Spatial Dynamics of Indoor Radio Channels

Invited Paper

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***Abstract*—The multipath components of wideband (2-17 GHz) non line of sight channel responses measured inside several buildings are stable along sections that are 9.5 cm long on average with a standard deviation of 8.1 cm. An analysis of measured channels that explicitly includes finite spatial areas of stability of the multipath components is superior to the classic analysis that attributes spatial dynamics to interference of the multipath. The spatial stability of responses with 1 GHz bandwidth decreases as the center frequency increases, i.e. the size of the typical area of stability of each multipath component tends to decrease with increasing carrier frequency.**

I. Introduction

The temporal dynamics of radio channels are intimately related to their variation in space. Temporal channel variation is usually attributed either to movement of the terminals, as in the case of a mobile telephone held while walking, or movement of objects in the environment of the communications system.

The analysis of measured or simulated wideband channels is normally carried out in the time domain, i.e. in the form of impulse responses. The angle of arrival of each multipath component, together with the motion of the receiving antenna, determines the shift in path arrival time as the receiver moves. The Doppler shift of a multipath component is a frequency domain concept; it is manifested in the impulse response by a location-dependent time of arrival of the multipath components. The spread of Doppler shifts of the different components that constitute a whole channel response is often thought to be the main cause of channel variation in space or time.

The common way of describing channel dynamics in time is the coherence period, that characterizes the typical period where the channel tends to be more or less constant. In the classic channel model, the coherence period is inversely related to the Doppler spread of the response. Channel analysis that is based on the Doppler spread implicitly assumes that each multipath component is received over the entire region of receiver locations [1]. We test this assumption empirically to find that it is not realistic in non line of sight (NLoS) indoor settings.

This paper offers an investigation of measured super-wideband indoor radio channels. We extracted the multipath components from measured responses taken along a one meter rail in NLoS indoor settings and studied their stability. The analysis described below shows that the multipath components typically have a short extent. We analyze our full band measurements (2-17 GHz) as well as channel responses over 1 GHz bands, and calculate the average size of stability areas of the multipath components and the standard deviation. These and related results are expected to enable a significant improvement of indoor channel models, that will include a realistic representation of their spatial dynamics.

The finite area of stability of multipath components appears to be a major source of channel variation across space. Our analysis shows average stability lengths on the order of 6–18 cm, in agreement with results from [2] that measured correlation lengths of 5-15 cm. Other related work has concentrated on the correlation of path amplitudes [3], [4] as they vary along space, and on the predictability of path amplitude values [5]. Our work is unique as it focuses on the existence of individual paths in adjacent areas in space. Instead of assuming that paths are stable and investigating the evolution of their amplitudes in space, we analyze the appearance of paths as the receiver moves.

Our results show a clear decrease, in the average and in the standard deviation of the length of the stability area, as the carrier frequency increases in the range 2 GHz to 17 GHz. We conclude that the channel is spatially more stable over low bands than it is over high bands.

The spatial dynamics of indoor radio channels were measured with a 120 MHz bandwidth and modelled by *Chong et al* [6] and *Herdin* [7], and with a 30 MHz bandwidth by *Nielsen et al.* [8]. *Zwick et al* [9] offer a birth and death characterization based on statistics taken from channels simulated by deterministic ray tracing in two buildings. This work models path birth and death using a marked Poisson process, also called an M/M/∞ process. The average stability areas of the components are found to be about 2 m in one building, and about 1 m in the second.

II. Measurement Environment and Equipment

A. The System

Our setup was based on an Agilent N5230 network analyzer, connected to two omni-directional antennas (Electro-Metrics EM-6865) in the 2-18 GHz band with suitable amplifiers. The receive antenna was placed on a meter long linear motorized

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positioner with millimeter accuracy that was moved between measurements but was kept immobile during the collection of each channel response. The transmit antenna was placed on a cart that was moved to different locations for different measurements, but was immobile during each measurement. Measurements were normally performed during nights, when movement of people around the system was minimal. Calibration was performed using measured responses of the cables and amplifiers, i.e. their responses were removed from the channel responses used for analysis.

