Experimental Evaluation of Rake Receiver Performance in a Line-of-Sight Ultra-Wideband Channel

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Abstract

This paper assesses the utility of signal processing techniques for multipath mitigation in an ultra-wideband (UWB) indoor radio channel. UWB systems have the ability to resolve rapidly arriving multipaths. Rake receivers can provide multipath diversity and integrate the energy from various multipaths, helping overcome fading and effectively increasing the received power. We report experimental studies of multipath propagation in an indoor UWB environment, based on which we predict the performance of Rake receivers with a variety of configurations and find that incremental gain is high only for low order Rakes.

1. Introduction

In a typical wireless channel, an electromagnetic signal traverses a multitude of paths from the transmitter to the receiver, whose lengths are, in general, unequal. The composite signal at the receiver is the superposition of time shifted, amplitude scaled, polarisation rotated and phase altered copies of the transmitted signal, and is therefore multipath distorted. The exact number of multipaths depends on the geometry of the environment, the location and separation of transceivers, the placement of obstructive and non-obstructive objects, and the properties of materials used in construction.

Multipath propagation has a deleterious effect on system performance and link budget. In a narrowband system, the multipath fading margin can be as high as 35 dB [1]. Here channel coding, equalisation, spectral shaping and diversity are frequently used for multipath mitigation. Multipath resolution and Rake combining provides an alternative technique for multipath mitigation in frequency-selective fading environments.

As time-resolution is inversely proportional to bandwidth, a system with high bandwidth is capable of resolving rapidly arriving multipaths. A receiver can then opt to use a number of techniques, such as selection diversity, to present to the demodulator an uncorrupted signal. However, in the case of power-limited systems, it is highly desirable to gather as much power as possible to the demodulator in order to optimise the signal-to-noise ratio (SNR) and hence maintain acceptable bit error rates (BER). A Rake receiver can integrate the energy of all or some of the resolved multipaths by tracking their delays, albeit at the cost of increased receiver complexity [2].

Ultra-wideband (UWB) systems can resolve more multipaths than narrowband systems due to their higher bandwidth. As signal bandwidth increases, a composite propagation path can be resolved into distinguishable paths with distinct propagation delays [3]. UWB therefore enjoys improved time-resolution: pulses arriving at the receiver separated by very short intervals of time can be resolved. As a result, the fading range in a UWB channel is as low as 5 dB [4]. Since fading is already less severe in UWB, it is important to investigate whether any complex processing to overcome fading and improve the link budget is justified, and what performance gain is achieved.

Several complex Rake architectures have been proposed for UWB systems in [5-7]. Theoretical studies of Rake performance are presented in [8, 9]. We analyse low-complexity Rake receivers using measured channel data. Our analysis is not specific to any modulation or coding scheme, as we use the captured energy and signal to noise ratio as performance metrics.

2. Experimental Configuration

An indoor measurement environment was used for recording propagation data for the analysis in this paper. It consisted of a medium-sized room that housed wooden desks, computers, and metallic filing cabinets. The receiving and transmitting antennas were at a 3.7 m separation, and were both 1.5 m above the ground. No operator was present during the measurements. A computer-controlled vector network analyser (VNA) [10] was used to sound the channel with 20 dBm power at 4 – 6 GHz, which corresponds to a 40% fractional bandwidth. The complex transfer function over this band was measured at 401 discrete frequency points, at a resolution of 5 MHz. An automated controller moved the receive antenna on a 50 cm x 50 cm positioning grid, and a total of 2500 measurements were taken using this arrangement with a 1 cm spatial resolution. This dense sampling meets the Nyquist criterion for spatial resolution. The locations of transmitter and receiver were chosen to imitate the typical deployment scenario for an indoor UWB communications system, as shown in *Fig. 1*. Vertically polarised, omnidirectional discone antennas were used at both ends. They were placed in each other's far field and an unobstructed line of sight was present throughout the measurement.

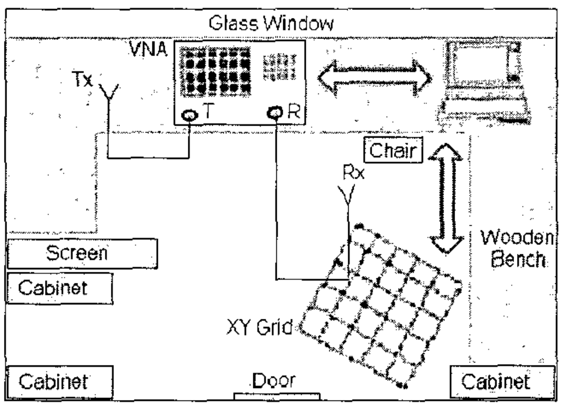

Fig. 1: Measurement Environment

3. MULTIPATH CHANNEL CHARACTERISTICS

The complex channel data captured from the VNA contains a complete description of the UWB propagation transfer function for the measured environment. An inverse fast-Fourier transform is used to derive time domain characteristics from the recorded frequency domain data. Band-limited channel sounding gives rise to extraneous time-domain sidelobes in the complex channel impulse response (CIR). To overcome this, a minimum three-term Blackman-Harris window is applied to the frequency-domain data for temporal smoothing [11]. The resulting CIR at one spatial point in the measurement is shown in *Fig. 2* as an example, with the magnitude normalised and the propagation delay removed. The direct path is followed by several other paths that arise from reflection and diffraction of the transmitted signal. Each measured CIR was power-normalised to make it independent of antenna separation and transmit power so that it only included the effect of multipath fading.

