Statistical Analysis of UWB Channel Measurements

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Abstract

This report presents statistical analysis of the UWB channel measurements (reciprocity, spatial correlation, and time correlation test) that are done specifically for security purpose. We are expected to have reciprocity in UWB communication even though there are none-linear components (like: frequency up and down converter) in the system; validation of reciprocity heads into accepting the UWB channel between two peers as a source of common randomness that is shared between them. Also, previous test results show that the measurements of two neighbor points from the channel where they are further than 15 cm, are almost uncorrelated. So, this supports the secrecy of the shared information (channel) when there is no third party located closer than 15 cm to actual peers. The second purpose of this work is to verify the spatial correlation based on our new channel measurement. Finally, we are calculating the time correlation over the measured channel to address the questions of how fast a new secret shared information can be generated in UWB communication.
0.1 Introduction

Characteristic of wireless communication channels helps engineers to design higher performance sub-systems in wireless communication systems. For example, by knowing the multipath characteristic of a wireless channel, it is possible to compensate the multipath effect in receiver and get the lower bit error rate at detector. So, in data communication, system designers are very interested in channel models. Channel models are mathematical expressions that are computed based on some measurements from the channel; channel models are low cost mathematical tools for theoretical and basic design of a system. They are usually a random process representation of the channel regarding statistical characteristics of channel impulse response.

The intention of this report is to focus on a specific kind of wireless communication channels that are called Ultra Wide Band (UWB) channels. Here, the transmitted signal BandWidth is from 3.1 to 10.6 GHz.

Recently, the channel characteristic has been used for secret sharing in wireless channels [1–10, 13, 14]. These works are based on the fact that a wireless channel between two points in the environment, specifically can be used as a source of shared secret between them. The reciprocity theorem of electromagnetic supports the random sharing where spatial correlation of the channel provides the secrecy.

Generally, the reciprocity theorem is valid when there is no non-linear component in the system. However, this assumption is not completely true for real communication systems where there are none-linearity. Thus, the non-linearity heads to different channel characteristic at each peer. The first objective of this report is to calculate the effect of the non-linear components in real communication on reciprocity of the system.

In addition, the theoretical analysis shows that as long as the signal bandwidth gets increased, the spatial correlation resolution in the wireless environment is higher. So, for indoor communications, the purpose of our work, UWB communication has high spatial correlation resolution to support the secrecy of common randomness in short distances. In [12], authors has done UWB measurements and claim when two points are separated by further than 15 cm distances, their channel measurements are almost uncorrelated. The other objective of this report is verifying the uncorrelated distance of new measurements and comparing the results over [12].

The last contribution of this report is the time correlation analysis of the measurements. This parameter gives us a good estimation from the
availability rate of shared secret.
0.2 Measurement Method

The measurements is performed by the propose of first, confirming the reciprocity in UWB communication in existence of non-linear components like frequency up and down converter; second, is to making sure spatially uncorrelated measurements in the range about 15 cm [12]; finally, the time correlation characteristic of UWB channel is determined. The rest of this section describes the test plan of the measurements.

0.2.1 Signal Constraints

Measurements should be obtained for UWB signals in the frequency band from 3.1 GHz to 10.6 GHz specified by the FCC/CRTC for UWB indoor communication. Based on FCC requirements, the EIRP emission over 3.1-10.6 GHz bandwidth must be kept less than $-41.3 \text{ dBm/MHz}$. Fig. 1 shows the emission boundries for indoor UWB propagation.

![UWB indoor emission constraint from FCC](image)

*Figure 1: FCC power emission constraints for UWB indoor propagation*

0.2.2 Pulse shaping and carrier shift

The ideal pulse for channel measurement is a dirac delta pulse, $\delta(t)$, however the practical constraints does not let to generate such a pulse. So, required
pulse at first must be satisfy the frequency specification of UWB and has a short time duration to be appeared in receiver side with high time resolution (higher time resolutions intensify the effect of multipath); also transmitters undertake aforementioned power constraints of FCC. Generally, if the radio transmitter sends a pulse, $p(t)$, from its antenna, the radio receivers will receive the signal,

$$y(t) = \int_0^\infty h(\tau) p(t - \tau) d\tau + n(t)$$  \hspace{1cm} (1)

where $h(\tau)$ is the impulse response of the radio channel and $n(t)$ is additive white Gaussian noise. In the frequency domain, the relationship is given by

