Hybrid Beamformer for TPMS Interference Suppression

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***Abstract*—The Tire Pressure Monitoring System (TPMS) is a type of the wireless communication device for vehicles, defined as a safety assist system for enabling drivers to efficiently check and manage tires. In the TPMS communications, external electric and electronic devices may interfere with the exact data transmission. In this paper, we propose a hybrid TPMS beamformer based on a switching beamformer and minimum-variance distortionless–response (MVDR) beamformer for selecting an efficient algorithm depending on circumstances in order to eliminate the interference and to transfer the accurate data to drivers. We also suggest an effective signal decision algorithm based on the signal-to-interference and noise ratio (SINR) in order to ensure the transferred data reliability. The performance of the suggested hybrid TPMS beamformer and the effective signal decision algorithm is identified through a computer simulation example.**

Keywords-Tire Pressure Monitoring System (TPMS); Hybrid Beamformer; Switching Beamformer; Minimum-Variance Distortionless-Response (MVDR); Interference Suppression.

I. INTRODUCTION

The Tire Pressure Monitoring System (TPMS) is a safety assist device for measuring tire temperature and pressure by means of a sensor in each tire of a vehicle, transmitting the measured data to the signal processing unit of the vehicle, and displaying them in the display unit to inform the driver about the tire state information in real time [1]. The TPMS employs various carrier frequencies such as 433.92 MHz in U.S.A and Europe, and 433.92 MHz and 447 MHz in Korea.

Most of TPMSs currently employ the one-way wireless communication technique with low data transmission efficiency and decision reliability. In order to overcome this problem, we suggest a method for deciding the TPMS data reliability of high performance based on the bidirectional communications. An advantage of the bidirectional communications is that it may save the power of the battery in the sensor unit installed in each tire, because it transmits the data when only it is required. Also, since it contains Ack/Nack data which indicates the effectiveness of the transmitted data and E/N data which indicates the condition of a tire, it may efficiently improve the data reliability. Decision of data efficiency by the suggested algorithm is based on the measured signal-to-interference and noise ratio (SINR).

The TPMS employing various frequencies across the globe may experience the serious interference by high-power signals from external electric and electronic devices utilizing the similar frequencies. Researchers have studied switching beamformers [2] and minimum-variance distortionless-response (MVDR) beamformers [3] in order to eliminate the aforementioned interference. Although the switching beamformer has low computational complexity, it has low interference elimination performance. Although the MVDR beamformer has high interference elimination performance, it has extremely high computational complexity due to the calculation of an auto-correlation matrix. In this paper, we propose a hybrid beamformer, which selects one out of the switching beamformer and the MVDR beamformer according to circumstances. Decision of selecting one out of two beamformers is based on the measured SINR. We consider a structure which has a layout of M receiving antennas in a line in the center of a relevant vehicle to use the beamformer for the TPMS. In order to eliminate the interference from other tires and reduce the power consumption of the battery in a sensor unit installed in each tire, we employ the Gold code to each tire.

The rest of this paper is organized as follows. In Section II, we define the received signal model for TPMS and the interference signals in additive white Gaussian noise (AWGN). In Section III, we describe effective signal decision algorithms in signal processing unit and sensor unit, including flow-charts. The hybrid beamformer based on the switching and MVDR beamformer is proposed to effectively suppress interference signals from external devices in Section IV. Computer simulations are provided in Section V to demonstrate the performance of the proposed technique. Finally, conclusions and the future work are outlined in Section VI.

II. RECEIVED SIGNAL MODEL

Fig. 1 shows an example of the structure with a layout of M receiving antennas in the center of a vehicle at given intervals in a line and one transmitting antenna in each tire, for using the hybrid TPMS beamformer. The black devices seen at the car hood and the door in Fig.1 are examples of the external electric or electronic interference sources. At the sample index k, the received signal is given by

$$\mathbf{z}(k) = \sum_{i=1}^{4} \mathbf{a}_i g_i(k) b_i(k) + \mathbf{A}\mathbf{j}(k) + \mathbf{n}(k) \qquad (1)$$

where $\mathbf{a}_i$ is an array response vector (size $M \times 1$) for the i th tire based on the uniform linear array (ULA), $g_i(k)$ is a cyclostationary Gold code (size N) for the i th tire, and $b_i(k)$ is a measured data bit for the i th tire, which remains

