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TITLE

DEVELOPMENT OF A FAST SAMPLING SYSTEM FOR ESTIMATION OF IMPULSE RESPONSES OF MOBILE RADIO CHANNELS

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Development of a Fast Sampling System for Estimation of Impulse Responses of Mobile Radio Channels

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#149300

1. SUMMARY

This paper describes the features of measurement equipment developed to measure impulse response estimates of mobile radio channels in less than a ms per measurement. The development of such equipment was required to measure mobile radio channels in realistic operating scenarios, in a normal sized vehicle moving at typical speeds in different environments. Up to speeds of 70 km/hr, the measurement period is short enough to assume the equipment is measuring the same channel during the whole sampling interval. At the transmitter end of the measurement system, a wideband signal (10 MHz) is produced by modulating a carrier frequency with a 511 bit pseudo random sequence at 5 Mb/s and transmitted through the radio channel. The received signal is down-converted to 70 MHz and demodulated by a complex demodulator. The quadrature baseband signals at the demodulator outputs are then filtered and sampled at high speed by two fast digitizers. During this process, the data are stored in large memory banks to allow a fast sampling rate during a long period of time. Data are transferred to laser disks for further processing in the laboratory. Impulse responses of radio channels are estimated by performing a software correlation between a measurement system back to back reference and real time measurements. A minivan was modified to hold the receiver, digitizers, memory banks and the computer. A shaft encoder was attached to its rear left wheel to trigger measurements while moving. Features of the system are discussed along with the effects of data block length, signal to noise ratio, sampling rate, memory size and phase stability on the design of the measurement equipment. Finally, some measurement results are presented and discussed.

2. INTRODUCTION

Mobile radio channels are particularly interesting to study because of the many impairments that cause rapid, significant degradations in communication signal quality. A short list of phenomena includes deep multipath fading, shadowing, random fm, frequency selectivity, multipath propagation and Doppler spread. Good estimates of radio channel impulse response functions are necessary to characterize these phenomenas. Based on such measurements, a radio engineer can predict signal degradation and loss of information.

Hardware correlators have previously been used [1,2,3] to estimate impulse responses in different environments, including: land mobile, cellular and indoor radio channels. Unfortunately, such measurement systems require long sampling times to estimate each impulse response. For example, a typical setup used for cellular radio channel measurements modulates a carrier at a chip rate of 10 Mb/s, uses a correlation rate of 10^{-4} the chip rate (1 kHz) at the correlator and a pseudo random sequence of 511 bits. This results in a sampling time of 511 ms. Consequently, it is not possible to measure a channel changing at a rate of even a few hertz. Only truly static environments can be measured.

This paper reports a measurement system similar to the equipment presented by Levy [4]. The operation is similar to a hardware correlator except it directly samples the received signal, stores the data on disk and processes it later by software. The system is very fast and sampling times of less than a half millisecond are possible for the implementation discussed here. The next section describes the impulse response measurement system. A discussion on the different tradeoffs in the design follows. Finally, some measurements are presented and discussed.

3. DESCRIPTION OF THE EQUIPMENT

Figure 1 shows the wideband transmitter configuration. It transmits a wideband radio signal which is produced by modulating a 910 MHz carrier with a pseudo random sequence. The Local Oscillator (L.O.) is modulated at 5 Mb/s by a 511 bits Pseudo Random Binary Sequence (PRBS). The resulting RF signal is then filtered by a 10 MHz bandpass filter (BPF) to keep only the first lobe of the signal. Then, it is up-converted to the frequency band of interest. A power amplifier provides a maximum output power of 20 W. Antennas used at the different frequencies are all omnidirectional monopoles with drooping radials. This type of antenna was selected because of its bandwidth, easy construction and radiation pattern which is practically independent of the location of the antenna on car roofs. Figure 2 shows the transmit output spectrum. The width of the first lobe is twice the chip rate (10 MHz) and the frequency separation between the frequency lines is 9.78 kHz. The spectrum has the sin(x)/x shape with a slight distortion due to the filters. Because non-linearity in the transmitter or receiver can cause false echoes [4], great care was taken to use linear amplifiers to reduce distortions. The clock generator and local oscillators are locked in phase to a highly stable rubidium frequency standard to enable phase measurements.

