# Performance Evaluation of MIMO Sensor algorithms for Indoor Intrusion Detection

#Ken OGAWA[1], Hiroyoshi YAMADA[1], Yuta KUROSAKI[1], Yoshio YAMAGUCHI [1]
[1] Graduate School of Science & Technology, Niigata University
Ikarashi 2-8050, Nishi-Ku, Niigata-shi, 950-2181 Japan,
ogawa@wave.ie.niigata-u.ac.jp
yamada@ie.niigata-u.ac.jp

## Abstract

Recently, several indoor intrusion/event detection methods using radio propagation change have been proposed. One of these methods with an array antenna employs SIMO system. Also, several methods use MIMO system. In this report, we propose a new detection method without channel estimation and compare its performance to the conventional ones.

**Keywords:** MIMO system, Intrusion detection, Signal-subspace, Security

## 1. Introduction

Recently, researches on indoor intrusion/event detection with radio wave sensor using array antenna have been attracting attention. These security sensors observe radio propagation, and detect intrusion using radio propagation change caused by the intrusion/event. These sensors enable to monitor wide area in comparison with video camera and infrared radiation sensors. Furthermore the radio sensor can detect the intruders in non-Line-of-Sight (NLOS) area from the sensors. Several methods for theses sensors have been proposed. One of the indoor intrusion/event methods with an array antenna detects intrusion by observed received signal-eigenvector change [1]. This method is the SIMO (Single-Input Multiple-Output) system. In contrast, several indoor intrusion/event detection methods adopt the MIMO (Multiple-Input Multiple-Output) system [2], [3]. These methods detect intrusion by using variation of MIMO channel matrix. Generally detection performance of the methods based on the MIMO system is superior to that of the SIMO based system. However, these methods require precise channel estimation for each transmitting channel. For this reason, hardware system and protocol often become complicated.

Therefore, in this report, we propose a new method for the MIMO system, which uses signal-eigenvectors like the SIMO system, hence no preamble/training symbols for channel estimation is not required. Performance of the proposed method in comparison with that of the conventional MIMO channel correlation method [2] is evaluated by computer simulations. The results show that the proposed method realizes almost the same detection performance as the conventional MIMO. Since the proposed method employs signal-subspaces, we call the method as Signal-subspace-MIMO (S-MIMO) in the followings. In this report, we use variable number $M$ as number of transmitter elements, and $N$ as that of receiver.

## 2. The Data Model

In this report, we consider $M$ distributed transmitters and $N$-element linear array antenna shown in Fig.1. We also assume that the $M$ transmitting signals by the transmitters are statistically independent with one another. Namely, intermittent or alternate transmission with the transmitters is assumed in the proposed method. This transmission has advantage in power consumption for the continuous operation. The received data vector of the array for the $m$-th transmitter can be modeled by sum of the $K$ multipath waves.

$$\boldsymbol{r}_m(t) = \boldsymbol{h}_m(t) s_m(t) + \boldsymbol{n}_m(t), \qquad m = 1, 2, \cdots, M, \tag{1}$$

$$\boldsymbol{h}_m(t) = [h_{m1}(t), \cdots, h_{mN}(t)]^T, \tag{2}$$

$$\boldsymbol{n}_m(t) = [n_{m1}(t), \cdots, n_{mN}(t)]^T , \tag{3}$$

where $\boldsymbol{h}_m(t)$ denotes the propagation channel vector, $s_m(t)$ is the transmitted signal by the m-th antenna, $\boldsymbol{n}_m(t)$ is the additive white Gaussian noise vector having zero-mean and power of $\sigma^2$. Also, $^T$ denotes the transpose.

The proposed method described in the next section uses the signal subspaces (signal eigenvectors). Each signal eigenvector can be derived by the dominant eigenvalue of the correlation matrix $\boldsymbol{R}^{(m)}$

$$\boldsymbol{R}^{(m)} = \mathrm{E}[\boldsymbol{r}_m(t)\boldsymbol{r}_m(t)^H] = \sum_{n=1}^{N} \lambda_n^{(m)} \boldsymbol{e}_n^{(m)} \boldsymbol{e}_n^{(m)H} , \qquad m = 1, 2, \cdots, M, \tag{4}$$

where $\mathrm{E}[\cdot]$ denotes the ensemble averaging, $\lambda_n^{(m)}$ is the $n$-th eigenvalue for the $m$-th transmitter/transmitting channel, $\boldsymbol{e}_n^{(m)}$ is the eigenvector corresponding to $\lambda_n^{(m)}$, and $^H$ is the complex conjugate transpose. Since propagation environment in event detection is almost static in each snapshot-observation, only one dominant eigenvalue, $\lambda_1^{(m)}$, appears in each transmitting channel. For the $M$ transmitters, we have $M$ signal eigenvalues, $\boldsymbol{e}_1^{(1)}$, $\boldsymbol{e}_2^{(1)}, \cdots$, $\boldsymbol{e}_1^{(M)}$. If we preserve the signal eigenvectors without events before operation, we can detect the events by using subspace change among the eigenvectors.

