# Intra-Vehicle UWB MIMO Channel Capacity

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*Abstract*—**In wireless communication, MIMO technology can improve performance by offering larger channel capacity without additional bandwidth or transmitting power. This paper presents the measurement of intra-vehicle ultra wideband (UWB) multiple-input multiple-output (MIMO) channels and evaluates channel capacity. The measurement was carried out in time domain for three scenarios: (1) in the car compartment, (2) beneath the chassis, and (3) inside the engine compartment. The results show that MIMO channel capacities increase while using more antennas and the capacity achieved by water filling is larger than that achieved by equal power distribution.**

***Keywords- UWB, MIMO, intra-vehicle, channel capacity***

## I. INTRODUCTION

Ultra-wideband (UWB) is radio technology which has bandwidth exceeding 500MHz or 20% of the arithmetic center frequency. In 2002, the Federal Communications Commission (FCC) authorized the unlicensed use of UWB in the range of 3.1 to 10.6 GHz [1]. UWB technology boasts high-data rate, low-cost transceivers, low-transmit power, and low interference [2]. UWB technology is more effective in the intra-vehicle environment than narrow band technologies because of its resistance to multi-path fading. This provides high channel capacity in the intra-vehicle wireless communication. By using impulses rather than modulating by carrier signal in communication, UWB technology can support low power applications. Since 2006, studies on intra-vehicle UWB channel measurement and experiment have been published continuously [3].

Multiple-input and multiple-output (MIMO) uses multiple transmitting and multiple receiving antennas. Early simulation studies about the potentially large MIMO capacity were conducted in 1980s. Later, a large number of papers explored the capacity analytically [3]. Comparing to single-input and single-output (SISO), MIMO technology improves communication performance because it increases channel capacity without additional bandwidth or transmitter and receiver power.

Intra-vehicle UWB single-input and multiple-output (SIMO) capacity was reported in a previous paper by our group [6]. This paper continues the study and focuses on UWB MIMO channel measurement and channel capacity evaluation. By using multiple antennas sending out the same signals, the quality and reliability of the wireless communication can be improved.

## II. SYSTEM SETUP

In our experiment, the measurement was performed in time domain. The block diagram in Fig. 1 illustrates the connections of the equipments.

At the transmitter side, an impulse generator triggered by a function generator creates narrow pulses of width 100 picoseconds. These pulses are sent to a scissors-type antenna. At the receiver side, a digital oscilloscope of 15GHz bandwidth is connected to the receiving antennas to display and record the received signals. The impulse generator and oscilloscope are synchronized with a low loss cable.

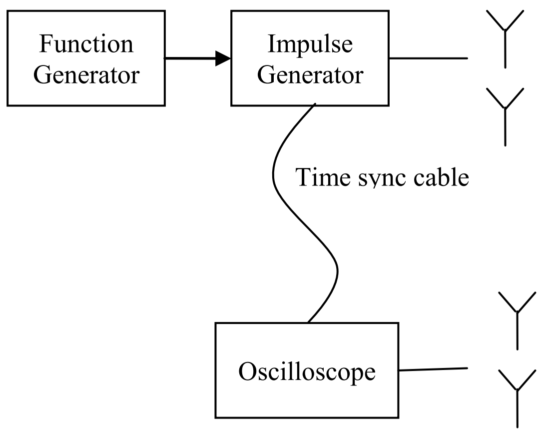


Figure 1. Connection of channel sounding apparatus

A 2003 Honda Odyssey is used for the experiment. The experiment was performed in three scenarios: (1) in the car compartment, (2) beneath the chassis, and (3) inside the engine compartment. Four antennas, two as transmitters and two as receivers, were placed at different locations in the measurement and data collection. For each location, the data were recorded five times. All the antennas were connected to the oscilloscope with cables of the same type and length.

In the first scenario, the antennas were placed in the car compartment, as shown in Fig 2. The transmitting and receiving antennas were set face-to-face. The transmitting antenna was placed at the front of the car, and the receiving antennas were placed on the seats and car floor. Both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios were included. The transmitting and receiving antennas were placed in seven different locations.

