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Joint Hardware-Software Implementation of Adaptive Array Antenna for ISDB-T Reception

Dang Hai PHAM[†a)], **Takanobu TABATA**[††], **Hirokazu ASATO**[†††], ***Nonmembers***,
Satoshi HORI[††], ***and*** **Tomohisa WADA**[†,†††], ***Members***

SUMMARY In this paper, an adaptive array antenna is implemented to enhance the performance of digital TV ISDB-T reception. Issues of realizing the proposed array antenna and its implementation by a joint hardware-software solution are also presented in this paper. Instead of using known reference signals, the proposed method utilizes the GI (Guard Interval) and a periodic property of OFDM signal as a constraint to realize MRC (Maximum Ratio Combining) and SMI (Sample Matrix Inversion) adaptive beam-forming algorithms. Experimental results show that the proposed system drastically improves the quality of reception. Moreover, the proposed system can achieve excellent performance under the conditions of strong interferences.

key words: *array antenna, OFDM, ISDB-T, MRC, SMI, FPGA, DSP*

1. Introduction

Terrestrial digital TV broadcasting in Japan (ISDB-T) was launched in three major metropolitan areas in 2003, and nationwide broadcasts will start in 2006. In ISDB-T standard, Orthogonal Frequency Division Multiplexing (OFDM), also referred as a multi-carrier modulation scheme, is adopted as a modulation method. OFDM is well-known as a high-spectral efficiency transmission method. Many subcarriers that are mutually orthogonal in frequency are modulated, thanks to FFT. Additionally, OFDM uses GI to effectively combat with ISI (Inter-Symbol Interference). Hence, the performance of OFDM is superior to that of a single-carrier modulation in the multipath environment [1], [2].

In real applications, however, there are some difficulties with both fixed and mobile reception. For example, since a high-gain antenna is set at a high position in most fixed reception, delayed waves with long spreading from remote transmitting stations are also received in SFN scenario (Single Frequency Network). Consequently, delayed waves exceeding GI duration cause a severe degradation of the quality of reception. As the scenario of mobile reception in which a typical omnidirectional antenna is deployed in vehicles or personal communication systems, one might experience non-LOS (Line-Of-Sight) and multiple delayed waves. Even with delayed waves within GI duration, the quality of reception also deteriorates if the value of DUR (desired-to-undesired ratio) decreases.

Recently, an adaptive array antenna is paid attention to as an attractive solution to suppress interferences and to enhance the quality of reception in the multipath environment [3], [4]. It usually requires in advance the knowledge of the characteristics of the desired signals to distinguish between them and undesired signals, i.e. AOAs (Angle of Arrival) of desired signals and undesired signals are required in order to form beams toward intended directions and nulls toward undesired directions [5]–[7]. However, due to their high complexity, these approaches cost lots of computations and efforts from a viewpoint of hardware implementation.

Another approach to realize the array antenna is a class of time-domain adaptive DBF (Digital Beam-Forming) algorithms. Using this approach, beam of the array antenna is mainly formed prior to FFT and OFDM demodulation. Hence, this method not only improves the quality of reception efficiently but also requires a low complexity of computation. In [8] and our previous work [9], MRC as DBF algorithm for OFDM receiver has been applied. Since the conventional MRC combines incoming signals in proportion to their amplitudes, under the circumstance that the power of interferences is stronger than that of the desired signals, it might form beam toward the strongest interference instead of the desired signals. In [10], MMSE adaptive array antenna for OFDM system was proposed. This method utilizes GI to form nulls toward undesired directions. Based on [10], we propose a joint hardware-software platform to implement adaptive array antenna for ISDB-T reception. Proposed MRC and SMI as DBF algorithms of the array antenna are derived without the necessity of reference signals. The remainder of this paper is organized as follows. In Sect. 2, the proposed DBF algorithms for the array antenna system are introduced including MRC and SMI. In Sect. 3, issues related to designing the array antenna are discussed. An implementation and experimental results of our prototype are also presented in Sect. 4. Finally, conclusions are given in Sect. 5.

2. Time-Domain Digital Beam-Forming Algorithms

In this paper, DBF algorithms that use the periodic property of OFDM signal are proposed. Figure 1(a) and (b) illustrate the periodic property of OFDM signal and the principle of

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[†]The authors are with the Faculty of Engineering, Dept. of Information Engineering, Univ. of the Ryukyus, Okinawa-ken, 903-0213 Japan.
[††]The authors are with Kojima Press Industry Co., Ltd., Aichi-ken, 470-0207 Japan.
[†††]The authors are with Magna Design Net Inc., Okinawa-ken, 901-0152 Japan.
a) E-mail: phdang@lsi.ie.u-ryukyu.ac.jp

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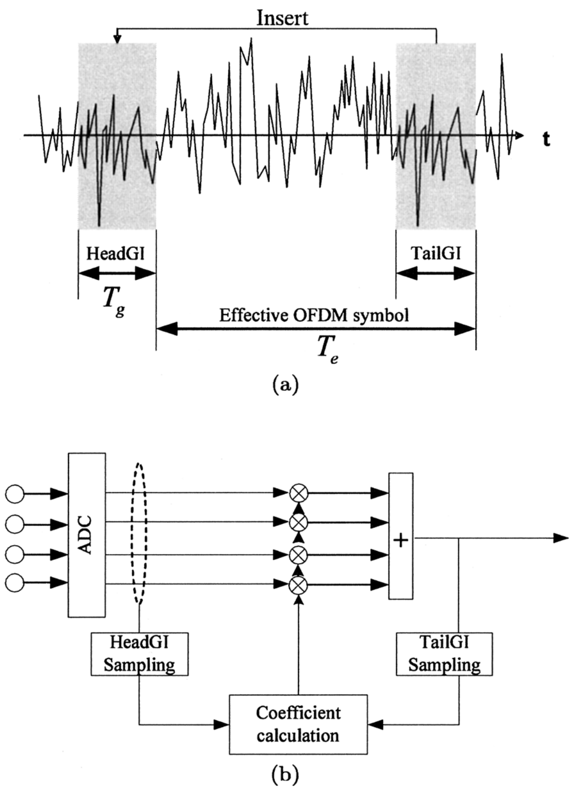


Fig. 1 (a) The periodic property of OFDM signal and (b) principal array antenna utilizing GI.

time-domain adaptive array antenna system. OFDM signal consists of GI with duration of T_g and an effective symbol with duration of T_e. GI is copied the same waveform from the last part of the effective symbol and is inserted ahead.

