Multipath Parameter Extraction and Correction from Frequency Dependent Amplitude Fading

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***Abstract* — Multipath interference can be a challenging problem in the determination of accurate outdoor and indoor localization. There are methods that exist to mitigate this problem by extracting the multipath parameters, namely, differential attenuation, carrier phase shift, and differential time-delay. One method is to transmit a narrow pulse and extract these parameters from the impulse response of the channel. Another well-established method is to use frequency dependent amplitude fading of a swept sinusoid for multipath parameters extraction. In this paper, we used the second technique for the suppression of multipath distortion. We implemented this scheme with an Ettus B120 software defined radio (SDR) and observed more than a factor of 8 (18 dB) reduction of multipath distortion under different indoor environments; our findings are supported by both simulation as well as experimental results.**

Keywords — amplitude fading; indoor location; multipath; software defined radio (SDR)

I. INTRODUCTION

Multipath propagation is frequently one of the limiting factors for determining accurate outdoor and indoor localization [1-2]. It causes interference of the direct line-of-sight (LOS) signal with reflected signals from objects such as buildings, ground, trees, and other obstacles. The destructive interference of the LOS and these reflected signals can create frequency dependent signal loss called multipath fading. Indoors, multipath fading is common and makes it difficult to accurately estimate the LOS path length needed for accurate localization. There are different indoor positioning technologies such as radio-frequency identification (RFID), ultra-wideband (UWB), Zigbee, wireless local area network (WLAN), continuous-wave frequency-modulated (FMCW) radar, etc. that use conventional measurement methods like received signal strength (RSS), time of arrival (TOA), time-difference of arrival (TDOA), angle of arrival (AOA), and carrier signal phase of arrival (POA) [3-11]. The AOA and RSS methods are highly vulnerable to multipath effects and cause significant position errors. To extract ranging information, one needs to determine the LOS time-delay to the ns-level in real time while subject to significant multipath interference. Bandwidth is the easiest leverage one has against rejecting or characterizing multipath. While the short-pulse duration, high bandwidth nature of UWB technique allows for rejection of some multipath echoes, multipath induced position errors can be devastating to narrow band location systems. Therefore, in narrow band systems, multipath compensation is an important step in accurate ranging of the distance from a beacon carried by an emergency first responder, for example. Different multipath compensation schemes have been proposed and implemented over the years to tackle the effect of multipath propagation for accurate location [12-20].

In this paper, we describe a method that utilizes multipath parameters extraction and correction from frequency dependent amplitude fading. We use the same approach as proposed in [20] for the radio interferometric positioning system (RIP) and implement this scheme with an Ettus B120 software defined radio (SDR). The simulation and experimental results of multipath parameters extraction and corrections for different indoor environments are presented.

II. MULTIPATH PARAMETERS EXTRACTION

Multipath can be described in terms of three parameters, namely, differential attenuation, carrier phase shift due to the reflector, and differential time-delay [12-13, 20]. With complete knowledge of these parameters, it is possible to correct for the effects of multipath and therefore obtain the LOS-equivalent. In Fig. 1 the signal propagation between transmitter (TX) and the receiver (RX) due to multipath is shown.

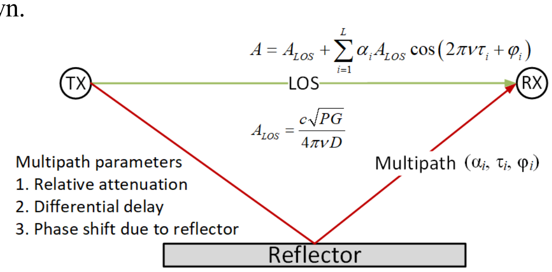

Fig. 1. Signal propagation in a multipath channel. The line of sight (LOS) signal interferes constructively and destructively with L delayed, attenuated and phase shifted multipath components. TX – transmitter, RX – receiver, A – amplitude of the signal at the receiver due to multipath, A_{LOS} – amplitude of the line of sight signal, α_i – relative attenuation of path i, τ_i – differential delay of path i, φ_i – carrier phase shift at reflector of path i.

