Beam-Tracking Technique for mmWave Cellular Systems with Intelligent Reflective Surface

Yeong Jun Kim
LG Electronics
Seoul, South Korea
yjkim81@gmail.com

Hosin Lee
School of Electrical and Electronics Engineering
Chung-Ang University
Seoul, South Korea
tommy0416@naver.com

Yong Soo Cho
School of Electrical and Electronics Engineering
Chung-Ang University
Seoul, South Korea
yscho@cau.ac.kr

***Abstract*—In this paper, a beam-tracking technique is proposed for millimeter-wave (mmWave) cellular systems with an intelligent reflective surface (IRS). A preamble design technique for IRS-assisted cellular systems is proposed using the complex conjugate property of the Zadoff-Chu sequence and reflecting nature of IRS. Moreover, a beam-tracking technique for mmWave cellular systems with a uniform planar array (UPA) is also proposed to track the variation in the angle of departure using sub-panel structures of the UPA.**

Keywords—Beam-tracking, intelligent reflecting surface (IRS), mmWave cellular system

I. Introduction

Intelligent reflective surfaces (IRS), also known as reconfigurable intelligent surfaces (RIS), have recently attracted considerable attention from the wireless communication research community owing to their ability to improve spectral and energy efficiencies [1]. An IRS is typically constructed by planar surfaces consisting of a large number of low-cost reflecting elements, requiring nearly no additional power consumption. In the mmWave frequency band, highly directional beamforming antennas are required at both the base station (BS) and mobile station (MS) to compensate for high attenuation. However, beam alignment easily breaks when the MS moves. Although a beam-training technique can resolve such problems, it consumes significant network resources if it is performed whenever the received signal experiences a power loss. Thus, several beam-tracking techniques that do not require a separate training period have been developed to track the beam after the initial beam alignment [2],[3].

However, existing beam-tracking techniques cannot be used directly for IRS-assisted cellular systems. Unlike a BS with an active power source, the IRS can only reflect signals from the BS and change the phase or amplitude of the reflected signals. The IRS cannot transmit its preamble signal [4]. This makes it difficult for an MS to distinguish the source (BS or IRS) of a received signal. In IRS-assisted cellular systems, it is challenging for the MS to track the AoD of the IRS because the IRS cannot transmit its preamble signal. Therefore, a different approach is required to track the beam in IRS-assisted cellular systems. In this paper, a new preamble design technique that considers the characteristics of the IRS is proposed to track the beam in IRS-assisted cellular systems with a uniform planar array (UPA). The proposed preamble is designed using the complex conjugate property of the Zadoff-Chu (ZC) sequence and the nature of the IRS. It allows the MS to distinguish between the signal directly received from the BS and that reflected from the IRS. The cell ID (CID) and beam ID (BID) information transmitted in the preamble allows the MS to track the beam corresponding to each source in multi-cell, multi-IRS environments.

II. Preamble Design for IRS-Assisted Cellular Systems

Fig. 1 shows an example of an IRS-assisted cellular system with one BS, one RIS, and two MSs (MS1 and MS2). MS2 receives a signal directly from the BS and there exist two paths (Path 1 and Path 2) for MS1. Path 1 is a direct link between the BS and MS1 whereas Path 2 is composed of two links: Link 1 between the BS and IRS and Link 2 between the IRS and MS1. In this example, it is assumed that the line-of-sight (LoS) link in Path 1 is blocked by some obstacles at the initialization stage. In this case, the IRS provides an alternative path (Path 2) and maintains the connection between MS1 and the network. It is assumed that the best beam pairs of the BS-IRS-MS links for MS1 are already found at the initialization stage. In this paper, we focus on the beam-tracking technique for the mobility case of MS1.

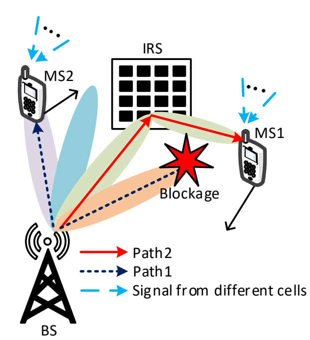

Fig. 1. Example of an IRS-assisted cellular system

A passive IRS can only perform phase shifts and amplitude variations in the incident signals. Thus, we can design the preamble sequence in IRS-assisted cellular systems by applying the phase change in a block-wise format when reflection occurs at the IRS. By changing the phase in the second half of the preamble in the IRS, the signals can be distinguished as follows.

$$x^r_{b,IRS}(n) = \begin{cases} x^r_{b,BS}(n), & 0 \le n < \lfloor N/2 \rfloor \\ -x^r_{b,BS}(n), & \lfloor N/2 \rfloor \le n < N \end{cases} \quad (1)$$