For convenience, in this paper, GI is referred to as "*HeadGI*". The last part of the effective OFDM symbol with duration of T_g is referred to as "*TailGI*".

In radio environment, OFDM signals are usually destructed by incoherent interferences. Also, the delayed waves of OFDM signal might be considered as co-channel interferences. For simplicity, we assume that only incoherent interference impinges on the array antenna, i.e. OFDM signals experience the flat fading condition.

Suppose that a linear array antenna is equipped with M element antenna. Thus the inputs of the array antenna are expressed as

$$\begin{aligned} \mathbf{X}(t) &= [x_1(t) \quad x_2(t) \ldots x_M(t)]^T \\ &= \mathbf{V}_s s(t) + \mathbf{V}_i i(t) + \mathbf{N}(t) \end{aligned} \tag{1}$$

where superscript $[.]^T$ denotes a transpose of matrix.
$s(t)$ and $i(t)$ are desired signal and incoherent interference, respectively.
$\mathbf{V}_s$ and $\mathbf{V}_i$ are the array response vectors of desired signal and incoherent interference, respectively. $\mathbf{N}(t)$ is AWGN vector of array antenna.

Hence, the output of the array antenna system is calculated as follow

$$\begin{aligned} y(t) &= \mathbf{W}^H\mathbf{X}(t) \\ &= \mathbf{W}^H\mathbf{V}_s s(t) + \mathbf{W}^H\mathbf{V}_i i(t) + \mathbf{W}^H\mathbf{N}(t) \\ &= a_s s(t) + a_i i(t) + n(t) \end{aligned} \tag{2}$$

where superscript $(.)^H$ denotes Hermitian.
$\mathbf{W} = [w_1 \; w_2 \; ... \; w_M]^T$ is coefficient vector of the array antenna.
$a_s = \mathbf{W}^H\mathbf{V}_s$ and $a_i = \mathbf{W}^H\mathbf{V}_i$ are constants during one OFDM symbol.

In [8], [9], the conventional MRC is derived directly from the cross-correlation of inputs and output of the array antenna as follow

$$\begin{aligned} \mathbf{W}_{convMRC} &= E\left[\mathbf{X}(t)y^*(t)\right] \\ &= E\left[(\mathbf{V}_s s(t) + \mathbf{V}_i i(t) + \mathbf{N}(t))\right. \\ &\qquad \left.(a_s s(t) + a_i i(t) + n(t))^*\right] \\ &= a_s^* P_s \mathbf{V}_s + a_i^* P_i \mathbf{V}_i \end{aligned} \tag{3}$$

where $P_s = E\left[|s(t)|^2\right]$ and $P_i = E\left[|i(t)|^2\right]$.

Apparently, from Eq. (3), the array antenna utilizing the conventional MRC combines not only the desired signal but also the interference. Under the circumstance that the power of interference is stronger than that of the desired signal, the interference will be emphasized at the output of the array antenna.
To overcome the limitation of the conventional method described above, by utilizing HeadGI of input and feedback of TailGI of output, the cross correlation of input and output is derived as

$$\begin{aligned} \mathbf{r}_{xy} &= E\left[\mathbf{X}_h(t)y_t^*(t)\right] \\ &= E\left[(\mathbf{V}_s s_h(t) + \mathbf{V}_i i_h(t) + \mathbf{N}_h(t))\right. \\ &\qquad \left.(a_s s_t(t) + a_i i_t(t) + n_t(t))^*\right] \\ &= a_s^*\mathbf{V}_s E\left[s_h(t)s_t^*(t)\right] + a_i^*\mathbf{V}_i E\left[i_h(t)i_t^*(t)\right] \end{aligned} \tag{4}$$

where subscripts $(.)_h$ and $(.)_t$ denote HeadGI and TailGI of signal, respectively.
Superscript $(.)^*$ denotes complex conjugate.

Since $i(t)$ is incoherent interference, the second term of Eq. (4) can be neglected. Employing the periodic property of OFDM signal, Eq. (4) can be expressed as follow

$$\mathbf{r}_{xy} = a_s^* P_s \mathbf{V}_s \tag{5}$$

It is worth noting that in case that the delayed wave exceeding GI duration impinges on the array antenna, Eq. (5) can be straightforwardly derived, too.

2.1 Maximum Ratio Combining (MRC)

As expressed in Eq. (5), the cross correlation of HeadGI of inputs and TailGI of output obviously presents the information of AOA of desired signal without the prior necessity of the reference signals. Therefore, the coefficient vector of the array antenna using MRC algorithm is derived as

$$\mathbf{W}_{MRC} = normalize\left(\mathbf{r}_{xy}\right) \tag{6}$$

2.2 Sampled Matrix Inversion (SMI)

We assume that a reference signal is $r(t)$. The error signal is given by

$$e(t) = r(t) - \mathbf{W}^H \mathbf{X}(t) \tag{7}$$

MSE (Mean Square Error) between the output of the array antenna and the reference signal is given as follows

$$\text{MSE} = E\left[|e(t)|^2\right] = E\left[|r(t) - \mathbf{W}^H \mathbf{X}(t)|^2\right] \tag{8}$$

Coefficients are adjusted such that MSE (Mean Square Error) between the output of the array antenna and the reference signal is minimized. Optimum coefficients are derived from the well-known *Wiener-Hoff* equation

$$\mathbf{W}_{SMI} = normalize\left(\mathbf{R}_{xx}^{-1}\mathbf{r}_{xy}\right) \tag{9}$$

where $\mathbf{R}_{xx} = E\left[\mathbf{X}_h \mathbf{X}_h^H\right]$ is auto correlation matrix of inputs. In real applications, $\mathbf{R}_{xx}$ is obtained by a simple averaging scheme [10].

