Project	**IEEE 802.16 Broadband Wireless Access Working Group**	
Title	**Multipath Measurements and Modelling for Fixed Broadband Wireless Systems in a Residential Environment**	
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Re:	Response to IEEE 802.16 PHY Task Group Call for Contributions on Modelling Issues, Nov. 22, 1999, in particular the call for models of channel multipath.	
Abstract	We describe and analyze measured wideband 29 GHz propagation data collected in Ottawa in 1997, to suggest a simple tapped delay line multipath channel model for residential environments.	
Purpose	To aid in the PHY Task Group's preparation of a detailed evaluation table for performance of PHY layer air interface proposals.	
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MULTIPATH MEASUREMENTS AND MODELLING FOR FIXED BROADBAND WIRELESS SYSTEMS IN A RESIDENTIAL ENVIRONMENT[1]

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1. Introduction

In order to design and evaluate effective PHY layer modulation, and reception techniques for fixed broadband wireless systems, it is important to understand and model the multipath environment which they will encounter. This is especially important in the difficult residential/small business environment, which is sensitive to CPE antenna installation costs. In [1] we discussed equalization requirements, based on samples of 29 GHz multipath responses measured in the Ottawa area. This contribution describes the collection and analysis of these measured data, and proposes a model for fixed broadband wireless multipath in residential environments. The result is a tapped delay line model with three to six taps, whose existence, delays and magnitudes depend on environmental and antenna beam pattern parameters. The model is limited in that it is derived from a relatively limited set of data and system parameters in several locations. We hope that the results can be usefully combined with others' propagation measurements to yield a more broadly based model for fixed broadband wireless channels.

2. Multipath Spread Measurements Made in Ottawa in 1997

The impulse responses used for this evaluation had been measured[2] at 29.5 GHz frequency in residential and industrial areas of Kanata and Parkwood Hills between a hub transmitter and many receive locations through the use of directional antennas at both ends. Many of the measured impulse responses in both areas, but especially in Parkwood Hills, were from non-line of sight (NLOS) locations, in which obstructions such as trees or buildings blocked the direct path between transmitter and receiver.

(a) Parkwood Hills Measurements

The Parkwood Hills area has mainly one- and two-floor houses, a few high-rise apartment buildings, and roughly 20% tree coverage, both deciduous and coniferous. Impulse response measurements were made at 8 main sites, between about 0.5 and 1 km. from the transmitter, with multiple measurements at each site, at different antenna heights and different locations several metres apart. In addition, at each receiver location in Parkwood Hills, impulse response measurements were made at 60 azimuthal bearings, 6 degrees apart, to detect and measure indirect signal components. Impulse response data was obtained from a total of 52 locations, each with 60 bearing angles.

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[1] [1] This research was supported by a grant from the Canadian Institute of Telecommunications Research (CITR) under the NCE Program of the Government of Canada.

[2] Research partners involved in the measurements included Carleton University, the Communications Research Centre, Newbridge Networks, Nortel Networks and Stentor.

In Parkwood Hills, the transmitting antenna, mounted on the rooftop of a 40 m. apartment building, was a vertically polarized horn antenna, with gain of 18 dBi, elevation beamwidth of ± 11.5 deg., and azimuth beamwidth of ± 8 deg. It was angled down at 5 deg. The receiver antenna was a vertically polarized horn with ± 5 degree beamwidth in both azimuth and elevation, with a 23 dBi gain. The receiver system was mounted on an adjustable-height (5 to 8 m.) pole on a moveable trailer. Most measurements were made with the receiver parked on a road near houses, within in the transmit antenna's boresight. A few measurements made on residential rooftops produced results not greatly different from the roadway results.

(b) Kanata Measurements

The Kanata measurements were done in an area with a mixture of woods, houses, low-rise apartments and small commercial/industrial buildings. The measurement range was from 1 to 3.5 km. The transmitting antenna, mounted at the rooftop of a 30 m. high Newbridge Networks building, was the same vertically polarized horn antenna as used in Parkwood Hills. The receiving antenna in Kanata was a vertically polarized cassegrain reflector antenna with beamwidth of ± 1 deg. in both elevation and azimuth, with gain of 36 dBi. Only one bearing angle was used at each location (the one yielding the maximum received power). In Kanata, the measurement locations were at 50 ft. intervals along a road which formed a radial path leading from the transmitter site, and in two arcs in residential areas at slightly different radii from the transmitter site. At least the first 3/4 of the radial road sites were LOS[3]. A total of 111 measurements were made in Kanata, but 79 were selected for analysis, since the remainder had inadequate received signal power.

