Characterization of Ultra Wide Band Communications in Data Center Environments

N. Udar[†], K. Kant[‡], R. Viswanathan[†], D. Cheung[‡]
{udarn | viswa}@engr.siu.edu, {krishna.kant | david.cheung}@intel.com

***Abstract*— In this paper, we present a measurement characterization of the Ultrawideband (UWB) channels in a data center environment and examine the accuracy of direct ranging using Time of Arrival (ToA) measurements. The expected deployment vehicle for UWB in data centers is expected to be the wireless USB technology that is expected to become as ubiquitous as wires USB today. Modern data centers present a unique indoor environment that to our knowledge has not been characterized so far. We find that although a modified Saleh-Valenzuela model can be used for UWB channel, some of the model parameters are somewhat unique to this environment.**

Key words: Ultra wide band (UWB), data centers, Saleh-Valenzuela channel model, path loss, ranging.

I. Introduction

In recent years, ultrawideband (UWB) communications has received great interest from both the research community and industry. UWB offers low cost, low power high data rate solutions and thus is a promising candidate for WUSB. The strength of the UWB technology lies in the use of bandwidths larger than 20% of carrier frequency or more than 500MHz. Larger absolute bandwidths results in high resolutions, improved position location and ranging, ability to handle multipath fading, high multiple access capability and easier material penetration. UWB transmission subject to strict power regulation was allowed by FCC in 2001. Because of these restrictions, UWB communications are best suited for short-range communications, though range extension via mesh networks is certainly possible. IEEE standards group on personal area networks (PANs) is actively working on UWB based communications under 802.15.3a and 802.15.4. Of these, the latter is concerned specifically with low-bandwidth applications that require physical location. The 802.15.3 standard supports data rates of up to 110 Mb/s at 10 m distance, 200 Mb/s at 4 m distance, and higher data rates at smaller distances.

Universal Serial Bus (USB) is an ubiquitous interface for PC and mobile devices with more than 2 billion wired connections. There are ongoing efforts to define a Wireless USB (WUSB) standard on top of a UWB based PHY specification developed by the Wi-Media Alliance (www.wimedia.org). In particular, stable specifications of WUSB 1.0 (www.usb.org/developers/wusb/) and WiMedia (www.wimedia.org/en/resources/eis.asp?id=contact) have existed for some time.[1] It is expected that WUSB will emerge as a low cost technology offering data rate of 450 Mb/s at 3 meters. Although WUSB is designed for the client space, it is possible to exploit it even in data centers for some unique purposes. In particular, if most servers are equipped with WUSB, it is possible to use this infrastructure to run a variety of management services, including physical asset location – a topic of particular interest for this work.

Large data centers typically have tens of thousands of rack mount or blade servers and other equipment (e.g., switches, storage devices, etc.). This equipmentdoesn't always stay in one place. There are a variety of reasons for movement including maintenance, handling major workload shifts, changes to deployed applications and services, etc. The net result of the movement is that keeping track of assets in a data center becomes very difficult or laborious. In fact, data center surveys have repeatedly pointed out asset management as a substantial problem. Thus, an automated asset location mechanism is highly desirable within a data center. The work reported here lays the ground work to assess the physical location errors within a data center. The issues of overall architecture for asset location using WUSB and cooperative physical location using multiple WUSB radios are not addressed here and will be treated in future works. In particular, although a management subsystem (e.g. BMC) based architecture can handle the location of unpowered/unbooted (but plugged in) servers as well, we do not discuss those aspects in this paper.

The most fundamental work required in exploiting UWB in the data center environment it is to determine the channel model. Apart from better design of WUSB transreceiver, the channel model will allow accurate ranging and asset location – a topic that is the primary motivator of this work. In the past there has been a lot of work on characterizing indoor wireless channel [3], [4], [6], [8], [9], [10]. However, a data center differs substantially from typical indoor environments like residential and office buildings and could follow a different channel model. The main purpose of the paper is to characterize the data center environment in the UWB frequency band (3-8GHz) via actual measurements and show some simple results on ranging.