The received signal given by (1) contains information from the multipath channel(s) encoded in the amplitude

$$A = A_{LOS} + \sum_{i=1}^{L} \alpha_i A_{LOS} \cos\left(2\pi\nu\tau_i + \varphi_i\right), \quad (1)$$

where A_{LOS} is the amplitude of the line of sight signal, L is the number of reflected paths between TX and RX, ν is the carrier frequency, α_i is the relative attenuation of path i, τ_i is the differential delay of path i, and φ_i is the carrier phase shift at reflector of path i. The amplitude A_{LOS} can be expressed from the Friis equation in terms of transmitted power P, gain of the antenna G, range D, and the velocity of light c as

$$A_{LOS} = \frac{c\sqrt{PG}}{4\pi\nu D}. \quad (2)$$

The main idea is to transmit a set of K sinusoidal frequencies monotonically increasing by $\delta\nu$, receive these signals, and finally measure the amplitude of each frequency in the set. The k^{th} frequency weighted amplitude of the received signal can be written as

$$\frac{\nu(k)}{\nu(0)} A(k) = A_{LOS}(0) + \sum_{i=1}^{L} \alpha_i A_{LOS}(0) \cos\left(2\pi\nu(k)\tau_i + \varphi_i\right), \quad (3)$$

where $\nu(k)$, $k = 0,1, \ldots, K-1$, is the series of measurement frequencies. Next, the following steps are implemented to extract the multipath parameters:

(i) Estimate a value for the LOS amplitude of the first frequency

$$\tilde{A}_{LOS}(0) = \frac{1}{K} \sum_{k=1}^{K-1} \frac{\nu(k)}{\nu(0)} A(k). \quad (4)$$

(ii) Calculate $A_{mp}(k)$ which is the frequency weighted error relative to the estimated LOS amplitude for each frequency

$$A_{mp}(k) = \frac{\nu(k)}{\nu(0)} A(k) - \tilde{A}_{LOS}(0). \quad (5)$$

(iii) Extract the delays (τ_i) of the multipath components from the peaks in $\mathcal{F}\left[A_{mp}(k)\right]$, where $\mathcal{F}$ is the discrete Fourier transform of the error series, $A_{mp}(k)$.

(iv) Extract the amplitude (α_i) and phase (φ_i) parameters from L multipaths by solving a set for $2L \times K$ equations. The matrix notation is given by

$$\overbrace{\begin{pmatrix} \cos\left(2\pi\nu(0)\tau_1\right) & -\sin\left(2\pi\nu(0)\tau_1\right) & \cdots & \cos\left(2\pi\nu(0)\tau_L\right) & -\sin\left(2\pi\nu(0)\tau_L\right) \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \cos\left(2\pi\nu(K-1)\tau_1\right) & -\sin\left(2\pi\nu(K-1)\tau_1\right) & \cdots & \cos\left(2\pi\nu(K-1)\tau_L\right) & -\sin\left(2\pi\nu(K-1)\tau_L\right) \end{pmatrix}}^{2L} \mathbf{x} = \begin{pmatrix} A_{mp}(0)/\tilde{A}_{LOS} \\ \vdots \\ A_{mp}(K-1)/\tilde{A}_{LOS} \end{pmatrix}, \quad (6)$$

where $\mathbf{x}$ designates a column vector of K variables.

Finally, the amplitude and phase components of each multipath is extracted from the expressions as follows

$$\alpha_i = \sqrt{x_{2i-1}^2 + x_{2i}^2}$$
$$\varphi_i = \tan^{-1}\left(x_{2i} / x_{2i-1}\right). \quad (7)$$

This approach of multipath parameter extraction is similar to that proposed by Zhang *et al.* for the RIP system [20] .

III. Multipath Correction Scheme and Results

The block diagram of the multipath correction scheme is shown in Fig. 2. Here, we first measure the three multipath parameters by transmitting a set of K sinusoidal frequencies as described earlier and create a correction signal from this information. The correction signal is then subtracted from the original signal of interest at the transmitter. Correction on the transmitter side allows the received signal to avoid SNR reduction due to multipath fading. However, it requires the correction signal to be communicated from the receiver to the transmitter. On the other hand, if correction at the receiver is applied after SNR degradation has occurred, the SNR cannot be recovered. In this section, we present the simulation and experimental results of the multipath parameters extraction and multipath mitigation using the proposed scheme.

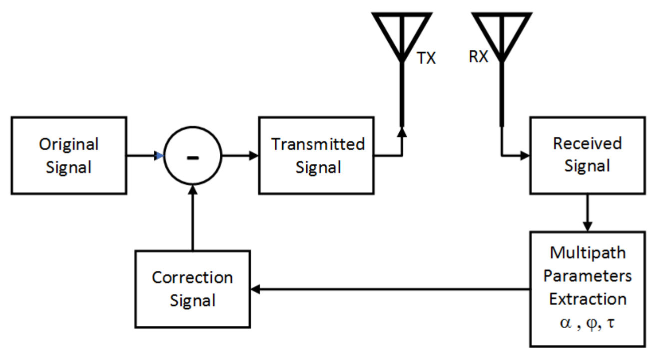

Fig. 2. Multipath error correction scheme.