The wideband receiver configuration is shown in Figure 3. In order to sample two channels quasi-simultaneously and make diversity measurements, two omnidirectional antennas are connected to a receiver with two separate front ends. Each front end amplifies and down-converts the RF signal to an IF frequency set at 70 MHz. An RF switch connects either one of the two input signals to a complex demodulator. At the demodulator output, the in-phase and quadrature baseband signals are filtered by two identical low-pass filters, each with a 3 dB cut-off frequency of 4 MHz to avoid aliasing. At 5 MHz, the rejection is 50 dB. These signals are sampled at 10 Msamples/s and the data is stored in memory banks of 32 MB (16 MB/channel). The data are transferred to laser disks with capacities of about 650 MB per disk. Laser disk storage was selected instead of a Digital Audio Tape (DAT) or 8 mm tape because of its random access feature. Data are processed simultaneously on several computers in the laboratory after field measurements. A single channel is measured by keeping the RF switch always connected to the same front end. Diversity measurements are taken by measuring the signal from one front end then switching to the other front end, then, after the measurement, the switch returns to its previous position and waits. Table I shows the measurement system specifications, each of which will be explained in the following section.

Presented at an AGARD Meeting on 'Multiple Mechanism Propagation Paths (MMPPs): Their Characterisation and Influence on System Design', October, 1993.