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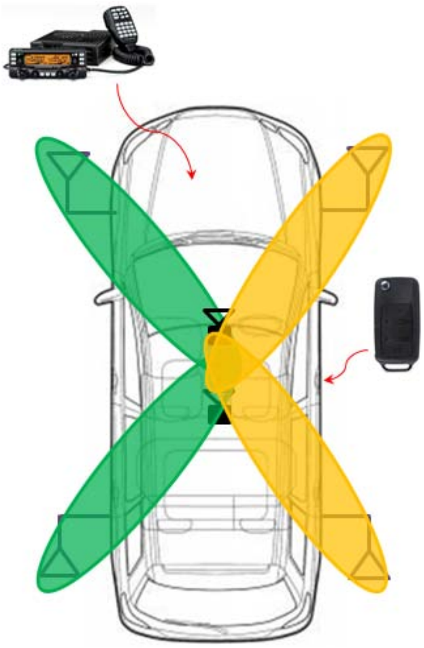

Figure 1. Antenna arrangement inside the vehicle for Hybrid TPMS beamformer

constant over the length of one cycle of the Gold code. The upper limit of the summation in (1) is four, because we assume that the number of tires is four. $\mathbf{A}$ is a $M \times P$ array response matrix, P is the number of interference signals, and $\mathbf{j}(k)$ is an interference signal vector (size P). Also, $\mathbf{n}(k)$ is an AWGN vector composed of independent and identically distributed components, each with zero mean and variance σ^2. The angle-of-arrival (AOA) array response vector uses the equation described in [4,5]. Although we generally assume that the interelement spacing is a half of the wavelength, we are currently investigating the effect for reducing interelement spacing to a quarter or one-eighth of the wavelength. In order to save the length of entire space for the antenna elements, we are studying to employ the rectangular or the circular antenna array structure in the center of a vehicle.

An equation of the received signal SINR [6] for deciding effective signals is given by

$$SINR = 10\log_{10}\left(\frac{S.Power}{N.Power + I.Power}\right) \quad (2)$$

where $S.Power$ (Signal Power) is the signal power transmitted from each tire, $N.Power$ is the noise power, and $I.Power$ is the interference power. The received signal SINR is measured using preamble data, which a receiver knows beforehand.

III. EFFECTIVE SIGNAL DECISION ALGORITHM

In this section, we propose a TPMS effective signal decision algorithm based on the duplex TPMS data architecture [2].

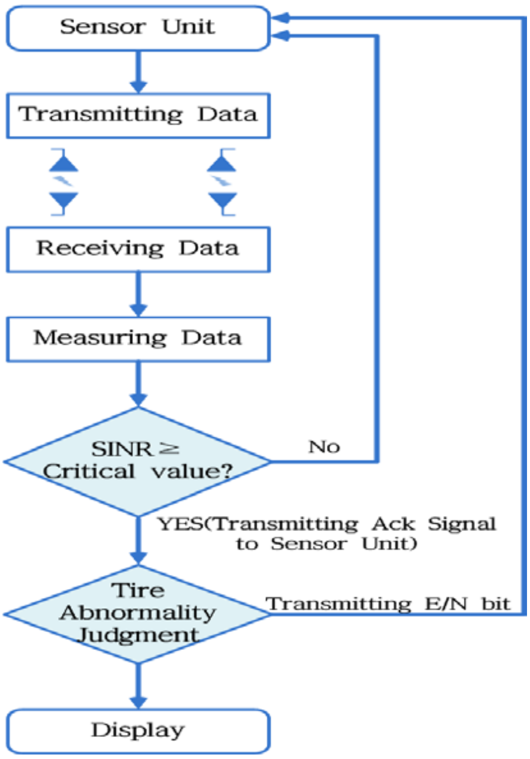

Figure 2. Flow-chart for determining the effective signal, based on the duplex TPMS wireless communication system (signal processing unit)

A. Effective Signal Decision Algorithm in Signal Processing Unit

A flow chart for the effective signal decision in the signal processing unit installed in a vehicle is shown in Fig. 2. The signal processing unit measures SINR of the received signal, compares the measured SINR with a threshold. If the measured SINR is greater than the critical value, it sends the Ack signal, which means that the transmitted signal is effective, to the sensor unit to request transmitting the main data. On the contrary, if the measured SINR is smaller than the critical value, it does not send any signal and the sensor unit recognizes Nack which means that the transmitted signal is not effective. In this case, the sensor unit requests retransmitting the reference data. After receiving the main data, the signal processing unit decides the normal or abnormal state of a tire using the main data. If the tire is decided normal, the signal processing unit transmits N bit (for example, bit 1) which indicates the normal mode, and operates in the normal mode which indicates the normal tire state (for example, receiving data once per minute). On the contrary, if the tire is decided abnormal, the signal processing unit transmits E signal (for example, bit -1) which indicates an emergency mode, and operates in the emergency mode which indicates a dangerous tire state (for example, receiving data once per second). The data processed in the signal processing unit is sent to the display unit to enable a driver to check the tire condition.