3. Measurement Procedure

The measurement method involved transmitting a BPSK signal at 29.5 GHz modulated by a 63 bit long PN sequence generated at 40 Mbps and then receiving the signal by employing a quadrature (I and Q) receiver. The demodulated quadrature signals were sampled at a rate of 100 M samples/sec. Following the I-Q demodulation process at the receiver, the resultant complex envelopes of the received signals were sampled and stored. The 100-MHz-sampled complex envelopes were crosscorrelated with a replica of the transmitted signal (including transmit and receive filtering), resulting in an estimate of the low pass equivalent of the radio channel complex impulse response, with a resolution of about 20 to 25 ns. The crosscorrelations were averaged over 6 PN sequence lengths to further reduce noise effects. A thresholding technique, described in [2] was applied to the recorded responses to reduce the impact of noise on measured data and extract the valid impulse response echoes. In the results to be shown subsequently, all responses are normalized to have unit energy, and shifted so that the maximum magnitude sample of each response is sample #19. Furthermore, the phase of each complex sample in each response is rotated by an amount for which the maximum sample has zero phase. The variance of each estimated impulse response sample due to receiver noise is estimated to be at least 25 to 30 dB below the main sample amplitude.

4. Parkwood Hills Multipath Results

Fig. 1 shows the CDF of the multipath spread for only the best (maximum received power) bearings in Parkwood Hills. Here, we define the multipath spread as the time interval in which the response is above the noise threshold. This definition generally results in a much larger numerical measure of delay spread than does

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[3] In this document, "LOS" (line of sight) paths are those with a clear, unobstructed, direct path between transmitter and receiver, and the transmitting and receiving antennas' boresights are aligned. All other types of paths are "NLOS" (non line of sight).

rms delay spread. The 96th percentile is 90 ns. in this plot. The vertical axis could be interpreted as the fraction of locations that would have acceptable multipath spread, given an equalizer capable of handling the delay spread given in the horizontal axis. It should be pointed out that the measured delay profiles only cover the propagation multipath, and that indoor-to-outdoor triple-transit cabling reflections could add to the overall multipath delay spread.

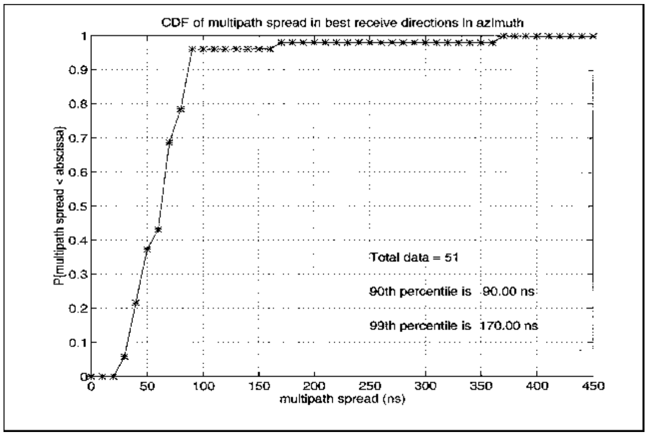


Fig. 1 Distribution of multipath spread in best receive directions in Parkwood Hills

Fig. 2 shows the average multipath delay profile; i.e. the averaged magnitudes of the Parkwood Hills responses.

