A Measurement-based Blocking Distribution for Improving Localization in Warehouse Environments

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***Abstract*—In a warehouse environment, blocked line-of-sight between targets and anchors, due to storage racks, is an impediment to localization. For ultrawideband signals, the stochastic nature of the blocking phenomenon - due to its material penetrating capabilities - can be characterized by a location-specific blocking distribution. Once such a distribution is available, the localization of a potentially unknown number of targets can be cast as a Bayesian estimation problem, where the blocking distribution plays the role of a prior. This paper presents the results of a ultrawideband measurement campaign conducted to obtain the blocking distribution in a warehouse environment.**

I. Introduction

Accurate localization of targets (e.g carts, products) has the potential to significantly improve the efficiency of supply chain management in warehouse environments (see [1] and the publications therein). Currently, the most frequently used technique to achieving this goal is narrowband RFID (radio-frequency identification), which allows localization with a precision on the order of meters. However, such systems face significant problems, such as failed detection due to fading, and sensitivity to narrowband interference [2].

Time-of-arrival (ToA) based localization, based on ultrawideband (UWB) signals, offers not only mitigation of these problems, but also much better accuracy than traditional RFID systems [3]. It has thus been widely investigated by both the industrial and the academic community (see [4] and references therein) and both active (where the tag is powered by a battery or energy harvesting) and passive (backscatter) solutions have been explored. The results of this paper hold for either solution.

A typical ToA-based localization network involves the deployment of anchors (transceivers) in such a way that a target has line-of-sight (LoS) to at least three anchors (i.e., *direct paths*), which is necessary for triangulating its location unambiguously. Due to the material penetrating capability of UWB signals, two points that do not have optical LoS may still have electromagnetic quasi-LoS, which can be exploited for localization. Thus, the existence of UWB LoS between two points in a warehouse that are obstructed by one or more storage racks is a stochastic phenomenon, which can be characterized by a location-specific blocking distribution. Such a distribution acts as a prior in the Bayesian localization of a potentially unknown number of targets [5].

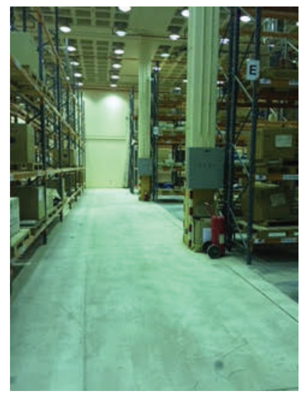

Fig. 1. Measurement region at the KACST warehouse

The characteristics of UWB propagation channels in a warehouse environment has been explored in [6], for both LoS and NLoS environments. However, the categorization was based on *optical*, and not UWB, LoS. Moreover, the LoS probability distribution was also not evaluated. In this paper, we address this gap by presenting a model for the joint LoS distribution, based on the results of our measurement campaign.

II. Measurement Setup

The measurement campaign was conducted at a portion of the KACST warehouse in Riyadh, Saudi Arabia (Fig. 1), whose floor plan is shown in Fig. 2. The floor, ceiling and walls are made of brick and reinforced concrete and the region is divided into three vertical and one horizontal aisle by a pair of steel storage racks, which typically contain cardboard boxes. The ceiling is at a height of $7.5\mathrm{m}$ from the ground and concrete pillars are situated at regular intervals for structural support. Over the course of the measurements, care was taken to keep the aisles clear of people and objects.

A frequency domain channel sounder setup, using a vector network analyzer (VNA) (Fig. 3), was used to measure the frequency response of the UWB channel between 6-8 GHz at 100 frequency points (Note: this is the frequency band assigned for UWB transmission in Saudi Arabia; it is smaller than the band assigned by the Federal Communications Commission in the US). This gives a range resolution of $15\mathrm{cm}$ and a maximum