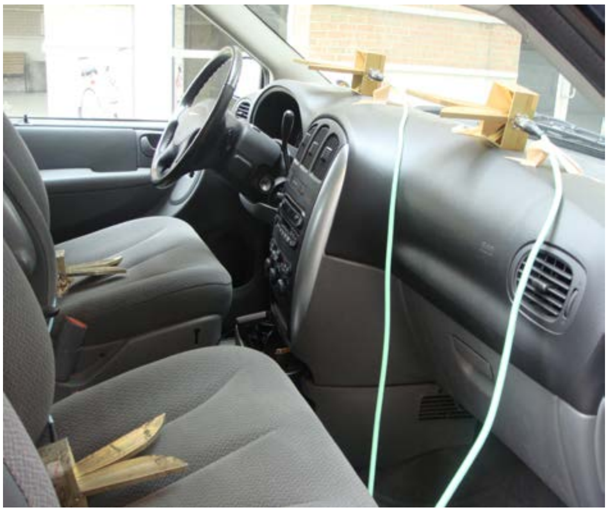

Figure 2. Channel measurement in the car compartment

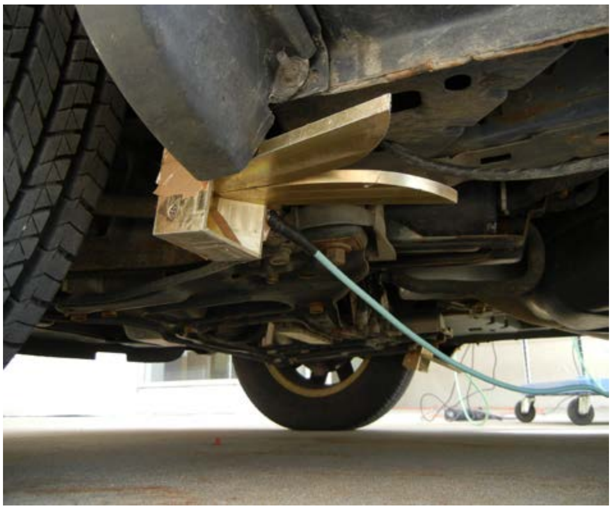

Figure 3. Channel measurement beneath the chassis

Figure 4. Channel measurement in the engine compartment

In the second scenario, the antennas were placed beneath the chassis, as shown in Fig. 3. The transmitters and receivers were set face-to-face in LOS scenario. They are fixed beneath the chassis about 5 inches above the ground. In this scenario, the transmitting and receiving antennas were placed in eight different locations. The transmitting antennas were placed at the front part of the car and the receiving antennas were placed symmetrically along the left and right side of the car with different distances.

In the third scenario, the antennas were placed inside the engine compartment, as shown in Fig. 4, with the hood closed. The transmitters and receivers were not face to face because the space availability in the engine compartment is very limited. There were metal parts and components sitting between the antennas. In this scenario, the transmitting and receiving antennas were placed in six different locations.

## III. DATA ANALYSIS

Channel impulse response is extracted from the recorded signals using the CLEAN algorithm as in [5]. The template waveform used by the CLEAN algorithm was achieved through one pair of antennas, setting face-to-face and 1 meter away from each other. Fig. 5 shows the template waveform used in the de-convolution algorithm.

Fig. 6 shows the corresponding received waveforms through the antenna in the three scenarios. Fig. 7 shows the de-convolved impulse responses of the three scenarios described in Section II. It can be observed from the three figures that the signal measured in scenario II has the fewest clusters and the signal measured in scenario III has the most clusters. Here a cluster is a group of multi-path components with similar arrival times and exponentially decaying amplitudes. It can be inferred that the signal has the most reflections in the engine compartment and has the fewest reflections beneath the chassis, which agrees with the practical intra-vehicle environment.

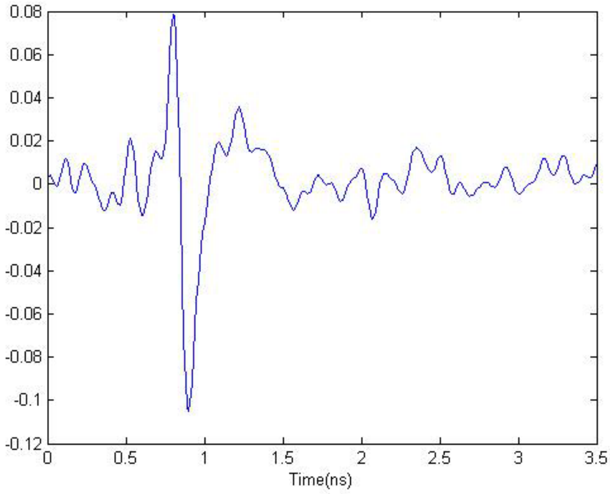


Figure 5. Template signal through the antenna

The UWB MIMO channel system with $N_t$ transmitting antennas and $N_r$ receiving antennas can be written as