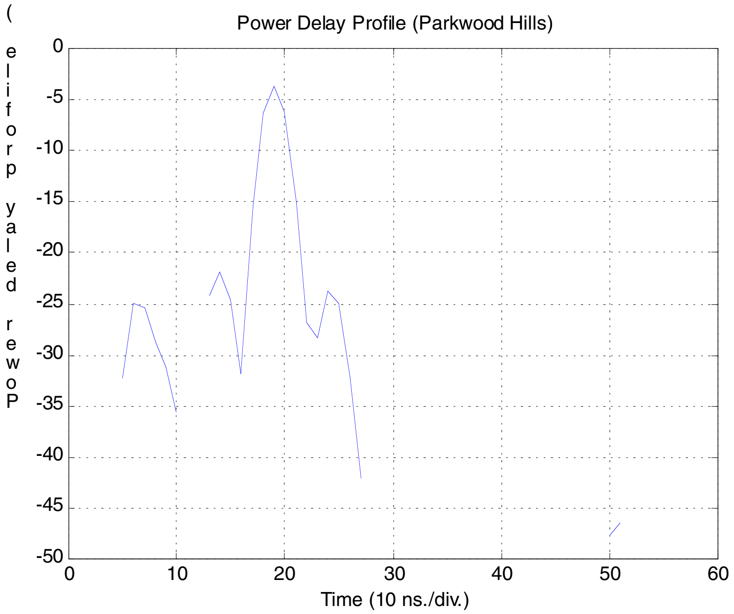


Fig. 2 Parkwood Hills average power delay profile

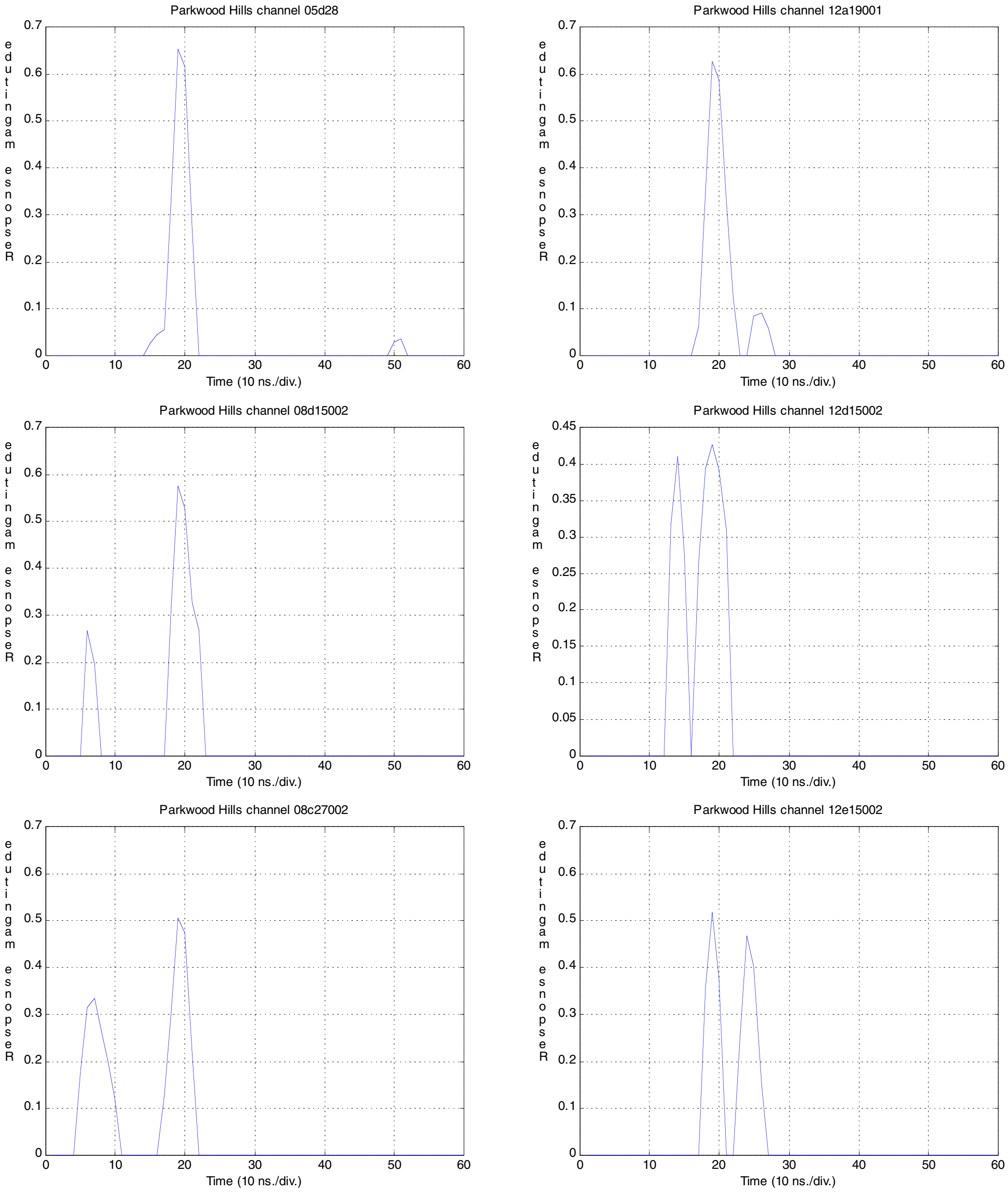
Another view of the Parkwood Hills response magnitudes is the contour plot of Fig. 3, with contours at 5 dB intervals. Several observations emerge from Figs. 2-3:

1. In the immediate vicinity of the central sample #19, the impulse response shapes are fairly similar.

2. There are however, several responses with substantial echoes at delays of up to 100 to 300 ns.
3. Some of the responses are "non-causal"; i.e. large echo components appear before the largest sample.

Fig. 3 Contour plot, showing multipath spreads of Parkwood Hills responses

The "worst" Parkwood Hills responses are depicted in Fig. 4. These include those for which the performance of DFE equalizers was relatively poor [1]. The Parkwood Hills channels are designated as follows: the first two digits identifies one of 8 main sites (e.g. '12'); the next letter (e.g. 'd') identifies the sublocation; the next two digits designate the receiver antenna height in feet (e.g. '15'); the final 3 digits identify the particular measurement. Most of the "bad" responses shown in Fig. 4 were at NLOS locations, where the maximum energy response was obtained at a bearing angle other than 0 degrees; i.e. at these locations and antenna heights, there was significant signal power arriving from multiple directions, and the highest power signal came from a non-direct path.