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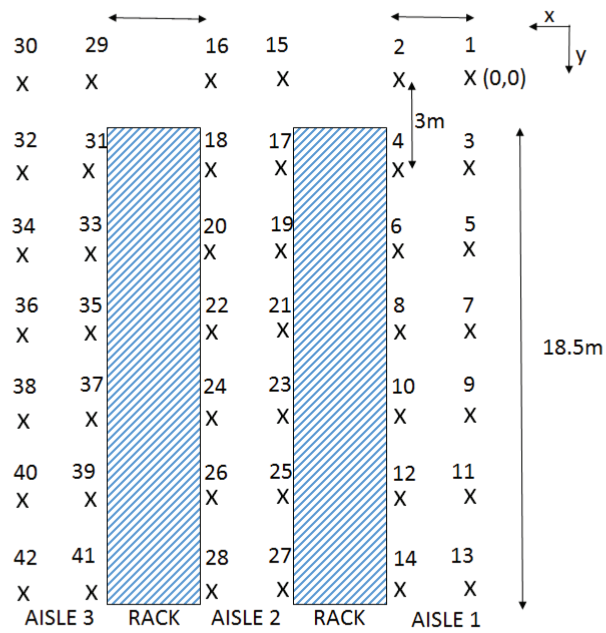

Fig. 2. Floor plan of measurement region. The origin is at the point marked 1.

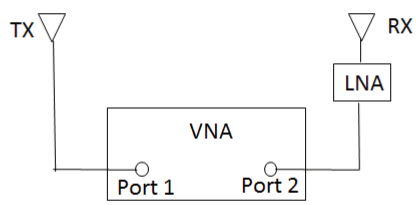

Fig. 3. Channel sounder setup

distance range of 15m, which was deemed sufficient due to the strong attenuation of longer-delayed multipath components.

A monopole omni-directional antenna was used for the TX and the RX, which was mounted on a stand of height 1.55m and placed at the grid points shown in Fig. 2. To the best of our abilities, we ensured that there was no relative motion between the TX, RX and the environment. Hence, it is reasonable to assume a quasi-static channel. The calibration was done from the transmit-reflection ports of the VNA to the antenna feed points of the coaxial cables. The list of equipment is summarized in Table I.

For each TX-RX configuration, the impulse response, $h[n]$, is obtained by computing the IFFT (inverse fast Fourier transform) of the measured frequency response. Let $i(d)$ denote the index of the delay bin corresponding to the LoS

TABLE I
LIST OF HARDWARE USED

Item	Manufacturer	Model No.
VNA	Agilent	N9918A
Antenna	SATIMO	UWB300-A
Cables (10m length)	SATIMO	
LNA	HD Communication	HD30059

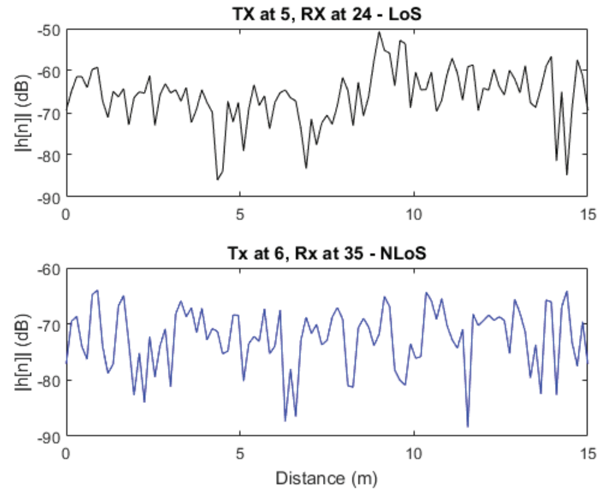

Fig. 4. Impulse response for a LoS and NLoS case

component for a TX-RX separation distance of d. Due to positioning and distance measurement errors, the LoS peak typically lies within a window of T bins, centered around $i(d)$. The signal power ($P_s(d)$) and the average noise power ($P_n(d)$) are evaluated as follows:

$$P_s(d) = \max |h[n]|^2, \quad n \in \{i(d) - T, \cdots, i(d) + T\} \quad (1)$$

$$P_n(d) = \frac{1}{i(d) - T - 1} \sum_{n=1}^{i(d)-T-1} |h[n]|^2 \quad (2)$$

$$\text{SNR}(d) = P_s(d)/P_n(d) \quad (3)$$

To avoid false alarms (i.e., false identifications of noise peaks as LoS indicators), we require that the SNR at the anticipated LoS delay exceeds 10 dB (note that this threshold is somewhat arbitrary). In other words, if $\text{SNR}(d) \geq 10\text{dB}$, then we conclude that LoS is present; otherwise, LoS is absent. The impulse response for a couple of TX-RX configurations are shown in Fig. 4.

