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Characterization of the 5-GHz Elevator Shaft Channel

Ruoyu Sun, *Student Member, IEEE*, and David W. Matolak, *Senior Member, IEEE*

Abstract—In this paper we provide channel characterization results for the elevator shaft channel in the 5-GHz band, based upon measurements conducted in four buildings. This channel is of interest for several applications, including WiFi and public safety. Although several authors have provided elevator shaft channel characteristics for lower-frequency bands (255-MHz, 900-MHz, 1.9-GHz), to our knowledge this is the first work that addresses the 5-GHz band. Moreover, prior work has not thoroughly addressed channel characteristics when the elevator car is in motion, whereas here we provide measurement and modeling results for this dynamic condition. Our measurements were of power delay profiles, from which we estimated propagation path loss and root-mean square delay spread (RMS-DS). Path loss exponents were approximately 2.5 in one building and 5.5 in the other three buildings, with standard deviations about the log-distance linear fits equal to approximately 3 dB and 5.5 dB, respectively. Mean RMS-DS values range from approximately 14-60 ns when the elevator car is motionless. Maximum RMS-DS values were 144 ns and 152 ns in the two different types of buildings when the elevator car is moving. The significant differences in these channel characteristics among the four buildings are likely attributable to the distinct physical features of the buildings.

Index Terms—Path loss, RMS delay spread, tapped delay line.

I. INTRODUCTION

ALTHOUGH research on indoor radio wave propagation has been ongoing since the early 1980s, not many studies have been done on channel characteristics for elevator shafts. The elevator shaft and its associated elevator car create a very reflective propagation environment for wireless communication systems. Research on radio propagation within elevator shafts is of interest for multiple applications, including public safety and 802.11a/n. Public safety spectrum in the US has recently been allocated in the 700 MHz and 4.95-5 GHz bands, and our results here pertain to the latter.

In [1], GSM signal propagation along an elevator shaft was analyzed for the purpose of network planning. Path loss models at 900 MHz and 1800 MHz were developed by the authors, and they found a path loss exponent of approximately 1.6. They also found that the attenuation caused by the lift car and persons inside it was 4-5 dB larger at 900 MHz than at 1800 MHz. Researchers have also studied the effects of the position and orientation of antennas on a GSM system at 900

MHz: in [2], the authors placed the base station antenna in the elevator shaft out of the elevator car and placed a mobile phone in the elevator car. They found that short dipole base station antenna locations and orientations do not significantly affect the field strength inside elevator cars, but they do have an effect on the network's handover parameter tuning.

In [3], [4], [5], propagation along an elevator shaft in the UHF band (255 MHz) was studied. The authors analyzed power delay profiles (PDPs) taken with the elevator car in different locations. The authors concluded that the main propagation mechanism is a waveguide effect along the elevator shaft. Their measured root-mean square delay spreads (RMS-DS) were in the range from 16.7 to 176.0 ns with transmitter-receiver (Tx-Rx) distance between approximately 3.5 and 17.5 m. Opening and closing the elevator door and the movement of the elevator car creates significant temporal variation of the signal. The Weibull distribution was found to be the most suitable statistical model to characterize the amplitude variation for several multipath components (MPCs) in a tapped-delay line (TDL) form of the elevator shaft channel during motion of the car and opening and closing of the car door (although no TDL models were explicitly defined). In [6], wideband channel sounding results at 255.6 MHz along an elevator shaft on board a ship were presented. The RMS delay spreads in this environment were found to be between 60.4 and 237.2 ns with Tx-Rx distance between 2.5 and 15 m. A path loss exponent of 2.25 was also found.

In [7] and [8], the effects of nearby buildings on inter floor radio wave propagation were analyzed using both experimental data and 3D FDTD simulations. The authors found that received power can be increased by up to approximately 10 dB when reflected signals from surrounding obstacles are present. Their simulations used center frequencies of 1.0 and 4.5 GHz, and results did not appreciably change over these frequencies.