Parkwood Hills channel 05d28

Parkwood Hills channel 12a19001

Parkwood Hills channel 08d15002

Parkwood Hills channel 12d15002

Parkwood Hills channel 08c27002

Parkwood Hills channel 12e15002

Fig. 4 Some of the “worst” Parkwood Hills impulse responses

CHANNEL AND ECHO	BEARING RELATIVE TO LINE OF SIGHT PATH	OTHER COMMENTS
05d28 (-25.7 dB echo at 320 ns., relative to center of response)	0 deg.	LOS. Maximum observed delay spread. A good response with no echo, but lower energy, was observed at –6 deg.
08c27002 (-3.8 dB echo at –120 ns.)	-54 deg.	NLOS. A good response with no echo, but lower energy, was observed at –6 deg.
12d15002 (-0.4 dB echo at –50 ns.)	-126 deg.	NLOS. A good response with no echo, but lower energy, was observed at –12 deg.
08d15002 (-6.6 dB echo at -130 ns.)	180 deg.	NLOS. A fairly good response with no echo, but lower energy, was observed at –174 deg
12a19001 (-17 dB echo at 70 ns.)	-6 deg.	NLOS. A fairly good response with no echo, but lower energy, was observed at 0 deg
12e15002 (-0.8 dB echo at 50 ns.)	-162 deg.	NLOS. A fairly good response with no echo, but lower energy, was observed at 0 deg

Table I Echoes, bearings and other comments for the worst-case Parkwood Hills channels

Table I lists the bearings, plus some other comments, for the 6 responses in Fig. 4. It is interesting that the response with the largest delay spread, (320 ns.), channel 05d28, was for a line of sight path, and that rotating the receive antenna by 6 degrees effectively removed the long-delayed echo, at the expense of slightly lower received signal energy. Table I indicates that all of the high energy, high delay spread channels could have their delay spreads drastically decreased by simply re-pointing the receive antenna. Changing the antenna height also can improve the delay spread.

5. Kanata Multipath Results

The results from Kanata are summarized in Figs. 5-7, which correspond to Figs. 1-3, respectively for Parkwood Hills. The 90th percentile is 80 ns. It is clear that the Kanata responses are generally “better” than the Parkwood Hills responses. There are three probable main reasons:

1. The receive antenna used in Kanata had a much smaller beamwidth - ± 1 deg. instead of the ± 5 deg. of the Parkwood Hills antenna.
2. A higher fraction of the Kanata sites were LOS.
3. The transmitter to receiver range in Kanata was generally longer than in Parkwood Hills. A substantial fraction of the Kanata measurements could not be used because of insufficient received power.

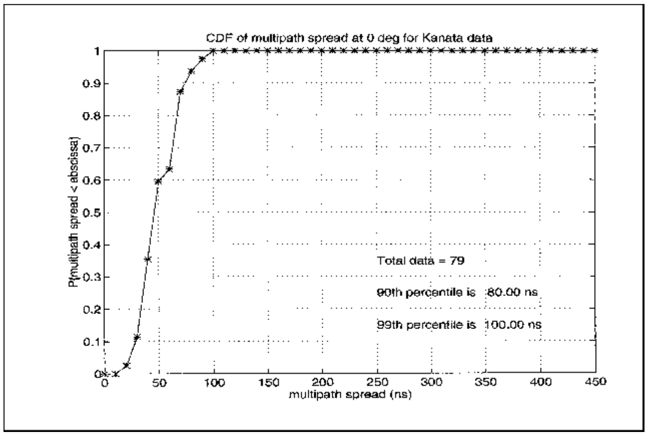


Fig. 5 Distribution of multipath spread in Kanata

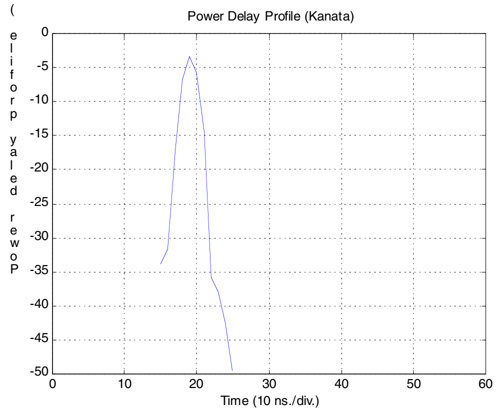


Fig. 6 Kanata average power delay profile

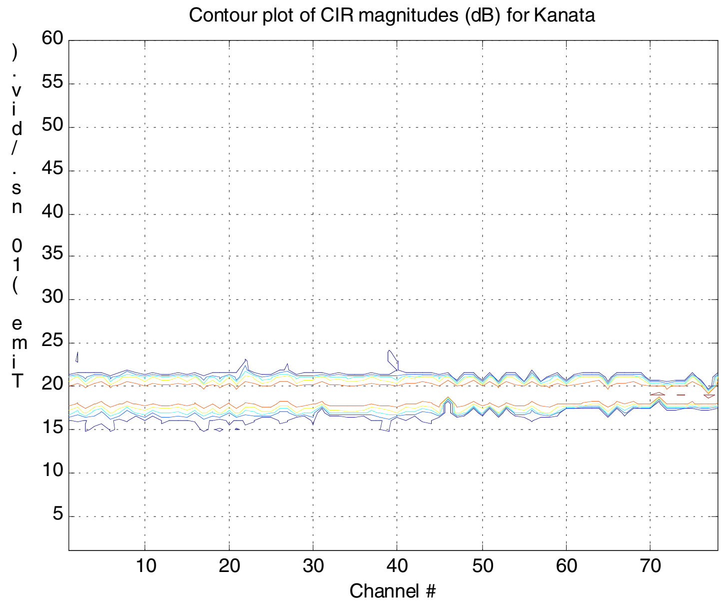


Fig. 7 Contour plot, showing multipath spreads of Kanata responses

Fig. 8 shows some of the Kanata responses with the greatest delay spreads. As in the Parkwood Hills files, the first two numerical digits in the Kanata files designate the receiving antenna height in feet.