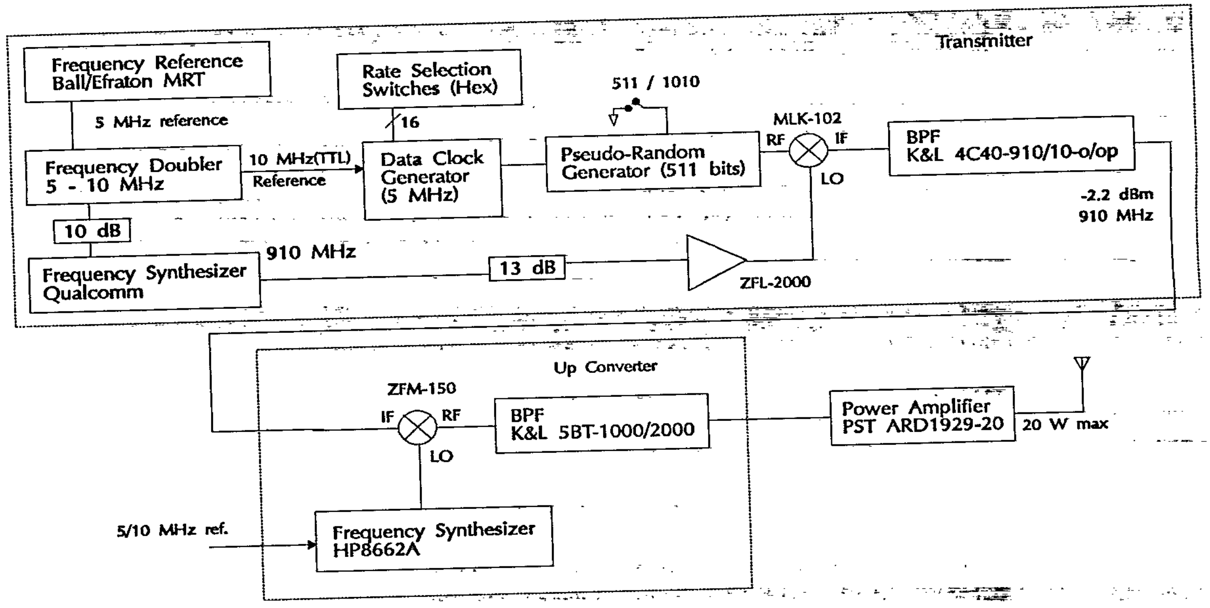

Figure 1: Wideband transmitter configuration

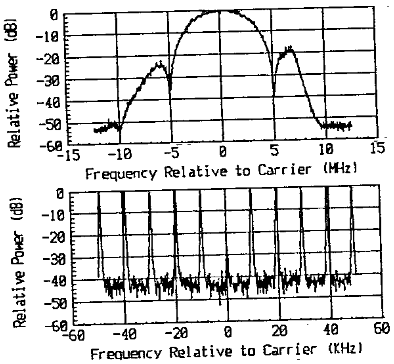

Figure 2: Output spectrum of transmit signal. The top plot shows the sin(x)/x shape of the output signal. The bottom plot is an expanded view of the top plot centered at the carrier frequency.

Measurements are triggered by either time or distance. In both cases, when sampling is triggered, a block of data is acquired and stored in memory. Since the memory banks are limited in size, the trigger rate determines the duration of, or distance travelled during, an experiment. For a block size of 4096 samples per trigger, the maximum number of blocks that can be sampled in one run is 4096 (32 MB / (4096*2 baseband signals)). If measurements are triggered every metre, the maximum distance travelled is then 4.096 Km, or if they are triggered at 100 Hz a measurement lasts about 40 seconds.

All equipment is mounted in standard 19 inch racks, 100 cm high. The transmitter fits in a special trailer equipped with a generator that can be set up at any transmitter site. The receiver racks are installed in a minivan. This is used instead of a normal van or truck so as to simulate operation from a sedan as closely as possible. The AC power is provided by two different sources. A DC-AC inverter, equipped with batteries, converts the 12 - 14 V dc power from the car generator to 120 V AC. It powers the computer, disk drives and frequency standard. This inverter is used as an uninterruptible power supply and maintains power in case of power failure from the car. It also keeps the frequency standard warm and stable. A gasoline powered AC generator is mounted on the back bumper of the minivan to power the rest of the equipment. Distance travelled is recorded by monitoring a shaft encoder. The trigger distance can be set from 1 cm to several metres. Except for the frequency standard which is mounted on a foam cushion, there is no special suspension system to protect the equipment against vibrations and road bumps. The minivan suspension was tested and found to be sufficient. A special suspension was rejected because it uses several cm of much needed vertical space.

In a typical run, the transmitter is set-up on the side of the road. Then the receiver, mounted in the minivan, travels at normal traffic speeds and records the received signal. The system is designed to always start sampling at the same position in the PRBS. When the distance encoder triggers a measurement, it enables the sampling of 1 block of data. The digitizers start sampling when a new PRBS starts, no later then 102.2 µs after the trigger. This feature permits ranging as explained in later paragraphs.

Figure 4 is an example of a measured impulse response estimate. Figure 5 is its Fourier transform. In figure 4, the Multipath Power Sensitivity Ratio (MPSR) indicates the power ratio of the strongest echo and the peak 'noise'. This 'noise' is composed of contributions from the correlation sidelobes as well as the receiver noise. In figure 5, the Fourier transform of a back to back reference measurement is superimposed on the plot. It clearly shows distortion due to multipath propagation. The reference curve is not a perfect $\mathrm{sinc}^2(x)$ because of the filters used in the measurement system.