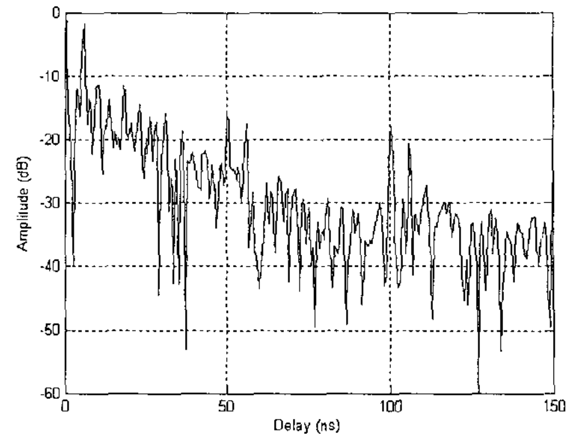

Fig. 2: A Normalised Channel Impulse Response

A -15 dB noise threshold below the peak amplitude was chosen as a limit for a realistic low complexity receiver. Based on the experimental conditions, it is fair to assume that the noise maintains a constant level in both time and frequency. A local maxima search algorithm was used to locate multipaths in the thresholded CIR. It is obvious from *Fig. 2* that the channel is highly dispersive, with several paths separated by short intervals. This is due to the presence of a large number of scatterers in the indoor environment that are closely located and the path differences between rays are therefore small. The time-resolution of the measurement system is the reciprocal of the sweep bandwidth, and was 0.5 ns in this case. The time-bins are therefore small enough for a number of multipaths to be resolved above the -15 dB threshold.

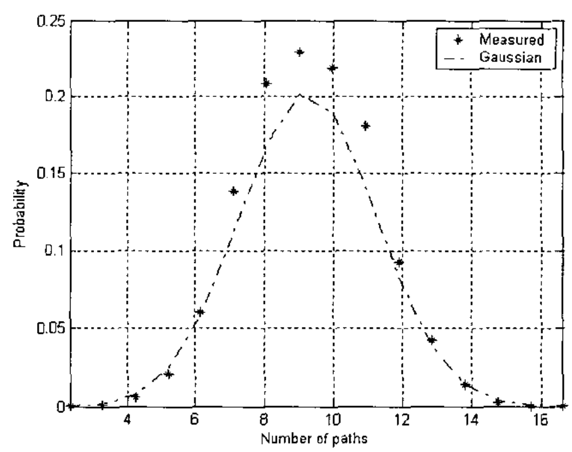

Fig. 3: Number of Multipaths – Probabilty Density Estimate

The probability distribution function (PDF) of the number of multipaths (L) is shown in *Fig. 3*, in which a Gaussian-like characteristic can be observed.

The mean value of L is 9 and its standard deviation is 2. The magnitude of skewness of the sample set is 0.026, which confirms that the PDF can be well approximated by a Gaussian distribution within acceptable error. This observation concurs with intuition, as it ascribes noise-like statistics to multipath arrivals: the locations of scatterers in the propagation environment are random and uncorrelated, and so are the times of arrival of the multipath components, and their number. L further converges to a Gaussian random variable as the receiver threshold is lowered.

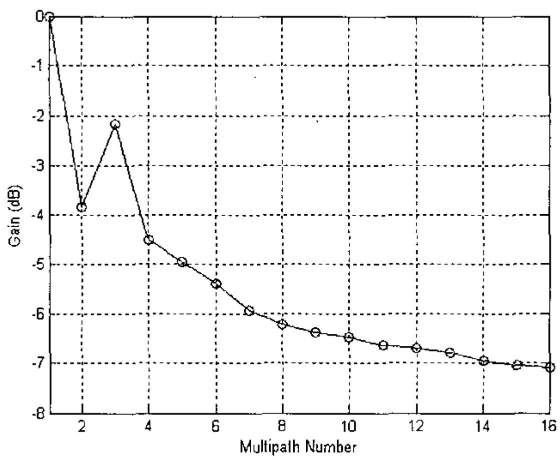

Fig. 4: Normalised Mean Path Gains

The mean values of gains corresponding to each path and normalised to the first path are shown in *Fig. 4*. It should be noted that this curve is the result of averaging the corresponding path gains over the measurement grid. Here, path 1 refers to line-of-sight and the subsequent paths are ordered by their times of arrival. The second path in general has lower amplitude than the third. The first four paths contain the most signal power, after which the respective path gain levels fall, as does their mutual difference. The values can be used to set the receiver threshold and thus the number of multipaths to track.