In this paper, we report on wideband channel sounding measurements that were conducted in the 5 GHz band for the purpose of quantifying the channel characteristics within several elevator shafts. We employed a 50-MHz spread spectrum signal with a stepped correlator receiver. The elevator shafts are classified into "interior" and "exterior" as described in Section II.A and Figure 3. The channel characteristics we report include path loss and channel impulse response statistics, for the case of both stationary and moving elevator cars; to the best of our knowledge, variation of RMS-DS for the moving elevator car has not been reported, nor have statistical TDL models been developed for use by communications engineers, particularly not in the 5 GHz band. This is the primary contribution of this paper.

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TABLE I
RELATIONSHIP BETWEEN LOCATION OF TX AND LINK DISTANCE.

Floor	Distance between Tx & Rx (Meters)			
	Stocker Center	Bromley Hall	Swearingen Center	Porter Hall
9	–	Tx	–	–
8	–	3	–	–
7	–	6	–	–
6	–	9	–	–
5	–	12	–	Tx
4	Tx	15	–	4
3	3	18	Tx	8
2	6	21	4.27	12
1	10	24.6	8.54	16
Ground	14	28.2	12.81	20

Section II describes the measurement environments and equipment setup. The third section provides measurement results and analysis, along with models for the channel characteristics. Conclusions appear in Section IV.

II. CHANNEL MEASUREMENTS

A. Measurement Sites

The measurements were performed along elevator shafts in three buildings on the Ohio University campus, Stocker Center, Bromley Hall and Porter Hall, and in one building on the University of South Carolina Campus, Swearingen Engineering Center. Measurements were made in March and October 2012. Stocker Center is a 5-story office building with classrooms and faculty offices on the first through the fourth floors, and laboratories on the ground (basement) floor. Bromley Hall is a 10-story dormitory with administration offices on the ground and first floor. Porter Hall is a 6-story building consisting primarily of faculty offices. Swearingen Center is a 4-story office building with laboratories and faculty offices around the elevator shaft. The shafts are mostly concrete. All elevator car doors, walls and bottoms are metal. Only Bromley Hall has multiple elevators in proximity it has three elevators side by side in the building core. Table I provides the location of the transmitter and the Tx-Rx distance in meters for the four buildings.

The transmitting antenna was always located at the top floor, with the antenna near the elevator car door in the hall just outside the elevator car itself. The transmitting antenna was located at position 1 in Figure 1. We took measurements with the elevator car in different conditions: (a) at the same floor as the receiver with door closed; (b) at the same floor as the receiver with door opened; (c) moving between the top floor and the ground floor with the Rx at the ground floor; and (d) moving between the top floor and the ground floor with the Rx inside the elevator car. Table II summarizes the measurement conditions for Stocker Center, Bromley Hall, Swearingen Center and Porter Hall. For cases (a) and (b), the receiving antenna was moved to a set of positions on each floor also near the door of the car for averaging. As shown in Figure 1, five positions with distance of 5 wavelengths (approximately 30 centimeters) have been used to average over

TABLE II
DESCRIPTION OF MEASUREMENT CONDITIONS; Y DENOTES PDPs TAKEN, N DENOTES NO PDPs TAKEN.

Receiver Location (Floor)	Elevator Car Status	
	Stocker Center / Bromley Hall / Swearingen Center / Porter Hall	
	(a) Car Motionless at same floor as Rx with door closed	(b) Car Motionless at same floor as Rx with door open
8	N / Y / N / N	N / Y / N / N
7	–	N / Y / N / N
6	–	N / Y / N / N
5	–	N / Y / N / N
4	N / Y / N / Y	N / Y / N / Y
3	Y / N / N / Y	Y / Y / N / Y
2	Y / N / Y / Y	Y / Y / Y / Y
1	Y / N / Y / Y	Y / Y / Y / Y
Ground	Y / Y / Y / Y	Y / Y / Y / Y

Fig. 1. Location of Rx and Tx antennas.

small-scale fading. For case (c), the receiving antenna was located at position 1 in Figure 1 at the ground floor. For case (d), the Rx was located at the middle of the elevator car. The antenna heights were approximately 0.9 m. Figure 2 shows a photograph of the receiver (Rx) and transmitter (Tx) outside the car doors.