3. Joint Hardware-Software Solution of Adaptive Array Antenna

In this section, the solution to implement the array antenna is discussed as it is approached from the viewpoint of hardware design. Figure 2 illustrates a block diagram of the array antenna concatenating with OFDM demodulator. DBF algorithm to generate the coefficients of the array antenna is executed prior to FFT. The output of the array antenna is fed to OFDM demodulation to retrieve the transmitted data.

The main goals of our solution are not only to achieve the improvement in the quality of reception but also to simplify the design task. Hence, it is expected to realize array antenna system of which operation is relatively independent of the operation of OFDM demodulator. This approach also ensures the success of modification and development in future.

To implement the array antenna, several issues arise as follows:

- The issues of realizing DBF algorithms by hardware: due to the nature of wireless transmission, RF (radio frequency) error and sampling rate error are inherently unavoidable. These greatly impact on the performance of the array antenna and are in urgent need to compensate. The compensation of RF error and sampling rate error is discussed thoroughly in Sect. 3.1.
- Joint hardware-software (HW-SW) solution to implement array antenna system: Our target is to provide an easily debugged and flexible platform. We choose joint HW-SW approach to architect the array antenna. Prefixed functions of array antenna, such as signal combining, timing control, memory access control, I/O etc. are provided by HW side. Meanwhile, SW side executes DBF algorithms. The discussion related to joint HW-SW solution is given in Sect. 3.2.

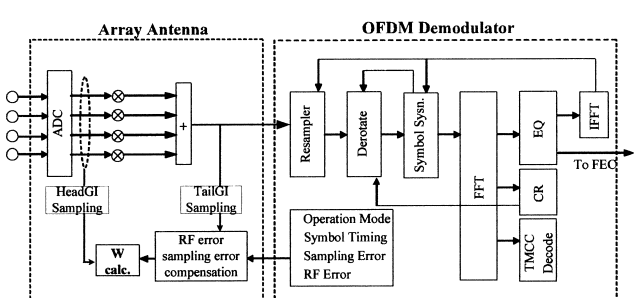


Fig. 2 Block diagram of OFDM reception.

3.1 Issues of Realizing DBF Algorithm by Hardware

In this subsection, the issues related to realizing the adaptive array antenna system will be discussed as follows:

- Compensation of RF error.
- Compensation of sampling rate error.
- The operation mode of ISDB-T and timing control to function the array antenna.

These problems would be considered as general problems to be solved when implementing time-domain DBF algorithm for OFDM reception.

3.1.1 Compensation of RF Error

As mentioned above, RF error between a transmitter and a receiver inherently exists in a wireless communication system. With the present of RF error, Eq. (5) is rewritten as follows

$$\begin{aligned} \mathbf{r}_{xy} &= E\left[\mathbf{X}_h(t) y_t^*(t)\right] \\ &= a_s^* \mathbf{V}_s E\left[s_h(t) s_t^*(t)\right] \\ &= a_s^* P_s \mathbf{V}_s e^{j\phi(t)} \end{aligned} \tag{10}$$

where $\phi(t) = 2\pi T_e \Delta f_{RF}(t)$
$\Delta f_{RF}(t)$ is RF error between transmitter and receiver.

As shown in Eq. (10), the cross correlation of HeadGI and TailGI of OFDM signals is affected by RF error. If RF error exists, time-domain OFDM signal rotates in time, i.e. TailGI, which should match HeadGI, has a phase shift from HeadGI. It causes the rotation of the coefficients of the array antenna. In other words, without compensating RF error, the coefficients of array antenna still vary in time, even though the array antenna experiences the stationary condition. Therefore, RF error must be compensated to enhance the stability of the reception.

RF error estimation, also referred as a "*frequency offset*" estimation in the literature, is thoroughly discussed in [14], [15]. In our design, based on [15], RF error and the starting point of FFT window are jointly estimated at the synchronization block and are fed back to array antenna. The output of the array antenna $y(t)$ is fed into OFDM demodulation. Thus RF error is derived as follow

$$\phi(t) = \arg\{E[y_h(t)y_t^*(t)]\} \tag{11}$$

The value of $e^{j\phi(t)}$ is estimated at OFDM demodulation. By multiplying TailGI of the output with the conjugate of the estimated $e^{j\phi(t)}$, RF error expressed in Eq. (11) will be compensated.

3.1.2 Compensation of Sampling Rate Error

As RF error, the error of sampling rate between a transmitter and a receiver is unavoidable in a wireless communication system. Decimation/interpolation is a digitally timing-adjustment process on the received signal and is covered extensively in the literature [16], [17], and [20]. Moreover, in our system, the sampling rate of received OFDM signals is always slightly higher than that of transmitted signals. The purpose of that is to simplify the time-adjustment process, only interpolation process is necessary to compensate sampling rate error.

Figure 3(a) illustrates an impact of sampling rate error on a sampled TailGI. Due to the drifting of sampling positions of TailGI, the samples of TailGI do not remain precisely. Therefore, it obviously deteriorates the cross correlation between HeadGI of the inputs and TailGI of the output. The block diagram of the compensation of sampling rate error is given in Fig. 3(b). This error is estimated in OFDM demodulation and accumulated on each OFDM symbol to measure the exact duration T_e. TailGI is then fed to a 13-tap polyphase FIR to eliminate the impact of sampling rate error. The coefficients of 13-tap FIR are determined by the value of the effective symbol duration T_e using LUT method (Look-Up Table).