$$Y(j\omega) = H(j\omega) P(j\omega) + N(j\omega)$$  \hspace{1cm} (2)

where $Y(j\omega)$, $H(j\omega)$, $P(j\omega)$, and $N(j\omega)$ are Fourier transforms of $y(t)$, $h(t)$, $p(t)$, and $n(t)$ respectively. To obtain useful information about the impulse response for all frequencies of interest, the magnitude of the amplitude spectrum $H(j\omega)$ should have no nulls in the band of interest. For signal processing on received signal measurements, we work on equivalent low-pass signal. The signal is down-converted digitally and a low-pass Chebyshev filter with 1 GHz bandwidth separates the frequency band of interest of the received signal. In reciprocity verification, all the statistical processes are done on equivalent base band signal.

### 0.2.3 Synchronization

In this test, for minimizing the measurement noise, we need synchronization between two radios. This requirement is satisfied by a direct cable cable between transmitter and measurement equipment. Transmitter sends a trigger pulse on the cable connection at the same time that it sends UWB pulse through the wireless channel. The measurement equipment, will start capturing its input port when it received the trigger signal. Based on the fact that the propagation time trough the cable is negligible regarding the space, synchronization is performed with very low error that its energy is negligible in front of thermal noise.

### 0.2.4 NLOS Obstacles

Based on Fresnel Zone theory, LOS is not only visual path between transmitter and receiver, but also contains 60 percentage of the first Fresnel Zone
in each point amide two antennae. Thus, the NLOS communication is the case that the obstacle covers more than 40 percentage of first Fersnel Zone in the specific point. The radius of First Fernel Zone is defined as follows:

\[ F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \] (3)

Where,
- \( F_1 \) = the first Fresnel Zone radius in meters
- \( d_1 \) = the distance of middle point from transmitter antenna in meters
- \( d_2 \) = the distance of middle point from receiver antenna in meters
- \( \lambda \) = the maximum wavelength in our transmitted pulse in meters.

As figure 2 shows, the shape of Fresnel Zone between two antennae is like a eclipse that the maximum cross section is appeared in the middle-distance of two antennas. The radius of this specific maximized region is:

\[ r = 27.385 \sqrt{\frac{D}{f}} \] (4)

Figure 2: Elliptic shape of Fresnel Zone
where,  
\( r = \) radius in centimeter.  
\( D = \) total distance between two antennas in meters.  
\( f = \) the minimum frequency in the transmitted pulse spectrum in GHZ.

For our measurements, the maximum \( r \), radius of the first Fresnel Zone, when maximum distance \( D \) between two antenna is 10 meters and minimum frequency in UWB spectrum is 3.1 GHZ, will be \( r_{max} = 49.18 \) cm.

### 0.2.5 Test Equipments

**Oscilloscope**

Test oscilloscope is an Agilent DSO81004A model. It has 10 GHZ bandwidth and four input channels. We briefly introduce key features of this model. For more details, the specification sheet is available on the company website. Fig. 3 shows the front panel of this model.

![Fig. 3: Agilent DSO81004A front panel](image)

**Key Features:**

- 10 GHZ bandwidth real-time oscilloscope with up to 40 Gsa/sec rate.
• Up to 2 Mpts MegaZoom deep memory at 40 GSa/s sample rates and 64 Mpts MegaZoom deep memory at 4 GSa/s.

• InfiniiMax II 1168A probing system with 10 GHz bandwidth.

• Electronic attenuators eliminate the reliability and ESD discharge concerns associated with mechanical attenuator relays.

• Trigger jitter less than 500 fs rms.

• Lowest vertical noise floor and lowest jitter measurement floor in the industry.

• Unrivaled InfiniiMax probing accessories support browsing, solder-in, socket use, and SMA use models.

**Arbitrary Waveform Generator**

Our test waveform generator model is Tektronix AWG7052. The following shows the specification of this equipment.

**Key Features:**

• 10 GS/s (20 GS/s) and 5 GS/s models.

• 1 or 2 Arbitrary Waveform Outputs.
  
  – Accurate Timing with only 20 psp-p Total Jitter (at 10-12 BER, Typical).
  
  – 45 ps Tr/Tf (20% to 80%).
  
  – 100 ps Range (1 ps Resolution) Inter Channel Skew Control.

• 2 or 4 Variable Level Marker Outputs.
  
  – Accurate Timing with only 30 psp-p Total Jitter (at 10-12 BER, Typical).
  