A. Simulation Results

For the simulation, we used a frequency sweep of $K = 1000$ points, each separated by $\delta\nu$ = 1 MHz. For this sweep the simulation parameters are chosen as follows:

- The maximum detectable delay is $1/2\delta\nu$. Longer delays will alias to a lower frequency.
- The minimum theoretical delay resolution is $1/K\delta\nu$.
- The required sweep bandwidth is $K\delta\nu$.

Therefore, for K = 1000 points at $\delta\nu$ = 1 MHz, the maximum delay = 500 ns (~500 ft.), minimum delay = 1 ns (~1 ft.), and the total bandwidth is equal to 1 GHz. For simulation, a set of known multipath parameters (α, τ, φ) for L = 6 was generated. The amplitude (A_{mp}) of the k frequency sweep and its FFT are shown in Fig. 3(a) and (b), respectively. The parameter τ of the multipath components were extracted from the peaks in the FFT of the error series $A_{mp}(k)$, and six distinct peaks are visible in Fig. 3(b) as expected.

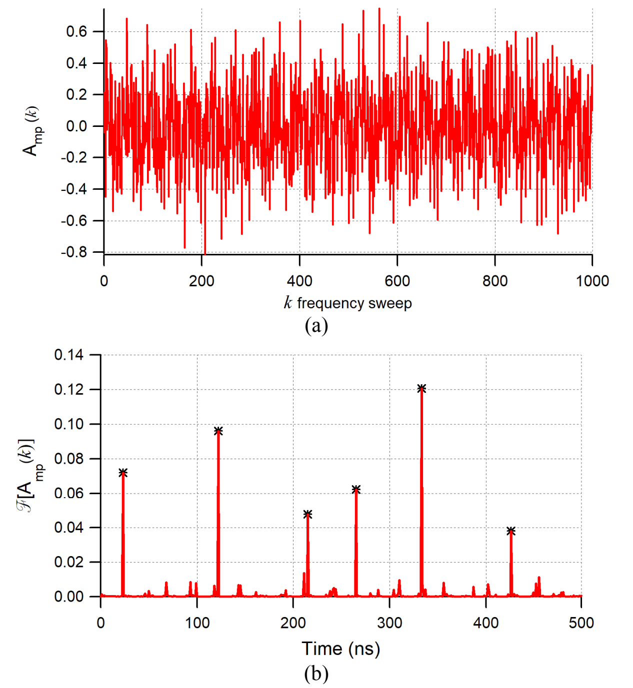

Fig. 3. (a) The amplitude A_{mp} of the k frequency sweep and (b) FFT of the error series $A_{mp}(k)$, showing a 6-component multipath. Here, $K = 1000$, $\delta\nu = 1$ MHz, and $L = 6$.

Using these delays, the remaining two multipath parameters (α and φ) were extracted. The generated multipath parameters and the corresponding extracted parameters are given in Table I, showing close agreement between the two.

TABLE I: GENERATED AND EXTRACTED MULTIPATH PARAMETERS.

FOR $K = 1000$, $\Delta\nu = 1$ MHz, AND $L = 6$

Generated Multipath Parameters			Extracted Multipath Parameters		
α	τ (ns)	φ (degree)	α	τ (ns)	φ (degree)
0.15	23	136	0.14	23	136
0.2	122	90	0.18	122	89.9
0.1	215	180	0.092	215	-179
0.13	265	75	0.12	265	75
0.25	333	23	0.23	333	23.1
0.08	426	45	0.073	426	44.1

Finally, a correction signal was generated using these extracted multipath parameters. This signal was then subtracted from the original signal prior to the transmission. Fig. 4 shows the RX signals before and after the multipath corrections.

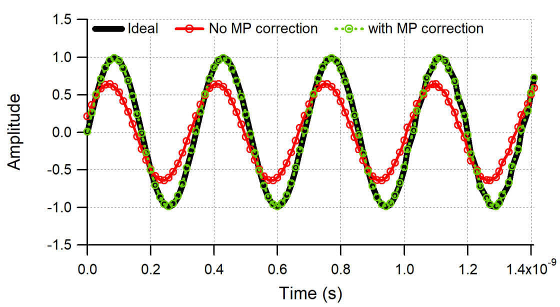

Fig. 4. Transmitted and received signals with and without multipath (MP) correction. Here, $k = 420$, $K = 1000$, $\delta\nu = 1$ MHz, and $L = 6$.