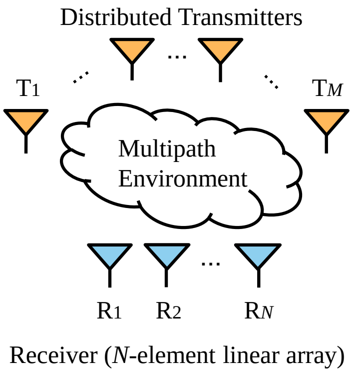


Figure 1: System model

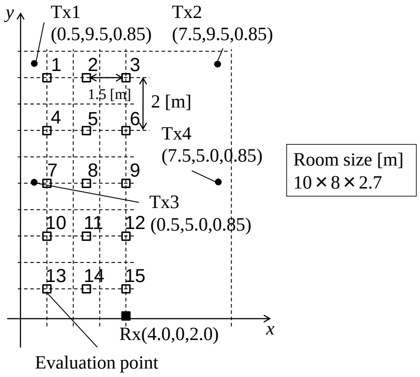


Figure 2: Evaluation model

# 3. Intrusion/Event detection methods

## 3.1 Proposed method

The proposed intrusion/event detection method called the S-MIMO employs the multi-channel signal subspace eigenvectors. The eigenvectors without events is collected before detection, and we detect the event by using variation of the eigenvectors. We define the signal subspaces without and with the event as follows

$$\boldsymbol{V}_{no} = [\boldsymbol{e}_{no,1}^{(1)}, \boldsymbol{e}_{no,1}^{(2)}, \cdots, \boldsymbol{e}_{no,1}^{(M)}], \tag{5}$$

$$\boldsymbol{V}_{ob} = [\alpha_1 \boldsymbol{e}_{ob,1}^{(1)}, \alpha_2 \boldsymbol{e}_{ob,1}^{(2)}, \cdots, \alpha_M \boldsymbol{e}_{ob,1}^{(M)}], \tag{6}$$

where $\alpha_m$ is the weight to be estimated by

$$\alpha_m = \exp(-j \arg(\boldsymbol{e}_{no,1}^{(m)H} \boldsymbol{e}_{ob,1}^{(m)})), \qquad m = 1, 2, \cdots, M, \tag{7}$$

This weight is necessary to remove the relative phase ambiguity of the observed signal eigenvector to the reference eigenvector without the event.

The variation of the signal subspaces can be evaluated by the correlation function given by

$$\rho_V(t) = \frac{\left|\sum_{n=1}^{N}\sum_{m=1}^{M} v_{no,nm}^{*} v_{ob,nm}(t)\right|}{\sqrt{\sum_{n=1}^{N}\sum_{m=1}^{M}\left|v_{no,nm}\right|^2}\sqrt{\sum_{n=1}^{N}\sum_{m=1}^{M}\left|v_{ob,nm}(t)\right|^2}}, \tag{8}$$

where, $v_{no,nm}$ and $v_{ob,nm}$ are $(m,n)$-th component of $\boldsymbol{V}_{no}$ and $\boldsymbol{V}_{ob}$ respectively. In this report, we also evaluate performance of the conventional method, the conventional MIMO, based on variation of channel matrix [2]. Detection criterion has the same form as shown in (8). In the conventional method, we just use the estimated channel in (2), given by $\boldsymbol{h}_{no,m}$, $\boldsymbol{h}_{ob,m}$ without and with the event, respectively, and evaluate (8) by using these elements instead of $v_{no,nm}$ and $v_{ob,nm}$. Note that the conventional method requires training symbols to estimate the channel vectors while the proposed method works without the symbols.

