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Sidelobe Manipulation using Butler Matrix for 60 GHz Physical Layer Secure Wireless Communication

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Abstract—With the help of the beam orthogonality characteristics associated with a Butler matrix, the concept of sidelobe manipulation is proposed. The method uses a Butler matrix parallel excited by an information data stream and artificial interference. The proposed system is implemented using a four by four Butler matrix MMIC and its secrecy performance characteristics are validated by bit error rate (BER) simulations for a 60 GHz QPSK transmission.

Keywords— bit error rate; Butler matrix; beam orthogonality; V-band

I. INTRODUCTION

The Butler matrix [1], [2], as a Fourier transform [3], [4], has been used extensively. The Butler matrix, consisting of passive four-port power couplers and fixed phase shifters, has N input ports and N output ports. When used as a beam-forming network, it excites an array of N antenna elements in order to steer an antenna array main beam along one of N discrete spatial directions. The Butler matrix can also function as a multiplexer/de-multiplexer [5] for many applications, e.g., OFDM. Recently, it is found that under various MIMO environments, adopting a Butler matrix at transmitter and/or receiver side [6], [7] can increase the diversity gain or the channel capacity of the system.

In this paper instead of applying parallel excitations at the input ports of a Butler matrix, each excitation containing information signals, artificial interference is injected into the system alongside the information data stream, in such a fashion to scramble signal formats along the sidelobe directions while simultaneously leaving main lobe information content preserved. Thus the proposed architecture in this paper can be viewed as an analogue directional modulation transmitter [8]–[10].

In Section II of this paper the beam orthogonality property of a Butler matrix is briefly described. By exploiting the orthogonality characteristic, a working mechanism, whereby far field sidelobe modulation content can be scrambled while leaving steered main beam information content unaffected, is presented. The impact of the injected interference choice on the constellation pattern manipulation is investigated in Section III, and further validated in Section IV using a SiGe four by four Butler matrix MMIC operating at 60 GHz. Finally, summaries and conclusions are drawn in Section V.

II. THE CONCEPT OF SIDELOBE MANIPULATION

A. Beam Orthogonality in a Butler Matrix driven Antenna Array

The transfer function between the n^{th} input port and the m^{th} output port of an N ($N = 2^p$) by N Butler matrix is

$$T_{mn} = \frac{1}{\sqrt{N}} \cdot e^{-j\frac{2\pi}{N}\left(m-\frac{N+1}{2}\right)\left(n-\frac{N+1}{2}\right)} \quad (m, n = 1, 2, \dots, N) \quad (1)$$

When taken in matrix form, the output signal vector $\mathbf{A}$ of this Butler matrix can be obtained by (2),

$$\mathbf{A} = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1N} \\ T_{21} & T_{22} & \cdots & T_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ T_{N1} & T_{N2} & \cdots & T_{NN} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_N \end{bmatrix} = \mathbf{T} * \mathbf{B} \quad (2)$$

where $\mathbf{B}$ is the excitation vector at the input ports of the Butler matrix.

Assume a one-dimensional (1-D) half wavelength spaced antenna array with isotropic element radiation pattern is connected at the output of the Butler matrix, the far-field pattern is

$$E(\theta) = \sum_{m=1}^N \left(A_m \cdot e^{j\pi\left(m-\frac{N+1}{2}\right)\cos\theta} \right) \quad (3)$$

Here θ is the spatial transmission direction ranging from 0° to 180° , with boresight at 90° . The phase reference is chosen to be the antenna array geometric center.

