Intra-, Inter-, and Extra-container Path Loss for Shipping Container Monitoring Systems

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Abstract—This paper presents empirical path loss models for an environment of stacked shipping containers. Specifically, a system for wireless monitoring of containers is considered for which three different types of wireless links are identified, namely intra-, inter-, and extra-container links. Furthermore, the inter-container link is investigated for the two most common types of container stacking: row and block stacking. Intra- and inter-container path loss is investigated at IEEE 802.15.4 frequencies of 433, 868, and 2400 MHz. Extra-container path loss is examined at GSM/UMTS frequencies of 900, 1850, and 2100 MHz. Distance-dependent path loss models are proposed for the inter- and extra-container links (high correlation coefficients between 0.76 and 0.86). The resulting path loss models can be used in link budget calculations for container monitoring systems.

Index Terms—Container, path loss, MoCo

I. INTRODUCTION

One of the major tasks of supply chain management is to follow goods, stored in shipping containers, from origin to final destination. This paper presents path loss modeling for a general wireless architecture for container monitoring and tracking, developed within the IBBT MoCo project. The architecture is based around so-called MoCo (for Monitoring of Containers) wireless devices. A MoCo device is mounted inside a container and is connected to an antenna outside through the container's ventilation holes (which are near the container's ceiling, at a height of about 2.5 m). These ventilation holes are almost always covered by a plastic cap, which is helpful to cover and protect the antenna. A MoCo device has three main functionalities: (i) it can wirelessly gather data from sensors inside the container that measure transport parameters such as temperature, humidity, shock, and door status, (ii) it can relay that data to other MoCo devices attached to other containers, and (iii) it can send data to a cloud for storage and retrieval. Obtaining enough wireless link budget for these functionalities is challenging because of the highly metallic (shielding) nature of the container environment. Because of the particularity of the container environment, well-known path loss models for outdoor environments (e.g. COST 231

Walfisch-Ikegami [1]) are an unsatisfactory fit for empirical path loss around containers [2].

Path loss models for container environments have only very recently become available in literature. In [3], path models based on measurements in a container terminal are proposed for frequencies between 1 and 4 GHz and for different antenna heights. In [4] and [5], path loss is investigated for Radio Frequency Identification (RFID) tags attached to containers. Finally, the work in [6] takes into account the shielding and waveguiding effects of metallic objects to improve location estimation accuracy in container environments. This paper presents path loss modelling in a container environments for different types of wireless links, frequencies, and container stacking configurations. In contrast to [3], path loss is investigated for containers in the near field of the transmitting and/or the receiving antenna. This is to reflect the actual operating scenario wherein the MoCo device's antenna is attached directly to the container surface. While [4] and [5] focus on path loss in and around a single container, this work is intended for larger stacks of containers.

II. PROPAGATION SCENARIOS

We distinguish between three types of wireless links between sensors, MoCo devices, and the cloud. Each link type handles one of the MoCo device's main functionalities:

- *Intra-container link*: a sensor inside the container transmits sensory data to the MoCo device's antenna which is attached outside to that container (IEEE 802.15.4).
- *Inter-container link*: relaying of data between MoCo device antennas attached to different containers (IEEE 802.15.4).
- *Extra-container link*: A MoCo device's antenna sends data to the cloud (GSM, UMTS).

In the above list, it is also mentioned which communication standard(s) is (are) suitable for implementing each link.

III. MEASUREMENT SETUP AND DATA PROCESSING

The measurement setup consists of a transmitting and a receiving part. At the transmitter, a signal generator (Rohde & Schwarz SMP22) creates a continuous wave which is fed to the transmitting antenna Tx. At the receiving end, a spectrum analyzer (Hewlett-Packard 8561B) samples the power at the receiving antenna Rx. As Tx and Rx, vertically polarized half-wave dipole antennas are used. In case the measured link is for one or both of the antennas attached to a container surface, a styrofoam spacer of thickness 1 cm is placed between the

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antenna and the container. Path loss PL in dB is calculated as:

$$PL = P_{Tx} - L_{Tx} - L_{Rx} - P_{Rx} \quad (1)$$

In (1), P_{Tx} is the transmit power (20 dBm), L_{Tx} and L_{Rx} are the Tx and Rx antenna feeder losses in dB, and P_{Rx} is the received power in dBm. It is important to note that the usual calculation of path loss also includes terms in the right-hand side of (1) which exclude the gains of the measurement antennas. This was however not done here: due to the proximity of the metallic container surface, antenna effects cannot be separated from the wireless propagation loss. This is highly similar to the definition of path loss for on-body propagation channels, where the proximity of the human body also prevents exclusion of antenna radiation patterns from the wireless propagation loss [7].