B. Experimental Results

For the proof-of-principle, we implemented the multipath correction on actual TX/RX data. The transmitter (TX) and receiver (RX) for multipath extraction is implemented in an Ettus B210 software defined radio (SDR) operating at a ~1 Hz rate. The transmitted signal was first split, then combined with an adjustable delayed version of itself, and finally received at RX and analyzed as shown in Fig. 5.

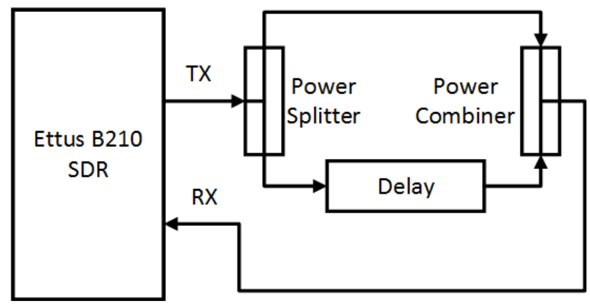

Fig. 5: Proof-of-principle experiment for generating mutipath for parameter extraction and correction.

Fig. 6(a) shows the amplitude fading due to a single fixed delay of ~28 ns between the direct (LOS) and delayed signals. Fig. 6(b) shows the fading profile after multipath extraction and correction, and it clearly demonstrates a significant reduction of the multipath distortion.

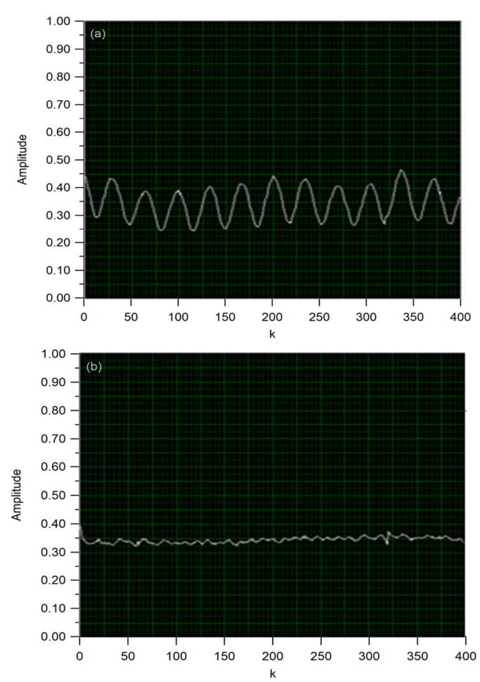

Fig. 6. Multipath fading profile (a) before and (b) after multipath correction.

We extended our experiment to measure multipaths inside a well-furnished house in a residential area as well as in a laboratory in the NIST building. The results of these two scenarios with and without multipath correction are shown in Fig. 7 and Fig. 8, respectively.

a) Residential House (mostly drywall over 2×4 wood stud construction)

We measured the multipath inside a well furnished house with dimensions of 25 by 40 ft. We used an SDR based measurement with printed circuit board (PCB) Vivaldi antennas (900 MHz - 12 GHz) [21]. The extracted multipath that we detected was highly dynamic with the position and orientation of the antennas. We typically observed 2 to 8 distinct, clearly defined multipath signals with delays (τ) of 1 to 64 ns and relative amplitudes (α) of 5% to 40%.