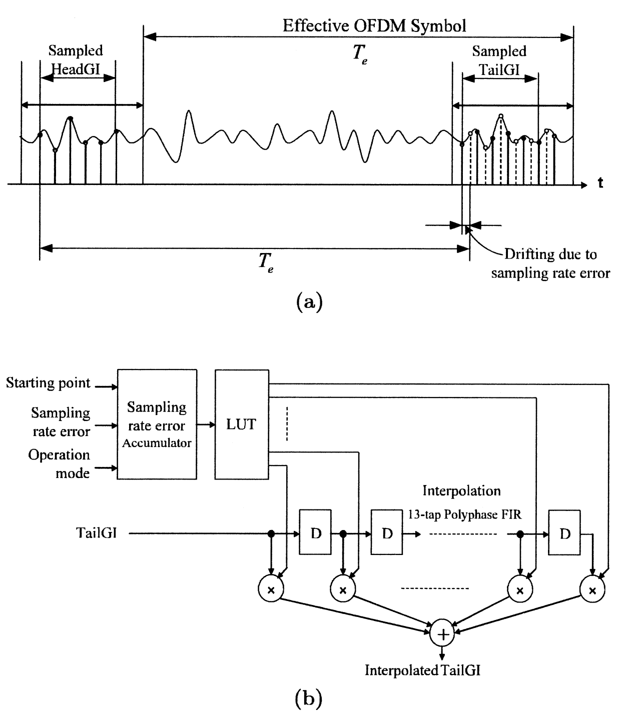


Fig. 3 (a) Impact of sampling rate error and (b) block diagram of the compensation of sampling rate error.

In addition to these issues mentioned in subsections above, the information of the operation mode of ISDB-T and the synchronization of OFDM symbols are also required to function DBF algorithms. In our design, solutions of RF error and sampling rate error have been solved and are built-in functions of OFDM demodulation [18], [19]. The estimated values of RF error and sampling rate error generated from OFDM demodulation are simply fed back to the array antenna. Again, this method is applied to deliver the operation mode and the synchronization of OFDM symbols to the array antenna.

3.2 Joint Hardware-Software Solution for Array Antenna System

Nowadays, FPGAs offer millions of gate densities and gigabit per second interface speeds. Although FPGAs are versatile and universal, their low-level programming is ill-suited to efficiently and quickly implementing complex tasks. On the other hand, because of the evolution of the modern compilers, DSPs are extremely flexible and easy to program with high-level languages, such as C/C++. However, they still cannot deliver the sheer computation load compared to FPGAs presently. Therefore, the joint HW-SW approach is certainly a natural solution capable of providing a robust and yet simply debugged platform to implement the array antenna. Figure 4 illustrates the functional block diagram of the array antenna, which compromises of HW and SW components. The HW side consists of prefixed functions of the array antenna including four multiplications and a combination of four-element array antenna. It also takes responsibility for accessing memory, timing in the SW side, and

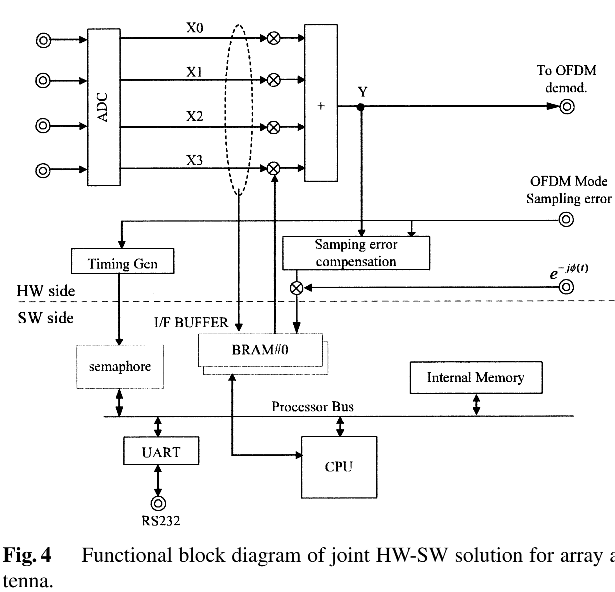


Fig. 4 Functional block diagram of joint HW-SW solution for array antenna.

I/O etc. Meanwhile, the SW side deliver the flexible functions corresponding to DBF algorithms in C programming language.

In detail, signals coming from 4-element array antenna are firstly analog-to-digital converted. Using the information of the starting point of OFDM symbol provided by OFDM demodulation, samples of HeadGI of the inputs and TailGI of the output are extracted and are stored into memory. The compensations of RF error and sampling rate error are conducted in the HW side as given in Sect. 3.1. The HW side also generates timing control signals to the SW side to trigger CPU. Then, the coefficients generated by the SW side are used to combine 4 branches of the array antenna. In the SW side, two banks of block memory storing samples of two successive OFDM symbols directly link to CPU. Using these samples, CPU performs DBF algorithm to generate the coefficients. They are stored back into the corresponding bank of memory and are delivered to the HW side at the starting

Figure 5(a) and (b) show the interface and the timing diagram of our HW-SW solution, respectively. As mentioned above, two banks of memory in the SW side are used to realize real-time operation of the array antenna. The operation of CPU is controlled by the HW side via 2 pairs of REQ/ACK (request/acknowledge) signals corresponding to two banks of memory. As illustrated in Fig. 5(b), samples are firstly stored to bank#0. Then, REQ signal coming from HW side indicates the availability of data and triggers CPU. Simultaneously, samples of next OFDM symbol are stored to bank#1. After calculating the coefficients, CPU sends ACK signal to the HW side and delivers the updated coefficients back into corresponding bank of memory. These coefficients are used by the array antenna in next symbol. Note that the process of computing coefficients with one memory bank and the process of sampling and storing data to the other are simultaneous.