The rest of the paper is organized as follows. In section II we briefly describe some basic concepts of wireless channel characterization and discuss previous work, particularly the

[†]N. Udar and, R. Viswanathan are with Southern Illinois University, Carbondale, IL. [‡]K. Kant and D. Cheung are with Intel Corporation, Hillsboro, OR

[1]The IEEE 802.15.3a group was shut down in Jan 2006 due to irreconcilable differences between the direct spread and multiband OFDM based PHYs, but this will not derail WUSB.

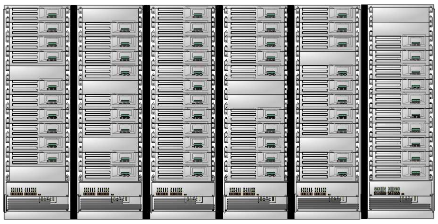

Fig. 1. A row of racks in a data center

IEEE 802.15.3a channel models. In section III we describe our measurement setup, methodology, challenges and results. In section III-C we apply the data center channel characteristics to the asset location problem in the data center. Finally, section IV compares data center model against the IEEE 802.3.15a indoor models and identifies future work required.

II. UWB Propagation Models

A. Outdoor vs. Indoor Models

Wireless propagation channels have been investigated extensively in the literature, particularly in the cellular communications context, and a large number of channel models are available in the literature. The signal that has propagated through a wireless channel consists of multiple replicas (echoes) of the originally transmitted signal; this phenomenon is known as *multipath propagation*. The different multipath components (MPCs) are characterized by different delays and attenuations. The correct modeling of the parameters describing the MPCs could provide a better understanding of radio propagation in these channels.

In cellular systems, where signal bandwidth is relatively small, the multipath components that arrive within short time intervals are not resolvable with smaller bandwidth signals and therefore combine to produce Rayleigh or Rician distribution of the overall amplitude.

With the employment of a wideband signal, a channel model that describes the radio propagation in an indoor medium can be described by one of three channel models: (a) tap-delay line Rayleigh fading model used in IEEE 802.11, the Saleh-Valenzuela (S-V) model [13], [3], and the -K model [9]. Based on a detailed set of studies, IEEE 802.15.3 committee settled on a modified S-V model to enable comparison of various technologies in the WPAN area (http://ieee802.org/15/). The SV model assumes that the MPCs arrive in clusters rather than in continuum, and this aspect has been verfied using indoor measurements and is shown even by our measurements. This is a result of the very fine resolution UWB waveforms provide. In particular, multipath reflections & diffractions from various indoor objects that differ by 0.3 m in traveled distance will arrive at the receiver 1 ns apart. However, for a 5GHz UWB signal, delay bin size is only 0.2 ns. Thus the rays arriving at the receiver could consist of clusters of reflections from obstacles located in different places.

B. Data Center Environment

A data center can be compared with a library room where we have several metallic racks containing servers. The racks are 78" high, 23-25" wide and 26-30" deep and are generally placed side by side in a row without any spacing (other than a supporting beam). A rack can be filled up with either rack mount or blade servers. Rack mounted servers go horizontally in the rack and have typical heights of 1U or 2U where a "U" is approximately 1.8". The high density blade servers go vertically in a 19" high chassis, with 14 blades/chassis. Fig 1 shows a single row of racks with 3U rack-mount servers and some empty slots. If all racks in the data center can be treated as essentially continuous metal blocks, the characterization could be relatively straightforward. Unfortunately, racks are not always filled up with servers, thereby creating many holes through which the radiation can leak. In fact, because of the increasing stress placed by high density servers on cooling and power distribution infrastructure, the racks in older data centers simply cannot be filled to capacity already. The net result is a unique environment with "organized clutter".

As stated above, much of the indoor UWB channel characterization work has been on home and office environment. An exception is [10] which provides a characterization of a cluttered industrial environment. Although the environment studied in [10] has a lot of clutter, the clutter does not have any organized pattern. In particular, the authors state that "the abundance of metallic scatterers causes dense multipath scattering. This can be seen to produce mostly Rayleigh distributed small-scale fading signal, with only a few paths exhibiting Nakagami distributions." This is different from data center environment, thereby confirming the need for direct measurements in the data center. The results in section III show that results are correspondingly different.

