Buried Object Sensing Considering Curved Pipeline

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***Abstract*—This letter presents design and implementation of a low-cost system solution, where light-weight wireless devices are used to identify a moving object within underground pipeline for maintenance and inspection. The devices such as transceiver operating at 2.4 GHz are deployed for underground settings. Finer-grained Channel State Information in conjunction with leaky wave cable detects any moving entity. The processing of the measured data over time is analyzed and used for reporting the disturbances. Deploying a leaky wave cable as the receiver has benefits in terms of a wider coverage area, covering blind and semi blind zones. The system fully exploits the variances of both amplitude and phase information of Channel State Information as the performance indicators for motion detection provided by Intel 5300 NIC. The experimental results demonstrate greater level of accuracy.**

***Index Terms*—Channel State Information (CSI), Leaky Wave Cable (LWC), Access Point (AP).**

I. INTRODUCTION

Underground object motion detection is one of the crucial problems for maintenance, repair and inspection of underground pipeline (coaxial or fiber optic cables). Several systems and methods have been designed to identify underground objects including microwave tomography based system for buried objects [1], a microwave imaging based system for underground targets [2] and radar based imaging system [3]. However, a technique that accurately identifies a moving object within a buried pipeline is still a posing challenge.

Recently, Wi-Fi Channel State Information (CSI) has drawn an increasing attention since it is a powerful indicator of electromagnetic (EM) propagation at multiple frequencies [4]. The rationale is any object in motion disturbs the wireless medium when present within the area of interest, and as a result induces multiple paths for signal propagation [5]. Leveraging Wi-Fi CSI in conjunction with a leaky wave cable (LWC), we introduce a low-cost method based on small wireless devices that accurately detect a moving object inside a pipeline. The CSI data are now available on Wi-Fi commodity Intel 5300 NIC and provide the Channel Frequency Response (CFR) for a 30 subcarrier group. In order to get precise and accurate results, we use the amplitude and phase information of CSI data as the two primary indicators for motion detection.

We also demonstrate the performance of LWC against the omni-directional antenna when deployed as a receiver. The experimental results show that LWC is highly sensitive to motion as compared to an omni-directional antenna particularly in the areas where turns or curves (blind and semi-blind zones) are encountered.

Manuscript received, 2017

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II. METHODOLOGY

This section gives a brief introduction to the background knowledge of CSI data and LWC that lays the foundation for determining moving object inside a pipeline with bends.

A. Feature extraction from CSI data

To extract amplitude and phase information from CSI data, we leverage Wi-Fi commodity Intel 5300 NIC by slightly modifying the driver and got a group of 30 subcarriers known as CFR in the form of raw CSI data. Let CSI represent one received packet:

$$CSI_{packet} = \mathbf{H} = \left[h_1, h_2, h_3, ..., h_{30}\right]. \quad (1)$$

Each CSI packet contains the amplitude and phase information as follows:

$$\mathbf{H}(f_i) = \| \mathbf{H}(f_i) \| e^{(j\angle H(f_i))}, \quad (2)$$

Here $\mathbf{H}(f_i)$ denotes the CSI data with central frequency f_i at subcarrier *i,* where $i \in$ [1 to 30]. $\mathbf{H}\|(f_i)\|$ represents the amplitude information and $\angle\mathbf{H}(f_i)$ describes the phase information.

The CSI data constantly recorded for *m* number of measurements within a particular time window form a CSI sequence to monitor an area of interest and serve as primary input for motion detection .The CSI sequence is described as:

$$\text{CSI}_{\text{sequence}} = [\mathbf{H}_1, \mathbf{H}_2, \mathbf{H}_3, \ldots, \mathbf{H}_m]. \quad (3)$$

B. CSI useful phase information

CSI has extensively been used for different applications by exploiting only the amplitude information. The reason for not considering the counterpart of CSI is due to the unavailability of useful phase information on wireless devices [6]. Due to the unsynchronized clock and random noise between the transmitter and receiver, the measured CSI phase data are largely random and are inapplicable for determining body motion. In this letter, we fully explore the amplitude as well as sanitized (useful) phase information for object motion detection by applying a linear transformation on raw CSI data to mitigate the random phase offsets as in [7].