The operation of CPU during one OFDM symbol's duration is denoted in Fig. 6. REQ signal is used to trigger the operation of CPU via interrupting services. The updated coefficients are then stabilized to avoid sudden changes caused by incidently strong interferences. ACK signal is used by HW side to control the process of updating the coefficients.

In our platform, CPU and HW side use different clock sources. Thus, it is important to synchronize the operation of CPU and HW side. Computation times of DBF algorithms are carefully measured and are shown in Table 1. In fact, computation times corresponding to MRC and SMI are approximately 10% and 20% of OFDM symbol's duration, respectively. Because the process of accessing memory and storing the coefficients only occupies small amount of time, total time duration to update the coefficients is certainly shorter than one OFDM symbol's duration. The coefficients are always available in the corresponding memory bank for the successive OFDM symbol. point of next OFDM symbol.

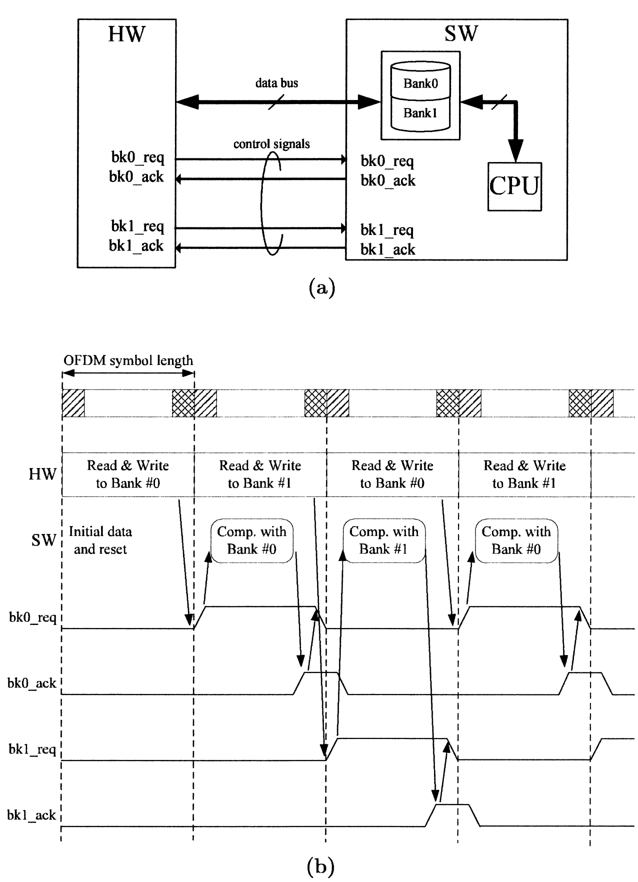


Fig. 5 (a) HW-SW interface and (b) timing diagram of array antenna.

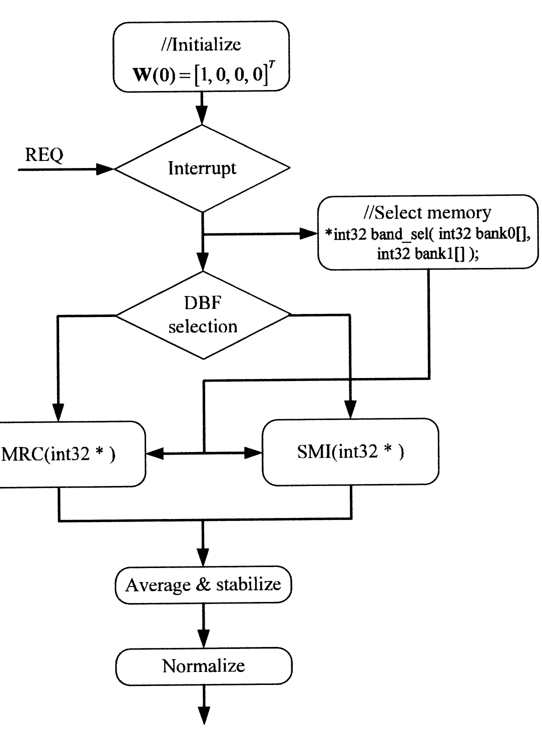


Fig. 6 Operation of CPU.

Table 1 Computation time of DBF algorithms.

Algorithms	Computation time
MRC	120 μs
SMI	260 μs

4. Hardware Implementation and Experimental Results

Coware Signal Processing Worksystem (SPW) is used as a developing EDA tool. SPW provides a flexible visualization environment with block-oriented design. More importantly, its ability to co-simulate multiple languages such as VHDL, Verilog HDL as well as C/C++ is one of the key features to create an extremely powerful tool covering a workflow from a system-level design to an implementation and verification by hardware. Therefore, it is possible to implement our system in a single design workbench and to verify its operation in co-simulating environment straightforwardly.

To implement the array antenna system in hardware, HDL code is synthesized by SPW and imported into FPGA Xilinx Virtex-II Pro board. An embedded IBM PowerPC microprocessor in this FPGA board is used to execute DBF algorithms in C programming language. Therefore we can take advantage of the highest performance from both FPGA and PowerPC core. Since clocks of FPGA and PowerPC core are 65 MHz and 260 MHz, respectively, the operation of FPGA and this core must be synchronized. In order to decouple the 65 MHz system with CPU, two banks of memory are utilized. In addition, the operation of CPU is triggered by a semaphore bit generated in FPGA. Two-pairs of REQ/ACK are also used as handshake signals between FPGA and CPU.

