This paper proposes a new system architecture to reduce the hardware cost for a digital beamforming (DBF) transmitter array. In a conventional DBF transmitter array, each signal channel requires a digital-to-analog converter (DAC) to convert the digital signal to the analog signal, so that the cost and power consumption for such systems are often prohibitively high as the array size increases. In the proposed DBF transmitter array system, code-division multiplexing (CDM) technique is used to combine digital signals from different channels, and thus the required number of DACs can be significantly reduced. The combined signal is separated by demodulation with the corresponding code sequences for each channel after the DAC. Principle of CDM for hardware reduction in a DBF array system is analyzed. A system-level simulation is performed in Simulink to verify the performance of the proposed system. Simulation results show that the beamforming accuracy and signal quality can be maintained with a reduced number of DACs.

*European Conference on Antennas and Propagation (EuCAP)*
Code-Division Multiplexing based Hardware Reduction for a Digital Beamforming Transmitter Array

Zhengyu Peng\textsuperscript{1,3}, Kyeong Jin Kim\textsuperscript{1}, Pu Wang\textsuperscript{1}, Rui Ma\textsuperscript{1}, Kazunari Kihira\textsuperscript{2}, Toru Fukasawa\textsuperscript{2}, Changzhi Li\textsuperscript{3}, Bingnan Wang\textsuperscript{1,*}

\textsuperscript{1}Mitsubishi Electric Research Laboratories (MERL), Cambridge, MA, USA \textsuperscript{*}bwang@merl.com
\textsuperscript{2}Information Technology R&D Center, Mitsubishi Electric Corporation, 5-1-1 Ofuna, Kamakura-shi, Japan
\textsuperscript{3}Dept. of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX, USA

Abstract—This paper proposes a new system architecture to reduce the hardware cost for a digital beamforming (DBF) transmitter array. In a conventional DBF transmitter array, each signal channel requires a digital-to-analog converter (DAC) to convert the digital signal to the analog signal, so that the cost and power consumption for such systems are often prohibitively high as the array size increases. In the proposed DBF transmitter array system, code-division multiplexing (CDM) technique is used to combine digital signals from different channels, and thus the required number of DACs can be significantly reduced. The combined signal is separated by demodulation with the corresponding code sequences for each channel after the DAC. Principle of CDM for hardware reduction in a DBF array system is analyzed. A system-level simulation is performed in Simulink to verify the performance of the proposed system. Simulation results show that the beamforming accuracy and signal quality can be maintained with a reduced number of DACs.

Index Terms—Digital beamforming, code-division multiplexing, phased array.

I. INTRODUCTION

Beamforming technology is critical for a phased array system. Conventional phase shifter based RF beamforming systems suffer from issues such as phase errors, resolution, and bandwidth \cite{1,2}. For large arrays, which has been adopted in the next generation cellular communication system, these issues will become even worse. By moving the beamforming part to the digital domain, which is referred to as the digital beamforming (DBF) system, the resolution limitation of the conventional phase shifter based RF beamforming systems can be overcome \cite{3,4}. However, a DBF system requires the duplication of major components for each signal channel, which makes the hardware extremely complicated. Moreover, high-speed analog-to-digital converters (ADCs) or digital-to-analog converters (DACs) are required for a broadband and large array DBF system. These high speed analog-digital mixed devices are known to have high cost and high power consumption \cite{5}. Innovations to simplify the hardware and reduce the required number of analog-digital mixed devices in a DBF system is highly appealing.

One approach to reduce the hardware of a DBF system is to adopt multiple-access techniques to share the hardware. Time-division multiplexing (TDM), code-division multiplexing (CDM), and frequency-division multiplexing (FDM) are three widely used multiple-access techniques in wireless communications to share a single wireless channel for different terminals. For example, the “spatial multiplexing of local elements array (SMILE)” system utilized TDM to share the RF paths \cite{6}. CDM has also been proposed in wideband and multi-band DBF receivers to reduce the number of ADCs \cite{7,8,9}. The performance of different code sets has also been analyzed in Ref.\cite{7}. However, all previous work based on multiple-access techniques focus only on the receiver system, in which de-muxing or the de-coding process can be realized relatively easy in digital domain. For a DBF transmitter array system, the de-muxing or the de-coding process has to be realized in analog domain. The idea of utilizing CDM in a DBF transmitter array system was not presented so far to the best of our knowledge.

In this paper, a method to reduce the hardware for a DBF transmitter array system is proposed. In the digital domain, signals from different channels are modulated with orthogonal codes and then combined...
The modulated and combined digital can be written as:

$$y[n] = x[n]w \times C[n]$$

where $$x[n]$$ is the modulated baseband signal, $$w = [w_1, w_2, ..., w_N]$$ is the beamforming weight array, $$n$$ is sample numbers, $$N$$ is the size of the array, $$C[n]$$ is the array of $$N$$ orthogonal code sequences, and

$$C[n] = [C_1[n], C_2[n], ..., C_N[n]]^T$$

where $$T$$ is the transpose of the array.