C. S-V and Related Propagation Models

As stated earlier, the Saleh-Valenzuela model [13] characterises the channel behavior via a superposition of clustered arrivals of various delay components. In particular, suppose that the received signal for a transmitted impulse consists of C clusters, and R_c MPCs (or "rays") within the cth cluster. Let T_c denote the arrival time of cth cluster (i.e., that of first ray within this cluster) and let τ_{cr} denote the arrival time of the rth ray within the cluster (relative to the arrival time of first ray). Then the impulse response $h(t)$ of the channel is given by:

$$h(t) = \sum_{c=1}^{C} \sum_{r=1}^{R_c} a_{cr} \delta(t - T_c - \tau_{cr}) \quad (1)$$

where $\delta(.)$ is the Dirac delta function, and a_{cr} is the relative weight (or multipath gain coefficient) of ray (c, r).

The essense of S-V model is to make specific assumptions about the cluster and ray arrival processes and multipath gain in the above equation. In particular, the basic S-V model assumes that both inter-cluster and inter-ray times are exponentially distributed, thereby making the corresponding processes as Poisson. That is,

$$P(T_c - T_{c-1} > x) = e^{-\lambda_c x} \quad (2)$$

$$P(T_{c,r} - T_{c,r-1} > y) = e^{-\lambda_r y} \quad (3)$$

where λ_c and λ_r are, respectively, mean cluster and ray arrival rates. As for the coefficients a_{cr}'s, the S-V model assumes an exponential decay for both cluster power and ray power within a cluster as a function of the delay. That is,

$$a_{cr}^2 = a_{00}^2 e^{-T_c/\Gamma} e^{-\tau_{cr}/\gamma} \tag{4}$$

where a_{00}^2 is the power of the very first ray, and Γ and γ are the cluster and ray decay constants. The a_{00} parameter comes from the path loss model and is not characterized by S-V model.

Several indoor measurements have shown that the assumption of Poisson process for ray arrivals does not yield a good fit. Reference [3] discusses a modified S-V model where the ray arrival process is modeled as a mixture of two Poisson processes. We shall see later that our data center mesurements agree well with this model.

In addition to MPC arrival characterization, there are several other aspects to consider in order to fully describe the channel. One such aspect is the *path loss model*, which indicates how the power decays as a function of distance. For free-space propagation, the path loss at distance d is given by $(4\pi d/\lambda)^2$, where λ is the wavelength. When considering individual UWB bands, it is okay to use center frequency for estimating λ, but perhaps not for the entire 3-8 GHz band. In a cluttered environment, the loss exponent could be significantly different from 2 because of reflection and diffraction. In fact, the exponent could vary depending on the location, shape, reflectivity, permittivity, etc. of the clutter and can be regarded as a normal random variable with certain mean and standard deviation [4]

Path loss, cluster power decay, and ray decay phenomena discussed above are all deterministic in nature. In reality, there are also small scale random signal variations or *amplitude fading* that must be considered. One way to characterise this is by considering cluster and ray power as a random variable with associated mean and standard deviation. The standard deviations σ_c and σ_r then become essential parameters of the S-V model and need to be estimated. The distribution of the amplitude itself is important and is typically found to be Lognormal, Nakagami or Rayleigh.

The third aspect of interest is *time variance* of the channel. Wireless channel characteristics are influenced by environmental factors such as temperature, humidity, air flow, movements, etc. Fortunately, in data center environments, such variations are expected to be small and infrequent, and time variance characterization may be unnecessary. Our measurements validate this conclusion as shown later.