$$\boldsymbol{r}(t) = \boldsymbol{H}(t) * \boldsymbol{s}(t) + \boldsymbol{n}(t) \quad (1)$$

where $\boldsymbol{r}(t)$ is the received signal, $\boldsymbol{s}(t)$ is the transmitted signal, and $\boldsymbol{n}(t)$ is the white Gaussian noise in frequency domain.

The channel transfer function is $\boldsymbol{H}(t)$ is

$$\boldsymbol{H}(t) = \begin{bmatrix} \mathrm{H}_{11}(t) & \cdots & \mathrm{H}_{1\mathrm{N_t}}(t) \\ \vdots & \ddots & \vdots \\ \mathrm{H}_{\mathrm{N_r}1}(t) & \cdots & \mathrm{H}_{\mathrm{N_r}\mathrm{N_t}}(t) \end{bmatrix} \quad (2)$$

where $N_t$ represents the number of transmitting antennas, and $N_r$ represents the number of receiving antennas. $\boldsymbol{H_{MN}}(t)$ is channel transfer function from the N-th transmitting antenna to the M-th receiving antenna. Its corresponding channel impulse response is $h(t)$.

The MIMO channel capacity depends on how power is allocated in the available bandwidth. First, when the channel information is not available to the transmitter, the transmitting antennas distribute the power throughout the whole band equally. The channel capacity is:

$$\mathrm{C}=\int_{\mathrm{B}} \log_2[\det\left(\mathrm{I} + \frac{\mathrm{S}}{\mathrm{N_0}} H(f)H^H(f)\right)]d(f), \quad (3)$$

where $B$ is the bandwidth, $\boldsymbol{N_0}$ is the noise power spectrum density (PSD) and $(.)^{\boldsymbol{H}}$ represents the matrix Hermitian. [6].

Second, when the channel information is available to the transmitter, the transmitting power is distributed by water filling to achieve maximum channel capacity [6][7]. The channel capacity is

$$\mathrm{C}=\max_{\int_B S(f)df=S} \int_B log_2[det\left(\boldsymbol{I} + \frac{S(f)\boldsymbol{H}(f)\boldsymbol{H}^H(f)}{N_0}\right)]d(f), \quad (4)$$

where $N_0$ is the noise PSD, $\boldsymbol{S}(f)$ is the optimum power spectrum density function achieved by water filling as [7]

$$S(f) = \left[\theta - \frac{N_0}{\boldsymbol{H}(f)\boldsymbol{H}^H(f)}\right]_+, \quad (5)$$

$$S = \int S(f)\, df, \quad (6)$$

where $[.]_+$ means taking the positive value and $\theta$ is a constant.

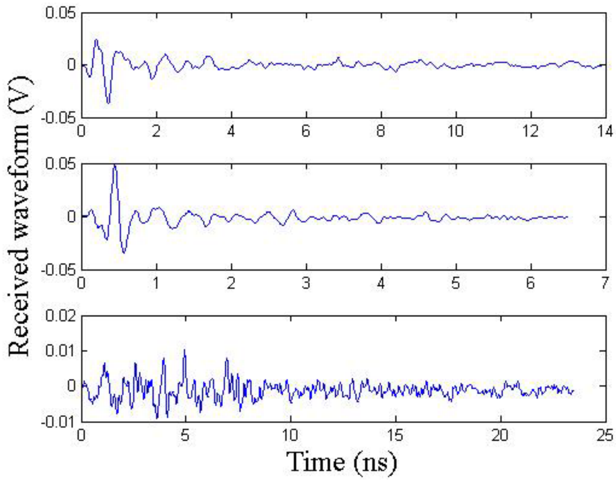


Figure 6. Received signal in three scenarios: (1) in the car compartment, (2) beneath the chassis, (3)in the engine compartment.