B. The Measurement Environment

The 62 measurements used in this paper were collected between 2006 and 2008 in four office buildings in the Givat Ram campus of the Hebrew University in Jerusalem and in the Holon Institute of Technology. We kept the equipment in a single floor of the building in most of the measurements, and separated them to adjacent floors in five measurements. Transmitter–receiver separation ranged from 2 to 30 meters. All measurement are non line of sight (NLoS).

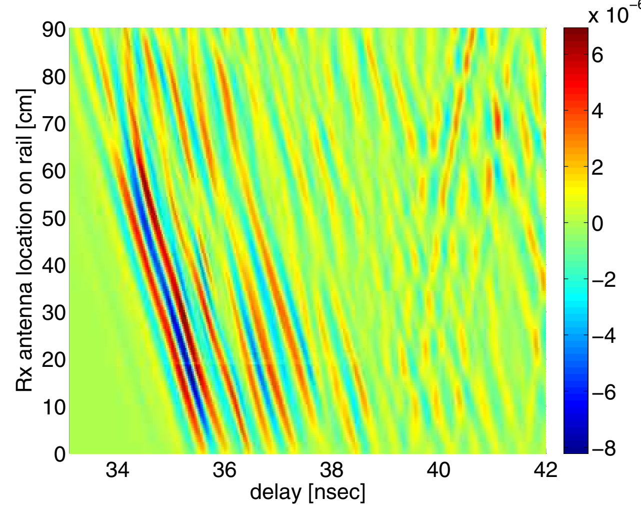

Fig. 1. An example of measured impulse responses. The horizontal axis has delay and the horizontal receiver positions. The responses are real with amplitudes that are shown in color. This measurement was taken with terminal separation of 9.8 m, and is typical of almost line of sight situations.

III. Analysis

The analysis is based on estimating the individual multipath components, and it focuses on their spatial area of stability. A *measurement* or *measurement matrix* in this work is a collection of responses with a stationary transmitter, and receiver positions that were uniformly spread over a one-meter rail, in steps of 2 mm to 10 mm. The receiver was held stationary during the measurement of each impulse response.

We analyze the measured channel responses using a raised cosine window. After filtering, the measured responses were converted to the time (delay) domain with a 28 psec time step, to generate a two-dimensional real representation of the channel as shown in the example in Figure 1. The delay range was set at 150 nsec around the maximal (absolute) response at one end of the rail, this seemed sufficient to include all the significant parts of the measurement.

The temporal resolution of 28 psec was maintained in all our analyses, i.e. responses with bandwidths of 1 GHz or lower are heavily over-sampled. Due to the over-sampling, multipath components with similar delays are correlated. Our analysis focuses on the spatial extent of the multipath components, and does not count the number of distinct components. All the measurements included in this analysis were of sufficient SNR, i.e. at least 16 dB, and above 20 dB most cases.

A significant feature of our measurements is the finite, and usually short, spatial extent of the multipath components. Figure 1 is typical in this sense as it shows short diagonal sections that correspond to the significant multipath components. These diagonals extend 3 – 60 cm over receiver positions in Figure 1. Line of sight (LoS) measurements have more stable components.

Our analysis is based on a software tool designed to extract the diagonal sections from the measurements. This tool received measured impulse responses of the type shown in Figure 1 and a few control parameters [1], and returned a list of diagonals, each defined by its endpoints, its width and a constant real (possibly negative) amplitude, this tool is described below.

Each multipath component forms a diagonal in the measurement matrix, composed of extremum points. Each diagonal can be represented in the form $x = at + b$, where t is delay and x is receiver location.

1) Preparing the Data: Starting from the measurement matrix, a new matrix containing the extremum points was constructed. This matrix was then searched for significant diagonal features, the search was performed anew for each value of the slope. The extremum points were searched from most to least energetic for the possibility that they are included in a significant diagonal. For each extremum point the location axis was searched in both directions for extremum points that line with it.