IV. RESULTS

A. Intra-container link

In the MoCo architecture, the intra-container link adopts the IEEE 802.15.4 standard. Penetration loss from outside to inside a container is investigated for three frequencies targeted by IEEE 802.15.4: 433, 868, and 2400 MHz. The antenna placement for the intra-container measurements is shown in Fig. 1. The Tx is mounted outside the container on the ventilation holes nearest to the container door. The Rx is installed alternately at two different locations inside the container. The first Rx location (Rx_1) is inside on the ventilation holes, directly facing the Tx on the outside. The second Rx location (Rx_2) is inside at the container's center.

Figure 1. Intra-container scenario

Intra-container measurements were carried out for two containers, one 20' (20 feet) container and one 40' container. The designations 20' and 40' refer to the (standardized) length of the container. Unlike the 40' container, the 20' container is an older type that was *not* fitted out with ventilation holes, so Tx and Rx_1 were mounted where the ventilation holes are expected to be on this type of container. Both containers were empty during measurements and their doors were closed. For each of the two Tx-Rx links, 200 samples of the received power P_{Rx} are recorded. These samples are used to calculate 200 path loss (penetration loss) values using (1). Fig. 2 shows bar plots of the maximum (worst-case)

penetration loss over the 200 samples for each frequency, container type, and Tx-Rx link. A transparent bar means that the maximum penetration loss exceeds the spectrum analyzer's sensitivity, and the value mentioned on top of the bar is the maximum measurable penetration loss. In Fig. 2, no clear relation between penetration loss and frequency is observed. This relation can be complicated and non-monotonic due to variation of the constitutive parameters of container steel with frequency, container geometry, and the presence of ventilation holes [8].

Figure 2. Maximum penetration loss for the intra-container link

The penetration losses in Fig. 2 are compared to typical values of the maximum path loss (corresponding to 10% packet error rate) of wireless sensor modules. A commercial sensor module operating at 433 and 868 MHz is the Amber Wireless AMB8423, which has a nominal maximum path loss of 105 dB. The Tmote Sky is a sensor module operating at 2400 MHz with a nominal maximum path loss of 94 dB. For the 40' container, the measured maximum penetration loss in Fig. 2 is sufficiently limited to allow for a reliable intra-container link. This is the case for all three frequencies, and for both Tx-Rx links. The penetration loss for Tx-Rx₂ is about 27 dB larger than for Tx-Rx₁. For the 20' container, it can be concluded that a reliable intra-container link is not possible for 868 and 2400 MHz. A reliable link is however possible for 433 MHz.

B. Inter-container link

Path loss for the inter-container link is investigated for the IEEE 802.15.4 frequencies of 433, 868, and 2400 MHz. The measurements are carried out for two common types of container stacking: row and block stacking.

1) *Container row stacking*: The measurements are carried out along the row of 4 containers (total length of 42.7 m) shown in Fig. 3. The Tx is mounted on the ventilation holes near the top of the first container. The Rx is then moved in steps of 0.5 m along the top of the container row at the same height above ground level as the Tx. At each Rx location, the median of 200 samples of received power is recorded. In total, 83 Rx locations are measured per frequency. Measured path loss in dB is found to correlate well with logarithmic distance (average correlation of 0.78 over the three frequencies). Path loss PL (in dB) is fitted to the following model as function of distance d (in m) between Tx and Rx:

$$PL(d) = b_0 + b_1 \cdot 10 \log_{10}(d) + \chi_s \quad (2)$$

Figure 3. Inter-container scenario for row stacking

In (2), b_0 and b_1 are regression parameters (b_1 is the path loss exponent) and χ_s is a zero-mean random variable that accounts for shadow fading. χ_s assumes a normal distribution with standard deviation σ_s . Fig. 4 shows measured path loss versus distance for the three frequencies. Also shown is the fitted regression line $b_0 + b_1 \cdot 10 \log_{10}(d)$ for each frequency. Table I lists estimated values for the parameters of (2), obtained by least-squares fitting.

Figure 4. Path loss versus distance for the inter-container link (row stacking)

frequency [MHz]	b_0 [dB]	b_1 [-]	σ_s [dB]
433	47.38	2.24	5.49
868	47.64	2.09	6.56
2400	54.58	1.48	6.19

Table I

INTER-CONTAINER PATH LOSS MODEL PARAMETERS (ROW STACKING)

The 95% confidence bounds on the vertical location of the regression lines are at most ± 2.80 dB over all frequencies and distances. Taking this uncertainty into account, it can be concluded from Fig. 4 that path loss is nearly identical for all frequencies at large distances. At small distances, path loss is similar for 433 and 868 MHz, but is higher for 2400 MHz. This can be attributed to the periodically ribbed structure of container surfaces (period = 27 cm, Fig. 3). At smaller distances, surface waves along the container dominate propagation. In contrast to 433 and 868 MHz, the wavelength at 2400 MHz is smaller than the ribbed structure's period, which means this frequency is more prone to diffraction losses at the rib edges. This results

in a comparatively gentler slope for the regression line at 2400 MHz and a path loss exponent b_1 smaller than 2.