  – 45 ps Tr/Tf (20% to 80%).
  
  – Up to 300 ps Range (1 ps Resolution) Delay Control.

• Vertical Resolution up to 10-Bit Available: 10-Bits (No Marker Output) or 8-Bits (with Two Marker Outputs).
• Up to 64 M (64,800,000) Point Record Length Provides Longer Data Streams.

• Down to 100 fs Resolution Edge Timing Shift Control.

• Sequencing Creates Infinite Waveform Loops, Jumps and Conditional Branches.

• Real-time Sequencing Creates Infinite Waveform Loops, Jumps, and Conditional Branches.

• Intuitive User Interface Shortens Test Time.

• Integrated PC Supports Network Integration and Provides a Built-in DVD, Removable Hard Drive, LAN, and USB Ports.

Vector Signal Generator

This set is used to shift the center frequency of the generated pulse to the UWB domain. The tested model is Agilent E8267D. Fig. 4 shows the front panel of the set.

![Agilent E8267D front panel](image)

Figure 4: Agilent E8267D front panel

Here, we give some key features of the equipment. More information is available on Agilent product website.

Key Features:

• Signal Characteristics
- 250 kHz to 20, 31.8, or 44 GHz (.001 Hz resolution)
- +22 dBm @ 20 GHz and +18 dBm @ 40 GHz output power (typ)
- 160 MHz (extendible to 2 GHz) RF modulation bandwidth

**Modulation and Sweep**
- AM, FM, M, and pulse
- ASK, FSK, MSK, PSK, QAM, custom I/Q
- Step, list, and ramp sweep frequency and power
- Source control using PSA Series spectrum analyzer

**Baseband Generation and Signal Creation**
- Internal baseband generator (80 MHz RF BW): arbitrary waveform and real-time I/Q
- Compatible with wideband (1 GHz) N6030A arbitrary waveform generator
- Create reference signals: radar, multi-tone, NPR, custom modulation, WLAN, and more - Signal Studio
- Digital I/O, fading, and PC HDD waveform streaming - Baseband Studio

**Automation and Communication Interface**
- 10BaseT LAN and GPIB
- SCPI and IVI-COM drivers
- Backwards compatible with all PSG signal generators

**Microwave System Amplifier**

To compensate system losses and to boost the received signal, we used a microwave amplifier from Agilent with model number 83017A. The set is capable of working on frequency range from 500 MHz to 26.5 GHz. Fig. 5 previews the set. also some characteristics of the set are as follows,

**Key Features:**
- Superior RF performance
Figure 5: Agilent 83017A, microwave amplifier

- Gain of more than 25 dB.
- P1 dB more than 18 dBm to 20 GHz.
- Noise figure of less than 8 dB to 18 GHz, 13 dB to 26.5 GHz (typ).

Antenna

The test antenna is a pair of EM-6865 Omni-Directional Wideband Antenna (Fig. 6) that is capable of operating as either a transmitting or receiving antenna over the 2 to 18 GHz frequency range. The electrical and mechanical characteristic of EM-6865 are as follow,

- Electrical
  - Frequency Range: 2 GHz - 18 GHz
  - Polarization: Vertical
  - Output Impedance: 50 Ohms, nominal
  - VSWR, average: < 2 : 1
  - Gain: 0 dBi, typical
- Connector: Type N, female
- Continuous Power: 5W

- Mechanical
  - Diameter: 10.16 cm (4”)
  - Length, Support Rod: 25.4 cm (10”)
  - Height, Shield Tube: 7.62 cm (3)
  - Overall Height: 33.0 cm (13)
  - (Antenna & Support Rod)
    * Weight: 0.45 kg (1 lb.)
    * Mounting: Standard $\frac{1}{4}$ - 20 Thread

0.2.6 Test Strategy for Reciprocity Measurements

In this case, we are looking for validation of reciprocity theorem in UWB systems.

Physical Scenario

Channel measurements are performed at several different antenna separations. It would optimal if, for each separation distance, measurements could be taken for both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) propagation conditions. Recommended antennae separations are:

(a) $d$ (distance between pair) = 1 meters.  
(b) $d$ (distance between pair) = 2 meters.  
(c) $d$ (distance between pair) = 4 meters.  
(d) $d$ (distance between pair) = 6 meters.  
(e) $d$ (distance between pair) = 8 meters.  
(f) $d$ (distance between pair) = 10 meters.

