an omnidirectional, mono-pole antenna with 2dB of gain and the second, a directional, helical antenna with around 8dB gain. The helical antennas are also circularly polarised with about 15dB of cross polar rejection. This means that any multipath signals which are the result of a single reflection will be polarised in the opposite sense, by the reflection [5] and will therefore be reduced in magnitude by the cross polar rejection. For both cases, the channel sounder was used to generate an approximation of the channel impulse response. Plots showing the received power versus time relative to the main (largest) signal received, were produced.

Figure 8 shows the responses between sites 3 and 4, an obscured path of around 10m separation. As one would intuitively expect, using omnidirectional antenna results in stronger multipath interferers. A very strong multipath at the same level as the main path is received with a delay of 40ns, with additional multipaths of 80ns and 120ns at levels of –18dBc and –12dBc respectively. The 120ns delay represents a path difference of 36m. The coherence bandwidth of the channel is approximately the reciprocal of the largest delay spread, in this case a maximum delay spread of 120ns translates to a coherence bandwidth of approximately 8.3MHz. Coherence bandwidths are really of most use as a figure of merit, but basically for transmitted signal bandwidths below this, the channel can be considered as a flat fading channel.

When the same locations, sites 3 and 4, are used with directional antennas, the multipath problems are much less severe. Delays of 30ns, 60ns and 80ns, with magnitudes of –11dBc, -16dBc and –20dBc are observed. The omnidirectional antennas result in a more severe multipath environment primarily because they have the opportunity to see more reflections. The directionality of the antennas can provide a degree of rejection to multipath signals, which are outside the main antenna beam. In addition to this, the fact that circular polarisation is used provides additional rejection of multipath signals which are the result of a single reflection.

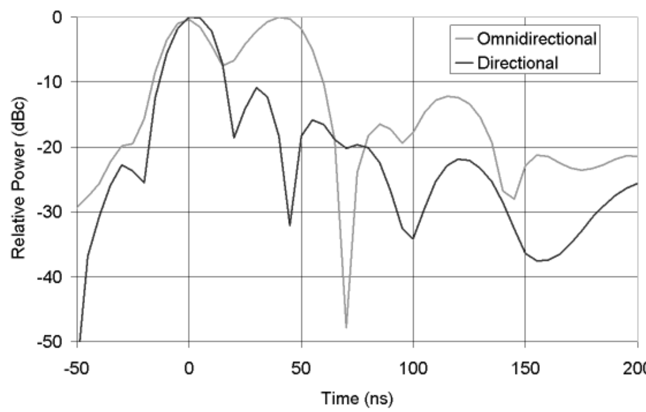

Figure 8. Impulse response of channel between sites 3 and 4

Although in general, directional antennas tend to reduce the severity of multipath interference in comparison to omnidirectional antennas, this is not always the case. Figure 9 shows the measured propagation results between sites 1 and 2, which offer a direct line of site with about 5m separation. In this case the directional antenna has one very strong multipath signal (at –2dBc) with a short delay spread (30ns), which translates to a coherence bandwidth of around 33MHz. With an omnidirectional antenna, there is still a multipath signal with a delay of 30ns present but the magnitude is around –10dBc. A spreading of the main lobe indicates the presence of some very short multipath signals. However, the delays are so short they will not cause significant ISI for data rates of below 100Mb/s. The omnidirectional antenna also has a longer multipath present at 80ns (12.5MHz coherence bandwidth) with a level of –19dBc.