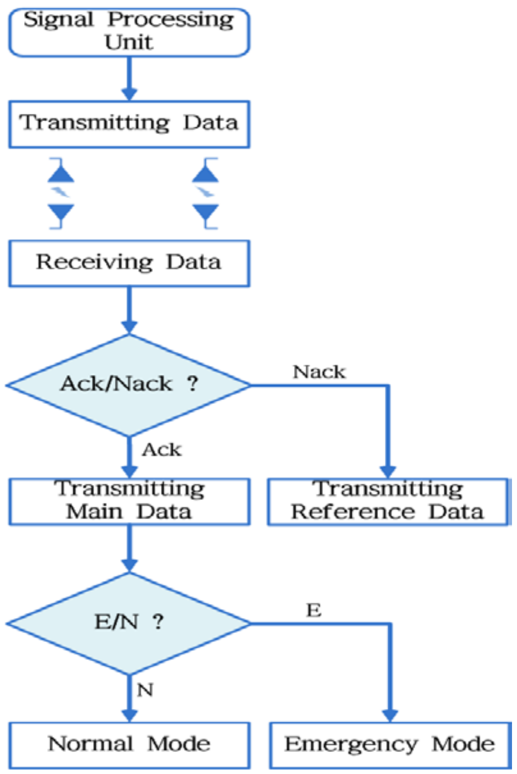

Figure 3. Flow-chart for determining the effective signal, based on the duplex TPMS wireless communication system (sensor unit)

B. *Effective Signal Decision Algorithm in Sensor Unit*

Fig. 3 shows a flow chart for the suggested effective signal decision method based on a duplex TPMS communication system in the sensor unit. The sensor unit receives Ack/Nack and E/N bits from the signal processing unit. If the sensor receives the Ack bit (for example, bit 1), it transmits main data to the signal processing unit. On the contrary, if the sensor unit receives Nack bit (for example, no bit), it retransmits reference data (preamble data) to the signal processing unit. If the signal transmitted from the main data is decided N bit (for example, bit 1), the sensor unit operates in the normal mode (for example, transmitting data once per minute). If it is decided E bit (for example, bit -1), the sensor unit operates in the emergency mode (for example, transmits data once per second).

IV. HYBRID BEAMFORMER

In order to efficiently suppress interference signals from external devices and receive the accurate data from the sensor unit, we propose a hybrid beamformer, which selectively uses the switching beamformer and MVDR beamformer after comparing the measured SINR and the given threshold. The switching beamfomer has obviously low computational complexity comparing with the MVDR beamformer, because it does not require an auto-correlation matrix but the MVDR beamfore requires that. Hybrid beamformer forms beam in a