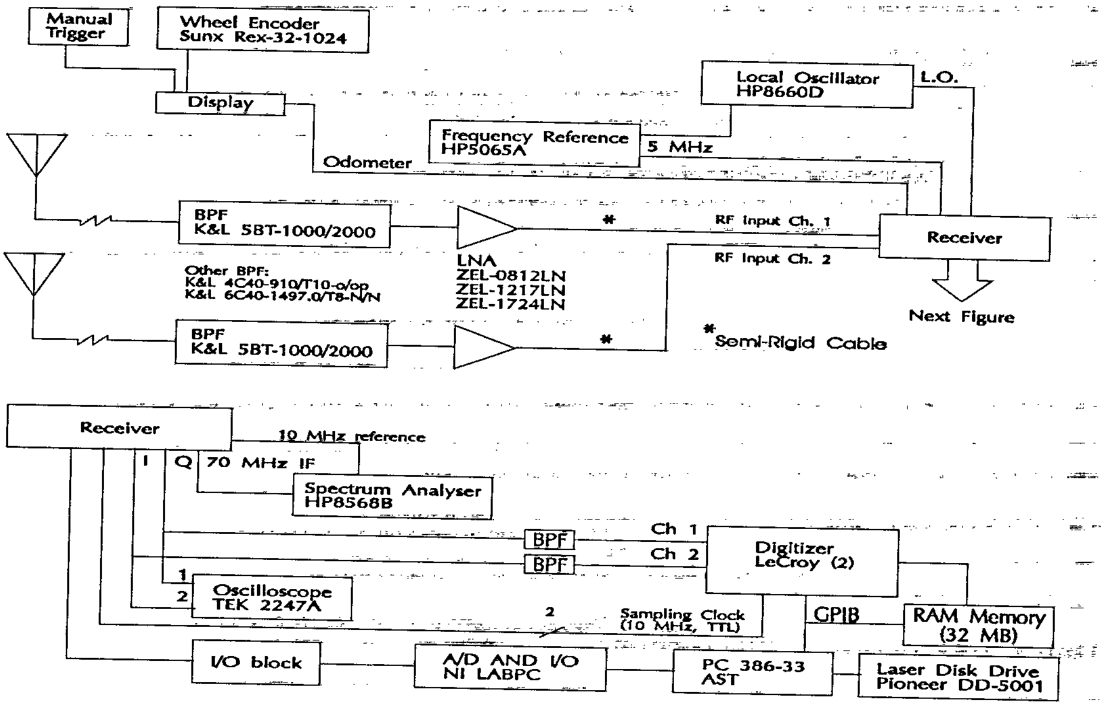

Figure 3: Wideband receiver configuration

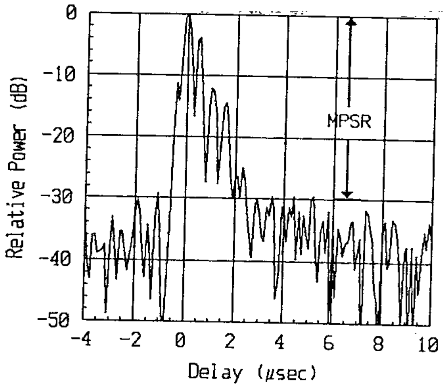

Figure 4: Example of a typical estimate of impulse response in a non line of sight path, downtown Ottawa. The MPSR is about 30 dB, delay spread is slightly more than 2 µs and the first path is not the strongest path.

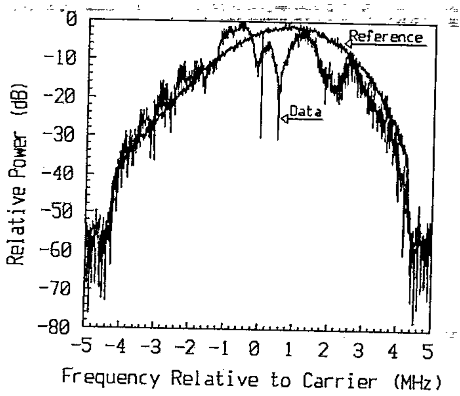

Figure 5: Spectrum of impulse response estimate shown in Fig. 4. The spectrum of the reference is superimposed to show the distortion measured.