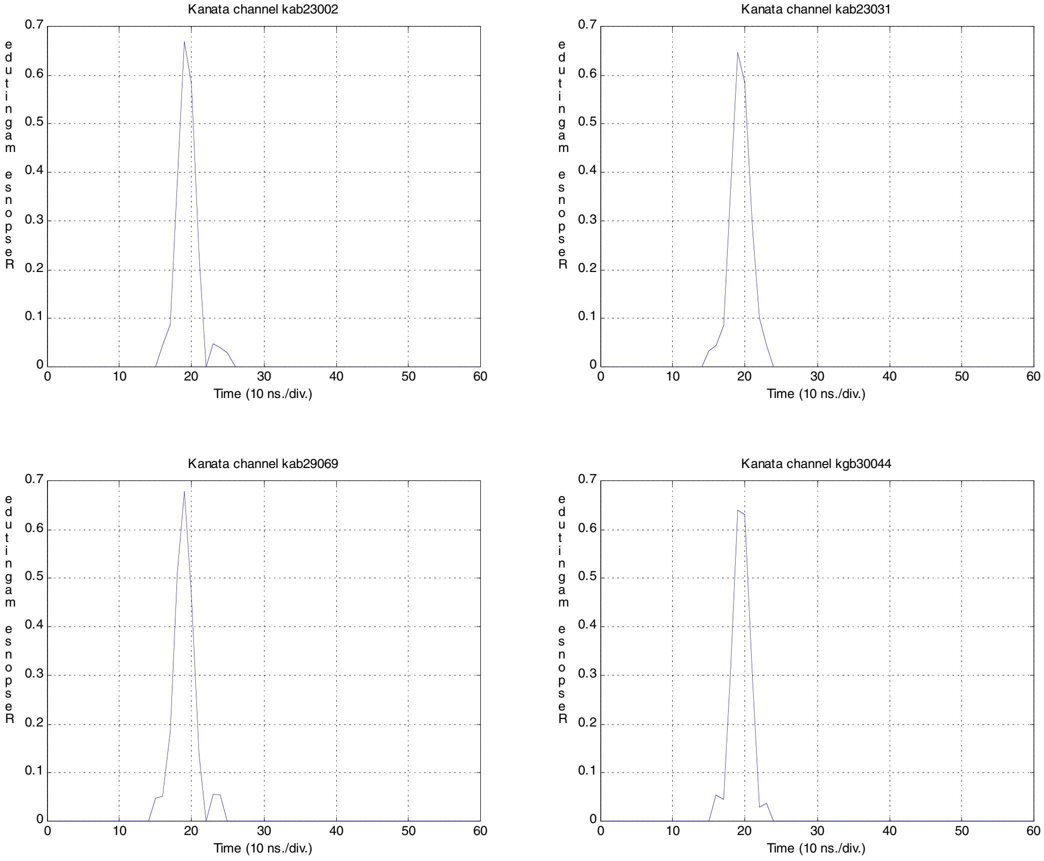


Fig. 8 Some of the “worst” Kanata impulse responses

6. Discussion of Results and a Proposed Multipath Model

The modelled complex sampled response has its time origin at *t*=0, and its energy (sum of squared magnitudes of its samples) is normalized to unity. Thus the modeled impulse response is of the form

$$\{h(k\Delta t) \equiv h_k\}_{k=-\infty}^{\infty} \text{, where } \Delta t = 10 \text{ ns. and}$$

$$\sum_{k=-\infty}^{\infty} |h_k|^2 = 1.$$

For any practical transmitter/receiver pair, the range of indices (which is equivalent to delay spread) is of course finite. The delay spread and the relative magnitudes of the complex echoes $\{h_k\}_{k\neq 0}$, will depend on factors such as antenna beamwidths, the nature of possible propagation paths (LOS, NLOS, obstructed, scattering, reflection and diffraction phenomena), distance between transmitter and receiver, and the expected receiver noise floor.

Our model is based on the statistics of the phase-rotated and normalized Parkwood Hills and Kanata measured responses. The averages of these responses are shown in Fig. 9 for Parkwood Hills and Kanata. Because of the phase rotation that was applied, the real average response is dominant at sample #19, and it is seen that this is true at most of the other sample instants as well. The mean responses in Parkwood Hills and Kanata are almost identical in their central regions around sample #19; deviations in the measured means at other delays are due to a very few echoes at larger delays. For this reason we assume that *the actual propagation channels can be inferred from deviations of the observed complex impulse response samples from their mean values.* Histograms made of the real and imaginary parts of these deviations, up to 40 ns. on either side of the central peak, where there were sufficiently large numbers of samples, indicated that they could be reasonably modeled as zero-mean complex gaussian random variables; i.e. the phases of the sample deviations are uniform in (-180°, 180°), and their magnitudes are Rayleigh-distributed.