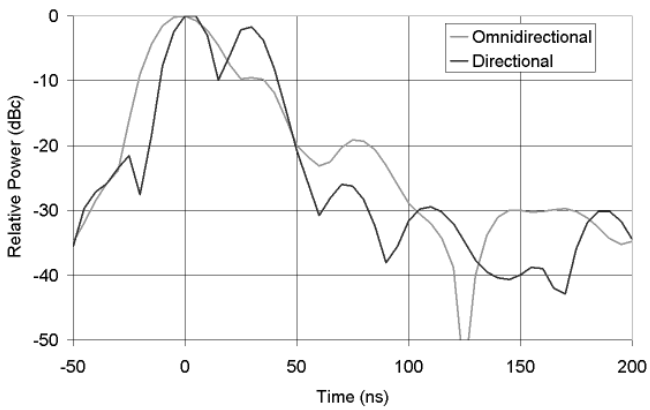

Figure 9. Impulse response of channel between sites 1 and 2

Numerous propagation measurements were made at various combinations of the site locations shown in Figure 7, the final set of results presented here are for sites 8 and 9, located in opposite corners of the office. In this case the path is obscured and the separation is around 25m. Figure 10 shows the impulse responses measured. With directional antennas the multipath does not seem too severe. There is one signal, which is sufficiently close to the main path that it merges producing an offset main lobe. The delay of this multipath is around 15ns, corresponding to a coherence bandwidth of 67MHz. With omindirectional antennas, there is evidence of severe multipath. Three delays are evident at 30ns, 45ns and 85ns, with levels of around -3dBc, -7dBc and –19dBc respectively.

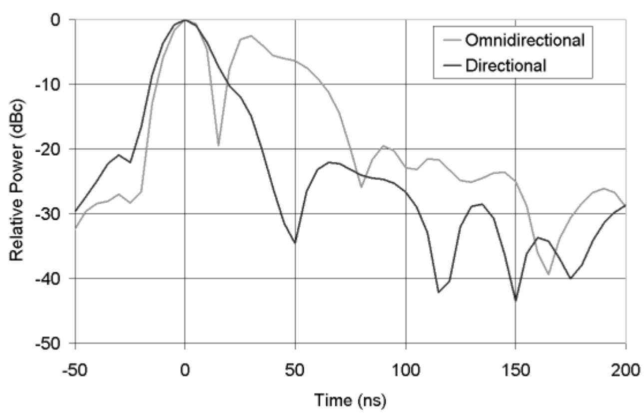

Figure 10. Impulse response of channel between sites 8 and 9

In order to try and show the results of all propagation measurements on a single graph, the magnitude of the impulse response at each time point for all measured results were averaged. Figure 11 shows a plot of these results. Considering only multipath signals above –20dB, the omnidirectional case has a strong likelihood of multipath signals arriving with delays of up to 125ns (a coherence bandwidth of 8MHz) at average levels as high as –5dBc. With directional antennas, delays of up to 90ns with magnitudes as high as –9dBc are likely. There is also a tendency for multipath signals with a longer delay, in the region of 160ns, to be present at levels of around –14dBc. This was primarily due to a very severe multipath (at around –1dBc) which was observed when the directional antennas were used between sites 2 and 3.

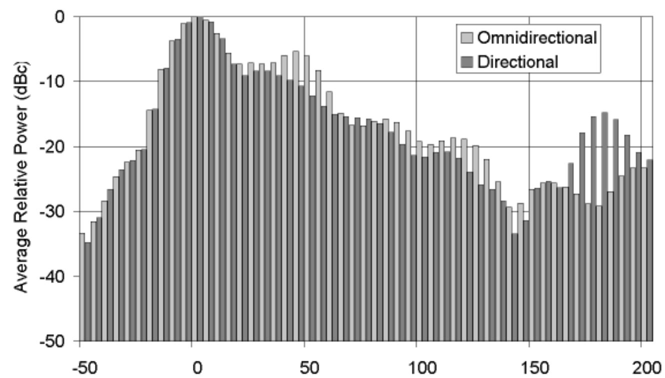

Figure 11. Averaged impulse responses of all channels

In summary, on average the limited directivity of the helical antennas does not provide much immunity to multipath. Also, with the multiple reflections which are found in an indoor environment, the use of circular polarisation does not appear to offer any significant immunity to multipath interference.

Fade rate measurements

Frequency selective fading measurements, were made by transmitting an unmodulated carrier signal, at 5.25GHz. The received signal strength was observed using a spectrum analyser set to zero span. An LNA was also used to reduce the noise floor of the analyser. With no movement in the channel, the response was static and did not present much of a propagation problem. However, when people walked through, or close by the propagtion path between the antennas, the fading could be significant.