While other methods, such as K-factor estimation [7], may exist for determining LoS, we observed that a determination of whether a quasi-LOS peak exists above the noise floor, as calculated in (1)-(3) was more reliable. This is because the K-factor determines whether a *dominant* component exists or not. Hence, it fails to identify an existing (quasi-)LoS component when it is not strong enough *relative to the other MPCs*, which can occur either when the (quasi-) LoS component is attenuated, and/or when a lot of energy is carried in several reflected components. On the other hand, estimation based on K-factor might erroneously declare an impulse response to belong to a LoS environment, namely when only one, very strong, reflected multipath component exists. Both of these phenomena are especially common in a warehouse environment, where a blocking obstacle can weaken the LoS component and the metal racks can give rise to strong multipath due to specular reflection.

We furthermore determine the required window size T for our setup from measurements: we utilize the fact that LoS exists whenever both the TX and RX are situated in the same

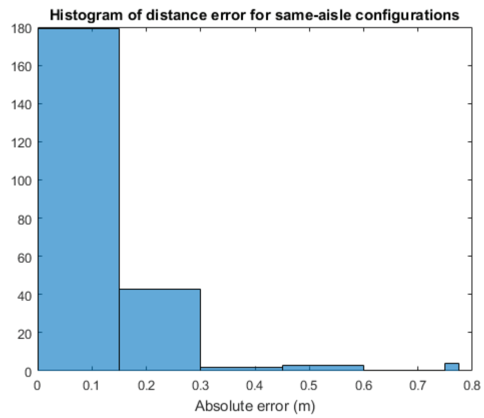

Fig. 5. Histogram of the errors due to TX/RX positioning and distance measurement.

aisle. A histogram of the distance errors for all the same-aisle configurations is plotted in Fig. 5. It can be seen that most of the errors occur within two delay bins, hence we assume $T = 2$.

III. Results

A. LoS probability of a single link

For a TX at (x_t, y_t) and RX at (x_r, y_r), we define the random variables $V(x_t, y_t, x_r, y_r)$ and $S(x_t, y_t, x_r, y_r)$ (abbreviated as V_{tr} and S_{tr}, respectively, for convenience) as follows:

$$V_{tr} = \begin{cases} 1, & \text{if LoS exists between } (x_t, y_t) \text{ and } (x_r, y_r) \\ 0, & \text{else} \end{cases} \tag{4}$$

$$S_{tr} = \text{No. of racks separating } (x_t, y_t) \text{ and } (x_r, y_r) \tag{5}$$

Then, the LoS probability between the TX and RX can be expressed as follows:

$$\mathbb{P}(V_{tr} = 1) = \sum_{k=0}^{\infty} \mathbb{P}(V_{tr} = 1 | S_{tr} = k)\mathbb{P}(S_{tr} = k) \tag{6}$$

The plot of $\mathbb{P}(V_{tr} = 1 | S_{tr} = k)$ as a function of distance, for $k = 1, 2$, is shown in Fig. 6, from which the following conclusions can be drawn:

- When the two points are separated by a single rack ($k = 1$), the LoS probability does not vary monotonically with distance. From the distance distribution of the LoS and NLoS outcomes in Fig. 7, it can be inferred that there is no distance dependence on the LoS probability (over 60% of the LoS and NLoS outcomes are at a distance less than 7m). This indicates that the major factor affecting the existence of LoS is the penetration loss of the rack and its contents. Hence, we assume $\mathbb{P}(V_{tr} = 1 | S_{tr} = 1) = \beta$, where β equals the empirical probability. For a 10dB SNR threshold, $\beta = 0.1365$.
- If the two points are separated by two racks, then the LoS probability is negligible.

