Array Configuration and Channel Model of MIMO Sensor for Home Security

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Abstract

This report discusses MIMO system as home security sensor. MIMO propagation channel is very sensitive to the environmental change. The proposed radio sensor called MIMO sensor utilizes this feature to detect events for home security. We report fundamental results for evaluation of array configuration and propagation channel.

Keywords : MIMO sensor Indoor Propagation Channel Matrix Security sensor

1. Introduction

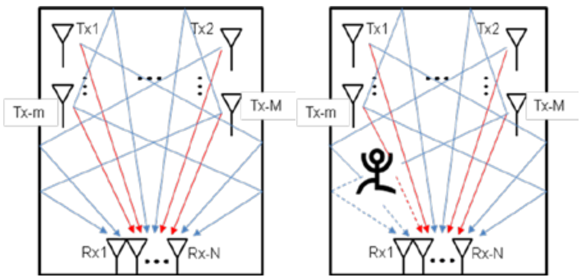
Recently, researches on radio wave security sensors by using array antenna or MIMO system have been attracting attention. Since so-called spatial signature of MIMO channel matrix is used in these security sensors, the sensors have realized high detection performance as well as robustness for practical sensors [1], [2]. Most of conventional radio sensors use receiving power directly to detect events/intrusions. On the other hand, newly developed sensors aim to estimate propagation environment, such as spatial signature (signal subspace) or MIMO channel matrix, to detect the events. These system are effective especially for indoor multipath environment, hence event/intrusion detection for home security will be one of the suitable applications. In this report we focus on the MIMO sensor for event detection.

Many systems and detection algorithms have been proposed. Their performance was evaluated in a particular system and propagation environment. Quantitative performance evaluation should be necessary to develop practically available/reliable MIMO sensors. However, evaluation/optimization of MIMO sensor is a difficult problem because the system performance depends on not only array configuration but also propagation environment and detection algorithm. In our group, we research on the MIMO sensor in several viewpoints. In this report, we provide fundamental results for array configuration and MIMO channel model [3] for home security application.

2. Problem Formulation for MIMO sensor

The MIMO sensor is assumed to be operated in indoor multipath rich environment. Assuming that M transmitter and N receiver, or MxN MIMO system, as shown in Figs.1(a) and (b). Figure 1(a) shows the propagation environment without the event/intruder. For the MIMO system, we can easily estimated the channel matrix, $\boldsymbol{H}_0$, given by

$$\boldsymbol{y}_0(t) = \boldsymbol{H}_0 \boldsymbol{x}(t) + \boldsymbol{n}(t), \qquad (1)$$



(a) without event (b) with event

Figure 1: Event detection by using MIMO sensor.

where $\boldsymbol{x}(t)$ is the M dimensional transmitting signal vector, and $\boldsymbol{y}_0(t)$ is the N dimensional receiving signal vector. $\boldsymbol{n}(t)$ is the additive Gaussian noise vector. Clearly the channel matrix $\boldsymbol{H}_0$ is stable when the propagation environment is stable.

The MIMO sensor uses $\boldsymbol{H}_0$ as a reference for event detection. When an event occurs at time t as shown in Fig.1(b), the receiving signal becomes:

$$\boldsymbol{y}(t) = \boldsymbol{H}(t)\boldsymbol{x}(t) + \boldsymbol{n}(t) = (\boldsymbol{H}_0 + \boldsymbol{H}_d(t))\boldsymbol{x}(t) + \boldsymbol{n}(t), \tag{2}$$

where $\boldsymbol{H}(t)$ is the channel matrix for this case. $\boldsymbol{H}_d(t)$ in (2) denotes the channel variation to $\boldsymbol{H}_0$. Detection performance of the MIMO sensor depends on the $\boldsymbol{H}_d(t)$-distribution in the observed room. Detection performance of the MIMO sensor will essentially depend on power of the $\boldsymbol{H}_d(t)$, hence effectiveness of array configuration for given elements will be roughly evaluated to check the cover area of power of $\boldsymbol{H}_d(t)$ in the room. This is the motivation to propose "event detection sensitivity map" in the section 3. In addition, statistical model for $\boldsymbol{H}_d(t)$ enable us to develop the channel model for MIMO sensor. Such a model is necessary to evaluate and compare detection algorithms without assuming a particular observed room. This motivates the discussion in section 4.