III. UWB Channel Characterization in Data Centers

A. Measurement Setup

The measurements were conducted in a medium sized data center using Agilent 8719ES vector network analyzer. The network analyzer was set to transmit 1601 continuous waves distributed uniformly over 3-8 GHz. This results in the frequency step of 3.125 MHz which gives maximum excess delay of 320 ns. This frequency range was chosen over 3-8 GHz due to limitation of available power amplifiers and low noise amplifiers. The 5 GHz bandwidth gives a temporal resolution of 500 ns. The experimental set up is shown in Fig. 2.

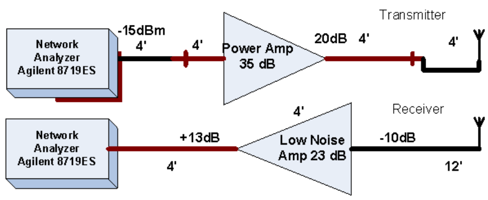

Fig. 2. Experimental Setup for Measurements

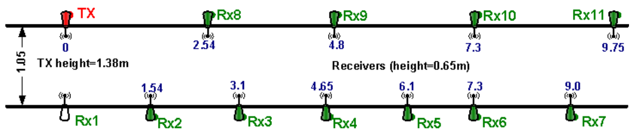

Fig. 3. Locations of transmitter & receivers

Antenna calibrations were performed in an anechoic chamber with 1m reference distance to remove the antenna effects and was saved for post processing. System Calibrations were performed using power amplifier, low noise amplifier and 30dB attenuator (to include channel loss) to remove the effect of amplifiers and cables. Measurements were conducted in the data center where transmitter (TX) was fixed towards one end of the aisle and multiple positions for the receiver (RX) were considered. Fig. 3 shows the location of the transmitter and receivers in xy dimensions. To measure the small scale statistics of the channel the Rx was moved 25 times around each local point over a 5 by 5 square grid with 5 cm spacing. Each point on the grid is referred as spatial point. Only line-of-sight scenarios were considered.

B. Channel Modeling

TABLE I
Delay Spread at Various Receiver Locations

Receiver	τ_{rms}	σ_{rms}	Receiver	τ_{rms}	σ_{rms}
RX1	4.4	0.11	RX7	17.90	0.28
RX2	15.60	0.23	RX8	10.11	0.29
RX3	20.68	0.29	RX9	15.07	0.23
RX4	14.69	0.23	RX10	23.39	0.28
RX5	17.61	0.24	RX11	22.96	0.30
RX6	17.07	0.25			

Measured data from experiments explained in section III-A is used to generate Figs. 4 and 5, which show the plots of complementary cumulative distribution functions of ray inter-arrival times and cluster inter-arrival times, respectively. Fig. 4 also shows the S-V model fit (labeled as Single Poisson Process), and a mixture of two Poissons, which was proposed as a modified S-V model for the indoor data in [3]. The Poisson mixture is based on the following equation:

$$P(T_{c,r} - T_{c,r-1}) = \beta e^{-\lambda_1 y} + (1-\beta) e^{-\lambda_2 y} \tag{5}$$