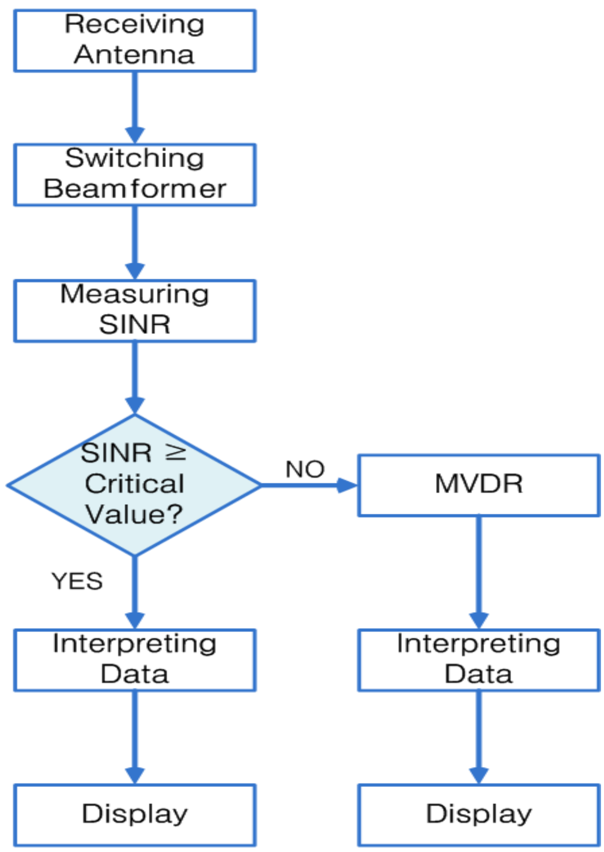

Figure 4. Flow chart of the hybrid TPMS beamformer

desired direction to receive TPMS data. The received signal includes TPMS signals of each tire, interference from external devices, and noise. The hybrid beamformer basically uses the switching beamformer to weaken interference signals. If the output SINR of the switching beamformer is greater than the threshold, the output signal of the switching beamformer is analyzed to display the data in the display unit and thus to inform a driver about the tire condition. However, if the measured SINR is smaller than the threshold, the hybrid beamformer changes the mode from the switching beamformer to the MVDR beamformer as shown in Fig. 4.

Since the switching beamformer has very low computational complexity and has the relatively good performance of interference suppression, it is used as a basic beamformer of the hybrid beamformer. That is, if the measured SINR is greater than a specific threshold, the hybrid beamformer operates in the switching beamformer mode. However, if the SINR of the switching beamformer output is smaller than the threshold, it results the low ratio of the accurate data reception due to the interference signals. In this case, we employ the MVDR beamformer, which forms beam in the desired direction and nulls in the directions of the interference signals to minimize them, at the same time [7]. The MVDR beamformer has excellent performance of interference elimination, but it needs calculation of an auto-correlation matrix resulted in very high computational complexity. The proposed hybrid beamformer optimizes interference elimination performance and computational

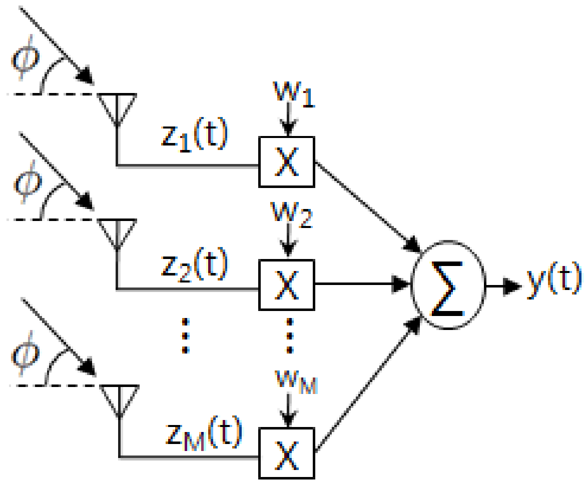

Figure 5. Conventional beamformer structure

complexity efficiency with two beamformers, which have obvious advantages and disadvantages.

A. Switching beamformer

The switching beamformer is defined as to alternately use more than one weight vectors based on the AOA vector to form beams to directions of interest. The switching beamformer weight vector for i th tire signal with a beamformer architecture shown in Fig. 5 is given by

$$\mathbf{w}_{s_i} = \frac{\mathbf{a}_i}{\sqrt{\mathbf{a}_i^H \mathbf{a}_i}} \tag{3}$$

where ^{H} denotes complex conjugate transpose. The aforementioned weight vector generates a beam factor of size one for the i th tire to receive TPMS signal.

B. MVDR Beamformer

The MVDR beamformer calculates a weight vector for minimizing the power of the beamformer output while maintaining the power of the desired signal. The MVDR weight vector is computed from

$$\min \mathbf{w}^H \mathbf{R} \mathbf{w} \text{ subject to } \mathbf{a}_i^H \mathbf{w} = 1 \tag{4}$$

where $\mathbf{R} = E[\mathbf{z}(k)\mathbf{z}^H(k)]$ is an auto-correlation matrix of the received signal [8]. The MVDR weight vector [9,10] for the i th tire is given by

$$\mathbf{w}_{MVDR} = \left[\mathbf{a}_i^H \mathbf{R}^{-1} \mathbf{a}_i\right]^{-1} \mathbf{R}^{-1} \mathbf{a}_i. \tag{5}$$

It forms a beam with the factor of size '1' to the direction of the i th tire signals and nulls interference signals to minimize them, at the same time. The hybrid beamformer output for the i th tire is given by