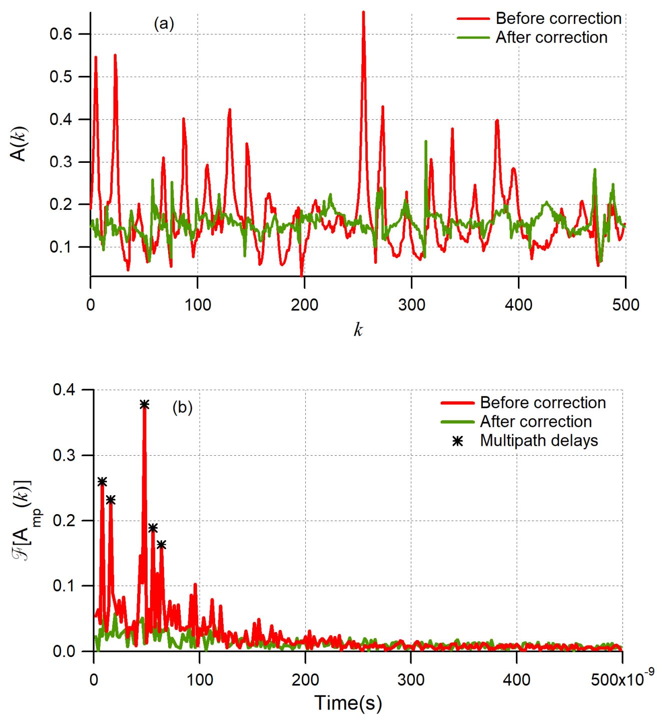

Fig. 7: Multipath inside a residential house (a) Multipath fading profile before and after correction. (b) FFT of multipath fading profile before and after multipath parameters extraction and correction.

b) NIST Laboratory (cinderblock construction)

We also measured the multipath between two rooms located in the NIST Building 1. We used the same SDR-based measurement system. The extracted multipath that we observed was also highly dynamic with the position and orientation of the antennas. In this case, the strongest observed multitpath signals were not as distinct and also had a broad background signature, most likely composed of many small convolved multipath contributions. The clearly defined and extracted multipath signals had typical delays < 20 ns and relative amplitudes of 5% to 35%.

In both of the above cases, we observed that the dominant multipath signals were reduced by more than a factor of 8 (18 dB). Also, we found that the residential house (mostly drywall over 2×4 wood stud construction) had more multipaths with longer delays (τ), and a clearly separated multipath fingerprint. It was also easier to compensate for the multipaths. On the other hand, for the NIST laboratory (cinderblock construction), we observed a less clearly defined multipath fingerprint and shorter delays. The multipath pattern was broader and comprised of many short, closely separated, unresolved τ values. In addition, it was harder to correct the multipath in this case. The results presented here demonstrate that the extraction of the multipath parameters encoded in the amplitude of the faded received signal is achievable in real scenarios. Also, the resolution of the extracted multipath delay is inversely proportional to bandwidth, and high bandwidth is still required to effectively correct the phase of a signal due to multipath distortion.

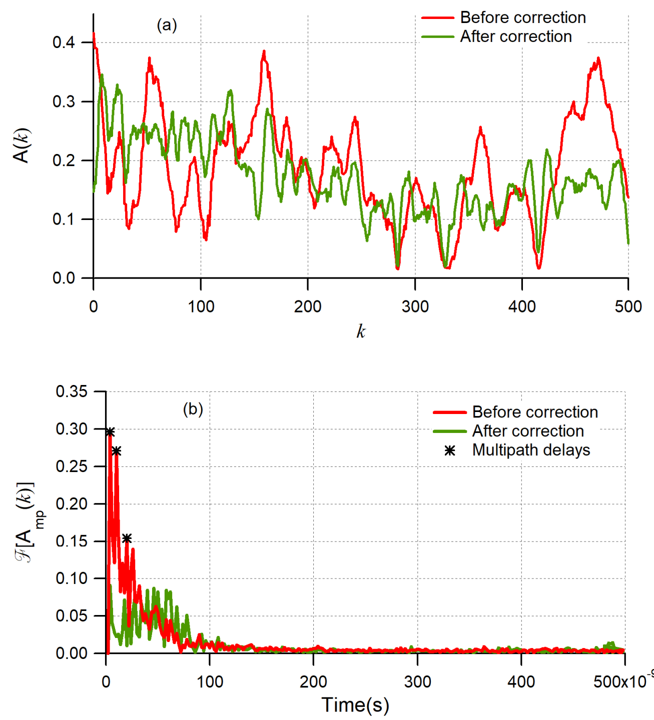

Fig. 8: Multipath inside the NIST laboratory (a) Multipath fading profile before and after correction. (b) FFT of multipath fading profile before and after multipath parameters extraction and correction.

IV. Conclusions

We demonstrated that the extraction of the multipath parameters encoded in the amplitude of the faded received signal is achievable and can be used to reduce the multipath distortion. We presented experimental results of real multipath scenarios, and an improvement by more than a factor of 8 (18 dB). We demonstrated that the residential house (mostly drywall over 2×4 wood stud construction) introduced more multipaths with longer delays (τ), and a clearly separated multipath fingerprint compared to the cinderblock constructions. For the latter case, we observed a less clearly defined multipath fingerprint and shorter delays. The multipath pattern observed was broader and comprised of many short, closely separated, unresolved τ values.

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