We divide the elevator shafts into two categories: interior and exterior, in terms of the potential existence of external signal components. As Figure 3 shows, "interior" represents the condition where the elevator shaft is located inside the building and surrounded by walls, rooms or corridors, and this pertains to Stocker Center, Bromley Hall and Swearingen Center. Significant external signal components do not exist in this case. The "exterior" category means the elevator shaft is near an external building wall, and this pertains to Porter Hall. In addition, in the case of Porter Hall, the waiting areas near the elevator are more open and some floors have windows that allow signals to travel out of the building and these signals can be reflected by surrounding buildings, and then re-enter Porter Hall through other windows. The nearest surrounding building for Porter is about 60 m away from the waiting area. These

Fig. 2. Photograph of Rx and Tx antennas.

types of signals are termed external signal components. This characteristic also pertains to the building measured in [3]. As noted, the effects of such reflected signals have been studied in [7] and [8].

B. System Setup

The measurement equipment is a modified version of the "Raptor" spread spectrum stepped correlator by Berkeley Varitronics Systems, Inc. [9]. The signal center frequency was 5.12 GHz, and the transmit power at the input to the transmitter antenna cable was 33 dBm. The signal chip rate is 50 Mcps, which corresponds to a delay domain resolution of 20 ns. The noise floor is approximately -95 dBm. The receiver dynamic range is approximately 65 dB. Omni-directional quarter-wave monopole antennas (DM2-5500 by MobileMark Inc.) [10] were used at both transmitter and receiver, connected to their respective RF components via a short length of coaxial cable (with loss approximately 2 dB), oriented horizontally. Worth nothing is that results for vertical polarization were statistically equivalent [2] and [11]; this is because the "scattering" (mostly reflections, but diffractions as well) is rich enough so that polarization is randomized at the receiver, regardless of the transmit polarization. The antennas were essentially longitudinally pointing toward the elevator door as shown in Figure 2.

The output from the receiver comes in the form of power-delay profiles (PDPs) [12], taken at a rate of approximately 6 PDPs/sec when the elevator car was motionless, and 12 PDPs/sec for the case of the elevator car in motion. During the measurements, one person was standing behind the Rx to operate the recording computer and another person was standing in the elevator car without any movement to operate the elevator car. Since the measurements were conducted in

Fig. 3. Schematic drawing of "exterior" and "interior" elevator shafts.

the evenings, we ensured that nothing was moving except the elevator car.

III. RESULTS

A. Example PDPs

The output of the receiver is in the form of PDPs, with several examples shown in Figure 4. We post process the PDPs to extract the channel parameters of path loss, RMS-DS, and the complete TDL channel model parameters. We applied a threshold to exclude noise and extremely weak samples, set at 25 dB below the level of the largest MPC [13]. (Use of a larger threshold that allows inclusion of the weaker MPCs did not significantly change results. Both thermal and environmental noise is not included in the processed data even when the largest MPCs were relatively weak.) Each resolvable MPC shown in Figure 4 is actually the resultant of all MPCs received within a 20 ns delay bin. As seen in Figure 4, for these particular example PDPs, a cluster of approximately 10 significant MPCs are present in Stocker Center, Bromley Hall and Swearingen Center, and approximately 15 in Porter Hall.

Approximately 2500 PDPs were taken for each floor (500 PDPs for each position) when the elevator car was in its motionless state. More than 200 PDPs were taken for each trip when the elevator car was in motion, traversing the entire elevator shaft distance. The in-motion measurements were repeated several times.