After measurements are made for one direction of signal propagation, say from antenna A to B, the connections should be reversed so that measurements are also made for propagation from antenna B to A.

Theoretical requirements

For this experimental set, all the measurements for a given set of antennae positions must be made within the coherence time of the radio channel.
Figure 6: EM-6865 Omni-Directional Wideband Antenna
In other words, in the time interval between two measurements, the channel must be stationary. To ensure this, object movement in the radio propagation environment must be eliminated if possible or at least minimized. (Temporal Stability: in this condition the coherence time of the channel gets increased). [hint: the measurement is done when the offices are closed]

0.2.7 Test Strategy for Spatial Correlation Measurements

The purpose of these measurements are to quantize or bound the spatial correlation properties of the indoor UWB radio channel.

Physical Scenario

In this test, one of the antennae is kept stationary while the other antenna is moved between measurements. The impulse response of the radio channel is measured for each of the antenna positions and the spatial correlation of the channel impulse response is calculated. To do this, one of the antennae is moved controlled distances and the impulse response is calculated. For our purposes, we measured the impulse response at 25 point (a 5 to 5 mesh; also in each point we got 10 measurements to have the better estimation in our statistical process by getting the average of the measurements to eliminate the Gaussian, zero mean, measurement noise in both side. The distance between the neighbor points in one row or column is 20 cm. In addition, the test is done for both LOS and NLOS scenarios when the basic distance between transmitter and receiver is less than 5 m (the further distances are not possible because of some environmental constraints of the test place).

Theoretical requirements

As in the previous set of measurements for reciprocity, movement in the radio propagation environment should be minimized so that all differences in the measurements are created as a result of the antenna movement and measurement noise. The measurement noise can be mitigated by averaging techniques so the remain, mostly, contains the effect of antennae positioning.
0.2.8 Test Strategy for Channel Coherence Time Measurements

The objective of these measurements is to determine the available rate of new shared secret generation in UWB radio channel.

Physical Scenario

In this test set, the position of both antennae will be kept stationary and controlled object or person movement introduced into the radio channel environment so that the effect on the channel coherence time can be measured. The exact nature of the movements to be introduced is currently under discussion.

To measure the coherence time, the impulse response of the radio channel will be measured every $T_s$ seconds with $T_s < 1000$ ms. The measurements are performed for both LOS and NLOS cases within different distances between transmitter and receiver.

Theoretical requirement

In this set, the antennae positions must be stable so that the changes are influenced by environment object movements and measurement noise. As aforementioned, the averaging technique can reduce the effect of measurement noise.
0.3 Statistical Analysis

In this section, we present our statistical analysis method, and the results obtaining from measurement data. Prior to talk about our measurements, to make our report comprehensive, we would like to restate some basic definitions for review. All the definitions are consistent with our text-book [11].

0.3.1 Definitions

Mean Ergodic Random Processes

Continuous:
A stationary random process \( X(t) \) is called mean ergodic process if the statistical average, \( \bar{X} \), is equal to time average \( \bar{x} \) of any sample function \( x(t) \) with probability one for all the sample functions.

\[
\lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t) \, dt = \bar{X}
\]

Discrete:
A discrete sequence is called mean ergodic if the time average of samples equals the statistical average with probability one,

\[
\lim_{N \to \infty} \frac{1}{2N+1} \sum_{n=-N}^{N} X[N] = \bar{X}
\]

Correlation Ergodic Process

Continuous:
A stationary random process \( X(t) \) with autocorrelation function \( R_{XX}(t) \) is called autocorrelation ergodic if and only if for all \( \tau \),

\[
\lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t)X(t+\tau) \, dt = R_{XX}(\tau)
\]

Discrete:
A wide sense stationary random sequence \( X[n] \) is autocorrelation ergodic if, and only if, for all \( k \),
\[ \lim_{N \to \infty} \frac{1}{2N + 1} \sum_{n=-N}^{N} X[n]X[n + k] = R_{XX}[k] \]

**Correlation Coefficient**

The correlation coefficient for real random variables \( X \) and \( Y \) is defined in term of expectation as,

\[ \rho = \frac{E[XY] - \bar{X}\bar{Y}}{\sqrt{\sigma_X^2 \sigma_Y^2}} \tag{5} \]

For uncorrelated \( X \) and \( Y \), the correlation coefficient is zero, otherwise two random variable has correlation (estimation of one from other is possible). In the case that \( X = Y \), the correlation coefficient, \( \rho = 1 \). In this report, for the case of reciprocity, we are expecting close to one correlation coefficient. On the other hand, for spatial and temporal correlations, we would like to have correlation \( \rho \) very close to zero.