Considering the expression for measured CSI phase data $\Phi_i^{`}$ for the i^{th} subcarrier:

$$\Phi_i' = \Phi_i - 2\pi \frac{S_i}{N}\sigma + \beta + M \ , \qquad (4)$$

Here Φ_i indicates the true phase, σ is the time lag, β denotes the unknown phase offset, and M is the measurement noise. The term S_i is the subcarrier index of the i^{th} subcarrier and N is the FFT size. The subcarrier indices S_i (for i = 1 – 30) and FFT size N can be obtained from the IEE 802.11n specification [8]. Due to the listed unknowns σ and β in equation - 4, it is not possible to obtain useful phase information solely from Intel NIC. To mitigate the impact of random noises, we perform a linear transformation on the raw phases, as described in [7]. We consider phase values for the entire frequency bandwidth to eliminate σ and β values. First, we introduce y and z terms representing the slope of the phase and the offset for entire frequency band, respectively [9].

$$y = \frac{\Phi'_n - \Phi'_1}{S_n - S_1} = \frac{\Phi_n - \Phi_1}{S_n - S_1} - \frac{2\pi}{N}\sigma \ . \qquad (5)$$

Note: n=30 indicates the total number of subcarriers.

$$z = \frac{1}{n}\sum_{j=1}^{n}\Phi'_j \ . \qquad (6)$$

By substituting the measured phase data Φ_i' into the offset for entire frequency band, we get:

$$z = \frac{1}{n}\sum_{j=1}^{n}\Phi_j - \frac{2\pi\sigma}{nN}\sum_{j=1}^{n}S_j + \beta + M \ . \qquad (7)$$

The expression $\frac{2\pi\sigma}{nN}\sum_{j=1}^{n}S_j = 0$ because the indices for 30 subcarriers are symmetrical in accordance to IEEE 802.11n [9], where the term z can then be expressed as:

$$z = \frac{1}{n}\sum_{j=1}^{n}\Phi_j + \beta + M \ , \qquad (8)$$

By subtracting the linear term $yS_i + z$ from measured phase data Φ_i', we obtain the sanitized phase information, expressed as:

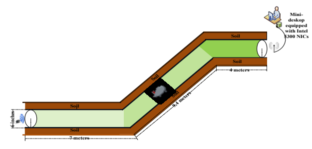
$$\tilde{\Phi_i} = \Phi_i' - yS_i - z \ . \qquad (9)$$

$$\tilde{\Phi_i} = \Phi_i' - \left[\frac{\Phi_n - \Phi_1}{S_n - S_1} - \frac{2\pi}{N}\sigma\right]S_i - \left[\frac{1}{n}\sum_{j=1}^{n}\Phi_j + \beta + M\right]. \qquad (10)$$

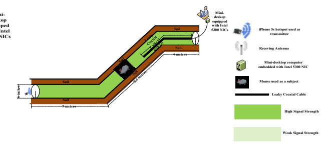
Putting equation - 4 in equation – 10 gives us:

$$\tilde{\Phi_i} = \Phi_i - \frac{2\pi}{N}\sigma S_i + \beta + M - \frac{\Phi_n - \Phi_1}{S_n - S_1}S_i + \frac{2\pi}{N}\sigma S_i - \frac{1}{n}\sum_{j=1}^{n}\Phi_j - \beta - M \ . \qquad (11)$$

$$\tilde{\Phi_i} = \Phi_i - \frac{\Phi_n - \Phi_1}{S_n - S_1}S_i - \frac{1}{n}\sum_{j=1}^{n}\Phi_j \ . \qquad (12)$$



(a)



(b)

(c)

(a). Buried pipeline for object motion detection using omni-directional antenna.
(b). Buried pipeline for object motion detection using LWC.
(c). Picture of the test field
Figure 1 – Experimental setup for identifying an underground moving object

III. LEAKY WAVE CABLE VS OMNI-DIRECTIONAL ANTENNA

The leaky wave cable has been used for fire, rescue, and mobile phone radio communications in tunnels for subways, trains, underground shopping arcades, buildings and so on [10]. The LWC comprises of a coaxial cable with zigzag period slots and acts as an array antenna [11]. The LWC also provides a wider wireless range and covers blind and semi-blind zones created by an omni-directional antenna when an obstacle is encountered in the area.