Digital signal $$y[n]$$ is converted into analog signal $$y(t)$$ through the DACs:

$$y(t) = \sum_{i=1}^{N} x(t)w_iC_i(t) + e$$

where $$C_i(t)$$ is the analog sequence of $$i$$-th orthogonal sequence and $$x(t)$$ is the analog baseband signal, $$e$$ is quantization noise.

In order to separate the combined signal, $$y(t)$$ is mixed with the corresponding code sequence:

$$s_k(t) = \sum_{i=1}^{N} x(t)w_iC_i(t)c_k(t) + C_k(t)e$$

where $$s_k(t)$$ is the separated signal on $$k$$-th channel.

Since the code has values either 1 or -1, the statistics of quantization noise term $$C_k(t)e$$ after the mixing does not change.

It has been discovered that the orthogonal codes are necessary to faithfully recover the signal on each channel. In this paper, Walsh codes are used. Table I lists the eight-bit Walsh codes. From Table I, it is easy to find:

$$C_i(t)C_k(t) = \begin{cases} 1 & \text{if } i = k \\ 0 & \text{if } i \neq k \end{cases}$$

For $$i \neq k$$, the minimal frequency of the square sequences of $$C_i(t)C_k(t)$$ is $$1/(8T_c)$$, where $$T_c$$ is code period and $$1/T_c$$ is code rate. Thus, if the bandwidth ($$BW$$) of the baseband signal $$x(t)$$ is smaller than $$1/(16T_c)$$, the contribution terms $$x(t)w_iC_i(t)c_k(t)$$ ($$i \neq k$$) can be filtered through a low-pass filter. Finally, the signal of each channel can be fully recovered:

$$s_k(t) = x(t)w_k + C_k(t)e$$
CDM Path Sharing (Baseband) Transmitter

Ideal Receiver

Fig. 3. Simulink model of the proposed DBF transmitter array system.

<table>
<thead>
<tr>
<th>Index</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 4. Antenna array configuration.

Fig. 5. Beam pattern of the ideal case for the proposed system.

III. SIMULATION RESULTS

A system-level model of the proposed CDM-based DBF transmitter array is created with Simulink. Fig. 3 shows the Simulink model of the proposed transmitter, as well as an ideal receiver. In the Simulink model, signals from eight channels \((N = 8)\) are combined to share one DAC. Eight-bit Walsh codes are used for modulation and de-modulation. The bandwidth of \(x(t)\) is 12 MHz. Code rate of the Walsh codes is \(1/T_c = 256\) MHz. The sampling rate of the DACs is 256 Msps.

An ideal case is evaluated, in which the resolution of the DACs is infinite and the de-modulation mixers are ideal multipliers. Fig. 4 is the array configuration. The eight-element array is linear distributed, and the distance between two adjacent elements is half-wavelength. Fig. 5 shows the beam pattern of the ideal case compared with the reference pattern, which is generated with an ideal conventional DBF transmitter array as shown in Fig. 1. In Fig. 5, the array elements are weighted with Chebyshev weighting, and the direction of the main lobe is tuned to \(-20^\circ\). The weighting values for all antenna elements are listed in Table II. It can be seen that in the ideal case, the formed beam pattern is perfectly matched with the reference.

Table II: Beamforming Weight Values

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58 + 0.00j</td>
<td>-0.40 + 0.91j</td>
</tr>
<tr>
<td>2</td>
<td>0.34 - 0.38j</td>
<td>0.53 + 0.69j</td>
</tr>
<tr>
<td>3</td>
<td>-0.48 - 0.73j</td>
<td>0.65 - 0.11j</td>
</tr>
<tr>
<td>4</td>
<td>-1.00 + 0.08j</td>
<td>0.19 - 0.53j</td>
</tr>
</tbody>
</table>

Fig. 6. Beam patterns for the system with different DAC resolutions.

Table III: Side Lobe Errors with Different DAC Resolutions

<table>
<thead>
<tr>
<th>DAC resolution (bits)</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side lobe error (dB)</td>
<td>4.16</td>
<td>1.18</td>
<td>0.19</td>
<td>0.01</td>
</tr>
</tbody>
</table>

As described in previous section, the key components of the proposed system are the DACs and the de-modulation mixers. Therefore, the requirements of
the EVM reaches to the minimal at 8-bit DAC resolution. The side lobe errors are below 1 dB as long as the P1dB is larger than 9 dBm. The EVMs of the transmitted are also calculated with different P1dB values. Fig. 9 shows the EVM results of 64QAM. The EVM is below ~35 dB when P1dB is larger than 12 dBm. In hardware implementation, passive mixers can be used to achieve high P1dB.

IV. CONCLUSION

In this paper, a method to reduce the hardware for a DBF transmitter array system has been proposed. By using code-division multiplexing technique, signals from different channels are combined together, which significantly reduce the required number of DACs, as compared with a conventional DBF transmitter array system. After the DAC, signals of different channels are separated through a de-modulation process. Design principle of the proposed code-modulation for hardware reduction in a digital beamforming transmitter system has been described; a system-level simulation has been performed to verify the performance; results show that the beamforming accuracy and signal quality can be maintained with reduced number of DACs in the proposed system.

REFERENCES