Three types of signal components are hypothesized: (i) signals passing through the ceilings, which are generally the first arriving signal components, and only likely appreciable

Fig. 4. Example power delay profiles. (a) Stocker Center. (b) Bromley Hall. (c) Swearingen Center. (d) Porter Hall.

when one or two floors are present between Tx and Rx; (ii) signals propagating through the elevator shaft; and (iii) external signals, which propagate outside the building and are reflected back by surrounding obstacles (these only exist in "exterior" type elevator shafts). We do not aim to identify each component explicitly, as that is difficult even in more detailed measurements; we only provide evidence to support existence of (iii), and have also checked that our statement regarding (i) is within ranges of free-space plus floor attenuation factor (FAF) estimate computations [14]. In Figure 4 (d), the latest (large delay) three components are likely the external ones, since the relative excess delay is approximately equal to that computed for a reflection from the nearby building. The existence of external signal components decreases the path loss exponents (as in [8], increases the RMS-DS significantly, and changes the trend of RMS-DS with Tx-Rx distance.

B. Path Loss Modeling

Propagation path loss can be used to determine link budget, and is well-known as a critical parameter in assessing communication link feasibility and reliability. Path loss has been studied by researchers for many years [14], and here we only describe some common modeling approaches. The idealized free space path loss in dB can be computed by the famous Friis transmission formula [15], yielding

$$L_{FS}(d, f) = 20 \log_{10}(4\pi df/c) \quad (1)$$

where d is the distance between transmitter and receiver in meters, f is the carrier frequency, and c is the speed of light, approximately equal to 3×10^8 m/s.

Another simple and widely used model is the "log-distance" model with path loss L in dB given by the following equation,

$$L(d) = A + 10n \log_{10}(d/d_{min}) + X \quad (2)$$

where A is the measured result for the path loss at d_{min} , d is the distance between transmitter and receiver, n is the dimensionless path loss exponent, and X is a zero mean Gaussian random variable in dB with standard deviation X . The minimum distance d_{min} occurs when the Rx is one floor away from the Tx. The minimum distance d_{min} is 3 m for Stocker and Bromley, 4.27 m for Swearingen and 4 m for

Fig. 5. Path loss vs. Tx-Rx distance on logarithmic scale. (a) Stocker Center. (b) Bromley Hall. (c) Swearingen Center. (d) Porter Hall.

TABLE III
PATH LOSS MODEL PARAMETERS.

Stocker / Bromley / Swearingen / Porter	n	σ_X (dB)
Door Closed	6.66 / 5.27 / 5.07 / 2.75	5.48 / 6.08 / 1.89 / 3.79
Door Open	5.76 / 4.52 / 3.03 / 2.40	5.14 / 5.52 / 2.37 / 2.85

Porter as shown in Table I. In our case, there's no line-of-sight (LOS), and the transmitted signals are not only attenuated by distance, but also by passing through the ceilings and as a result of reflections and possibly scattering by walls and diffractions around edges. Since the locations of transmitter and receiver are in an approximately (vertical) straight line, we model path loss as a function of distance for convenience.

Using built-in Matlab® functions for linear least squares regression fitting, measured data along the elevator shaft is used to fit (2) for parameters n and σ_X . We sum the received power of all multipath components in the PDPs, and using known transmit power and cable losses, compute received power and then path loss. The idealized free space path loss (1), log-distance fits of the form of (2), and the measured data are all shown in Figure 5. Table III lists all the log-distance path loss parameters for Stocker Center, Bromley Hall, Swearingen Center and Porter Hall.

The path loss exponent n_{DC} is always greater than n_{DO} , where "DC" represents door closed and "DO" represents door open. This illustrates the fact that the closed door does not allow as much energy to couple into the shaft as when the door is open. This coincides with the conclusion in [3].

The path loss exponent n and standard deviation σ_X in Porter Hall (exterior elevator shaft) are smaller than those in Stocker Center, Bromley Hall and Swearingen Center (interior elevator shafts). As discussed in the next section, "external" MPCs that go through windows and are reflected by nearby buildings likely exist in Porter Hall but not in Stocker, Bromley or Swearingen (these types of MPCs were also reported in [3]). These MPCs experience less attenuation than MPCs that enter the elevator shaft. Moreover, different building materials and building structures pertain for the four buildings, and this may

Fig. 6. RMS delay spread vs. Tx-Rx distance. (a) Stocker Center. (b) Bromley Hall. (c) Swearingen Center. (d) Porter Hall.

allow more energy to propagate through the actual floors in Porter Hall.