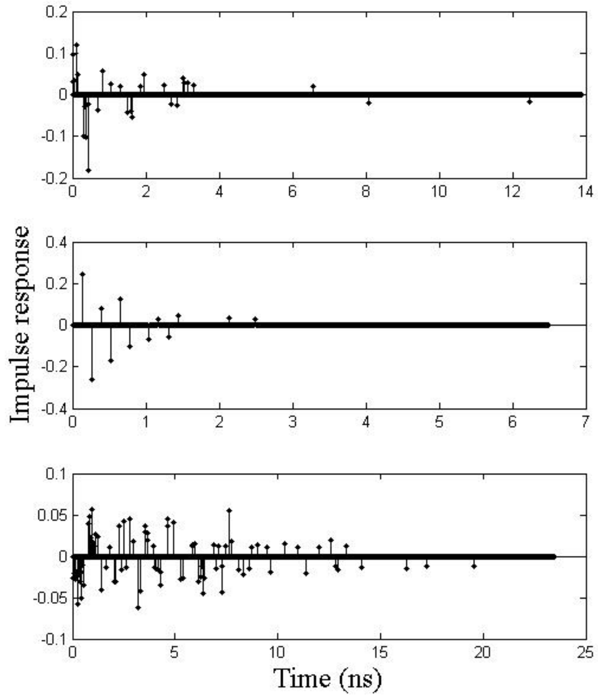


Figure 7. Channel impulse response in three scenarios: (1) in the car compartment, (2) beneath the chassis, (3)in the engine compartment

We have calculated the MIMO channel capacity for both cases in the three scenarios.

## IV. EXPERIMENT RESULT

The calculated channel capacities in the three scenarios are plotted in Fig. 8-13.

It is observed in these figures that the system with 2-input and 2-output has the lowest channel capacity and the MIMO channel capacity increases when the number of transmitting and receiving antennas increases. In the 2-input and 2-output case, the channel capacity in the engine compartment is 1.8 bits/sec/Hz when SNR is 5dB (within equal power distribution case), which is the largest compared to 0.8 bits/sec/Hz in the car compartment and 0.9 bits/sec/Hz beneath the chassis. This is gained by the relatively smaller space and more signal reflections in the engine compartment. With the number of antennas increasing to 6-input and 6-output, the channel capacity in the car compartment increases to 8.1 bits/sec/Hz while the channel capacity in the engine compartment only reaches 6.9 bits/sec/Hz and the capacity beneath the chassis reaches 3.5 bits/sec/Hz. From the results of three scenarios, we can infer that the channel capacity will still have great increase when more antennas are used in the measurement. We can also find out that the channel capacity in the car compartment increases faster by employing more antennas than in the engine compartment and beneath the chassis. By observing the channel capacity increasing rate of the three scenarios when SNR is 5dB, we can find out that the channel capacity increasing rate is getting larger in car compartment and engine compartment from 2-input 2-output case to 7-input 7-output or 6-input 6-output case, respectively. The capacity increasing rate beneath the chassis reaches the maximum at 6-input 6-output and then decreases when more antennas are employed. Because of the space limit in the engine compartment, the measurement was only taken up to 6-input 6 output. By comparing the first two scenarios, which is in the car compartment and beneath the chassis, we can infer that the number of the antennas used to reach the maximum channel capacity in the car compartment is greater than that used beneath the chassis.

Another observation is that the channel capacity achieved by water filling is larger than that achieved by equal distribution, which verifies that water filling method produces a better channel capacity. As the number of transmitters and receivers increases, the gap between the capacities calculated by the two methods grows larger, which means that this capacity advantage appears more obvious when employing more transmitters and receivers. The study of SIMO system shows that the advantage of using water filling method becomes hard to tell when the system reaches more than 3 receivers [6]. While in the MIMO system, this is not the case. This is because the power of one transmitter is constant. When the number of receivers is far larger than the number of transmitters, the additional receiving antennas do not provide more independent communication channels with the transmitters.