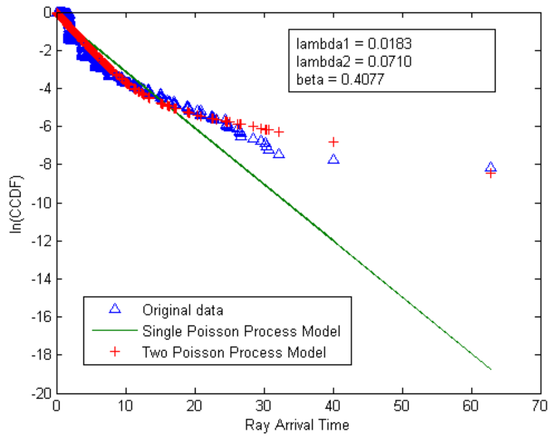

Fig. 4. RayInter-arrival Times for S-V Model

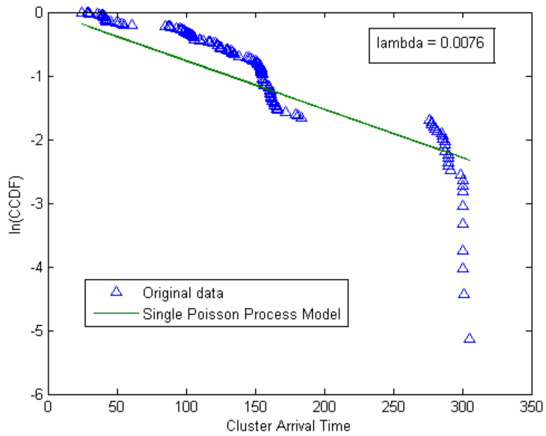

Fig. 5. Cluster Inter-arrival Times for S-V Model

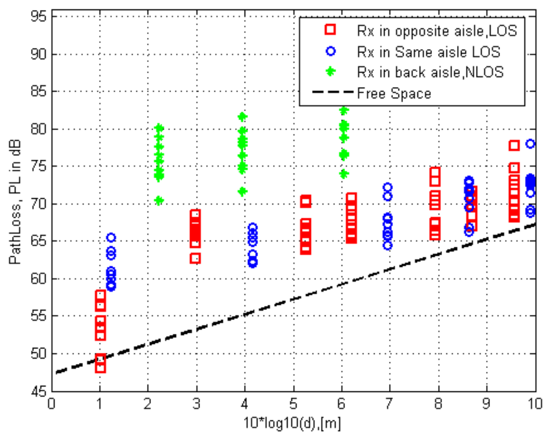

Fig. 6. Pathloss vs. distance from transmitter

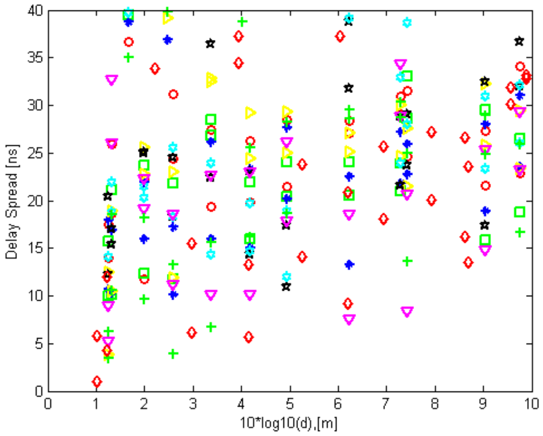

Fig. 7. Delay spread vs. distance from transmitter

Fig. 4 shows clearly that the modified S-V model provides a better fit to the data than the single Poisson process. For cluster inter-arrival times in fig. 5, a single Poisson process provides a reasonable fit only if the clusters arriving at times greater than 250 ns are ignored. However, the latter cluster arrivals correspond to multipaths due to reflections from the wall of a data center. Hence, a cluster of clusters will be a better description for this behavior than a pure Poisson model.

Fig. 6 shows the path loss (PL) in dB versus the distance between different receivers (RXs) and the transmitter (Tx). If we express the path loss as $P_L(dB) = 10nlog(d) + const$, where n is the path loss exponent and d is the distance between the TX and the Rx, Fig. 6 shows that the exponent is less than 2 and is slightly more than 1. That is, the path loss in a data center decreases much slower with distance than in free space. This is due to the fact that a large number of diffractions and reflections taking place in the metallic racks and other components present in the vicinity of TX and RX contribute to a much increased received power than is possible in free space. Fig. 7 shows the measured delay spread against the distance between the Tx and the Rx. In general, delay spread increases with distance. This means that the Rxs at locations further from the Tx receive multipath signals arriving at small as well as large time separations.

Fig. 8 shows the temporal characteristics of the channel. For this, channel characteristics were measured repeatedly over a 43 minute period and both the power and phase variations derived from the measurements. This was done for a number of receive locations. Fig. 8 shows one such measurement of both power and phase variations. It is seen that variations in both power and phase are extremely small and can be ignored for all practical purposes. Strangely, the variations show increasing or decreasing trends over 10s of minutes; however, in all cases the trend flattened out and and did not suggest any instability. The major significance of these results is that we do not need multiple or frequent measurements for ranging purposes within a data center. However, a much more reliable estimation of distances is possible through cooperative measurements.