## 4. Simulation

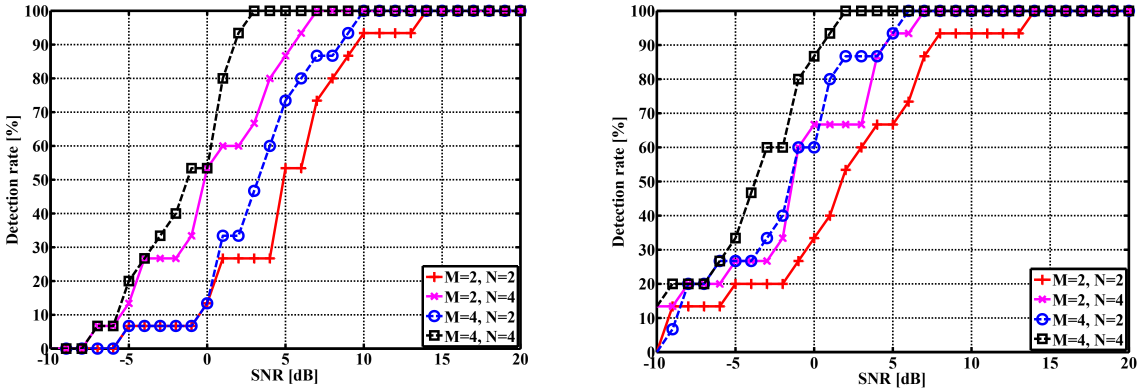
In this section, we show computer simulation results of the proposed method, the S-MIMO and the channel matrix method, the conventional MIMO, to evaluate the detection performance. We consider the simple indoor environment shown in Fig.2. The propagation channels/eigenvectors without and with the intrusion are calculated by using the ray tracing method. The 15 positions of the intrusion shown in Fig.2 are evaluated. Simulation conditions are listed in Table 1. Since the number of snapshots is limited in the actual measurements, the estimated $\rho_V$ also distributes statistically. Therefore a suitable threshold is often required to detect the intrusion for the given SNR and snapshots. This is also the critical and difficult problem for performance evaluation. To avoid this difficulty, we use the detection criteria as $\sigma$ distribution of $\rho_V$ estimated without and with the intrusion by 2000 trials. In this report, we adopt the assumption that the intrusion can be clearly detected when the $\sigma$ areas of $\rho_V$ without and with the intrusion are not overlapped.

Figure 3 (a) and (b) show detection rate of the proposed and the channel matrix method, respectively. The transmitter Tx1 and Tx2 are employed for the 2 transmissions ($M$ = 2) in each analysis. Element separation of receivers (Rx) is 0.5$\lambda$. As can be seen in these figures, the 4×4 system attains high detection ratio at lower SNR in comparison with that of the 2×2 system. The channel matrix method, or the conventional MIMO, attains better detection ratio than that of the proposed method, the S-MIMO, especially in relativity low SNR. This is because the conventional MIMO uses the known training symbols to estimate the channels. This performance difference becomes large when $M > N$, or 4×2 system in this simulation. However, the required SNR to attain high-detection rate will be the most important property for realizing reliable security sensors.

Table 2 shows the required SNRs for the both methods. The detection rate is estimated with only 2000 trials. Hence the estimated SNR will be biased in a few dBs. However, these results show that the required SNR of the S-MIMO for these high detection rates is almost the same as that of the conventional MIMO. Therefore, we can conclude that the channel estimation with training symbols, like the conventional MIMO, is not necessary for the security applications.

Table 1: Simulation parameter

| | | | |
|---|---|---|---|
| Receiving array form | ULA | Number of maximum reflection | 5 |
| Number of array elements | 2, 4 | Number of reference point | 15 |
| Frequency [GHz] | 2.4 | Room depth , width, Height [m] | 10×8×2.7 |
| SNR [dB] | -10~20 | Intruder depth, width, Height [m] | 0.3×0.3×1.7 |
| Number of snapshots | 50 | Conductivity of wall [S/m] | 0.0814 |
| Number of trial | 2000 | Conductivity of intruder [S/m] | 0.514 |
| Element separation | 0.5$\lambda$ | Relative permittivity of wall | 6.25 |
| | | Relative permittivity of intruder | 42.1 |



(a) Proposed method (S-MIMO) (b) Channel matrix method (Conventional MIMO)

Figure 3: SNR vs Detection rate

Table 2: Required SNRs to attain given detection rate

(a) Proposed method (S-MIMO)

| System | Detection Rate | | | |
|---|---|---|---|---|
| | 70 % | 80 % | 90 % | 100 % |
| 2×2 | 7 dB | 8 dB | 10 dB | 14 dB |
| 2×4 | 4 dB | 5 dB | 6 dB | 7 dB |
| 4×2 | 5 dB | 6 dB | 9 dB | 10 dB |
| 4×4 | 1 dB | 1 dB | 2 dB | 3 dB |

(b) Channel matrix method (Conventional MIMO)

| System | Detection Rate | | | |
|---|---|---|---|---|
| | 70 % | 80 % | 90 % | 100 % |
| 2×2 | 6 dB | 7 dB | 8 dB | 14 dB |
| 2×4 | 4 dB | 4 dB | 5 dB | 7 dB |
| 4×2 | 1 dB | 1 dB | 5 dB | 6 dB |
| 4×4 | -1 dB | -1 dB | 1 dB | 2 dB |

## 5. Conclusion

In this report, we proposed a simple indoor intrusion detection method without channel estimation by training symbols called the S-MIMO, and evaluate detection performance of the method by computer simulation results using ray tracing method. These results show that the S-MIMO has almost the same detection performance when the number of elements in receiving array is equal to or greater than that of the transmitters in comparison with the conventional MIMO. The S-MIMO does not require training symbols for the channel estimation. This feature enables us to realize simpler control and management of the system.

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