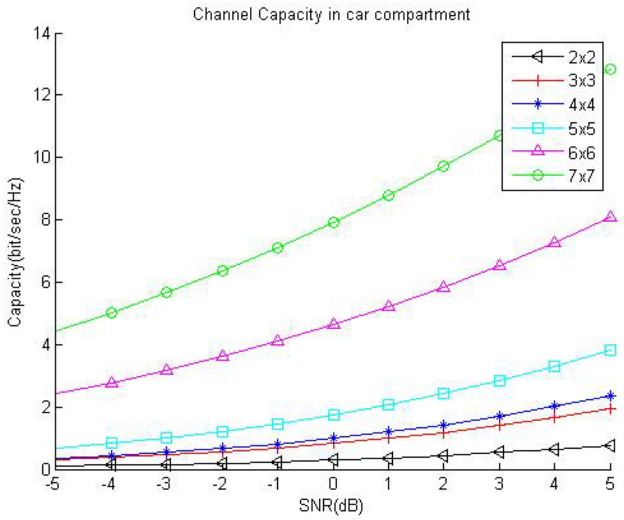


Figure 8. Channel capacity in the car compartment

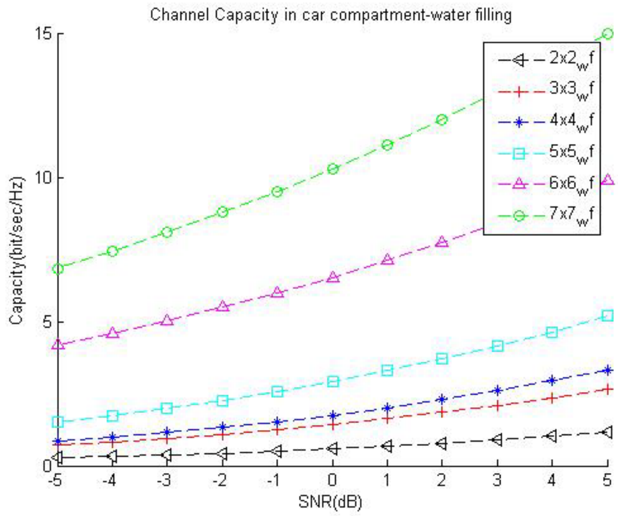


Figure 9. Channel capacity in the car compartment (water filling)

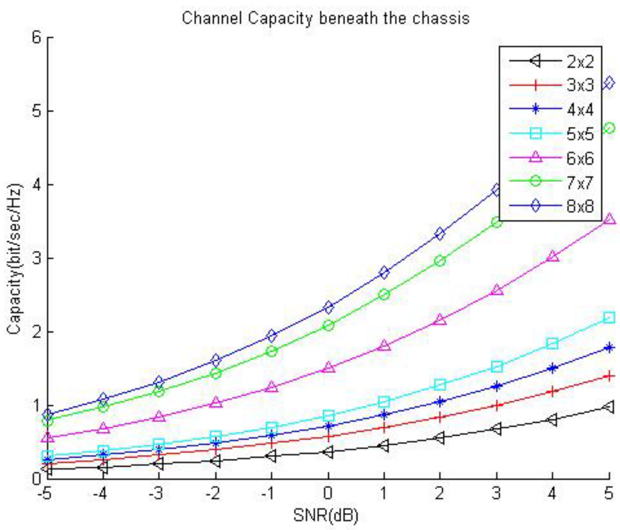


Figure 10. Channel capacity beneath the chassis

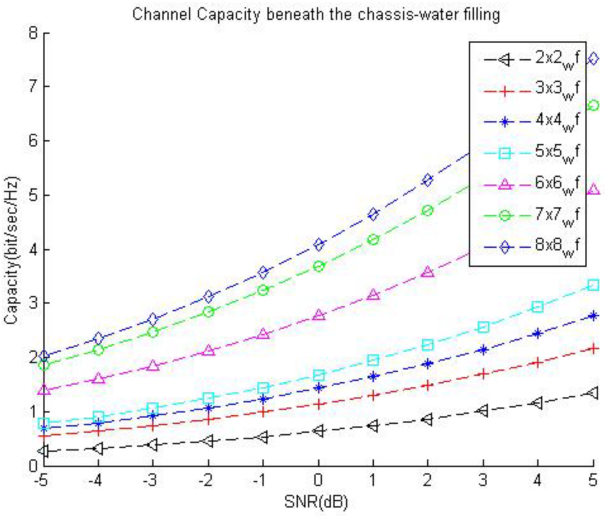


Figure 11. Channel capacity beneath the chassis (water filling)