C. RMS Delay Spread

In wideband channels, the delay dispersion parameter RMS-DS plays an essential role in quantifying the dispersiveness of the multipath channel. Figure 6 shows plots of the RMS-DS vs. distance with the elevator car in a motionless state for four buildings. The values at each distance are the average delay spreads taken over 2500 PDPs for each floor.

It is shown in Figure 6 that RMS delay spread generally increases with Tx-Rx distance in Porter Hall (a similar effect was observed in [4]) except for the last two points. We hypothesize that this can be explained by considering the structure of this building. Windows exist just outside the elevator door on the 2nd to the 5th floors of Porter Hall so that a LOS exists between the receiver and a nearby building. Hence, the transmitted signal is likely reflected by this nearby building back to the receiver; this explanation is similar to one given in [3], aided by ray-tracing analysis, where in that building in [3], the elevator door actually opened out into a courtyard outside. These signal components propagating outside Porter Hall, reflecting off the nearby building, and then re-entering Porter Hall have a relatively large delay, and hence increase the RMS-DS. This is not the case for the 1st and ground floors of Porter Hall where the windows have been replaced by cement walls. The LOS between the nearby building and the receiver is hence obstructed for these two floors, yielding smaller RMS delay spreads for the bottom two stories (largest two Tx-Rx distance values).

This type of outside-building multipath component (MPC) is unlikely to exist in Stocker Center, Bromley Hall and Swearingen Center since the elevator shafts in Stocker, Bromley and Swearingen are in the building interior, and are surrounded by corridors, walls and rooms. This difference between the locations of the elevator shafts in the two kinds of buildings hence may yield a larger RMS delay spread in exterior elevator shaft buildings than in interior elevator shaft buildings. (Note there may be buildings that have shafts adjacent to exterior building walls without either windows or openings to the outside; these may represent additional building types that should be characterized in the future.)

Fig. 7. Instantaneous RMS delay spread when the elevator car & Rx (inside the car) is in motion. (a) Stocker Center. (b) Bromley Hall. (c) Swearingen Center. (d) Porter Hall.

For the other buildings in this motionless case, we cannot categorically state that RMS-DS increases with distance for all cases, although the simplest linear fits to the measured points would indeed show positive slopes. In cellular cases, RMS-DS typically increases with distance [16], whereas in narrow confined environments such as corridors or tunnels, RMS-DS decreases with distance once beyond a distance larger than the corridor/tunnel width [17]. In the classic indoor channel work of [11], RMS-DS was found to be generally not correlated with distance in the indoor environment with transmitter and receiver located in the same floor without LOS. Although the environments of [11] and our elevator shafts are distinct, both are sufficiently complex, and do not yield an obvious relation between RMS-DS and distance.

D. Moving Elevator Car, Rx inside Moving Car

The receiver inside the elevator car with all doors closed is a "more interior" condition. Almost all external MPCs are blocked by the elevator car and shaft. Figure 7 shows instantaneous RMS delay spread vs. time as the elevator car and Rx are in motion; the instantaneous RMS-DS is that computed for an individual PDP [18]. The "averaged RMS-DS" in the plots is that obtained with a moving average filter of length of 10; this is shown to more clearly illustrate the trends.

Statistics of instantaneous RMS-DS for the elevator car in motion are listed in Table IV. Although the Tx-Rx distances are different in the four buildings (Stocker with max of 14 m, Bromley with max of 28.2 m, Swearingen with max of 12.8 m, Porter with max of 20 m), RMS-DS statistics are comparable. Generally we can observe that as the elevator car moves up and Tx-Rx distance decreases, RMS-DS also decreases, and conversely for the downward movement case.