Once we have collected a set of extremum points that manifests a diagonal (multipath component), we collect non extremum points in their vicinity, in order to make the diagonal 'wider', or increase its span of delays. Depending on runtime parameters, we obtain up to a million diagonals from a single measurement with 2 mm spatial resolution (501 impulse responses measured at different receiver positions) and a 150 nsec span of delays.

2) Filtering the multipath components: The diagonals found in the previous step usually overlapped, in the next step we remove those diagonals that have most of their energy shared with other diagonals. For each diagonal, the ratio R of

[1] The parameters used by our software are the minimal spatial extent of diagonals, set at 3 cm, the minimal amplitude of the diagonals, set at 0.1 of the maximal amplitude in the measurement (-20 dB) and the minimal measured amplitude along each diagonal, set at 0.5 of its maximal amplitude (-6 dB)

the energy it shares with other diagonals and its total energy is calculated:

$$R = \frac{\text{Energy the diagonal shares with other diagonals}}{\text{Total energy of the diagoanl}}$$

If R is above a threshold the diagonal was removed. The threshold was fixed at 0.5 for the results shown below.

Prior to removing diagonals we sorted them from shortest to longest, and removed diagonals with a large ratio R starting from the short ones. When the routine reached the longer diagonals, their ratio R has decreased and they are less prone to removal.

3) Linear Weighted Fit of multipath components: Each diagonal of the filtered set is a collection of (t_i, x_j) coordinates, where each such coordinate has an amplitude in the measured response matrix. We perform a weighted linear fit on these coordinates in order to estimate the parameters a and b. The amplitude of a fitted diagonal is calculated as the quadratic (RMS) average of the amplitudes of its coordinates.

4) Output: The software tool returns a table where each diagonal is represented as two (t_i, x_j) pairs representing its endpoints, a thickness in the delay axis and an amplitude.

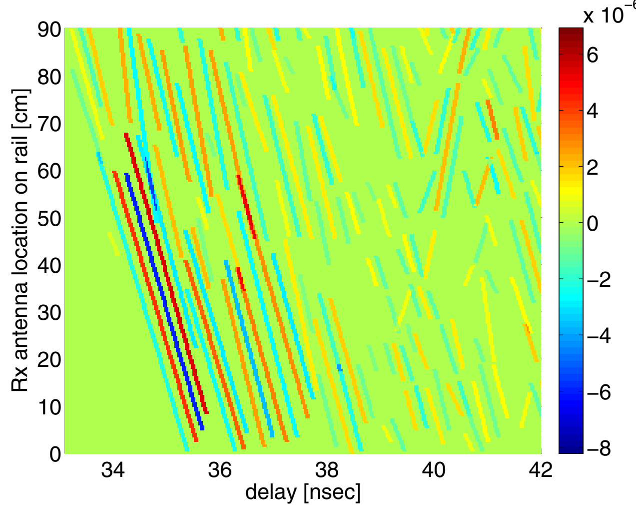

Fig. 2. Bounded multipath components reconstruction of the measurement from Figure 1. In this reconstruction multipath components are represented by diagonals with a fixed amplitude and a finite extent in the delay domain and in receiver locations.

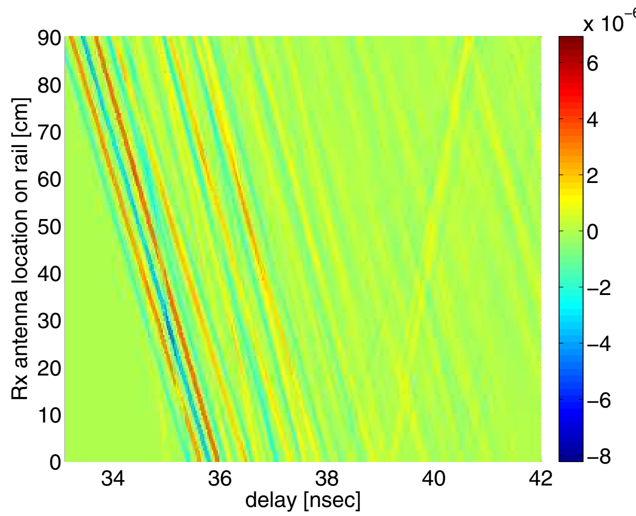

Fig. 3. Unbounded multipath components reconstruction of the measurement from Figure 1. In this reconstruction multipath components are represented by diagonals with a fixed amplitude that extend along the entire range of receiver locations.