Substitute (1) and (2) into (3) we can obtain the far-field pattern for the n^{th} Butler matrix input port excitation B_n , (4), this electric field pattern is denoted as $E_n(\theta)$,

$$\begin{aligned} E_n(\theta) &= \sum_{m=1}^N \left[(T_{mn} \cdot B_n) \cdot e^{j\pi\left(m-\frac{N+1}{2}\right)\cos\theta} \right] \\ &= \sum_{m=1}^N \left[\left(\frac{B_n}{\sqrt{N}} \cdot e^{-j\frac{2\pi}{N}\left(m-\frac{N+1}{2}\right)\left(n-\frac{N+1}{2}\right)} \right) \cdot e^{j\pi\left(m-\frac{N+1}{2}\right)\cos\theta} \right] \end{aligned} \quad (4)$$

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The main beam pointing direction α_n can be calculated by

$$-\frac{2\pi}{N}\left(m - \frac{N+1}{2}\right)\left(n - \frac{N+1}{2}\right) + \pi\left(m - \frac{N+1}{2}\right) \cdot \cos\alpha_n = 0$$

$$\therefore \cos\alpha_n = \frac{2}{N}\left(n - \frac{N+1}{2}\right) = \frac{2n - N - 1}{N} \quad (5)$$

Similarly, by replacing n in (4) and (5) with q , the electric field $E_q(\theta)$ generated by the q^{th} Butler matrix input port excitation with main beam pointing to α_q can be acquired.

We can verify that $E_n(\alpha_q) = 0$ when $n \neq q$, which means that the $E_q(\theta)$'s main beam is projected along the null radiation direction of $E_n(\theta)$. Ditto $E_n(\theta)$'s main beam and $E_q(\theta)$'s null direction. This is the beam orthogonality in beam space occurring from the Fourier transforming relationship of a Butler matrix.

B. The Concept of Sidelobe Manipulation using a Butler matrix

When using a Butler matrix as a beam-forming network, the information signal, driving the n^{th} input port of a Butler matrix, can be radiated into the whole space with the maximum power projected along the prescribed direction α_n . Since the same well formatted signal also exists at other directions, even though power is suppressed, eavesdroppers positioned along these directions still have a reasonable chances to decode the signal and recover the information data by the means of , for example, equipping themselves with more sensitive receivers.

In order to reduce the probability of interception, we can inject interference signals into the Butler matrix at ports other than the n^{th} input port, illustrated in Fig. 1. With the benefit of the beam orthogonality property we described earlier in this

Fig. 1. Proposed sidelobe scrambling architecture using Butler matrix.

section, we arrange that the interference signal is radiated with a null power direction along α_n , meaning that the information signal transmitted along this selected communication direction α_n is unaffected, while, simultaneously, the information leaked into other directions is submerged in multiplicative artificial interference.

III. SIMULATION RESULTS AND DISCUSSIONS

The simulation results in this section are based on an ideal four by four Butler matrix model with a 1-D half wavelength spaced antenna array connected at the output ports. Each array element has an isotropic radiation pattern. In Fig. 2, the calculated far-field power patterns for each of four input port excitations are given. It can be clearly observed that four main beams, pointing along 41° , 76° , 104° and 139° respectively, also predicted by (5), are orthogonal to each other in beam space.

When an information data stream to be transmitted with QPSK modulation scheme is injected into the Butler matrix at the second input port, while constant interference is allowed to excite the remaining ports, the far-field power and phase patterns associated with each unique QPSK symbol are depicted in Fig. 3. The interference level in this example is chosen to have a power of 10 dB lower than that of the information signal and to have a constant phase of 60° . Gray coding is assumed throughout, hence QPSK symbols '11', '01', '00' and '10' should lie in the first to the fourth quadrants in IQ space respectively along the direction pre-assigned for transmission. It can be seen in Fig. 3 that the uniform magnitudes for four QPSK symbols and 90° phase intervals between each two consecutive symbols only occur along α_2 , 104° in this example. This indicates that the constellation patterns in all spatial directions other than α_2 are scrambled, even though the average symbol power is 1.14 dB higher in this system than that in the non-interference system, which is also shown in Fig. 3 (a).

To visualize the impact of the injected interference, the constellation diagrams detected along spatial directions of 30° , 60° , 104° and 150° are illustrated in Fig. 4. It can be clearly

Fig. 2. Normalized radiation power patterns for each Butler matrix input port excited separately ('—●—': for the first input port; '---□---': for the second input port; '....×....': for the third input port; '-.-△-.-': for the fourth input port).