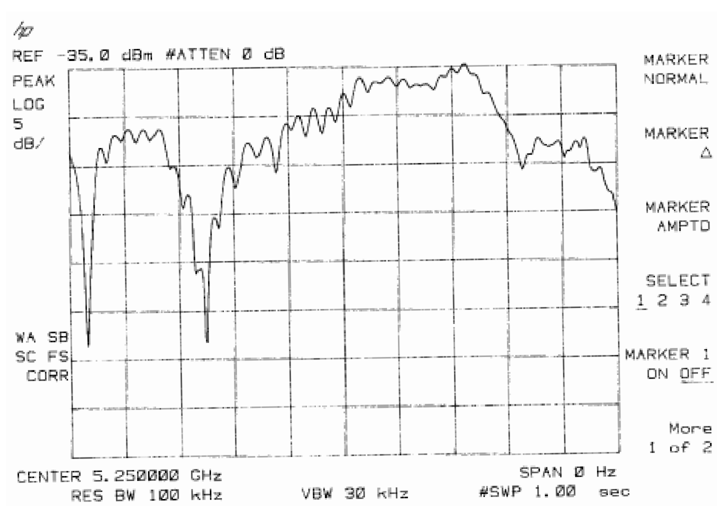

Figure 12: Fade rate measurement, with one person passing through propagation path

The measured fade rate and depth were very similar for both the directional and omnidirectional antennas. The only thing, which substantially affected the fading, was the number, direction and rate of people moving in the channel. Figure 12 shows a plot of the received signal strength, versus time, with one person walking between the two antennas, in the direction of propagation.

In addition to the two deep fades which are evident in Figure 12, there is also a regular ripple at about 30Hz. This ripple is a beat frequency resulting from the doppler shift imposed on the transmitted signal as it reflects off the moving body. Equation (1) shows the relationship between the shift in Frequency (Fd), the transmission frequency (Fo), the speed of light (c) and the radial velocity (Vt) of a moving object causing the doppler shift [6]. It is valid for velocities which are small compared with the speed of light. The 30Hz ripple in Figure 12 translates to a velocity of 3.1km/h.

$$V_t \cup - \frac{F_d.C}{2.F_0} \qquad (1)$$

The two deep fades are at a relative level of around –25dB and are separated in time by around 200ms. Figure 13 shows the received signal strength with two people simultaneously crossing the propagation path, moving in opposite directions, perpendicular to the direct path between the antennas. There are numerous fades across the 1s time sweep, the deepest of which again approach a relative level of around –25dB. The shortest time between any two fades is around 20ms. Various fade rate measurements were made and the fastest fading observed was around 10ms between fades.

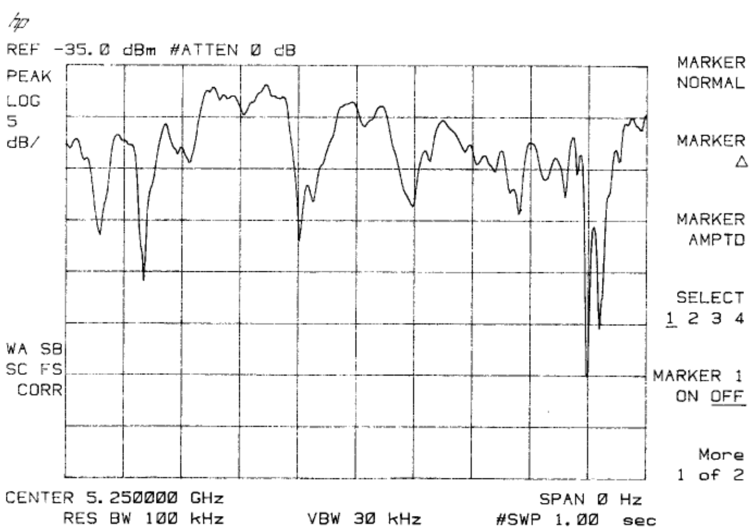

Figure 13. Fade rate plot, two moving bodies crossing propagation path

Equaliser Requirements

Equalisers can either compute the impulse response of the channel from a synchronisation sequence, or iteratively adjust the weights of a digital filter is response to the errors in a demodulated, known training sequence. Only the trained equalisers will be considered here, a more detailed discussion of equalisers can be found in [7] and [8].

If all of the significant multipath components arrive within 1 or 2 symbol periods, a linear transverse filter equaliser is appropriate. This works in the frequency domain flattening the radio channel's multipath generated gain and phase response. Such a filter must be free to adapt without constraint over the whole signal band, so samples must be fractionally spaced, i.e. less than a symbol period apart. A spacing of half the symbol period is usually a good choice, and this is known as a T/2 equaliser. The number of taps should be such that a complete set of multipath components can be fitted inside the equaliser.

Where discrete multipath components arrive over a period of several symbols, extra symbol-spaced equaliser taps can be added after the symbol decision point to allow corrective decision feedback from earlier symbols. The number of feedback taps required is equal to the delay, in symbol periods, of the latest significant multipath component.