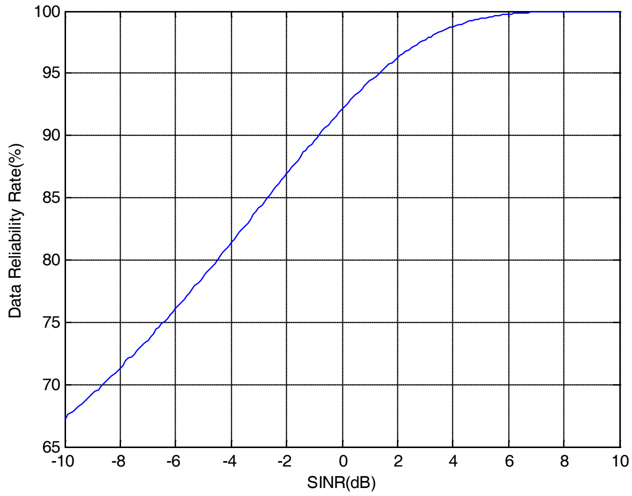

Figure 6. Data reliability rate via SINR

$$y_i(k) = \mathbf{w}_i^H \mathbf{z}(k). \tag{6}$$

This output contains the TPMS signal of the i th tire, noise, and residual interference signal. $\mathbf{w}_i$ selectively uses the weight vector of the switching beamformer or MVDR depending on circumstances. The output of the hybrid beamformer is despreaded using the unique Gold code for the i th tire.

V. COMPUTER SIMULATION

Computer simulation result is described below to identify the performance of SINR threshold decision for an effective data decision method and the hybrid beamforming technology. We use a million received signal data for determining the SINR threshold for the suggested effective data decision method and set the number of antennas as one. Fig. 6 shows data reliability from –10 dB to 10 dB with respect to SINR. From the figure, we observe that increasing SINR results in rising data reliability. This result is utilized to determine the threshold for the proposed hybrid beamformer.

Six receiving antennas are used to identify the performance of the suggested hybrid TPMS interference suppression. It is based on the assumption that the received signal included three interference signals and noise, and a Gold code of $N = 15$ is given to the TPMS signal of each tire. The incident angles of transmitted signals for each tire are assumed 60°, 120°, 240°, and 300°, respectively. The incident angles for 3 interference signals are randomly assumed 89°, 175°, and 340°, respectively. It is identified that the output SINR threshold value, which is a reference of data reliability 99% is about 4.4 dB from Fig. 6. This value is assumed as a threshold in the simulation for evaluating hybrid beamformer performance.

Fig. 7(a) and 7(b) show beampatterns for the switching beamformer which forms beams to direction of incidents angles 60° and 300° with respect to the right-front and right–rear tire TMPS signals and which forms beams to direction of incident angles 120° and 240° with respect to the left-front and left–rear tire TMPS signals, respectively. Fig. 8(a) and 8(b)

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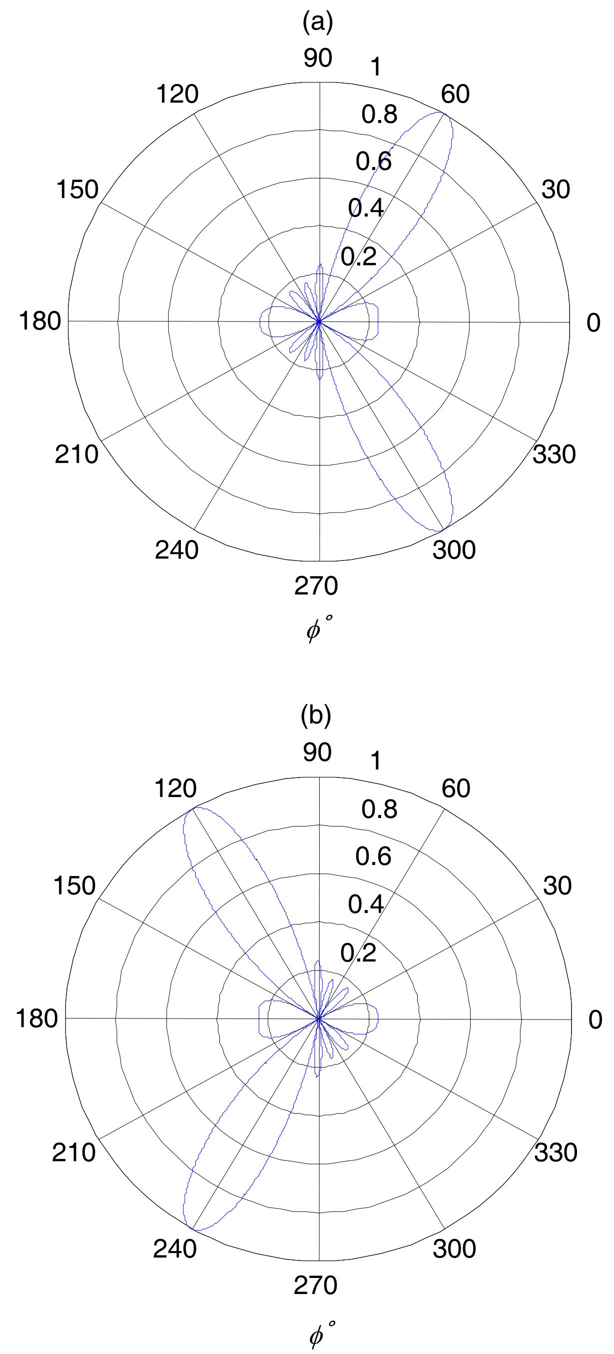