(a) Power patterns in the system with the constant interference injected (‘—○—’: for symbol ‘11’; ‘-□-’: for symbol ‘01’; ‘...×...’: for symbol ‘00’; ‘-▲-’: for symbol ‘10’), and the power pattern for the same system without interference injection (‘-●-’).

(b) Phase patterns in the system with the constant interference injected (‘—○—’: for symbol ‘11’; ‘-□-’: for symbol ‘01’; ‘...×...’: for symbol ‘00’; ‘-▲-’: for symbol ‘10’).

Fig. 3. Normalized radiation power and phase patterns for each QPSK symbol.

Fig. 4. Constellation diagrams detected along spatial directions of 30°, 60°, 104° and 150°. Information signal with QPSK modulation excites B_2 . Interference at each remaining input port has a magnitude of -10 dB and a constant phase of 60° (‘○’: symbol ‘11’; ‘□’: symbol ‘01’; ‘×’: symbol ‘00’; ‘▲’: symbol ‘10’).

Fig. 5. Constellation diagrams detected along spatial directions of 30°, 60°, 104° and 150°. Information signal with QPSK modulation excites B_2 . Interference at each remaining input port has a magnitude of -10 dB and a random phase in 0° to 360° range (‘○’: symbol ‘11’; ‘□’: symbol ‘01’; ‘×’: symbol ‘00’; ‘▲’: symbol ‘10’).

observed that the constant phase injected artificial interference does not alter the shape of the constellation patterns, but it acts as a DC offset to shift them in the IQ plane.

To avoid the possibility of decoding these IQ constellations by more complex QPSK receiver technology, which may have the ability of re-centering constellation diagrams, we can randomly update either the magnitude or the phase, or both, of injected interference at the information data rate. With this manipulation, QPSK symbols no longer form a square, and appear randomly in IQ space. For example, Fig. 5 shows 20 QPSK symbols (5 for each unique symbol state) transmitted along the same spatial directions of 30°, 60°, 104° and 150°. The information signal excites the second input port B_2 of the Butler matrix, and the interference, injected into each remaining input port, has the same magnitude, -10 dB, but random phase is applied per symbol transmission in 0° to 360° range. It can be seen that the symbols are randomly scattered in IQ space along all spatial directions other than α_2 , 104°, making the interception and successful decoding by eavesdroppers significantly more difficult.

IV. EXPERIMENTAL VALIDATION AT 60 GHz

In this section, a four by four Butler matrix designed for V-band operation via 0.35 μm SiGe bipolar process [11], Fig. 6, is used to verify the proposed architecture with sidelobe scrambling capability.

For comparison, the normalized far-field power and phase patterns at 60 GHz for each QPSK symbol with the same information and interference excitation settings for Fig. 3 are calculated based on the measured S-parameters of the Butler matrix and shown in Fig. 7. The patterns well resemble their counterparts in Fig. 3. Phase shifts up to 2° along the 104° spatial direction are due to the fabrication error of the Butler matrix, which causes interference leakage due to imperfect coupler directivity.

Fig. 6. Microphotograph of the manufactured Butler matrix.

(a) Calculated power patterns based on measured S-parameters of the Butler matrix with the same constant interference injection as for Fig. 3 ('—○—': for symbol '11'; '---□---': for symbol '01'; '·····×·····': for symbol '00'; '-.-△-.-': for symbol '10'), and the power pattern for the same system without interference injection ('—●—').

(b) Calculated phase patterns based on measured S-parameters of the Butler matrix with the same constant interference injection as for Fig. 3 ('—○—': for symbol '11'; '---□---': for symbol '01'; '·····×·····': for symbol '00'; '-.-△-.-': for symbol '10').

Fig. 7. Normalized radiation power and phase patterns, calculated based on the measured S-parameters of the Butler matrix at 60 GHz, for each QPSK symbol.