A pseudorandom synchronising waveform is ideal both for establishing the presence and timing of a transmission and training the equaliser: presence and timing come from the narrow autocorrelation peak, and training comes from the wide bandwidth (i.e. the rich bit pattern content). The training is done by passing this waveform (when detected) through the equaliser and observing the difference between what would ideally be expected (i.e. the symbol sequence originally used to construct the waveform), and the actual output. Note that the phase of the detected correlation peak indicates the absolute carrier phase so the symbol constellation is known. The difference is most conveniently handled in Cartesian (I & Q) space. In the LMS algorithm this difference is scaled by a gain constant and then added to each equaliser coefficient in proportion to the data in the equaliser at that coefficient. As this process is repeated symbol by symbol the filter is constructed to minimise the error. The gain constant allows a trade off between speed of convergence and final accuracy. The waveform can be passed through the equaliser more than once.

The gain constant is usually set for rapid convergence when training on the known sequence and then significantly reduced for continued equalisation over subsequent data (which is unknown but should be demodulated correctly), to allow the equaliser to track minor changes without responding to noise. The gain constant is in many ways like the bandwidth of a Phase Locked Loop (PLL), which can usefully be varied between acquisition and lock modes.

Equaliser requirements have been considered for two systems, a 10Mb/s system and a 25Mb/s system, both using QPSK modulation. The propagation environment presented in this paper is assumed and a maximum delay spread of 200ns is considered. In reality a large number of representative locations would need to be surveyed. This would allow a clear picture to be developed, of the likely propagation scenario in any location where the system may be deployed. The system could then be designed to cope with all of the different propagation environments.

With the 10Mb/s system, the symbol length (T) is 200ns. A linear transverse filter with a tap spacing of 100ns would require a minimum of 3 taps in order to contain a complete set of multipath components within it. However because of various implementation issues, in practice the filter needs to be longer than this to handle uncertainties. Using an additional two taps on either end of the filter would be reasonable, resulting in a filter with a total of 6 taps.

With the 25Mb/s system, the symbol length (T) is 80ns. A linear transverse filter with a tap spacing of 40ns would require a minimum of 6 taps in order to contain a complete set of multipath components within it (assuming a maximum delay spread of 200ns). Once again, because of the various implementation issues, additional taps would be incorporated and a total of 10 taps would be more practical. A delay spread of 200ns represents 2.5 symbols. For delay spreads any longer than this, it becomes appropriate to also use a decision feedback equaliser in conjunction with a smaller linear transverse equaliser. This would allow a reduction in the required number of taps, as compared to an equaliser realised entirely as a linear transverse filter.

Data Rate	Modulation	Equaliser Type	Tap Spacing	No. of Taps
10 Mb/s	QPSK	Linear transverse	100ns	6
25Mb/s	QPSK	Linear transverse	40ns	10

Table 1. Summary of equaliser requirements

The length of the training sequence, which is required, is dependent on the gain constant of the equaliser. This in turn depends on the modulation scheme, the filter length and the trade off between speed of convergence and BER. If too fast a training of the equaliser is attempted, it doesn’t converge accurately and is noisy. Detailed simulations are required to resolve these issues in practice but in general, the length of the training sequence required is several times the length of the filter. So in the case of 25Mb/s QPSK, with a 10 tap filter, a training sequence of 40 symbols may be chosen.

In terms of the frequency with which the equaliser must be trained, this depends on over what time period the channel can be considered as static. The fade rate measurements conducted suggest that the channel appears static for periods of 1 or 2ms. In the case of Time Division Multiple Access (TDMA) systems, the training sequence is often sent with every time slot of data. However, there are many other factors which also effect the choice of timeslot length, and it may not be appropriate to always send the training sequence. Whether the training sequence is sent every time slot or not, the equaliser must be trained at least this often. At 25Mb/s, with a 1ms timeslot, 40 symbols represents an overhead of just 0.32%. For a mobile environment, training would be required more frequently and the overhead would go up.

Conclusions

A channel sounder capable of measuring multipath signals and interpolating delays of 5ns, has been developed. When augmented with appropriate frequency converters and antennas, multipath measurements can be made at any desired frequency. Detailed knowledge of the propagation environment is required before any effective wireless communications system can be designed. This paper has presented a means of assessing a propagation environment to determine the requirements of a digital wireless communications system operating at data rates of up to 50MS/s.

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