4. DATA PROCESSING

Impulse response estimates are obtained by computing the correlation between a block of sampled data and the reference signal. The reference is used in correlation computation instead of a copy of the baseband PRBS because it includes distortion due to the system hardware. Software correlation is done in accordance with the following algorithm:

1. Let x(t) and b(t) be finite-duration functions, where x(t) is the data sampled during an experiment, and b(t) is the back to back measurement. (Both blocks have the same length to simplify the data processing and this length is equal to 2^N, where N is an integer value. Data blocks contain more than one PRBS to reduce the noise level by averaging.)

2. Add zeros to double the length of each block. (These zeros are necessary to avoid overlap in the correlation process.)

3. Compute the Fast Fourier Transform (FFT) of each block, X(f) and B(f).

4. Compute $H(f) = X(f)\,B^*(f)$, where $B^*(f)$ is the complex conjugate of B(f).

5. Obtain the correlation h(t) by computation of the inverse FFT of H(f). (Since each data blocks is longer than one sequence, the resulting correlation has several sidelobes due to partial correlations.)

6. The highest peak is selected and the impulse response estimate is extracted by selecting 1022 points (the sampling period is 100 ns and the PRBS lasts 102.2 μs) starting 100 before the main peak (Fig. 4) to include all precursors.

The execution time of this algorithm is long because of the large number of multiplications. Typically, on a 486/50 MHz PC, it needs about 3.5 s/impulse response, which means days of CPU time for a few hours of measurements.

5. SPECIFICATIONS OF THE MEASUREMENT SYSTEM

At 910 MHz, the maximum distance travelled during one sampling interval is less than a tenth of a wavelength at normal traffic speeds. It is assumed the radio channel does not change significantly over that distance. The minimum spatial sampling distance is set at a tenth of wavelength (3.3 cm). Previous measurements show that multipath spreads rarely exceed 30 μs, except for a few measurements in mountainous terrain. The required unambiguous delay window must therefore be greater than 30 μs. In order to enable the computation of good estimates of correlation bandwidth, which has been recorded to be as low as few tens of kHz [6,7] in urban areas, the spectral density of the probing signal is required to be less than 10 KHz. The minimum measured bandwidth is set at 6 MHz, equivalent to a TV channel. Diversity measurements (2 channels) are required to study space, pattern or polarization diversity as means to improve communications. A multipath signal power sensitivity ratio of at least 30 dB is necessary to achieve measurements at least as good as estimates from a hardware correlator. For measurements every half wavelength, with diversity, the recording distance required is greater than 200 m.

The pseudo random sequence length is 511 bits and its clock rate is 5 Mb/s. These two parameters set several specifications of the measurement system and they were carefully selected to fit our requirements. The 511 bits per sequence set the correlation sidelobes at -54 dB, well below the MPSR requirements. The 5 Mb/s was selected after several chip rates were tested to obtain the best time resolution for a bandwidth of 8 MHz. Fig. 7 shows the system output for chip rates of 1,2, 5 and 10 Mb/s. Five Mb/s was selected because it results in a narrow peak. Interestingly, high bit rates, such as 10 Mb/s, show a thinner peak but at the cost of a wider section at -30 dB. This is different from the correlation triangle because an important part of the first lobe is filtered out. The unambiguous delay is automatically set at 102.2 μs (511 x 200 ns) and the spectral density is set at 9.785 kHz (1/102.2 μs).

Sequence length	511 bits
Chip rate	5 Mb/s
Unambiguous delay	102.2 μs
Spectral density	9.785 kHz
Frequency range	100 MHz to 2 GHz
Measured bandwidth	8 MHz
No. of rf channels	2
Minimum trigger distance	1 cm
Maximum trigger rate	500 Hz
Sampling rate	10 Ms/s
Digitizer	8 bits/100 MHz
Data block length	4096/8192
Block sampling time	~0.5ms/~1.0ms
Maximum number of blocks	4096/2048
Memory size	16 MB/ channel
Multipath Power Sensitivity Ratio	>30 dB.
Stability	$1*10^{-11}$ Hz/ 1 s

Table I : Specifications of the impulse response measurement equipment.