### 0.3.2 process evaluation

When the stochastic characteristics of a random process are not available to realize the process, ergodicity will be applied. In real world, any measurements are time limited, so we do not have any information about the past and future values of the measurements. As long as assuming the unknown measurements do not have strange characteristics, the measured samples during the time period of measurements can be assumed as the sample space of a random variable. Thus, the time average is equivalent to statistical average and such a process is called mean ergodic process. Furthermore, for real time limited measurements by using the definition of autocorrelation ergodicity, the time correlation is equivalent to statistical correlation. To understand the autocorrelation ergodicity, suppose that all the measurements in time interval \( T_1 = (t_1, t_2) \) are shown as time limited random variable \( X_{T_1} \) and similarly, all the measured samples in time interval \( T_2 = (t_3, t_4) \) are supposed as \( X_{T_2} \) where \( t_2 < t_3 \). Now suppose that we are intended to find the autocorrelation of,

\[ R_{X_{T_1}X_{T_2}}(T_1, T_2) = E[X_{T_1}X_{T_2}] \]
where both of the random variables are real. The correlation of these random
variables can be derived with probability one when two random variables are
independent. In the case of independence random variables, time correlation
obtained instead of unavailable statistical correlation.

In our measurements, we suppose that channel measurements are mean
and correlation ergodic. So, we are using time equivalences to deduce the
correlation coefficients.

Consequently, in simulations, the measured signal is replaced in 0.3.1 and
0.3.1 definitions as input signals. Also in all the cases, the average of at least
ten measurement sets is obtained to cancel the measurement noise. Measure-
ment noise is supposed to be Gaussian with zero mean and $N_0$ variance, so
that the averaging can alleviate measurement noise.

0.3.3 Measurement system

Fig. 7 shows the block diagram of measurement system. Some important
parameters of these measurements are:

- The sampling rate of measured data is 40 GS/sec.
- The carrier frequency is 4 GHZ that is provided by vector signal gen-
erator.
- The output of vector signal generator is set to have 10 dBm power.

![Figure 7: Block Diagram of measurement system](image)

The synchronization will be provided by the dashed link, Synch, from
transmitter. The pulse generator simultaneously transmits a synch signal
through a coaxial invariant length cable, synch link. The oscilloscope begin to capture at the time it receives the synch pulse.

In the next chapter, we are presenting the simulation results of these measurements.
0.4 Simulation Results

In this section, we present the three set of simulation that we have done to verify the reciprocity theorem, calculate spatial correlation coefficient, and time correlation coefficient.

0.4.1 Transmitted pulse characteristic

The transmitted pulse is measured in electromagnetic chamber with our oscilloscope. The sampling rate of the measured signal is 40 GHz. Fig. 8 shows the measured pulse.

![Transmitted Pulse Shape](image)

Figure 8: Transmitted pulse shape

0.4.2 reciprocity in UWB communication

The simulation is done with MATLAB. At first, the reciprocity theorem is verified on the gathered measurements. The down-conversion and filtering process has been done by software. The received signal is down-converted by 4 GHz zero phase oscillator (we do not care the phase of carrier) and then it is filtered with an IIR low pass Chebyshev filter to get the baseband frequency response. The specification of required Chebyshev filter are as follows:

- Double side bandwidth: $W = 1$ GHz.
• Normalized passband edge frequency: \( \omega_p = \frac{W}{2f_s} = 0.0125 \).
• Normalized stopban ripple: \( \omega_a = 2 \times \omega_p \).
• Maximum bandpass ripple: \( A_p = 0.1 \text{ dB} \).
• Maximum stopban ripple: \( A_a = 60 \text{ dB} \).
\[
- D = \frac{10^{0.1 \times A_a - 1}}{10^{0.1 \times A_p - 1}},
- K_0 = \frac{\tan \left( \frac{2\pi f_p T_s}{2} \right)}{\tan \left( \frac{2\pi f_a T_s}{2} \right)}.
\]
• Filter order: \( n = \left\lceil \frac{\cosh^{-1}(\sqrt{D})}{\cosh^{-1}(\frac{1}{K_0})} \right\rceil = 9 \).