The electric field around an LWC with periodic slots is given as [12]:

$$E(r,z) = -\frac{j}{4}\sum_{i=-\infty}^{\infty}\zeta_i M H_1^{(2)}(\zeta_i z)e^{-jk_i'} \ , \qquad (13)$$

Here $H_1^{(2)}$ describes the Henkel function of the second order, M is the magnetic current, r is the radial direction and z is the axis of direction of periodic function. However, $\zeta_i = \sqrt{k_0^2 - k_i'^2}$ and $k_i'^2 = k' + \frac{2\pi i}{P}$. The term $k' = 2\pi f\sqrt{\frac{\grave{o}_r}{c}}$ and $k_0 = \frac{2\pi f}{c}$ is the wave number of the LWC in free space respectively. $\grave{o}_r$ is the relative permittivity , c is the speed of light and P denotes the periodicity of the slots.

IV. EXPERIMENTAL SETUP

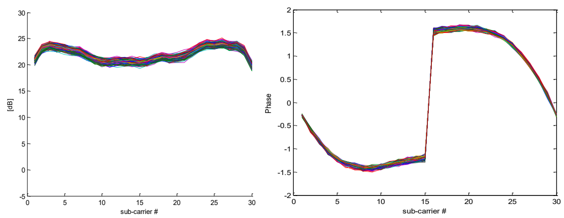
We have used three pieces of PVC pipe, 7 meters, 9.4 meters and 4 meters in length with bends at two points as shown in figure – 1(a) (b). Figure 1(c) shows picture of the test field and two people present at a distance of 3 meters from the buried pipeline for recording CSI data using host computer. During the process of obtaining data, the two persons avoided any movement. Grass was the only object closest to the pipeline. A rat (mouse) was selected as an object in motion inside the pipeline. We have used an HP desktop computer (CPU: Intel Core i5 3.30 GHz, RAM: 8 GB, Ubuntu 14.04) equipped with Intel 5300 NIC with one external antenna (scenario I) and LWC (scenario II). A Samsung S5 mobile phone hotspot operating at 2.4 GHz frequency is used as the wireless access point (AP). AP and the receiver are deployed at each end as indicated in figure – 1(a)(b). To collect CSI measurements, the client pings the AP at 20 packets per second. A modified driver is used to collect client side data

[13].

V. EXPERIMENTAL RESULTS AND DISCUSSION

To identify any moving object inside the pipeline, we analyze both amplitude and phase information by exploiting equation - 3 and equation – 12, respectively. We also compare the performance of the omni-directional antenna and LWC at the receiver side.

A. Object motion detection using the omni-directional antenna



(a) (b)

(a) The CFR traces obtained during experiment.

(b) The phase information after applying linear transformation.

Figure 2 –The CFR and phase values recorded when no moving object was present in the pipeline.

The constant values of the channel frequency response and phase information in figure - 2 obtained during the experiment reflects that no moving object was present. We further examine the phase information in figure - 3.

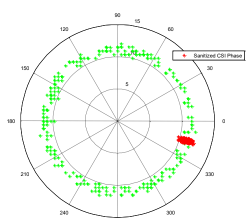
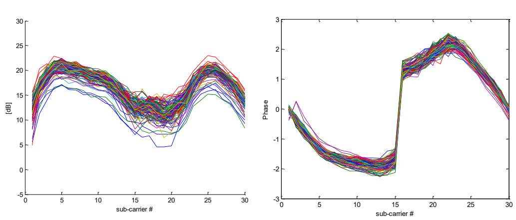


Figure 3 – The CSI phase information before and after linear transformation.

The random values in “green” indicate the phase information collected using Intel 5300 while a cluster of data in “red” shows the phase values after the applying linear transformation. The data are placed at one point and do not indicate any variation as a result of no moving object that is present in the area of interest. On the contrary, CFR values for all 30 subcarriers and phase information in figure - 4(a) and figure - 4(b), respectively, show significant variances as the subject moves inside of the pipeline.



(a) (b)

(a). Variances of CFR data due to subject motion.

(b). Variation in phase information.

Figure 4 –The CFR and phase information gathered when the subject was moving within the wireless range.

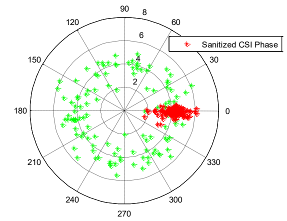


Figure 5 – The CSI phase data for the subject in motion

The object movement disturbs the wireless medium as a result of the sanitized phase information showing variances in figure - 5. To analyze the amplitude vs. time history for object motion detection, we consider figure - 6.