Figure 7. Beam pattern for switching beamformer with six antennas (a) Beam pattern for right tire TPMS signals with 60° and 300° incidence angles, (b) Beam pattern for left tire TPMS signals with 120° and 240° incidence angles

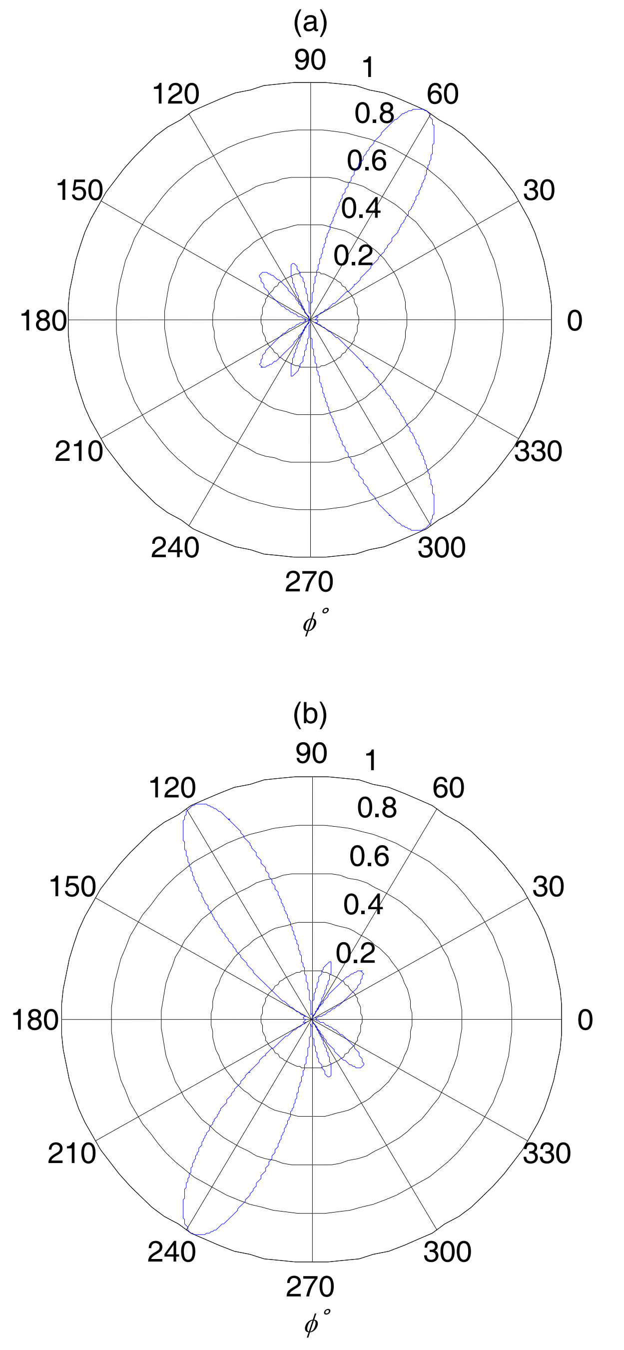

Figure 8. Beam pattern for MVDR beamformer with six antennas (a) Beam pattern for right tire TPMS signals with 60° and 300° incidence angles, (b) Beam pattern for left tire TPMS signals with 120° and 240° incidence angles

show beampatterns for the MVDR beamfomer which forms beams for right and left tire TPMS signals, respectively. Note that the MVDR beamformer forms nulls to incident angles of interference signals, unlike the switching beamfomer. Since the array response vector includes the cosine function, the proposed hybrid beamformer alternately uses two weight vectors (not four weight vectors) for the front tire in the right side and the front tire in the left side to receive the data from all four tires [2].