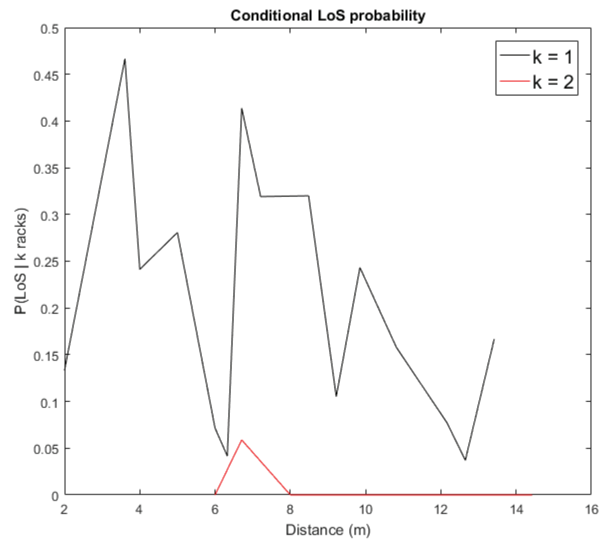

Fig. 6. $\mathbb{P}(V_{tr} = 1 | S_{tr}^{(k)})$ versus distance

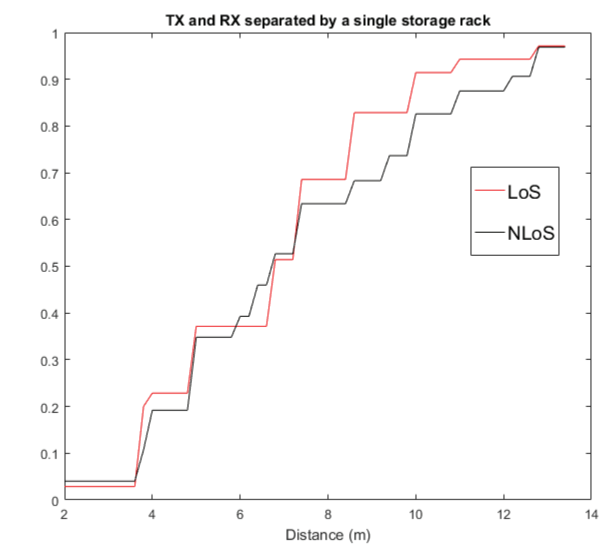

Fig. 7. Distance distribution for the LoS and NLoS cases when the TX and RX are separated by a single storage rack.

Hence,

$$\mathbb{P}(V_{tr} = 1 | S_{tr}) = \begin{cases} 1, & S_{tr} = 0 \\ \beta, & S_{tr} = 1 \\ 0, & S_{tr} \geq 2 \end{cases} \tag{7}$$

The term $\mathbb{P}(S_{tr} = k)$ depends on the geometry of the warehouse environment. A typical warehouse may have a mixture of regularly spaced horizontal and vertical aisles. Let Δ_v and Δ_h denote the width of a vertical and horizontal aisle, respectively. If all the racks are vertically oriented (as in our case), the following cases may arise:

- If $|y_t - y_r| > \Delta_h$, then at least one of the two points is in a vertical aisle. Thus, the number of racks separating the two points is proportional to $|x_t - x_r|$ and can be

TABLE II
JOINT DISTRIBUTION OF $V_{t,r1}$ AND $V_{t,r2}$, WHEN $S_{t,r1} = S_{t,r2} = 1$

	Empirical	Independent Assumption
$\mathbb{P}(V_{t,r1} = 1; V_{t,r2} = 1)$	0.0100	0.0186
$\mathbb{P}(V_{t,r1} = 1; V_{t,r2} = 0)$	0.1655	0.1179
$\mathbb{P}(V_{t,r1} = 0; V_{t,r2} = 1)$	0.0584	0.1179
$\mathbb{P}(V_{t,r1} = 0; V_{t,r2} = 0)$	0.7661	0.7456

determined by solving for k in the following set of inequalities

$$kW_r + (k-1)\Delta_v \leq |x_t - x_r| \leq kW_r + (k+1)\Delta_v, \quad (8)$$

where W_r denotes the width of a rack. If multiple solutions exist for k, we assume all of them to be equally probable.