Table 2 and Fig. 7 show the specification and photograph of the prototype, respectively. We conducted several experiments to verify and evaluate the performance of our system. Table 3 summarizes the conditions of experiments and Fig. 8 shows the block diagram of the experiment system. Fading simulator is used to generate delayed waves. Note that noise generator is not used in these experiments. However, because of the limitation of fading simulator, each branch of the array antenna inherently contains AWGN noise with SNR (Signal-to-Noise ratio) of roughly 30 dB. Each delayed wave is associated with a phase rotation corresponding to its AOA. In next subsections, beam-patterns of the proposed system are measured. Experimental results in different wireless environments are also disclosed in [11]–[13], in which the proposed MRC is referred to as ABF (Array Beam-forming) algorithm.

4.1 To Verify the Proposed DBF Algorithms

In this subsection, the operation of the array antenna is verified. The multipath environment for this experiment is shown in Table 4. Since we proposed and implemented a class of time-domain beam-forming algorithms, beam-patterns of MRC and SMI can be used to verify the operation of the developed array antenna.

Using this condition, we generate beam-patterns of MRC and SMI algorithms. Moreover, to compare the per-

Table 2 Specification of the prototype.

Array Antenna	ADC	Channel	4
		Resolusion	10 bit
		Sampling rate	32 MHz
	FPGA	Xilinx Virtex-II Pro VP70, VP20	
	CPU	PowerPC405 260 MHz	
OFDM Demod.	FPGA	Xilinx Virtex-II 4000x2, V3000	

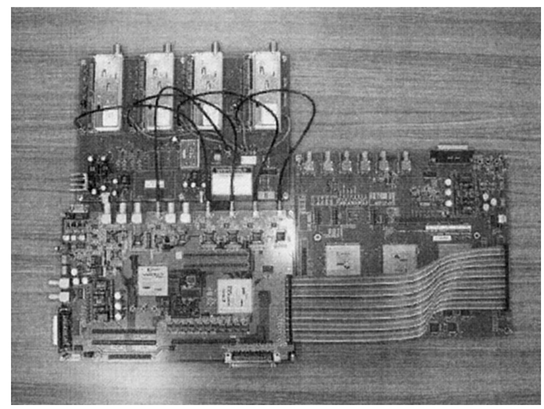


Fig. 7 Prototype of the array antenna.

Table 3 Experimental conditions.

Array Antenna	4-element linear array with equal space	
	Antenna element	Isotropic
	Distant	0.2662 m
ISDB-T	DTV28CH Mode3	
	Frequency	563.143 MHz
	Number of subcarrier	5617
	Effective duration T_e	1008 μs
	GI duration $T_g = T_e/8$	126 μs
	Modulation scheme	64QAM

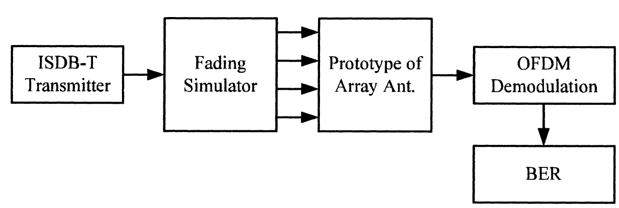
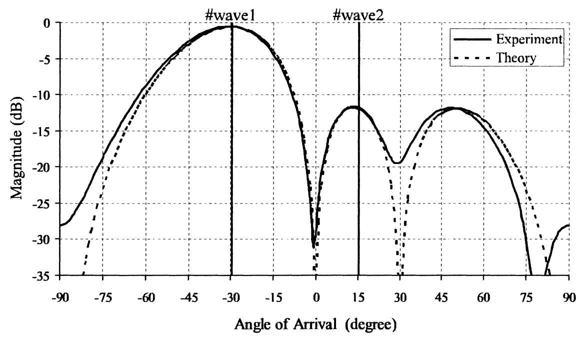


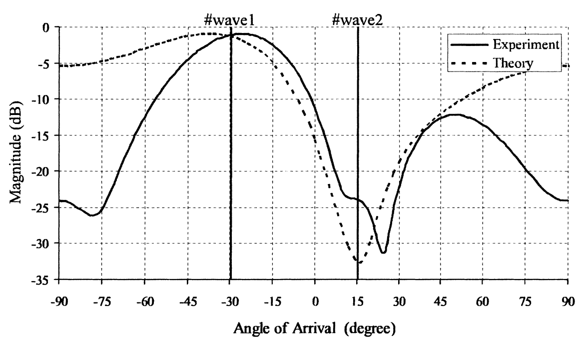
Fig. 8 Block diagram of the experiment system.

Table 4 Multipath environment to verify the operation of the array antenna.

Wave	Angle of Arrival	Delay spread	Power
1	−30°	0 μs	0 dB
2	15°	141.75 μs ($9T_g/8$)	0 dB



(a) Proposed MRC.



(b) Proposed SMI.

Fig. 9 Beam-patterns of the proposed (a) MRC and (b) SMI algorithms.

Table 5 Radio environment I.

Wave	Angle of arrival	Delay spread
1	−30°	0 μs
2	15°	21 μs ($T_g/6$), 147 μs ($7T_g/6$)

formance of DBF algorithm, we also conduct a simulation in the same multipath environment to measure the beam-pattern in the ideal condition. Beam-patterns of the proposed MRC and SMI are illustrated in Fig. 9(a) and (b), respectively. In the proposed MRC case, beam-patterns generated by simulation and experiment are matching. Moreover, the desired wave are emphasized by the array antenna. In the proposed SMI case, null positions generated by simulation and experiment are slightly mismatched. There are many factors that impact on the performance of the array antenna, such as RF error and sampling error. The starting point of the FFT window, which is a feedback from OFDM demodulation, might be slightly misadjusted. However, the delayed wave is suppressed by about 25 dB at the output of the array antenna.

4.2 2-Arrival Wave Environment

In this subsection, BER performance of our system in 2-arrival wave environment is measured. Moreover, BER performance of the conventional MRC algorithm is measured to compare. Table 5 and Fig. 10 show details on the radio environment in which delay time of second wave is changed to evaluate the performance of our system.