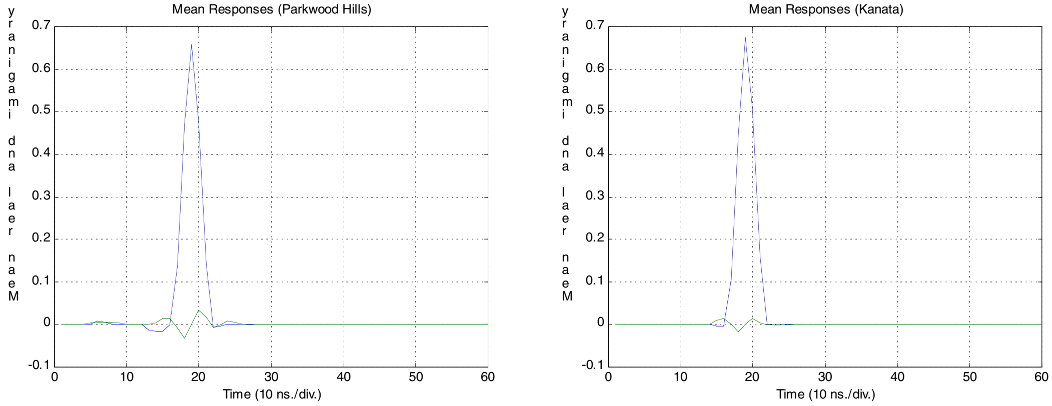


Fig. 9 Mean Parkwood Hills and Kanata responses

Fig. 10 shows the standard deviations of the real and imaginary parts of the Parkwood Hills and Kanata responses. In both sets of data, the standard deviations at samples 17, 18, 19, 20 and 21 (within 20 ns. of the central peak) are approximately 0.08. Squaring and doubling (real plus imaginary) puts this at -15 dB relative to the central peak magnitude of about 0.65. In the Parkwood Hills measured data, Fig. 10 shows significant additional standard deviation components about 20 dB down from the peak around samples #14 and #24 (±50 ns.).

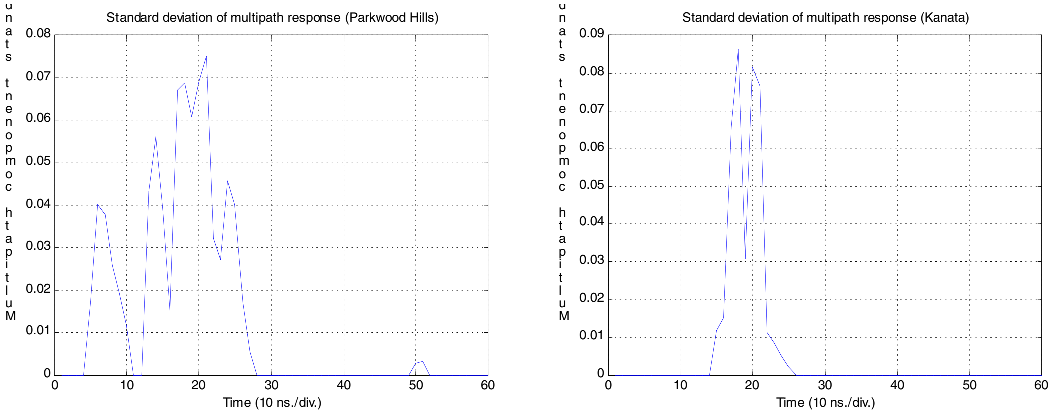


Fig. 10 Standard deviations of real and imaginary parts of Parkwood Hills and Kanata responses

The multipath response data that has been described is admittedly limited in quantity and in numbers and types of sites. However it does indicate that where non line of sight paths exist, there may exist relatively large echoes, 10's or 100's of nanoseconds before or after the main response peak, even if the transmitter and receiver have directive antennas. This is somewhat analogous to “ghost signals” in television reception. Accordingly, we postulate a model of impulse responses with up to two types of echoes:

1. Type I echoes: two zero-mean complex gaussian echoes at ±20 ns. from the main peak, whose energies (variances) are respectively at –15 dB relative to the main peak. Furthermore, *with probability p*, there are two more zero-mean gaussian echoes, at ±50 ns. whose energies are at –20 dB relative to the main peak. We suggest that *p*=1 for systems with wider subscriber beamwidths, such as the ±5° beamwidths used in Parkwood Hills; and that *p*=0.15 for systems with ±1° beamwidths such as those used in Kanata. These suggested parameters are based on the standard deviation results of Fig. 10 and the contour plots of Figs. 3 and 7.
2. Type II echoes: relatively large echoes with delays, relative to the main peak, of up to several hundred nanoseconds, such as those Parkwood Hills echoes listed in Table I. Further discussion of these types of channel responses is given below.