In the proposed preamble sequence design, the ZC sequence is considered because it has been widely used in orthogonal frequency-division multiplexing (OFDM)-based cellular systems owing to its perfect autocorrelation and good cross-correlation properties. The proposed preamble is designed using the complex conjugate property of the ZC sequence and reflecting nature of IRS (phase change in a block-wise format). The complex conjugate of the ZC sequence with the root index r becomes another ZC sequence with the root index $-r$. Thus, the complex conjugate of ZC retains the correlation property of the ZC sequence. Using this property, the proposed preamble sequence can be defined as

$$\begin{aligned} x^r_{b,BS}(n) &= (-1)^n \left(x^r_{b,0}(n) + (x^r_{b,1}(n))^*\right)/\sqrt{2} \\ &= \begin{cases} (-1)^n\sqrt{2}\,\mathrm{Re}\{x^r_{b,0}(n)\}, & 0 \le n < N/2 \\ -j(-1)^n\sqrt{2}\,\mathrm{Im}\{x^r_{b,0}(n)\}, & N/2 \le n < N \end{cases} \end{aligned} \tag{2}$$

where $x^r_{b,0}(n) = e^{-j\pi r n(n+1)/N} e^{j2\pi B_b n/N}$, $x^r_{b,1}(n) = x^r_{b,0}((n)_{\%M})$, $N = 2M$, and B_b denotes phase shift corresponding to BID b. From (2), it can be observed that the first and second halves of BS preamble $x^r_{b,BS}(n)$ are given by the real and imaginary parts of $x^r_{b,0}(0 \le n < M)$, respectively. The IRS preamble $x^r_{b,IRS}(n)$ is given by (1), which changes only the second half, that is, polarity of the imaginary part of the BS preamble. Because the BS preamble $x^r_{b,BS}(n)$ and IRS preamble $x^r_{b,IRS}(n)$ are constructed using the sequence $x^r_{b,0}(n)(0 \le n < M)$, this sequence is referred to as the original preamble sequence $\tilde{x}^r_b(n)$ in this paper.

On the receiver side, the original preamble sequence is reconstructed by combining the real and imaginary parts of $x^r_{b,BS}(n)$ or $x^r_{b,IRS}(n)$. The original sequence of BS preamble $\tilde{x}^r_b(n)$ is obtained by combining the real part $x^r_{b,BS}(n)(0 \le n < M)$ and imaginary part $x^r_{b,0}(n)(M \le n < N)$ as follows:

$$\begin{aligned} \tilde{x}^r_{b,BS}(0 \le n < M) &= x^r_{b,BS}(n) + x^r_{b,BS}(n+M) \\ &= \sqrt{2}(-1)^n(\mathrm{Re}\{x^r_{b,0}(n)\} + j\,\mathrm{Im}\{x^r_{b,0}(n)\}) \\ &= \sqrt{2}(-1)^n e^{-j\pi(r/2)n(n+1)/M} e^{j2\pi(B_b/2)n/M} \\ &= \sqrt{2} e^{-j\pi(r/2)n(n+1)/M} e^{j2\pi(B_b/2+M/2)n/M} \end{aligned} \tag{3}$$

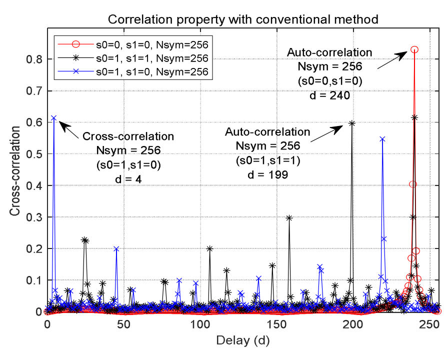

Fig. 2. Cross-correlation functions of conventional preamble

Fig. 2 and Fig. 3 shows correlation properties of the conventional and proposed preambles, respectively. In this paper, the preamble generated by (1) with a prime length ZC sequence is called a conventional preamble. Here, $s0 = 0$ corresponds to BS signal and $s1 = 1$ corresponds to IRS signal. When the source is BS, the correlation peak occurs at the correct position (240). However, when the source is IRS or the sources are different, there exist several large side peaks in the cross-correlation result, which can degrade the information acquisition and beam tracking performance. The side peak occurred with conventional method makes receiver unable to distinguish the source. Due to the error of source, angle of departure (AoD) cannot be estimated correctly with the conventional preambles. However, it can be seen from Fig. 3 that the cross-correlation between the BS and IRS preamble sequences are small. For the values other than the peak position, the cross-correlation functions decrease quickly. In this paper, AoD is estimated using phase difference between sub-panels that are shown in Fig. 4.

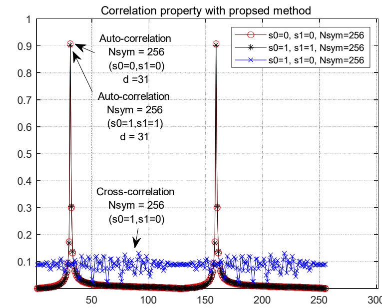

Fig. 3. Cross-correlation functions of proposed preamble

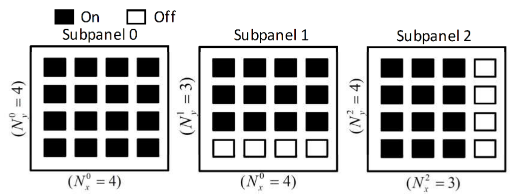

Fig. 4. 2-D subpanel configurations (4X4 UPA)

III. Conclusion

In this paper, a preamble design technique for IRS-assisted cellular systems was proposed using the complex conjugate property of the ZC sequence and reflecting nature of an IRS. It was demonstrated that the proposed preamble has the desired correlation properties (small cross-correlation), which allows the MS to detect the correct source (BS or IRS) of the received signal. An efficient beam-tracking technique was proposed for mmWave cellular systems with UPA using the phase difference between subpanels in the horizontal and vertical directions.

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