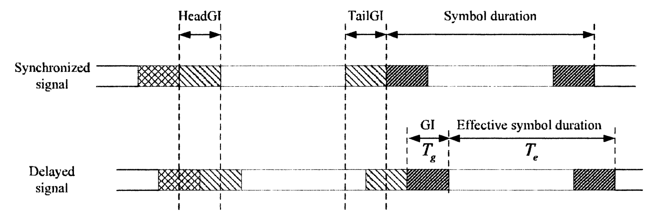


Fig. 10 Illustrate of 2-arrival wave environment.

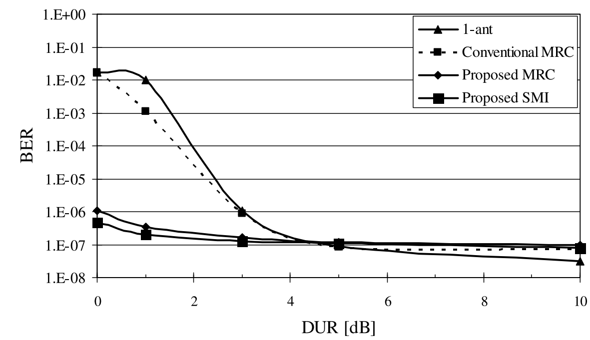


Fig. 11 BER evaluation in radio environment I with Delay=21 μs.

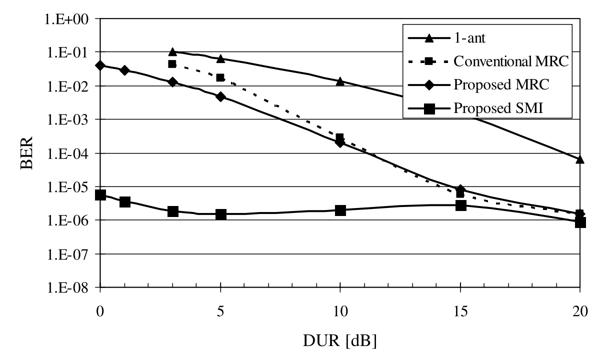


Fig. 12 BER evaluation in radio environment I with Delay=147 μs.

To compare the BER performance of the conventional MRC and the proposed MRC, as shown in Fig. 11 and Fig. 12, the proposed MRC outperforms the conventional MRC as the value of DUR decreases. Notably, the BER performance of the proposed MRC is almost unchanged in case of a small delay time as shown in Fig. 11. Moreover, in case that the delay time exceeds GI duration as illustrated in Fig. 12, OFDM system is still able to capture the desired signal in the region of small DUR. In case of the proposed MRC, only part of delayed wave can contribute to the cross-correlation between HeadGI of inputs and TailGI of output as illustrated in Fig. 10. The impact of the delayed wave thus varies upon the position of samples of HeadGI and TailGI and its delay time. On the other hand, the conventional MRC can not distinguish between the direct wave and the delayed wave as the value of DUR decreases. As a result, the performance of the proposed MRC is improved compared with that of the convention MRC.

The BER performance of the proposed SMI is also measured in this radio environment. As shown in Fig. 11

Table 6 Radio environment II.

Wave	Type of signal	Angle of arrival
1	Digital TV	−45°
2	Analog TV	0°

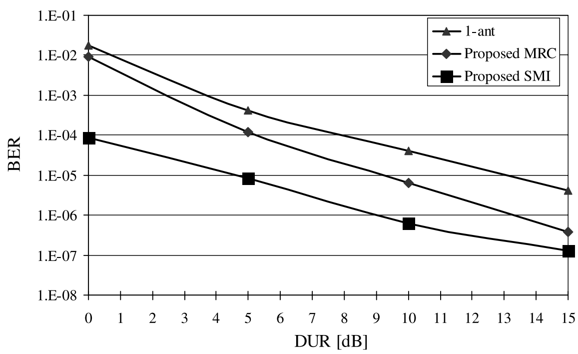


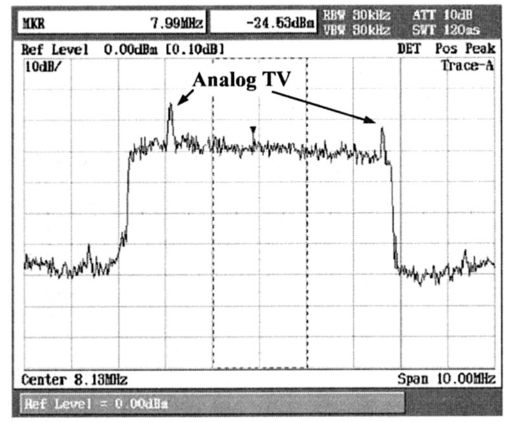
Fig. 13 BER evaluation in radio environment II.

and Fig. 12, the performance of the proposed SMI is not affected by the delayed wave. In other words, the proposed SMI is capable of suppressing the delayed wave. Thus, our proposed method of using GI and the periodic property of OFDM signal can improve the performance of the reception in this radio environment.

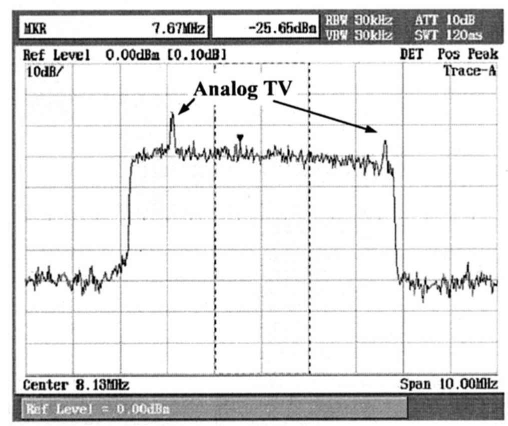
4.3 Co-channel Interference Environment

Next, we examine the performance in the radio environment with co-channel interferences. Table 6 presents the condition of the radio environment, in which analog TV signal occupies the same bandwidth with digital TV signal and can be considered as a strong incoherence interference. Figure 13 shows BER performance of the proposed MRC and SMI. The evaluation is also accompanied by BER performance of one element antenna. It is indicated that SMI algorithm outperforms MRC algorithm in term of suppressing the incoherent interferences.