C. Ranging in Data Centers

Asset location consists of two subproblems (a) ranging – or estimating distnace between a pair of devices, and (b) location determination using a large number of range estimates with a goal to minimise errors (e.g., see [2], [7], [5], [11]. In this paper we concentrate only on (a) and provide some results on achievable ranging accuracy in data centers.

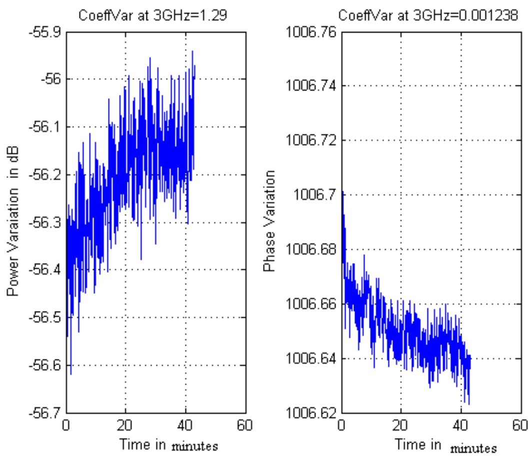

Fig. 8. Time variation of channel characteristics

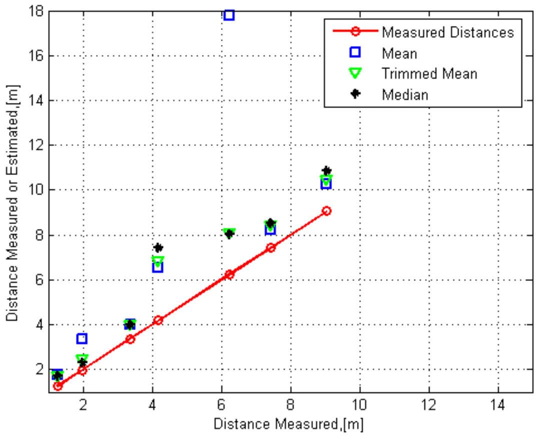

Fig. 9. Range Measurements based on TOA for receives in opposite aisle

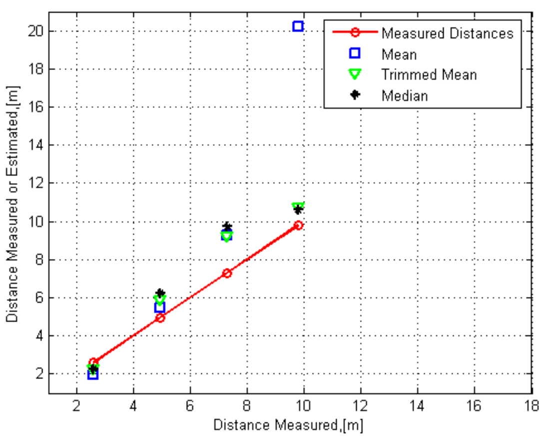

Fig. 10. Range Measurements based on TOA for receives in same aisle

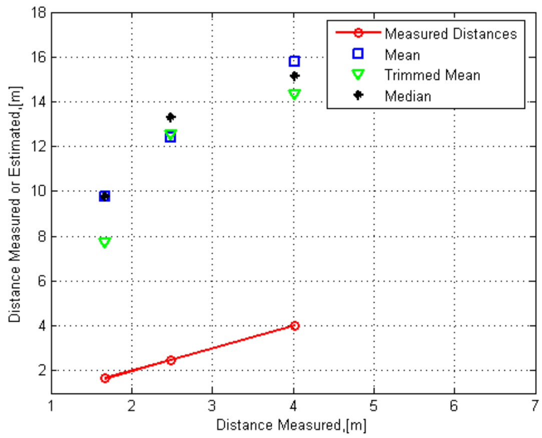

Fig. 11. Measurements based on TOA for receives in back aisle

With UWB, range measurement can be made either using RSS (received signal strength) or TOA (time of arrival) or a combination of the two (assuming that the WUSB radios are equipped with these capabilities). The accuracy of TOA measurement is complicated by the absence of line of sight (LOS) as well as by the presence of multipath components (briefly termed as non-line-of-sight, NLOS) condition. NLOS leads to a positive bias and a larger variance in the estimated range parameter [11], [12], [5]. TOA measurement error seems to obey Gaussian distribution reasonably well, with a positive mean and a higher variance associated with NLOS as compared to zero mean and a smaller variance associated with LOS (Fig. 5 in [11]). The RSS technique suffers significantly higher errors due to a variety of influences on transmitted and received power. Furthermore, RSS errors tend to be multiplicative (as opposed to additive for ToA) [12]. Neverthless, RSS based measurements can help weed out outliers in ToA based measurements.

The problem of estimating ranging error in ToA is considered in [1]. The paper models the errors due to multipath as zero mean Gaussian with magnitude proportional to $log(1+d)$. In case of NLOS, the first received signal peak is not the strongest and may not be used for ToA measurement since the measurements usually pick out the strongest received signal. In other words, the bias in distance measurement will have a positive mean. In general, it is not known whether a given received signal falls in LoS or not. Thus, the individual estimations may include both LoS and NLoS (biased) estimates. The subsequent step of doing estimation from collective measurements (not discussed in this paper) can be used to estimate the bias.