E. Moving Elevator Car, Rx Stationary Outside Car

Figure 8 shows the instantaneous RMS-DS vs. time for the case of the moving elevator car in Stocker Center, Swearingen Center and Porter Hall, with the Rx stationary outside the car. The instantaneous RMS-DS is that computed for an individual PDP. We didn't include Bromley Hall data in this

TABLE IV
STATISTICS OF INSTANTANEOUS RMS DELAY SPREAD FOR THE
ELEVATOR CAR IN MOTION, RX INSIDE CAR.

Units in ns	Stocker	Bromley	Swearingen	Porter
Mean	24.51	26.31	50.02	26.10
Max	70.29	61.56	109.24	58.17
Standard Deviation	7.71	8.41	9.94	7.86

TABLE V
STATISTICS OF INSTANTANEOUS RMS DELAY SPREAD FOR THE
ELEVATOR CAR IN MOTION, RX STATIONARY OUTSIDE CAR.

Units in ns	Stocker	Swearingen	Porter
Mean	33.46	56.72	109.91
Max	94.80	143.86	152.45
Standard Deviation	10.74	21.12	17.78

Fig. 8. Instantaneous RMS delay spread when the elevator car is in motion, with Rx motionless outside the car. (a) Stocker Center. (b) Swearingen Center. (c) Porter Hall.

section because with the Tx positioned at the top and the Rx at the bottom, the long link distance made the received power relatively low for the largest distances, and the low SNR would have reduced the accuracy of the resulting model. The PDPs in Fig. 8 were obtained by combining the measurement results over 4 trips of the car from the bottom floor to the top floor.

It took approximately 21.5 seconds in Stocker, 18 seconds in Swearingen Center and 23 seconds in Porter Hall for one elevator car trip from top to bottom (or vice-versa). Maximum Doppler shifts are 10.9 Hz in Stocker, 11.9 Hz in Swearingen and 14.5 Hz in Porter, negligible for most modern communication systems that use signaling rates well above

1 kbps. For the computation of instantaneous RMS-DS, we assume the channel is stationary for the duration of each PDP.

Statistics of instantaneous RMS-DS for the elevator car in motion with the Rx stationary outside the car are listed in Table V. The mean RMS-DS is 33.46 ns in Stocker Center, 56.72 ns in Swearingen Center, and 102.91 ns in Porter Hallnote that these are larger than the values obtained for the elevator car in the motionless state (Figure 6). A potential explanation is the effect of the metal bottom of the elevator car. For the case of the motionless elevator car, the car's metal bottom is lower than the receiver antenna (the car is at the same floor as the Rx), hence the metal bottom won't block the MPCs between the Tx and Rx; in fact some MPCs rely on this reflection to reach the Rx. For the case of the elevator car in motion, the metal bottom of the elevator car is between the Tx and Rx, and the MPCs that enter the shaft will be at least partially blocked by the metal bottom. The dominant MPCs that propagate through the shaft are strongly attenuated by the moving car's metal bottom, and hence the strong attenuation on these lower-delay MPCs increase the RMS delay spread when the elevator car is moving.

Figure 9 shows the instantaneous RMS delay spread distribution. The lognormal distribution fits the Stocker and Swearingen data best, whereas the Weibull distribution fits the data in Porter Hall best¹. Measured delay spreads up to approximately 176 ns were reported in [3] for the motionless case (with Tx-Rx distance of approximately 17.5 m), and this exceeds the RMS-DS values measured in Stocker (Tx-Rx distance 14 m) and Swearingen (Tx-Rx distance 12.8 m), but is comparable to that in Porter Hall (Tx-Rx distance 20 m) (see Fig. 6). This shows that different building characteristics elicit different RMS-DS results. The large range of values of RMS-DS in Fig. 8 illustrates the strong effect of the moving elevator car; variation in elevator car position was also found to strongly influence the PDPs in [3] (RMS-DS results for the car in motion were not reported in [3]).

For creation of TDL models, we select the number of MPCs as follows [19]

$$L = [T_m/T_c] + 1 \quad (3)$$

where L is number of taps for the TDL models, T_m is the mean of the instantaneous RMS-DS, and T_c is chip duration, equal to 20 ns. By (3), the number of taps L is 2 for Stocker Center, 3 for Swearingen Center and 6 for Porter Hall.