The maximum reliable trigger rate was found to be 500 Hz. This rate is set by the measurement period and triggering delay in the system. The minimum distance between two measurements is 1 cm. Two 8 bit high quality digitizers sample the in-phase and quadrature baseband signals at 10 Ms/s. They are rated at a maximum sampling rate of 100 Ms/s and yield 40 dB s/n at 5 Msamples/s for an input signal amplitude at 80% of maximum input. Each digitizer is connected to 16 MB of random access memory. Limited memory means that the number of samples per block of data is important. Data cannot be acquired continuously. At 10 Ms/s, digitizers will fill the memory in a little more than 1.6 s. Fig. 8 shows the effect of different block lengths on the impulse response estimate. Based on these plots, a block size of 4088 or more is considered sufficient to maintain a 30 dB MPSR. At 4096 samples/block and 16 MB of memory per digitizer, a maximum of 4096 blocks of data can be stored in memory. The block length also sets the duration of one measurement period and the maximum distance travelled during one experiment or run. For long runs and/or high speed measurements, 4096 samples/block was chosen to be the most suitable. This leads to a sampling period of 0.5 ms. Therefore, at 30 m/s, the distance travelled during one measurement interval is 1.5 cm, less than the tenth of a wavelength requirement at 910 MHz. For a trigger distance of 15 cm or around half a wavelength, the maximum distance travelled is 614 m for single channel measurements or 307 m for two channels diversity recordings.

The multipath power sensitivity ratio is required to be greater than 30 dB. Once the data block length sets the correlation gain, the only other way to improve the MPSR is to maintain a large signal to noise ratio at the input of the receiver. At first, it was thought an Automatic Gain Control (AGC) was necessary to maintain input signal levels to the digitizer above 80% of the maximum input. This was reasonable since the signal fades continuously. Unfortunately, this gain had to be tracked and recorded because different gains also mean different phase shifts. However, it was verified that if the receiver is set at a constant gain, the MPSR is not degraded very much. Measurements show that if an AGC is set to maintain the signal above 80% of the maximum level and under saturation, the MPSR is greater than 30 dB for input signal power levels above -100 dBm (Fig. 6). For power levels below -100 dBm, the receiver noise becomes important and the MPSR decreases linearly with the input signal power. On the other hand, if the receiver gain is set manually the MPSR is still more than 30 dB for strong signals and as the signal power decreases, only a 2 dB degradation is measured for input signal powers lower than -100 dBm. A similar test on a hardware correlator showed rapid degradation of the MPSR if the gain is not adjusted. Therefore, for a software correlator, the noise floor is set mostly by the correlation process, at least down to -100 dBm. This remarkable feature of a software correlator greatly simplifies measurements, which can be done over long distances even with fading and shadowing of the signal. The maximum propagation loss the equipment can tolerate with a MPSR greater than or equal to 30 db is then, for a transmit power of 10 W (40 dBm), about 140 dB (40 dBm - (-100dbm)).

Two rubidium frequency standards are used to phase lock all the oscillators used in the measurement system. If only envelope information is required, local oscillator frequency offsets of up to 1 kHz are acceptable.

6. TYPICAL MEASUREMENT RESULTS

This section presents examples of impulse response estimates measured with the system described above. Figure 9 compares the output of a hardware correlator measurement system to the output of the software correlator. The two impulse response estimates are for the same transmitter - receiver configuration and both system show very similar results. The differences between the two plots are due to a better time resolutions of the hardware correlator. This measurement shows that both systems have the same output for static radio channels.