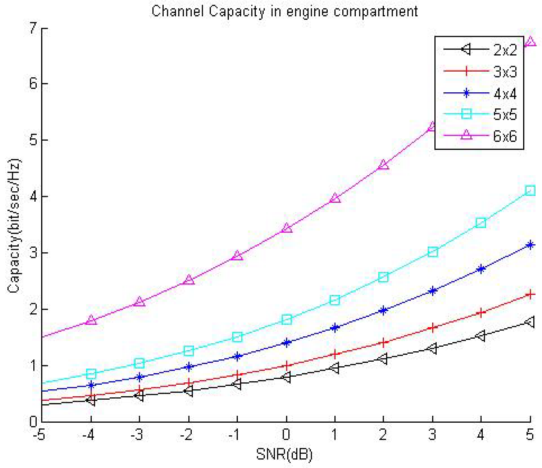


Figure 12. Channel capacity in the engine compartment

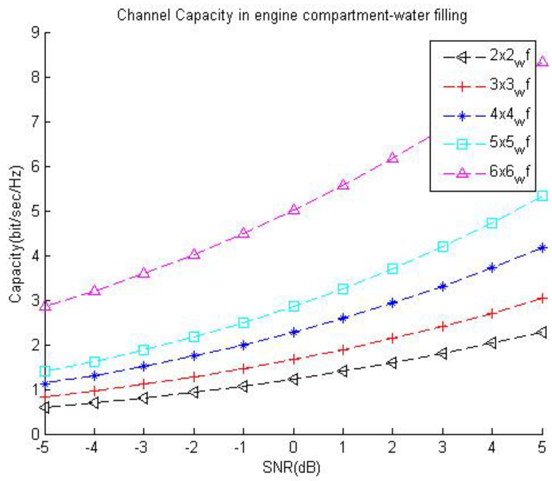


Figure 13. Channel capacity in the engine compartment (water filling)

## V. CONCLUSION

In this paper, the measurement of intra-vehicle UWB MIMO channel and the channel capacity evaluation are presented. The experiment was carried out by sounding the intra-vehicle channel with periodic impulses and recording the response results with a digital oscilloscope. The measurement was done in three scenarios: in the car compartment, beneath the chassis, and inside the engine compartment. For each case, antennas were placed at several different locations to collect signals for calculating MIMO channel capacity. The channel capacity is studied for the three scenarios. The capacities of the three scenarios with 2-input 2-output when SNR is 5dB are 0.8 bits/sec/Hz, 0.9 bits/sec/Hz and 1.8 bits/sec/Hz, respectively. The capacities increase to 8.1 bits/sec/Hz, 3.5 bits/sec/Hz, and 6.9 bits/sec/Hz with 6-input 6- output. The results reveal that in the intra-vehicle environment, the capacity of MIMO channel depends on the number of transmitters and receivers. Larger channel capacity can be achieved by using more antennas. In a relatively closed area, better channel capacity can be achieved by using more antennas than relatively open area. If the channel information is known at the transmitter side, using water-filling method to allocate power can lead to larger channel capacity. Their capacities can reach 9.9 bits/sec/Hz, 5.1 bits/sec/Hz, and 8.4 bits/sec/Hz with 6-input 6-output case.

## REFERENCES


[1] L. Yang and F. Wang, "Driving into intelligent spaces with pervasive communications," *IEEE Intelligent Systems*, vol. 22, no. 1, pp. 12–15, January-February, 2007.

[2] R. C. Qiu, R. Scholtz, and X. Shen, "Ultra-wideband wireless communications–a new horizon," *Editorial on special session on UWB, IEEE Trans. Veh. Technol*, vol. 54, no. 5, September, 2005.

[3] A. F. Molisch, M. A. Win, J. H. Winters, "Capacity of MIMO systems with antenna selection," *IEEE International Conference on Communications*, vol. 2, 2001, pp. 570-574, July, 2005.

[4] Z. Hu, D. Singh, and R. Qiu, "MIMO capacity for UWB channel in rectangular metal cavity," *SoutheastCon, IEEE*, pp. 129s–135,April, 2008.

[5] W. Niu, J.Li, and T.Talty, "Ultra-wideband channel modeling for intra-vehicle environment," *EURASIP Journal on Wireless Communications and Networking*, vol. 2009, January, 2009.

[6] F. Qu, J. Li, L. Yang, T. Talty, "Measured channel capacity of SIMO-UWB for intra-vehicle communications," *Antennas and Propagation (EUCAP)*, pp. 3056-3060, Apri, 2011.

[7] F. Zheng, T. Kaiser, "On the evaluation of channel capacity of UWB indoor wireless systems," *IEEE Trans. on signal processing*, vol. 56, no. 12, pp. 6106-6113, December, 2008.