Fig. 9-11 show the estimated distances of the RXs based on the time of arrival (TOA) data and the measured (actual) distances. The raw distance estimate is based on c times the arrival instant of the first ray with significant power, where c is the speed of light. Because of multiple diffractions and reflections encountered in a data center environment, the first ray with significant power could be multipath signal and not a direct path signal. As explained earlier, the non-line of sight measurements (NLOS) lead to larger bias and variance in range estimates. For each Rx location, 9 different measurements and hence range estimates, corresponding to nine, 520 MHz bands in 3- 9 GHZ spectrum, were obtained. Fig. 9 shows the true distances of the Rxs, the mean, the median, and the trimmed median (mean of the remaining data after throwing out the largest and the smallest observations) of the nine band raw estimates for the receivers in the opposite aisle. Fig. 10 shows results for receivers in same aisle whereas Fig. 11 shows results for receivers in the back aisle. For receivers in back aisle (Fig. 11) range estimates based on any method are off from true value, because of the absence of any LOS. For the other two cases, Rxs in same or opposite aisle, in general, mean of the average of the raw estimates overestimates the true distance by a significant margin, in some situations, thereby implying that at least one raw range estimate corresponds to ray arrival time that is significantly larger than the arrival time of the direct path signal between the Tx and the Rx. Perhaps this data point corresponds to a stronger multipath arrival, which is picked up by the receiver as the first ray with significant power. A convenient way of excluding such outlier points is to use the median or the trimmed mean, rather than the mean of the whole sample, as the estimate of the range. For opposite aisle Rxs (Fig. 9), with median or the trimmed mean, the range estimates are close to the true values except for one Rx at 4.1m. Similar observations can be made for Rxs in same aisle (Fig. 10) (in this case the trimmed mean and median estimates are off from true by significant values for Rx at 7.2m). Further measurements coupled with improved estimation procedures that address NLOS conditions are needed before we could convincingly propose UWB measurements as a range estimation tool in data center environments.

IV. Discussion and Future Work

In this paper we characterized the UWB propagation within the data center environment via direct measurements over the UWB band in an actual data center. The characterization shows that the data center environment is similar but not identical to other indoor environments that have been studied in the past. We also examined the question of UWB based ranging within data centers and showed kind of ranging errors one can expect in this environment. To our knowledge, this is the first study of its kinds and lays the ground work for Wireless USB based asset location that we are interested in. The future work on the subject consists of an in depth examination of cooperative ranging within the data center while exploiting the invariant properties of this environment. This will allows us to locate assets with much greater accuracy than the isolated ranging explored in this paper.

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