- If $|y_t - y_r| \leq \Delta_h$, then the two points may lie on a horizontal aisle. Let α_h denote the fraction of the y-axis occupied by horizontal aisles. Then, $\mathbb{P}(S_{tr} = 0)$ with probability α_h and with probability $(1-\alpha_h)$, $\mathbb{P}(S_{tr} = \hat{k})$, where $\hat{k}$ is the solution(s) to (8).

Similar expressions can be derived for a warehouse containing only horizontal racks or any combination of the two.

B. Joint LoS probability

Consider a TX at (x_t, y_t) and two RXs at (x_{r1}, y_{r1}) and (x_{r2}, y_{r2}). Without loss of generality, let (x_{r1}, y_{r1}) be closer to (x_t, y_t). From (7), the only non-trivial joint distribution for $V_{t,r1}$ and $V_{t,r2}$ occurs when $S_{t,r1} = S_{t,r2} = 1$. It is intuitive to expect $V_{t,r1}$ and $V_{t,r2}$ to be correlated when (x_{r1}, y_{r1}) and (x_{r2}, y_{r2}) subtend a small angle at (x_t, y_t). To test for correlated blocking, we consider two TX locations each in Aisles 1 and 2 (grid points 3 and 4 in Aisle 1, 17 and 18 in Aisle 2, see Fig. 2) and for each TX location in Aisle 1 (Aisle 2), we consider all pairs of grid points in Aisle 2 (Aisle 3) for the RX locations. From Table II, we observe that over the range of angular separations arising from the grid points in Fig. 2 (i.e. $> 6.87°$), the blocking of two or more links can be assumed to be independent.

IV. IMPROVING LOCALIZATION PERFORMANCE

The fact that correlation of LoS is correlated can be exploited to improve the localization accuracy. Consider N anchors at (x_1, y_1) through (x_N, y_N) (Fig. 8) and suppose that a *tentative* target location (x, y) has been obtained based on the signals received at the anchors. Depending on whether the signal at the i-th anchor contributes to the triangulation of (x, y) or not, we can define a binary variable $V(x_i, y_i, x, y)$ (abbreviated as $V_i(x, y)$) as in (4), on the assumption that the signal peak in question is a direct path to (x, y). Let $\mathbf{v}(x, y) = [V_1(x, y) \cdots V_N(x, y)]$ denote the estimated LoS vector at (x, y). If $\mathbb{P}(\mathbf{v}(x, y))$ is high (i.e. exceeds a threshold μ), then our confidence in the existence of a target at (x, y) increases. Hence, the blocking distribution can be used as a prior to improve localization performance. The reader is referred to [5] for a more detailed treatment.

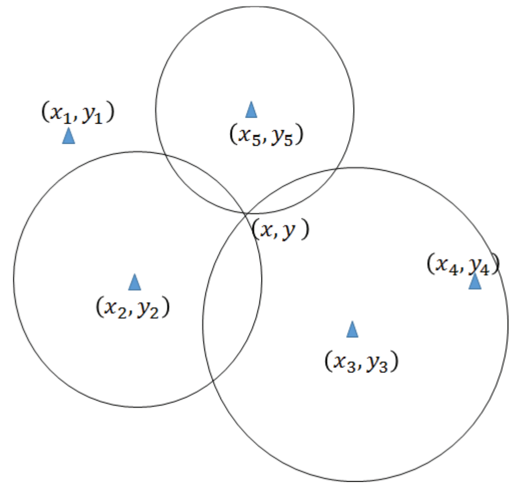

Fig. 8. $N = 5$. A direct path from (x_i, y_i) to (x, y) (i.e. $V_i(x, y) = 1$) corresponds to a circle centered on (x_i, y_i) and passing through (x, y). In this example $\mathbf{v}(x, y) = [0\ 1\ 1\ 0\ 1]$.

V. SUMMARY AND CONCLUSIONS

In this paper, we have investigated the LoS probability for UWB radiation in a warehouse environment. We pointed out the importance to distinguish between *optical* LoS, which can be easily determined, and *UWB* LoS, which requires RF measurements, and which is the relevant quantity for localization systems. We showed that UWB LoS probability can be quite high even when the two link ends are not in the same isle of a warehouse, and developed a model for the *joint* blocking probability of two links. These results can be used to improve deployment of readers in UWB-RFID systems, and well as to improve localization accuracy in such systems.

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