In Fig. 9, the amplitude of frequency response of the realized filter is presented so that satisfies the specification constraints.

Figure 9: Frequency response of designed 9-th order Chebyshev LP filter.

The correlation coefficient is calculated from 5 based on test plan physical and theoretical scenarios, Section 0.2.6. The results for both LOS and NLOS
cased are given in Table 1 and 2, respectively. In LOS case, the results got averaged over 16 measurement sets where in NLOS, the averaged is calculated with 64 measurement sets. SNR column shows the output power ratio of vector signal generator, our carrier modulator.

<table>
<thead>
<tr>
<th>distance (meters)</th>
<th>average</th>
<th>SNR (dBm)</th>
<th>correlation coefficient $-1 \leq \rho \leq 1$</th>
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Table 1: Correlation coefficient results in reciprocity test for LOS measurements.

<table>
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<th>distance (meters)</th>
<th>average</th>
<th>SNR (dBm)</th>
<th>correlation coefficient $-1 \leq \rho \leq 1$</th>
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<td>64</td>
<td>10</td>
<td>0.910</td>
</tr>
<tr>
<td>8</td>
<td>64</td>
<td>10</td>
<td>0.959</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
<td>10</td>
<td>0.965</td>
</tr>
</tbody>
</table>

Table 2: Correlation coefficient results in reciprocity test for NLOS measurements.

The results show that except 2 meters LOS and NLOS measurement, all the other cases are highly correlated (at least the correlation coefficient is calculated 90 percent). In 2 meters LOS and NLOS measurements, I could not find any reasonable evidence to explain the variation so a possibility is that the measurements in these case have not done in appropriate conditions as explained in reciprocity physical scenario, Section 0.2.6. Thus, generally, the results approve the reciprocity in our communication and it means that from key generation point of view, the measured channel can be a common randomness for end to end peers.
## 0.4.3 Spatial correlation in UWB communication

The other expected result is spatial correlation characteristic of our UWB communication. In this test, transmitter position is stable and the receiver antenna is located on 25 different positions. Fig. 10 shows the positioning of receiver antenna. Technically, the channel is measured at every circle shown in Fig. 10 and the correlation of measurement is calculated over the measurement obtained at the red filled circle (center of the measurement square shape plan). In this case, also we have 10 set of measurements in each point to averaging over them. The distance between the measurement point is 20 cm in horizontal and vertical direction.

![Figure 10: The receiver antenna positioning for spatial correlation test scenario.](image)

In our simulation, we found out that the best way to show the spatial correlation coefficient is to fit the coefficient in a color image consist of 25 squares. We suppose that at the middle of each square, there is one of our measurement points. The color of the square present the value of correlation coefficient.

Fig. 11 shows the simulation results for the case that the distance between transmitter and receiver antennae is 1 meter and there is LOS path. Also, Fig. 12 and 13 are sketched for antennae distances 3 and 5 meters, respectively. For 5 meters case, we have 4 measurement points in one of the direction so there is totally 20 measurement points in our simulation.
Furthermore, we calculated the spatial correlation coefficient for NLOS case. The results are taken for the transmitter and receiver antennae distances of 2.5, 3.0, 3.5, 4.0, and 5.0 meters (Fig. 14, 15, 16, 17, 18).

Figure 11: Spatial Correlation Coefficient (LOS, distance = 1 m).

The results show that the similarity of received measurements are reduced when the receiver takes far from reference point, red circle of Fig. 10. However, there is no general relation between spatial correlation and distance of the antenna from reference point; we can not claim that spatial correlation decrease continuously for further distances from reference point but the fact is that the correlation reduces significantly as soon as the receiver antenna position is changed.

On the other hand, previous measurements [12] show that the relation, correlation reducing for further distances from reference point, exists in UWB channel measurements.

We have two different explanations of the unexpected spatial correlation measurements. The first is based on the differences between measurement methods. Technically speaking, the spatial correlation should be determined between two measurements in different space positioning results from a pulse transmission. So, to satisfy this, previous works used an array antenna and the output of each of antennae is captured simultaneously. But in our mea-
Figure 12: Spatial Correlation Coefficient (LOS, distance = 3 m).

Figure 13: Spatial Correlation Coefficient (LOS, distance = 5 m).
Figure 14: Spatial Correlation Coefficient (NLOS, distance = 2.5 m).

Figure 15: Spatial Correlation Coefficient (NLOS, distance = 3.0 m).
Figure 16: Spatial Correlation Coefficient (NLOS, distance = 3.5 m).