4. RAKE ANALYSIS

A Rake receiver consists of a number of channels, also referred to as its fingers or branches, each of which tracks and selects power from one of the received multipath components. The instantaneous output of a Rake receiver is the sum of the instantaneous branch signals weighted with adaptive combining coefficients. Several linear combining schemes have been proposed for calculating these coefficients, such as selection combining (SC), equal gain combining (EGC), maximum ratio combining (MRC) etc., any of which can be used in ideal, selective or partial configurations as described in [12].

An ideal Rake receiver has BT_d fingers, where B is the bandwidth and T_d is the delay spread. It therefore has the capability of combining all resolved multipaths. Such a receiver is often unrealistic due to its complexity. Sub-optimal implementations are preferred which process only a subset of the available multipath components. A PRake-L_p has L_p fingers that track the first L_p paths out of the L paths resolved, while an SRake-L_s selects the L_s best paths. SRake requires fast adaptability, knowledge of instantaneous value of all multipaths and efficient channel estimation, and is therefore more complex than PRake.

Multipath energy capture can be used as a basic measure of a Rake receiver's performance [13]. This corresponds to the total energy of the received symbol waveform within the detector's threshold [14]. This approach can be extended to assess performance on the basis of other metrics such as SNR, channel capacity and BER. For the validity of this analysis, the implicit assumptions are that the waveform transmitted from the transmit antenna, and received over a single propagation path, is matched to the template waveform used by the Rake correlators, and the medium is linear.

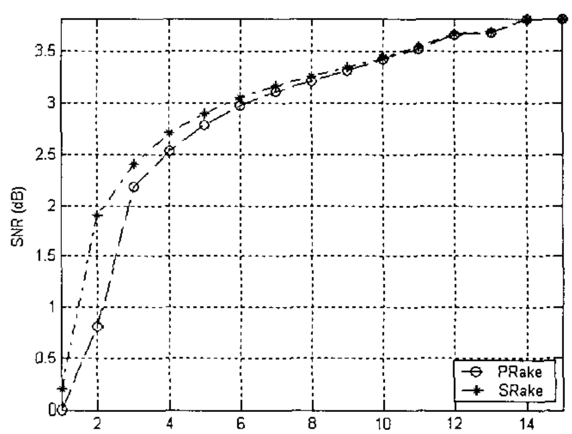

Fig. 5: Increase in SNR with MRC Rake Combining

Fig. 5 shows the increase in the output SNR as a function of the number of fingers in an MRC Rake. As the noise power is assumed to be constant, the increase in SNR corresponds directly to an increase in received signal power. In the graph, the characteristic is a double-slope curve, with the break-point occurring at three fingers, after which the slope becomes less steep, yielding an SNR gain of 3 dB with six fingers, and reaching an asymptotic value of roughly 4 dB. It is important to notice that the addition of ten fingers after the first five yields an SNR increase of only 1 dB. The values are normalised with respect to the first finger to show the incremental gain in SNR. The first Rake finger tracks the first path in the case of PRake and the strongest path in the case of SRake. The 0.2 dB difference in the first finger's SNR for the two types of Rakes shows that the first path does not always coincide with the strongest path even in an LOS scenario. A composite path – the result of constructive interference of the signal from two or more scatterers – may sometimes be stronger than the LOS freespace path. This effect is more pronounced in the case when the LOS path is partially or completely obstructed. It can be inferred from *Fig. 5* that an SRake is able to provide a slight advantage over a PRake in this situation.

From the Shannon expression [15], a high order Rake receiver achieves an asymptotic increase of 1.25 bps/Hz in channel capacity where a constant noise floor is assumed. For the bandwidth and transmit power used in this study, this corresponds to 2.5 Gbps.

As the UWB fading margin is only 5 dB, and the use of a Rake receiver can provide up to 4 dB of additional power at the receiver, power fades due to multipath interference are ameliorated to a large extent. A Rake receiver is quite adequate for multipath mitigation without any supplementary techniques.

5. CONCLUSIONS

One of the properties of the UWB channel is its resistance to multipath fading. Consequently highly complex receiver architectures cannot be easily justified. Indeed, as these measurements show, the use of a Rake receiver only yields marginal advantage in our typical environment, which, it may be argued, is not commensurate with the increase in receiver complexity. An indoor LOS UWB system can resolve many more multipaths than a narrowband system in its -15 dB power delay profile, a typical number being nine multipaths. The number of multipaths at each spatial point in a cluttered indoor channel follows a normal distribution. Most of the power in our example is always delivered in the first four paths. An MRC Rake that gives more weight to these fingers would perform better than an EGC Rake but at the cost of increased complexity. A 15-finger Rake provides a 4 dB SNR gain approximately, increasing channel capacity by 1.25 bps/Hz. The bulk of this performance increase can be achieved by the first four fingers, after which the increase in complexity is disproportionate to the performance gain. Complex Rake architectures such as Selective-Rake are also unnecessary if the number of fingers is large, and a simple Partial-Rake structure is sufficient. A Rake receiver of high diversity order can almost completely compensate for multipath fading in a dense multipath UWB channel. However, due to the extra electronics required for only a marginal gain in system performance, a Rake receiver offers little advantage for a UWB communications system in a line-of-sight fading channel.

6. REFERENCES

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