Fig. 10 shows impulse response estimates recorded quasi-simultaneously on two diversity channels, a specification unique to the measurement system. The main features of these measurements are very similar, but because of different vectorial additions of multipath within the equipment time resolution the exact position and amplitude of each path group is slightly different. Fig. 11 shows the instantaneous coefficient of cross-correlation between the structure of impulse response estimates measured from two antennas separated by 1.0 and 1.5 wavelength (15 cm and 22.5 cm) at 1.980 GHz. Measurements were made every cm and coefficients of cross-correlation were also computed every cm for a total distance of 64 cm. The two antennas were installed side by side across the roof of the vehicle. Measurements were done in line of sight (LOS) and non line of sight (NLOS) environments. For an antenna separation greater than or equal to 1.5 wavelength, it was found the two radio channels are uncorrelated, for both LOS and NLOS conditions. For a 1 wavelength separation the cross-correlation coefficient is very high (>0.9) for LOS and varies from low to high (0.2 to 0.7) for when there is NLOS.

The final feature to be discussed here is ranging. It is possible to determine direction of arrivals and distance the echoes travelled by taking multiple measurements and using artificial aperture techniques. Fig. 12 shows some examples. The top plot is a reference measurement. It was measured at a known location, close to the transmitter with line of sight path. Because the phase stability is maintained with Rb frequency standards and sampling always starts at the same position in the PRBS, the software correlation does not drift and always maintains the same excess time delay for the same echo. The bottom plot shows an example of an impulse response estimate measured behind a hill, about 50 m from where the middle plot was sampled. Because the shortest path signal was greatly attenuated, the echoes from distant buildings have greater relative power. It follows that the received signal power decreased and the channel transfer function would be much more distorted by the presence of a longer multipath spread.

7. CONCLUSIONS

This paper discussed a fast data acquisition measurement system for the estimation of impulse responses of mobile radio channels. The most important feature of the equipment is its short measurement period of less than a millisecond. Estimates measured for time varying radio channels are believed to be more relevant than those measured with a hardware correlator because data are acquired on the move at speeds comparable to realistic operating speeds in mobile environments. In static environments, both systems give identical results.

The system is very versatile. It operates at any frequency between 100 MHz and 2 GHz with a bandwidth of 8 MHz. This bandwidth can be easily changed and adapted for other applications. The system can also measure two channels quasi-simultaneously.

8. REFERENCES

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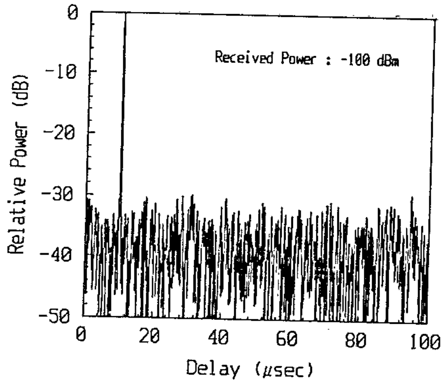

Figure 6: Impulse response estimate for a back to back measurement with an input signal of -100 dBm.

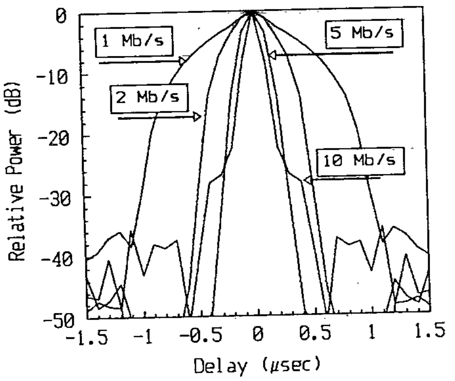

Figure 7: Effect of chip rate on time resolution.