Figure 17: Spatial Correlation Coefficient (NLOS, distance = 4.0 m).
Figure 18: Spatial Correlation Coefficient (NLOS, distance = 5.0 m).

measurement, because we did not have any array antenna, we had to measure in one point and then minimize the movement in radio propagation environment to change the position of the receiver to the new point and get another set of measurement. There are two weak assumptions (or the assumptions that contradict each other) in our measurement:

- control (minimize) the movement of the environment.
- the environment is changed when we move the antenna to new position (there is no antenna, as a reflector in the space, in the previous position).

Consequently, it can be concluded that our result does not support any order or relation between spatial correlation and displacement distance (like previous done works [12]), because in our test method we did not use array antenna.

The second proposed reason to explain the unexpected results is concentrated on the shadowing effect in the test place. We know that shadowing has long term fading characteristic. The high amount of correlation might be cause by powerful shadowing reflection that is a characteristic of the test
environment. In other words, there are numbers of smooth reflector in the environment that cause high correlation. This hypothesis can be studies easily when we return to the test environment and capture, in the same position of transmitter and receiver, new set of measurements. If the new measurements are correlated as previous results then it shows that the correlation is caused by shadowing effect of the environment and is a characteristic of our test place. If so, then we should find a signal processing method to discard the correlated part of measurements (the parts that are appeared by smooth reflector in the space) and get the result as uncorrelated shared secret for security process.

0.4.4 Time correlation in UWB communication

To get the time correlation measurements, a pulse is transmitted every 500 msec so then the channel is measured with lower time resolution (to save the memory of the oscilloscope for more than one measurements). During the test, we asked people to walk around the antennae positioning place and by calculating the correlation coefficient, our interest is to find how the environment movements change the channel in UWB communication. The correlation coefficient is obtained between the first channel measurement at $\tau = 0$ and channel measurements at $\tau = n$ msec. In this test, we also considered both, LOS and NLOS scenarios. Fig. 19 and 20 show the LOS and NLOS time correlation coefficient, respectively. In this test, the channel is measured in 1000 sec. The results show that in LOS scenario, the channel measurements are highly correlated for most of the time differences, $\tau > 0$; also there is no large scale reduction in correlation coefficient over time. For NLOS measurements the results are different; the time correlation is reduced to 70 percent; also a large scale decreasing is appeared in the correlation over time in NLOS scenario. However, both of the results are not satisfactory with our desired security method where short correlated time period is desired. Our tests demonstrate that in the 1000 seconds (almost 17 minutes) the measurements are mostly correlated with correlation coefficient of at least 60 percent although, there are $\tau$s that have small correlation but they are random.

One description for unexpected results in time correlation test might be time resolution reduction that has been noted in the beginning of this section to keep the capacity of oscilloscope for getting more measurements. We guess that in lower resolution, we missed some helpful changes in received signal
Figure 19: Time Correlation Coefficient, LOS channel.

Figure 20: Time Correlation Coefficient, LOS channel.
that may be neglected in the current resolution.

In addition, we present in Fig. 21, schematic of the decision maker circuit for security purpose applications. In such applications, time correlated channel measurements are not useful and key generation process cannot obtain new key (uncorrelated with previous keys) from correlated measurements so, based on the following graph, we drop the correlated measurements upon previous stored measurement and ask for new pulse transmission; otherwise we accept the measurement as uncorrelated one to head up to the key generation system. The threshold of decision will be set regarding the capability of regenerating the key from correlated symbols in the system.

Figure 21: Schematic of the decision maker circuit for security purpose applications.
0.5 Conclusion

We conclude our report by summarizing the results of analysis:

- Reciprocity test
  
  In this test the results are satisfactory and we have shown that the reciprocity is valid within 98 percent of confidence even if there is none-linear components in the system.

- Spatial Correlation test
  
  Our results are different with previous results in this test. There is no relation between the correlation and the distances between measured points (our desire is to have less correlation within further distances). So that, we proposed two reasons to explain this inconsistency.
  
  1. Using the array antenna for spatial correlation test.
  2. Redo the measurement to characterize the shadowing effect that has long term effects on the results.

- Time correlation test
  
  The results in this part are very environment based. As we expected earlier, correlation is not low in all times so, we proposed an algorithm to distinguish the low correlation and using low correlated measurements for security purpose.
Bibliography