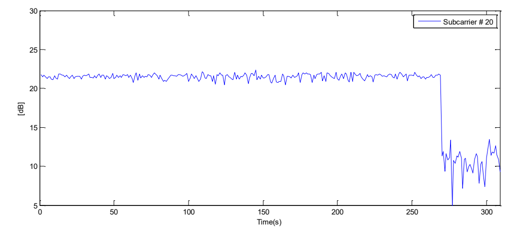


Figure 6 – The CSI time history for the individual subcarrier when the moving object was absent and present, respectively.

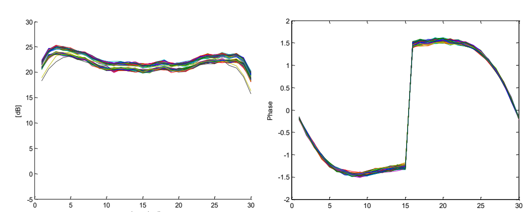
Figure-6 gives a good indication of the time history when the experiment was performed. In absence of any object in motion, the CSI amplitude for subcarrier # 20 is static till the 270^{th} second. As the moving object was subjected within the wireless range, the CSI amplitudes started to vary significantly.

The time history indicates that the object was present for a period of nearly 45 seconds. Since we know the CSI data for different curved pipeline will be different. But considering this particular scenario, when the power level remains stationary around 22 dB it means no moving object was present but as it starts fluctuating around 5 dB and 12 dB as in figure - 6 it means moving object was there in the area of interest. The power level is strongly related to object movement.

Subcarrier selection strategy: A particular subcarrier against time was selected by examining CFR values of 30 subcarriers in figure - 2(a) and figure - 4(a) for no moving object and an object in motion, respectively, in the area of interest. In the former case, the CFR values are constant while in the latter the values vary significantly for all subcarriers. Thus, to analyze the time history, we can choose any subcarrier between 1 and 30.

B. Object motion detection using a leaky wave cable

We further analyze the results of object motion detection when leaky wave cable was used as a receiving antenna.



(a) (b)

(a). The CSI data recorded using LWC

(b). The sanitized phase information obtained during the experiment

Figure 7 – The CSI data and phase information collected using LWC.

The CFR values obtained in the absence of any object motion in figure - 7(a) are marginally different from the data collected using an omni-directional antenna.

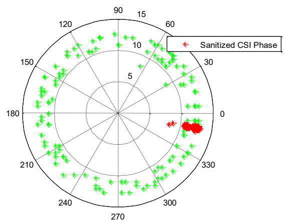
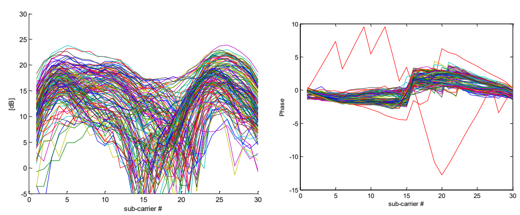


Figure 8 – Phase information obtained using LWC in the absence of any object in motion

Comparing the phase information obtained through LWC with using the omni-directional antenna when no object in motion was present, the values are slightly different. The difference in values is due to the longer length of the LWC wired into one end of the pipeline. On the other hand, we see more variations when the subject was moving within the pipeline as shown in figure - 9. The primary reason for having significantly large variances as compared to the omni-directional antenna is due to the fact that it covers the blind and semi blind zones due to the bends in the pipeline.



(a) (b)

(a). Variances of CFR data due to subject motion.
(b). Variation in phase information.
Figure 9 – Variances in amplitude and phase information obtained using LWC in the presence of any object in motion

The CSI and phase data obtained using LWC are highly sensitive to object motion. More variation of amplitude and phase information can be observed as compared to omni-directional antenna.

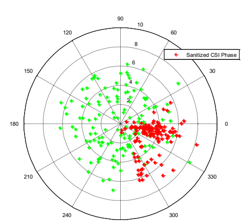


Figure 10 - Raw phase and sanitized phase information

The sanitized phase information collected using a leaky wave cable shows more variations as a result of object identification.

VI. Conclusion

The underground object motion detection system using wireless channel state information in conjunction with leaky wave cable efficiently and reliably helps in identifying an entity in the premises. In our work, we presented channel state information measurements for a period of nearly 5 minutes and observed the subject's movements for a particular subcarrier. A wireless signal in an underground environment reaches the receiver through reflections. The radio signal scattering effects are captured and analyzed for making inferences. The signals via multiple paths are a superimposed signal that is averaged out over time. The experimental results showed that by deploying a leaky wave cable at the receiver side, high classification accuracy could be achieved since the results indicated more variations as compared to omni directional antenna and work better when curves are encountered.

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