3. Event Detection Sensitivity Map

Detection probability of the MIMO sensor will mainly depends on the variation of $\boldsymbol{H}_d(t)$ which is given by $G_d = \|\boldsymbol{H}_d(t)\|_F^2$, where $\|\cdot\|_F$ is the Frobenius norm. To optimize the MIMO sensor, we should find an array configuration which cover wide area of the room with high G_d or maximize the minimum G_d in the room. G_d depends on the antenna elements and propagation environment as well as antenna arrangement. Therefore, EM simulator, such as ray trace method, will be required to derive exact value. However, the exact analysis is often time consuming and we have another problem for selection of event model.

To judge the effective antenna arrangement, relative distribution of G_d for the given room will be enough. We propose an approximated G_d distribution map in the given room called "Event detection sensitivity map". To derive this map, we also use ray trace method. Derivation of this map can be divided two parts; 1) Transmitting property, and 2) receiving property.

In the transmitting property we evaluate the power of the elementary waves by the transmitters at the evaluated point k in the room, which can be given by

$$G_t^{(k)} = \sum_{m=1}^{M} G_{t,m}^{(k)} = \sum_{m=1}^{M}\left(\frac{1}{|x_m|^2}\sum_j \left|s_j^{(k)}\right|^2\right), \tag{3}$$

where x_m is the transmitting signal at the m-th transmitter and $s_j^{(k)}$ denotes the j-th element wave at location k. This map visualizes how the transmitter illuminates the room. Note that we should evaluate sum of the power for the elementary waves, not total power of multipath wave itself because the event/intruder intercepts, or absorbs, the elementary waves. Figures 2 and 3 show the evaluation model and its transmitting property map for 4 transmitting dipoles at 2.5 GHz with 0.8 m antenna height. Locations of transmitters are marked as red circles in Fig.3.

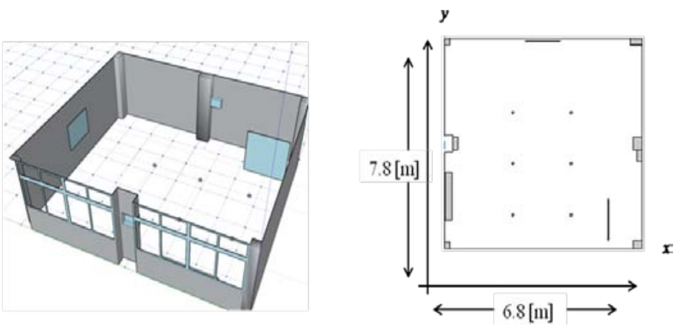


Figure 2: Evaluation room model.

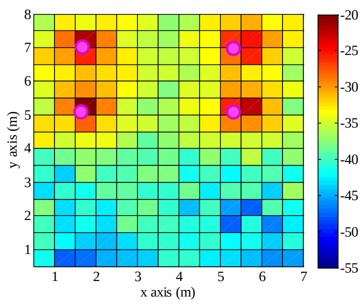


Figure 3: Transmitting Proverty Map.