IV. Results

The analysis of the set of 62 non line of sight measurements resulted in multipath components that were 9.5 cm long on average, with a standard deviation of 8.1 cm. The following section compares reconstructions of impulse responses based on the multipath components extracted from them. The motivation is a comparison of two types of reconstruction, one of them incorporating multipath components with bounded areas of visibility at the receiver.

A. Full Band Results

This paper demonstrates the finite area of stability of the multipath components by comparing measured responses to their reconstructions. A 'reconstruction' of a measurement, as seen in Figures 2 and 3, is a collection of synthetic impulse responses generated from the simplified multipath components returned by our software tool.

We compare two types of reconstruction: A *Bounded Multipath Component Reconstruction* as the example in Figure 2, is a reconstruction of a measurement matrix based on multipath components that are present over finite areas of space. An *Unbounded Multipath Components Reconstruction* as the example in Figure 3, is a reconstruction of a measurement matrix that includes multipath components present over the *entire* range of receiver locations. This reconstruction corresponds to the classical assumption that the multipath components of the channel are 'seen' by the receiver over its entire range of locations. The amplitude of each multipath component in the unbounded reconstruction was calculated from the amplitude given by the extraction software using $A_{UB} = A_B \frac{L_B}{L_{UB}}$ where A_B is the amplitude returned by the diagonal extraction tool, L_B is the spatial extent of the diagonal and L_{UB} is the length of the entire receiver range, usually one meter. This choice of amplitude is best in the sense that the square error between the two types of reconstruction is minimal. The unbounded reconstruction corresponds to the classic viewpoint, that attributes the spatial dynamics of the channel to 'fading' or interference between multipath components that are individually stable.

The figure of merit we use to appreciate the two different reconstructions is the squared error (SE). The squared error is calculated from the squared difference between a measurement and its reconstruction, summed over receiver locations and delay values.

The sum of square differences in normalized by the energy

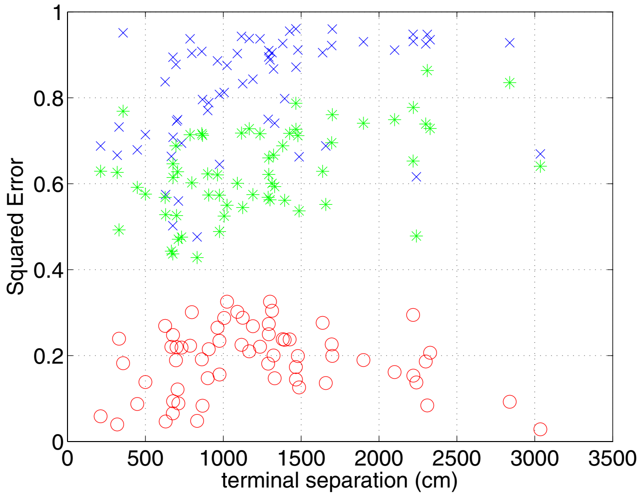

Fig. 4. Performance of channel reconstruction based on the extracted multipath components. The exes show squared error results of the unbounded multipath components reconstruction. The stars show results of the bounded multipath components reconstruction, and the circles show the difference of squared error between the two types of reconstruction. The bounded multipath components reconstruction is superior as it achieves lower squared error.