Table VI provides the channel model parameters for the case of the Tx and Rx fixed with the elevator car in motion. This table contains tap energies and the fading amplitude

¹We used the built-in Matlab® distribution fitting tool, which computes a maximum-likelihood fit.

Fig. 9. Instantaneous RMS delay spread distributions when the elevator car is in motion, with Rx motionless outside the car. (a) Stocker Center. (b) Swearingen Center. (c) Porter Hall.

parameters for the L taps (all tap phases were found to be well-modeled by a uniform distribution on $[0, 2\pi)$). The parameters in Table VI can be used to construct statistical TDL models in analysis or simulation for the purpose of evaluating the performance of different communication systems. The delay index corresponds to 20 ns. Two sets of model parameters are provided, based upon two amplitude distributions, Weibull, and Nakagami. The larger the value of the Weibull distribution shape factor β (or Nakagami m -factor), the more benign the fading. A value of $\beta = 2$ ($m = 1$) yields the Rayleigh distribution, and β values less than 2 ($m < 1$) are worse than Rayleigh, or severe fading [19].

The MPC with the smallest delay is the one that travels a straight line between Tx and Rx—if detectable; our conclusion is that this is likely only when transmission goes through one or two floors due to the large typical floor attenuation factors [14], e.g., example values for FAFs for signals through one floor are 16.2 dB, through two floors 27.5 dB, and through three floors 31.6 dB. In addition, we have a non-zero rise time due to finite bandwidth and pulse shape filtering of the signal,

TABLE VI
TDL MODEL PARAMETERS FOR THE ELEVATOR CAR IN MOTION.

Stocker Center			
Tap Index	Nakagami m factor	Weibull β factor	Relative Energy
1	3.54	3.32	0.7595
2	1.33	2.32	0.2405
Swearingen Center			
Tap Index	Nakagami m factor	Weibull β factor	Relative Energy
1	2.41	2.92	0.6920
2	1.03	1.99	0.2081
3	0.93	1.88	0.0999
Porter Hall			
Tap Index	Nakagami m factor	Weibull β factor	Relative Energy
1	3.92	4.07	0.5474
2	1.37	2.54	0.1985
3	1.29	2.44	0.1424
4	1.33	2.35	0.0481
5	1.37	2.39	0.0434
6	1.23	2.15	0.0201

hence it is difficult to distinguish between the early-arriving "through-floor" MPCs and filtered stronger MPCs. Based on analysis in Section III.B and on analysis and results in [3], the strongest MPC may be the one that enters the shaft, and this may be reflected or scattered several times.

IV. CONCLUSION

In this paper, channel responses from wideband channel sounding measurements in the 5 GHz band along elevator shafts in four buildings have been presented. "Exterior" and "interior" elevator shafts have been classified by their location in the buildings. We developed path loss models of the log-distance form, and found path loss exponent n is between 2.40 - 2.75 in the exterior shaft building and is between 3.03 - 6.66 in interior shaft buildings, depending on whether or not the car door is closed. The path loss exponent n with door closed is greater than that with the door open. The time dispersion parameter RMS delay spread has been calculated, and the mean value of instantaneous RMS-DS lies in the range from 14 ns to 60 ns when the elevator car is motionless. This delay spread generally increases with Tx-Rx distance in exterior shaft buildings, while this trend doesn't necessarily exist in interior shaft buildings. Data for the case of the receiver inside the moving elevator car has also been presented. Results for this case support the conclusion that the RMS-DS generally increases with Tx-Rx distance for all buildings. RMS delay spreads also increase when the elevator car is in motion and the Tx and Rx are fixed in position outside the car. For this case, maximum RMS-DS values are approximately 95 ns and 144 ns in interior shaft buildings (Stocker Center and Swearingen, respectively), and approximately 152 ns in one exterior shaft building (Porter Hall). Tapped-delay line channel models for these elevator shaft channels with the elevator cars in motion and the Tx and Rx fixed have also been presented. The models specify tap delays, energies, and amplitude fading parameters.

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