In order to further evaluate the system performance, we simulate the bit error rate (BER) performance under various system settings. BER is calculated by transmitting a data stream of random QPSK symbols in an AWGN channel. Calculating BER via the data stream approach makes Gray-code inspection for each symbol pair possible, and facilitates calculations for different receiver types. In this paper two types of receivers are assumed. The first is a standard QPSK receiver that decodes received noisy symbols based on which quadrant the constellation points locate into. The second is a more advanced receiver that is able to detect the absolute magnitude and phase of each received symbol. The advanced receiver allows 'minimum Euclidean distance decoding'. For the BER simulation results in this section, a data stream with 10^6 random QPSK symbols is used, which allows BER down to 10^{-5} to be calculated.

Fig. 8 shows calculated BER spatial distributions, based on the measured S-parameters of the Butler matrix, for systems with and without the application of constant interference injection used above. The signal to noise ratio (SNR) is set to 12 dB, and then 20 dB, along the 104° direction. It is noted that the BER along the information main beam pointing direction, 104° , can be well predicted by $BER = Q(\sqrt{SNR})$ [12], 3.4×10^{-5} .

In Fig. 8 it can be observed that for the standard receiver type, the injected constant interference help narrow the BER main beam and suppress the sidelobes, particularly for high SNR case. However, it does not have any impact when detected by a system equipped with an advanced receiver, since, as we mentioned in the last section, these sophisticated receivers have the ability to re-center constellation diagrams, which leads to the same performance as that of the system with no interference injected.

When the phase of the interference is updated randomly at the information rate using a uniform distribution with phase

Fig. 8. BER spatial distributions for information signal at the second input port and interference at each remaining input ports. The phase of the interference is kept constant, 60° ('—○—': -10 dB interference, standard receiver and SNR=12 dB; '---□---': -10 dB interference, advanced receiver and SNR=12 dB; '·····×·····': no interference and SNR=12 dB; '-.-△-.-': -10 dB interference, standard receiver and SNR=20 dB; '---□---': -10 dB interference, advanced receiver and SNR=20 dB; '—●—': no interference and SNR=20 dB).

Fig. 9. BER spatial distributions for information signal at the second or the fourth input port and interference at each remaining input ports. The phase of the interference is updated randomly. SNR along information beam directions is set to 12 dB (‘—●—’: -5 dB interference, standard and advanced receivers; ‘- - -▲- -’: -10 dB interference, standard and advanced receivers; ‘- - -△- -’: -∞ dB interference; ‘- - -×- -’: -5 dB interference, standard and advanced receivers; ‘- - -+ - -’: -10 dB interference, standard and advanced receivers; ‘- - -▽- -’: -∞ dB interference).

selected from the range 0° to 360° , Fig. 9 depicts the BER spatial distributions obtained for information applied at the second and the fourth input ports of the Butler matrix, respectively. The phase of the interference at each remaining input port is updated randomly and the magnitude is kept constant, but set to -5 dB, -10 dB and $-\infty$ (corresponding to the non-interference case) respectively. The SNR along the directions of main information beams is set to 12 dB. From Fig. 9 it can be concluded that the randomly updated interference reduces the probability of decoding by standard and advanced receivers along unselected directions, and thereby enhancing physical layer secrecy performance, with regards to BER beam-widths and maximum sidelobe levels.

V. CONCLUSIONS

By employing Butler matrix, a means for scrambling the digital modulation content in the sidelobes of a wireless transmission was presented. Injected interference radiates along all spatial directions other than the main information direction, and hence contaminates the leaked information in such a fashion to prevent eavesdroppers from signal decoding through interception. It is also shown by extensive BER simulations, based on the measured S-parameters of a Butler matrix MMIC

operating at 60 GHz, that dynamic random interference updating is highly effective at returning high BER along unselected communication directions. The approach suggested here opens the way for a new means for securing Gigabit per second data transmissions associated with V-Band short range communications while preserving beam steering. The method is generally applicable to any radio communication systems applying an orthogonal beam forming network.

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