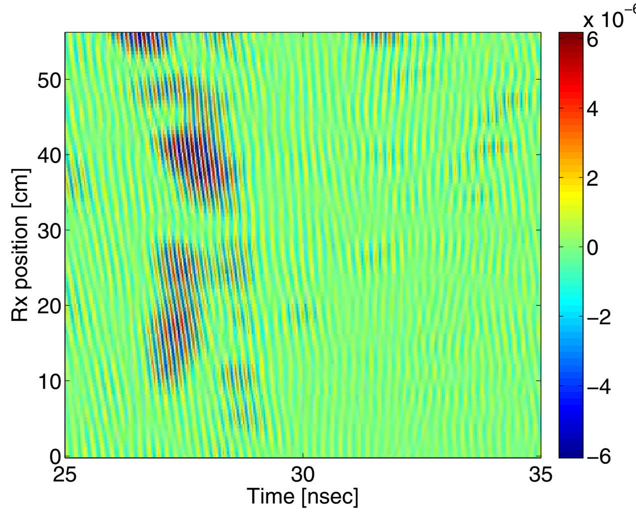

Fig. 5. An example of measured impulse responses in the 5-6 GHz band. This example is non line of sight, with terminal separation of about 6.3 meters. The figure shows pass–band impulse responses measured over a one-meter rail with receiver positions separated by 5 mm. The vertical axis represents positions along the rail, the receiver was located closer to the transmitter at the top part of the picture than at its bottom. The carrier frequency (5.5 GHz in this case) was not removed, so the impulse response is real and shows a strong 5.5 GHz oscillation.

(sum of squares) of the measured data.

$$\mathrm{SE} = \frac{\sum_{\text{Rx Positions}} \sum_{delay} (\text{measured data} - \text{reconstruction})^2}{\sum_{\text{Rx Positions}} \sum_{delay} (\text{measured data})^2}$$

Figure 4 presents the squared error of the entire set of measurements with the two types of reconstructions. The unbounded reconstruction is clearly inferior to the bounded one in terms of squared error, and the difference of squared error for the two types of reconstruction averages (over the set of measurements) to 0.19. The unbounded reconstruction appears to have similar performance to the bounded reconstruction for some measurements with terminal separations up to 10 meters.

The measurements with terminal separations of up to 10 meters are sometimes close to line of sight (LoS) in the sense that the most significant path is stable and contains a significant part of the response energy. Such measurements are represented with fair accuracy by the unbounded reconstruction, that contains only stable multipath components. The additional performance (lower squared error) offered by the bounded reconstruction in such settings is small.

B. Sub–Band Results

The investigation described in this section focuses on the apparent size of the stability areas of the multipath components, when the analyzed responses were filtered to different bands that are 1 GHz wide. We show that the stability areas tend to shrink as the carrier frequency increases.

We analyze the measured channel responses in 1 GHz bands, using a raised cosine window with 3 dB-bandwidth of 1 GHz and $\beta = 0.1$. The responses measured per each receiver location along the rail were filtered and converted to the time (delay) domain, to generate a two-dimensional representation of the channel as shown in the example in Figure 5.

We bring results on the per-measurement average spatial extent of the multipath components and the standard deviation of the spatial extent. Both the mean length of the stability area and the standard deviation decrease as the center frequency increases. We conclude that the area of stability of the multipath components tends to *decrease* as the sub-band carrier frequency increases.

An example of the sub-band dependent behavior is shown in Figure 6, that shows the measurement from Figure 5 in a higher band.

We show a typical result in Figure 7, were the average diagonal length is shown against sub-band center frequency, along with the standard deviation. This example is typical in the sense that it shows a reduction of the mean and standard deviation of the size of the stability areas of the multipath components. The reduction of both parameters appears stronger in the lower bands (2-7 GHz); the behavior of higher bands is less consistent.

In order to appreciate the behavior of the mean diagonal length and the standard deviation per each measurement against sub-band carrier frequency, we fitted them to a linear trend. Figure 7 shows one example of a linear fit of the average length of the diagonals. 59 out of the 62 measurements show a negative slope of the average diagonal length, and all the measurements have a negative slope of the standard deviation of diagonal lengths. The negative slopes indicate the reduction in the size of the stability areas as the carrier frequency increases. No clear connection is apparent between the SNR and the slopes, or between terminal separation and slope. These results are in line with the work published in [10]