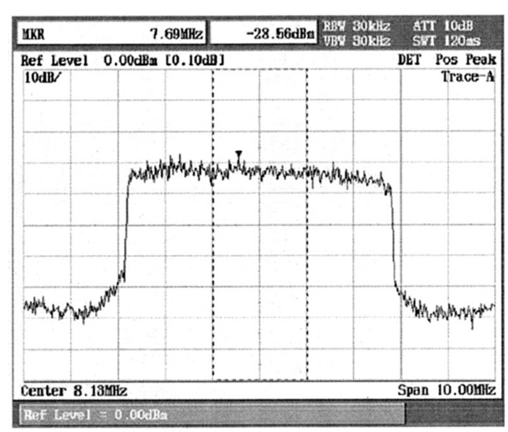
In addition, the spectrum of ISDB-T signals is probed at OFDM demodulation in order to illustrate the performance of our proposed system. ISDB-T signal is destructed by analog TV signal with DUR of 0 dB. Figure 14(a), (b) and (c) show the spectrum of ISDB-T signals with one-element antenna, and with the proposed MRC and SMI, respectively. In Fig. 14(b) the appearance of analog TV signal is clearly noticeable. Meanwhile, in Fig. 14(c) the peaks of analog TV spectrum are successfully suppressed.



(a) One-element antenna.



(b) Proposed MRC.



(c) Proposed SMI.

Fig. 14 Spectrums of ISDB-T signal measured at OFDM demodulation with analog TV as interference (DUR=0 dB).

5. Conclusions

In this paper, the joint HW-SW solution to realize two DBF algorithms as MRC and SMI is proposed. The proposed solution streamlines the flow from a system-level design to hardware implementation. We have successfully implemented our system in hardware. Experimental results are conducted and are shown that the proposed MRC achieves excellent performance even in the radio environment where value of DUR is small in comparison with the conventional MRC. Moreover, the performance of the proposed MRC is drastically improved in the radio environment in which multipath delay exceeds GI duration. It is also shown that the proposed SMI is capable of suppressing the strong interferences.

In future, we plan to evaluate and verify the performance of the proposed system in different radio environments. In addition, a methodology to automatically select the DBF algorithm suitable for each individual radio environment is also a subject of future study.

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Dang Hai Pham was born in Hanoi, Vietnam, on June 7, 1977. He received B.S. degree in Hanoi Univ. of Technology, Vietnam in 2000 and M.S. in Univ. of the Ryukyus, Okinawa, Japan in 2003. He is currently a Ph.D. student in Department of Information Engineering, Univ. of the Ryukyus. Currently, his research activity is supported by Magna's Working Student Support Program (Magna's WSSP). His research interests are channel estimation, adaptive array antenna with its application to OFDM. He is a student member of IEEE.

Takanobu Tabata was born in Mie, Japan on September 3, 1976. He received B.E. degree in Electrical Engineering from Nagoya Institute of the Technology, Nagoya, Japan, in 2000. He joined Kojima Press Industry Co., Ltd. Aichi, Japan, in 2000. Currently, he is engaged in development of a system for mobile reception of ISDB-T.

Hirokazu Asato was born in Okinawa, Japan on Jun 20, 1976. He received B.S. degree in Electrical Engineering, Univ. of the Ryukyus, Okinawa, Japan, in 1999. He joined Nihon Synosys Co., Ltd. Tokyo, Japan, in 1999. From 1992 to 2002, he was engaged in technical support of ASIC design. In 2002, he joint Magna Design Net Inc., Okinawa, Japan. Currently, he was engaged in developing and programming related to wireless communication LSI.

Satoshi Hori was born in Aichi, Japan, on November 4, 1964. He received B.E. degree in Electronics and Information Science and Ph.D. from Toyota Technological Institute, Nagoya, Japan, in 1989 and Nagoya Institute of the Technology, Nagoya, Japan, in 2006, respectively. Since he joined Kojima Press Industry Co., Ltd. in 1982, he has been engaged in research and development on antenna systems for automobile use such as adaptive array antenna and vehicle communication. He is a member of the IEEE.

Tomohisa Wada was born in Hiroshima, Japan, on December 2, 1959. He received B.S. degree in electronic engineering from Osaka Univ., Osaka, Japan, in 1983, M.S.E.E. degree from Stanford Univ., Stanford CA, in 1992, and Ph.D. in electronic engineering from Osaka Univ. in 1994. He joined the ULSI Laboratory, Mitsubishi Electric Corp., Itami, Japan, in 1983. From 1983 to 1999, he has been engaged in the development of CMOS/BiCMOS static RAMs, 3-D graphics controller ASIC, flash memory, low-voltage static RAM, and synchronous burst static RAMs. In 1998, he joined Mitsubishi Electric Corp., Semiconductor Group, Memory IC Division, Itami, where he has been working on the development of application specific synchronous burst static RAMs. In 1999, he became an Associate Professor with the Department of Information Engineering, Univ. of the Ryukyus, Okinawa, Japan. Since 2001, he has been a Professor at the Department of Information Engineering, Univ. of the Ryukyus, Okinawa, Japan. In 2001, He was the founding member of Magna Design Net, Inc., which is a fab-less LSI design Company for communication related digital signal processing such as OFDM. Currently, he is also the chief scientist of Magna Design Net, Inc. From 1999 up to now, he has been engaged in the research and development of high band-width communication systems such as terrestrial video broadcasting receivers and wireless LAN. Currently his research interests include system-level large-scale VLSI design, digital signal processing for high-bandwidth communication, error correction algorithm and circuit, networking software and protocols.