Fig. 9 shows output SINR curve per signal-to-noise ratio (SNR) for interference-to-signal ratio (ISR) = 3 dB, for 99% data reliability (4.4dB SINR). From the figure, we observe that the switching beamformer is used when the SNR is greater than -4 dB because the output SINR is greater than the threshold. In

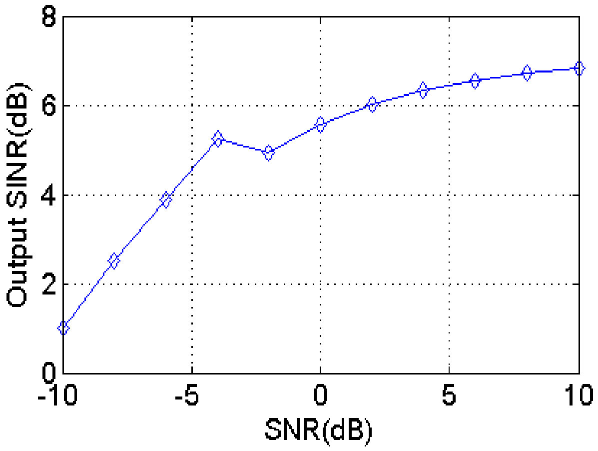

Figure 9. Output SINR per ISR for ISR = 3 dB

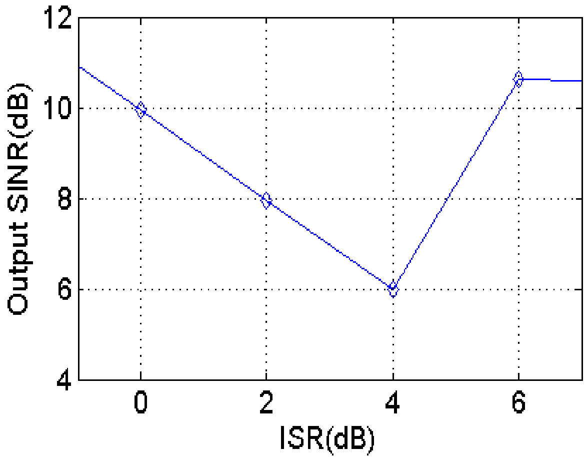

Figure 10. Output SINR per ISR for SNR = 0 dB

the section SNR = -4 dB or lower, the SINR is smaller than the threshold and the switching beamformer mode is converted to the MVDR beamformer mode. Fig. 10 shows the output SINR curve per ISR for SNR = 0 dB, for 99% data reliability (4.4dB SINR). It has a section where SINR decreases and then increases at ISR = 4 dB, which shows the result that the hybrid beamformer operates in the switching beamformer mode and then is converted to the MVDR beamformer mode where SINR is below the threshold.

VI. CONCLUSION AND FUTURE WORK

Enactment for compulsory use of TPMS to inform a driver about the tire condition in real time is globally underway in order to prevent serious traffic accidents due to abnormal tires. Since the TPMS employs wireless communication technique, it is essential to ensure the data reliability. For the high TPMS data reliability, we considered the duplex wireless communication technique, which is more developed than the one-way wireless communication method used in the conventional TPMS, and suggested a data reliability decision method according to the threshold based on SINR of received signals. We also proposed a hybrid TPMS beamformer based on the switching beamformer and MVDR beamformer in order to effectively eliminate interference caused from external devices. An optimum algorithm between two beamformers is selected based on the measured SINR according to circumstances for exact data transmission. The unique Gold code is employed to each tire in order to eliminate interference signals from other tires and to reduce the power consumption of a battery in the sensor unit of TPMS. The performance of the proposed hybrid TPMS beamformer was illustrated via the computer simulation example. In the future work, we will consider the effects of the car body and the ground, and the coupling between antennas for TPMS.

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