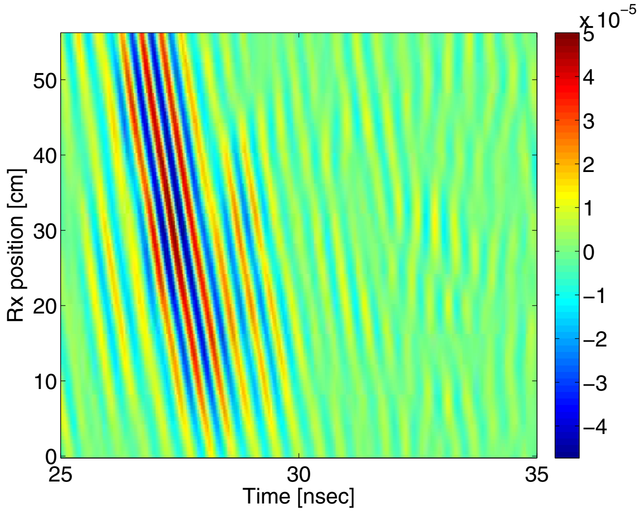

Fig. 6. The measurement shown in Figure 5, in the 2-3 GHz band. Note that the diagonal features (that correspond to multipath components) are *longer* in this band than in the higher band shown in Figure 5. See comments below Figure 5.

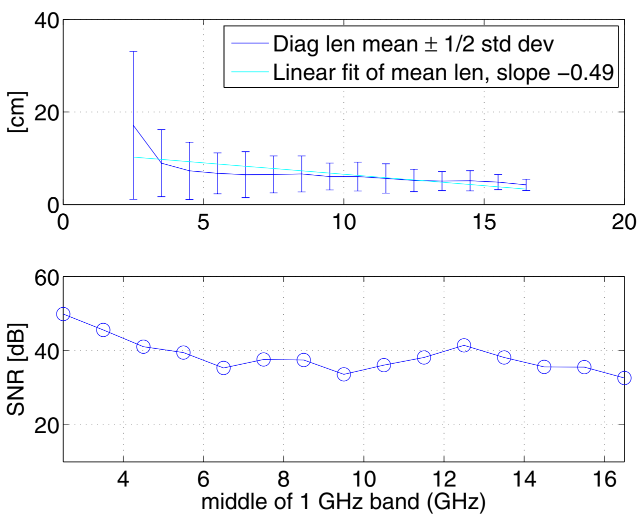

Fig. 7. The average spatial length of multipath components from a single typical measurement and the standard deviation, plotted in the top graph against sub-band carrier frequency. The signal to noise ratio (SNR) is indicated in the bottom graph.

where it is shown, based on some arguments related to UWB propagation mechanisms, that the spatial dispersion of UWB wave decreases if the average of UWB signal wavelengths decreases.

V. Summary

This paper offers analysis of measured wideband radio channel responses, with an emphasis on the spatial stability of the multipath components.

The analysis of full-band (2-17.2 GHz) measurements extracted the significant multipath components from each measurement using a software tool designed for this purpose, and compared two simplified representations of the channel to the original measurements. The simplified measurement reconstructions were performed in two ways: (1) by considering spatially limited multipath components, i.e. paths that are 'seen' by the receiver over small areas in space, and (2) by considering multipath components that are 'seen' over a (one meter) range of receiver positions. The second (spatially unbounded) channel representation corresponds to the currently accepted philosophy of channel models, i.e. the implicit assumption that multipath components are stable over some range of receiver motion. The range of receiver positions where the multipath structure is assumed to be stable is sometimes termed 'small-scale' without a quantitative characterization. Our results indicate that multipath components are stable over areas of space on the order of 10 cm. Line of sight components are much more stable than non line of sight ones, in fact they are 'seen' across the entire one-meter range of our measurements. The spatial dynamics of non line of sight radio channels appear to be dominated by the appearance and disappearance of multipath components.

The analysis of the responses with a bandwidth of 1 GHz showed that the size of the areas of stability of the multipath components decreases as the carrier frequency is increased in the range 2 GHz – 17 GHz. The results also show that the decreasing trend is stronger (steeper) at low carrier frequencies than at high frequencies.

This work is an initial step towards a spatially-dependent channel model, that will enable better design of indoor MIMO system and systems with terminal mobility.

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