2) *Container block stacking*: The measurements were carried out on a three-dimensional stack of sixteen 20' containers (4 long, 2 wide, and 2 high), shown schematically Fig. 5. Measurements are done for two scenarios. In the first and second scenario, the antennas of the MoCo devices are mounted outside on the containers' ventilation holes (black symbols) and doors (white symbols), respectively. For both scenarios, path loss is measured between the Tx on container 1 (squares) and the Rx's on the other containers (circles). For each Tx-Rx link, the median of 300 samples of received power is recorded.

Figure 5. Inter-container scenario for block stacking

Fig. 6 shows measured path loss versus distance for the three frequencies and both scenarios. The path loss samples are fitted to the regression model in (2): Fig. 6 shows the fitted regression lines and Table II lists the estimated regression parameters. The average correlation between path loss and logarithmic distance for the six fits in Fig. 6 is 0.76. The 95% confidence bounds on the vertical location of the six regression lines are ± 4.94 dB on average over all frequencies and distances.

For the vent-mounted scenario, path loss is nearly the same at 433 and 868 MHz and comparatively smaller at 2400 MHz. Propagation between Tx and Rx for this scenario occurs mainly along the small gaps between two containers (with widths of around 10 cm), due to the fact that both Tx and Rx are closed in between containers. Propagation in small gaps is less lossy at 2400 MHz due to the smaller wavelength.

For the door-mounted scenario, path loss is similar at all frequencies for smaller distances and relatively smaller at 433 MHz for larger distances. Since the Tx for the door-mounted scenario faces free space on one side (Fig. 5), part of the propagation path runs in the free space around the container stack, and part of the path runs in the gaps between the containers in order to reach the Rx. For smaller distances, a larger part of the path runs in the gaps where 433 MHz experiences high loss (large wavelength in small gaps). For larger distances, a larger part of the path runs in free space where 433 MHz experiences low loss (low frequency in free space). This difference in relative path loss between smaller and larger distances causes the regression line at 433 MHz to tilt and results in a path loss exponent b_1 smaller than 2.

C. Extra-container link

In the MoCo architecture, the extra-container link is implemented with GSM and/or UMTS. Path loss is investigated for

Figure 6. Path loss versus distance for the inter-container link (block stacking): vent-mounted and door-mounted scenario

frequency [MHz]	vent-mounted			door-mounted		
	b_0 [dB]	b_1 [-]	σ_s [dB]	b_0 [dB]	b_1 [-]	σ_s [dB]
433	55.46	2.52	7.76	53.36	1.64	3.98
868	58.10	2.38	7.98	43.93	3.25	4.94
2400	42.69	2.90	9.30	45.50	2.95	8.33

Table II
INTER-CONTAINER PATH LOSS MODEL PARAMETERS (BLOCK STACKING)

the GSM/UMTS frequencies of 900, 1850, and 2100 MHz. Path loss measurements for the extra-container link were carried out outside a large stack of 40' containers. Fig. 7 presents a top-down view of the container configuration. The stack varies in height from 4 to 7 containers. The pathways between the container rows are about 1.5 m wide. The Tx is mounted near the ventilation holes at the top of one of the containers on the ground level. The Rx is attached to a mast on a cart and is at the same height as the Tx. The cart is pushed along several tracks outside the stack (the striped area in Fig. 7) while the spectrum analyzer continuously samples the received power.

Extra-container path loss is smoothed out using a sliding window of length 3 m to remove small-scale fading. Per frequency, on average 973 smoothed path loss samples are obtained. These path loss samples cover distances between the Tx and Rx from 10 up to 63 m. Path loss is found to correlate well with logarithmic distance (frequency-average correlation coefficient of 0.86) and is therefore fitted to the model in (2). Table III lists the estimated parameters of (2). It is observed that the path loss exponent b_1 is smaller than 2 for all three frequencies. This points to a waveguiding effect. In Fig. 7,

Figure 7. Extra-container scenario

frequency [MHz]	b_0 [dB]	b_1 [-]	σ_s [dB]
900	70.19	1.82	3.22
1850	85.34	1.27	3.17
2100	85.88	1.22	3.30

Table III
EXTRA-CONTAINER PATH LOSS MODEL PARAMETERS

part of the propagation path between Tx and Rx runs along the narrow pathways flanked by the highly-reflective container stacks (i.e. the white space between the 40' containers). These pathways function as a low-loss waveguide.

V. CONCLUSIONS

In this work, path loss has been investigated for three types of wireless links in a shipping container environment: intra-, inter-, and extra-container links. The intra- and inter-container links are investigated for the IEEE 802.15.4 frequencies of 433, 868, and 2400 MHz. Intra-container penetration loss is generally sufficiently limited to allow for intra-container communication. For the inter-container link, path loss is lowest at 433 MHz in the pathways between container rows, and lowest at 2400 MHz in the small gaps between adjacent containers. Furthermore, path loss models for the extra-container link have been developed for the GSM/UMTS frequencies of 900, 1850, and 2100 MHz. Qualitative explanations for the observed frequency- and distance-dependence of path loss have been given. Future work includes testing these assumptions against full-wave simulations of the three container links.

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