In the second part, receiving property, we evaluate how the change propagates to the receiving array. To evaluate this effect we employ rough approximation in this report. Vertical polarization is dominant because we employ dipoles as transmitter in this example, then variation of $\boldsymbol{H}_d(t)$ is also dominant at each point. Therefore we estimate the receiving property G_r of given receiving array for location k by the receiving power of the array from a dipole transmitter at location k:

$$G_r^{(k)} = \boldsymbol{y}_d^{(k)H} \boldsymbol{y}_d^{(k)} \Big/ \left| s^{(k)} \right|^2 , \qquad (4)$$

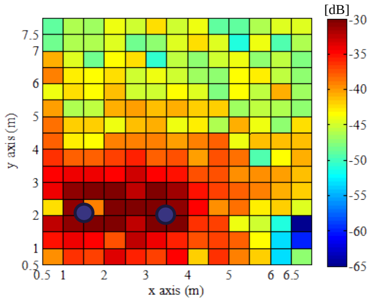


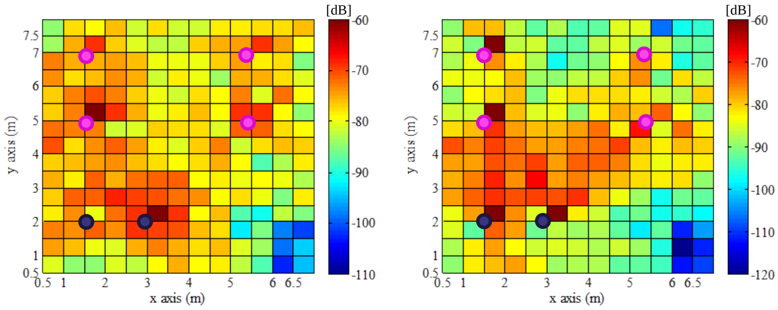
Figure 4: Receiving Property Map.

where $\boldsymbol{y}_d^{(k)}$ is received signal vector of the array and $\left| s^{(k)} \right|^2$ is the transmitting power of the dipole at the location k. Obviously, one important factor is dropped here. The transmitting wave at location k emulates the intercepted elementary waves by the event. The directional distribution of the waves is varied at every point. However, above dipole approximates the pattern as omni-directional pattern. Figure 4 shows an example for two receivers for the evaluation model in Fig.2, where receivers are marked by black circles.

The total map, or event detection sensitivity map, can be derived by

$$G_d^{(k)} = G_t^{(k)} G_r^{(k)} . \qquad (5)$$

This approach evaluates the effect of transmitter and receiver separately, therefore combination of transmitting and receiving array configurations can be easily calculated. This enables us to find better array configuration easily. Disadvantage of this approach may be accuracy due to pattern of transmitter at receiving property evaluation. Figures 5(a) and (b) show the estimated map by using proposed scheme and exact analysis, respectively. In the exact analysis, we use a 0.2x0.45 x1.8(m) dielectric pole as a human intruder model to calculate $\boldsymbol{H}(t)$. Mean value of each map is adjusted to show the difference clearly. Although we employ rough approximation at receiving property evaluation in the proposed scheme, global tendency of the power distribution can be matched satisfactory. Therefore the proposed Event Detection Sensitivity Map will be available to evaluate, or search optimal array configuration. Directional pattern for elementary waves will be considered when more accuracy is required, that is the future work to be done.



(a) Proposed method (b) Exact solution

Figure 5: Event Detection Sensitivity Map

4. MIMO Propagation Channel for Event Detection

In the MIMO communication system, performance of the system can be easily evaluated statistical channel models such as Rayleigh or Nakagami-Rice distribution model. In the MIMO sensor for event detection, we can also evaluate its detection performance without assuming a specific propagation environment, or room size, if the channel model(s) for $\boldsymbol{H}_0$, $\boldsymbol{H}(t)$, and $\boldsymbol{H}_d(t)$ can be properly modeled. To check the typical statistical distribution of the elements in these matrices, we carried out indoor experiment. The propagation environment in this experiment was the same size as shown in Fig.1, and the transmitting and receiving array configuration was also the same as shown in Fig.5. In this experiment we employ sleeve dipoles as the elements. The MIMO channel matrices were collected at 2.5 GHz band. Figure 6 shows the cumulative distribution function (CDF) of the estimated $\boldsymbol{H}_0$ and $\boldsymbol{H}(t)$, respectively, where $\boldsymbol{H}(t)$ was measured with a