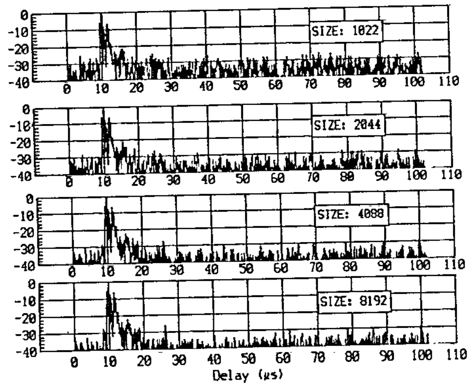

Figure 8: Effect of block size on the impulse response estimate. Block sizes of 4088 of larger are necessary to maintain a minimum MPSR of 30 dB.

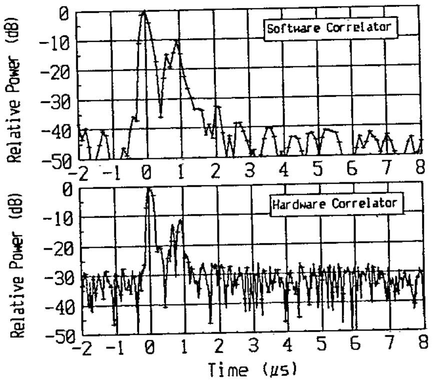

Figure 9: Comparison between impulse responses computed by a 10 MHz software correlator and a 20 MHz hardware correlator, for the same transmitter - receiver configuration.

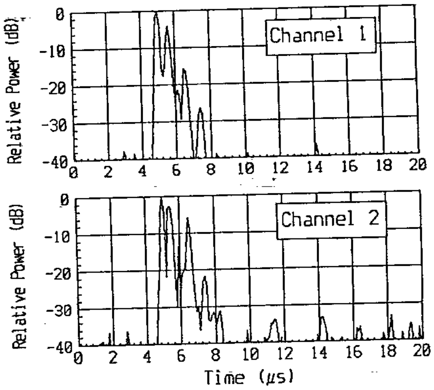

Figure 10: Comparison of two impulse responses measured simultaneously from two antennas separated by one wavelength.

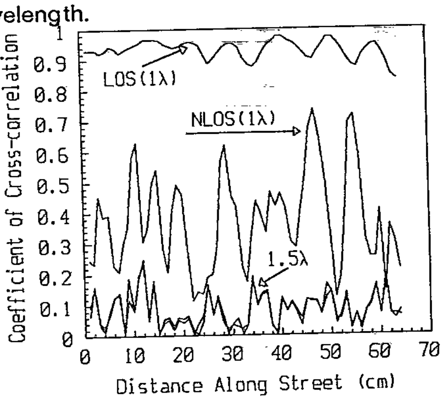

Figure 11: Cross-correlation between impulse responses measured from 2 antennas separated by 1.0 and 1.5 wavelength in LOS and NLOS configurations.

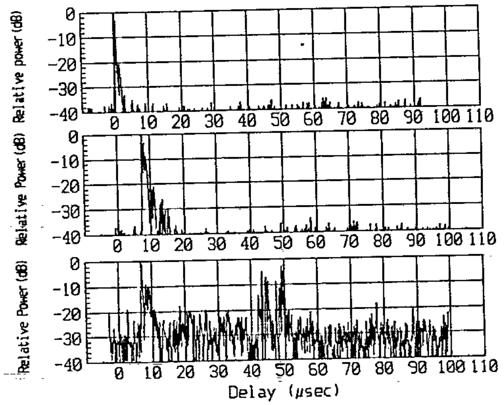

Figure 12: Ranging capability of the measurement system. The top plot is a reference at close range. The middle plot is at 2.25 km in LOS and the bottom plot is at 2.2 km in NLOS, where long excess delay echoes are from buildings located at 10 km from the transmitter.

DISCUSSION

Discussor's name : G. S. Brown

Comment/Question :

Are you reasonably certain that the paths and scatterers which are causing your multiple returns are frequency independent over the bandwidth of your transmitted signal? If they are not, this could degrade the theoretical resolution of your system.

Author/Presenter's Reply :

Since the measurement system has only a 10 MHz bandwidth, I assume the returns are frequency independent.