Type I echoes in systems with directive antennas might typically be expected to occur as a result of reflections, diffraction or scattering at small angles of incidence within beam patterns, as illustrated in Fig. 11 for a line of sight path plus a reflected path. Simple geometric calculations [3] show that for beamwidths of less than ±6° at the subscriber antenna and ±45° at the hub antenna, and path lengths of about 1 km., echo delays of up to about 130 ns. could occur, corresponding to a path length differential of about 42 m. For respective beamwidths of ±6° and ±8°, the maximum echo differential delay would be about 22 ns. In such cases, the major relative attenuation suffered by the echo would be from the reflection coefficient, or scattering or diffraction losses.

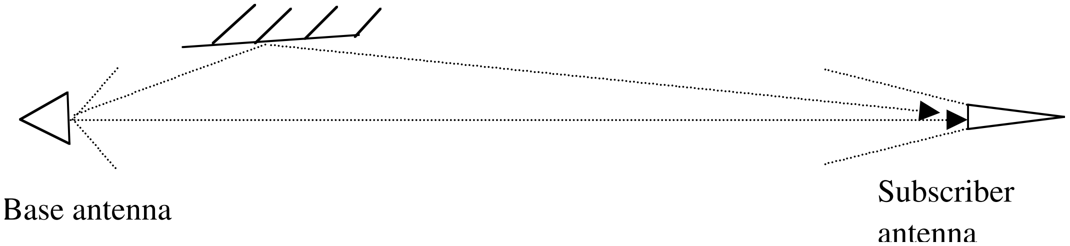


Fig. 11 Type I reflection scenario

Possible mechanisms for longer echo delays in Type II cases are illustrated in Figs. 12. In both cases the maximum differential delay is limited more by echo path loss or by antenna sidelobe attenuation than by antenna beamwidth. Fig. 12 also illustrates situations in which troublesome reflections could perhaps be eliminated by rotating the subscriber antenna slightly, or by changing its height or position. Examples for the worst-case Parkwood Hills responses are given in column 3 of Table I.

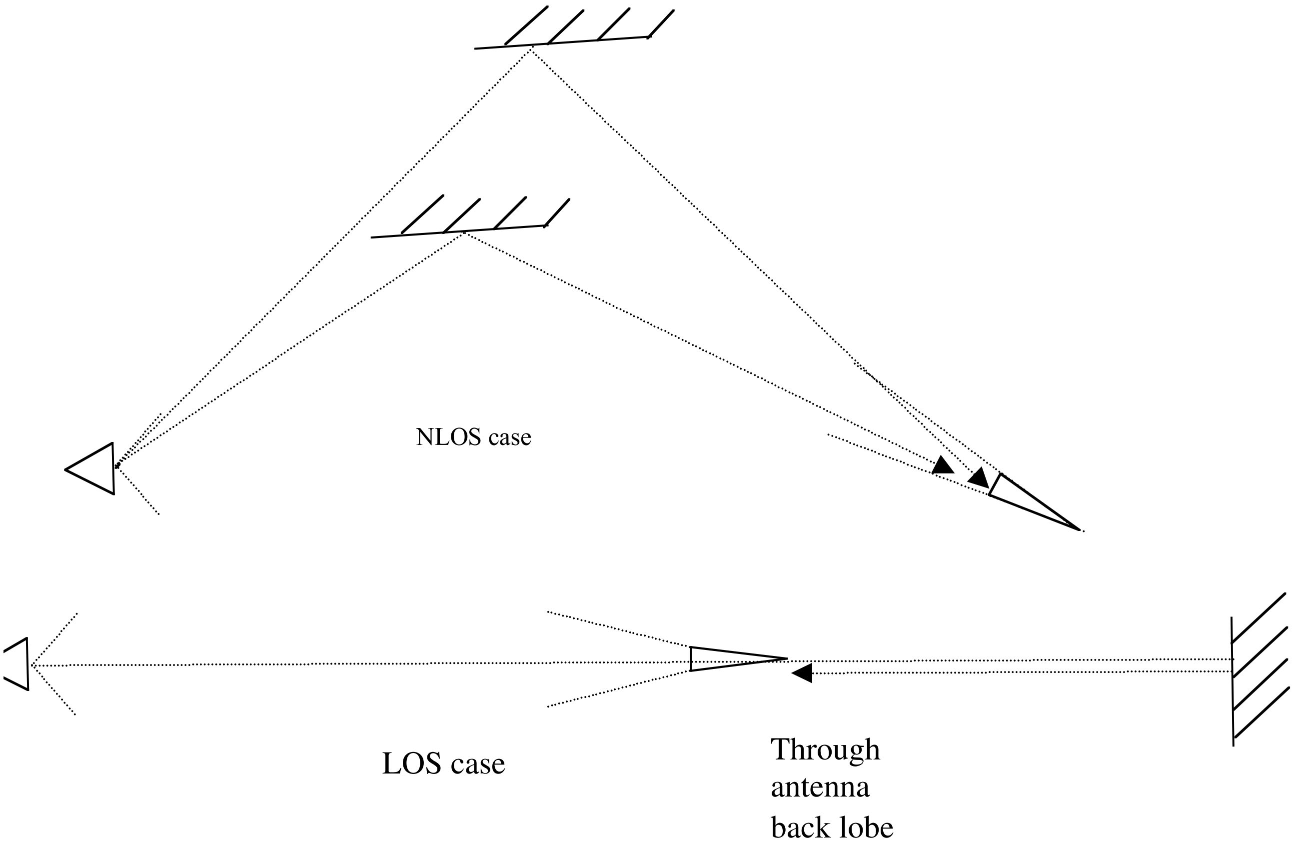


Fig. 12 Type II reflection scenarios

Type II echoes were not observed in Kanata. They occurred in six locations in Parkwood Hills (those in Fig. 4 and Table I). Conditions <u>favouring</u> the occurrence of Type II echoes might include:

1. Non line of sight paths, especially ones where the subscriber antenna is pointed at a reflection instead of directly at the hub site.
2. Subscriber antenna beamwidths of at least ±5°.

Conditions <u>not favouring</u> Type II echoes might include:

1. Line of sight paths.
2. Careful "tuning" of subscriber antenna bearing and position to eliminate troublesome echoes.
3. More highly directive subscriber antennas, such as ±1° beamwidth.

We do not have enough data to assign a precise probabilistic model, although the presence of six types II echo responses in a total of 52 Parkwood Hills responses suggests that they might occur with a probability on the order of 10%, under the favourable conditions listed above. The only data we have on the range of delays and amplitudes of Type II echoes is encapsulated in Fig. 4. It suggests delays are at least in the range of -130 ns. to 320 ns., with energies of 0 dB to –25 dB relative to the main peak.

7. Summary of the Proposed Model

A tapped delay line model with taps at the following time instants

- Time zero: Unit (0 dB) amplitude, random phase sample, h_0.
- ±20 ns.: Zero-mean complex gaussian-distributed samples, $h_{\pm 2}$, 15 db down from the peak at time zero; i.e. independent real and imaginary parts each have standard deviations of 0.126.
- ±50 ns.: With probability *p*, zero-mean gaussian samples, $h_{\pm 5}$, 20 dB down from the peak. With probability 1-*p*, no sample at ±50 ns. *p*=1 for beamwidths of greater than ±5°, and *p*=0.15 for beamwidths of ±1°. In general, assume *p*=min(1, beamwidth/5°).

If Type II echoes are likely according to the conditions listed in the previous section, insert a complex sample with probability 0.1 in the range (0, -25 dB) at a delay (-130 ns., 320 ns.) relative to the peak.

Once the taps are formed, the resulting response can be normalized to unit energy, and used in evaluating modulation and adaptive equalization strategies in PHY proposals.

8. Time Variability

Time variability arises as a result of movement of scatterers and reflectors near the propagation paths as a result of wind or movement of vehicles, people, etc. It can also arise due to wind-induced motion of highly directive antennas. In contrast to the time variation in dense scattering environments in moving vehicle 1-2 GHz cellular scenarios, time variation in broadband fixed wireless systems with directive antennas tends manifest itself as “time varying shadowing”, nearly independent of signal bandwidth, with rates of change which are consistent with doppler shifts resulting from the velocity of moving reflectors and scatterers such as trees [4],[5]. The results reported in [5] suggest that signal level (and multipath component) temporal variation follow a Ricean distribution, and have typical fading bandwidths of less than about 100 Hz.

9. Comparison with Others’ Results on Delay Spread in Outdoor Environments

For narrow beam systems our model of Type I echoes is fairly consistent with a model of a typical “bad” channel found in Northglen, Colorado by Papazian et al [6] and also with multipath responses seen in downtown Denver by Violette et al [7]; the measured responses have 1 or 2 ns. resolution. The Papazian model had 0 dB, -2.8 dB and –16.2 dB taps at 0, 3.6 and 15.3 ns., respectively. It was based on measurements with a –20 dB noise threshold, at path lengths up to 0.5 km., using ±1.2° receive antennas. The measured responses in [7] were for LOS sites, while those of [6] included some NLOS residential sites. Observed delay spreads were generally under 10 ns. in these sets of measurements.

Measured multipath responses reported in [2] were in an urban high power 1-2 km. cellular 900 MHz environment, with omnidirectional or 60° sector base station antennas. Typical delay spreads ranged up to several tens of µs. The large spreads result from large antenna beamwidths and relatively high transmitted signal power.

A recent study and model of delay spread profiles in fixed 2 GHz wireless channels in suburban New Jersey and Illinois was carried out by AT&T researchers[8]. Their measurements included a total of 32 receiver sites over path lengths in the 0.5 to 2 km. range. Measurement time resolution was about 125 ns., and antennas used included ±32° transmitter and ±16° and omnidirectional receiver antennas. For measurements made with the directive antennas, multipath delay profiles tended to have a fixed main component at time zero and delayed components with path gains exponentially decreasing as a function of delay. The ratio of fixed compont to delay components and the rate of decay of the latter were statistically modelled. A rate of decay of about 20 dB/µs was typical.

10. Acknowledgements

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