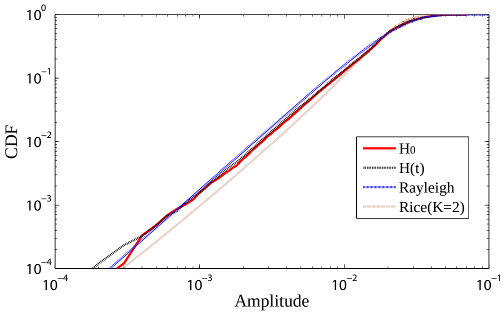
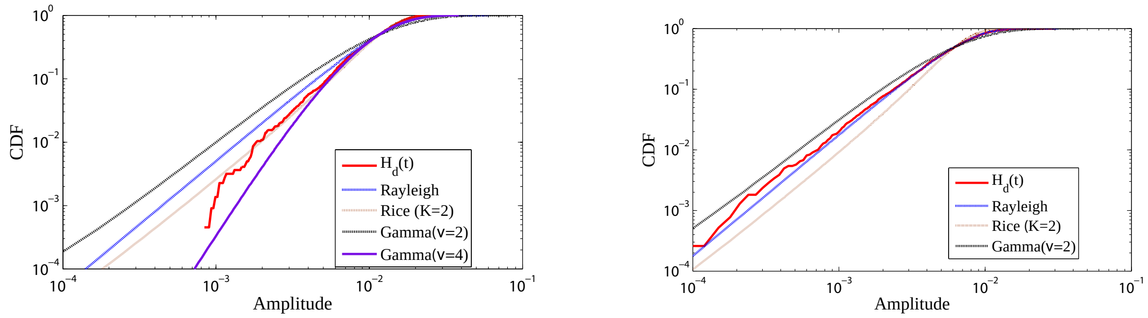


Figure 6: CDFs for $\boldsymbol{H}_0$ and $\boldsymbol{H}(t)$

human intruder at (x,y)=(3.0, 3.4) m. Note that these CDFs are normalized at 50 % value. It is clear that the both CDFs almost obey Rayleigh distribution though it was the Line-of-Sight (LOS) propagation environment. It was because that the transmitting array is widely distributed and the intercepted elementary waves by the intruder were weak in comparison with the remaining waves. To derive the channel variation model the CDF of $\boldsymbol{H}(t)$ is not so important. We should focus on the CDF of the channel variation matrix, $\boldsymbol{H}_d(t)$. Figures 7(a) and (b) shows the CDF of the $\boldsymbol{H}_d(t)$ when the intruder intercepts the direct wave(s) and multipath waves, respectively. As expected by the indoor MIMO communication researches, amplitude of the elements in $\boldsymbol{H}_d(t)$ have the Nagkagami-Rice distribution, K=2 in this case, when the direct wave is intercepted. To derive canonical channel matrix models for several typical events, we should consider the shape of $\boldsymbol{H}_d(t)$. Experimental study for $\boldsymbol{H}_d(t)$ will be also reported in [3].



(a) Direct wave interception (b) Multipath wave interception

Figure 7: CDFs for $\boldsymbol{H}_d(t)$

5. Conclusion

Fundamental study of MIMO sensor for event detection has been provided in this report. To evaluate and optimize performance of the MIMO sensor, array configuration and MIMO channel model are important. The proposed “Event Detection Sensitivity Map” is the approximate method to evaluate the detected power distribution by the event. The map has makes evaluation for various combinations of transmitting and receiving array configuration easy, therefore it will be a powerful tool to find an optimal array configuration for a given environment. In addition, experimental results of MIMO propagation channel for the sensor have been also provided. They will be available for derivation of canonical channel model for MIMO sensors.

References

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