Multi-Bit Unit-Cell Configurations for Efficient Sub-Millimeter-Wave Reconfigurable Reflective Surfaces

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Large-scale reflectarrays and intelligent surfaces (LISs) are expected to play a key role in millimeter-wave (mmWave) and terahertz (THz) bands for 5G and beyond applications, serving as either high-gain base stations or relays. As such, these reconfigurable apertures consist of switch activated antenna elements that enable beamforming by modulating the phase of the impinging waves. Unlike phased arrays that consist of multiple components (e.g. mixers, local oscillators, circulators, etc.) and exhibit high DC power consumption and RF losses, these surfaces are advantageous in terms of DC power consumption due to the use of simple switches, and exhibit lower RF losses as demonstrated in − V. Jamali et al., "Scalable and Energy-Efficient Millimeter Massive MIMO Architectures: Reflect-Array and Transmit-Array Antennas," 2019. However, the phase modulation is usually carried out using single-bit ($0^o/180^o$) quantization, leading to undesired quantization lobes. The effects of the quantization errors in the case of single-bit phase modulation are more pronounced especially for LISs, where the illumination is a plane-wave, leading to quantization lobes that have the same level as the main lobe (SLL=0 dB). To overcome this issue, higher bit configurations (e.g. 2-bit−$0^o/90^o/180^o/270^o$ phase states) have been used reducing quantization lobes by 10 dB. However, when further improvement is necessary, reconfigurable surfaces with 3-bits or more are required.

In general, single-bit reconfiguration is achieved by embedding a single switch (e.g. PIN diode) within the unit-cell at the feed of the antenna, and by controlling the switch state (ON/OFF), the phase of the reflected waves is modulated. In the case of multi-bit configurations, more switches are needed to acquire the desired multi-bit quantization (e.g. 2-bits with 5 diodes). However, when multiple switches are placed in series configurations, losses increase and the undesired amplitude modulation is unavoidable. In addition, in the case of mmWave/THz frequencies (above 100 GHz), the use of multiple switches leads to high-loss designs with pronounced amplitude modulation, since the deployed switches have worse performance than microwave PIN diodes.

In this work, we propose a multi-bit antenna topology that offers one bit per integrated switch and places these switches in a shunt configuration, leading to reduced system complexity and minimizing the exhibited losses. The proposed multi-bit unit-cell consist of a patch antenna, from which we draw two symmetric feed lines from the non-radiating edge (differential feed points), with an embedded switch at the end of each line. The impinging waves on the unit cell, are evenly split (3 dB) between the two lines and have 180^o phase difference. These lines have different lengths leading to an extra 90^o phase difference, to acquire quadrature modulation. Moreover, this design can be modified by placing extra lines with embedded switches (with variable lengths) on the other non-radiating edge of the patch antenna, leading to more bits. By optimizing the length of each feed line we are able to acquire one bit per embedded switch (up to 4-bits), enabling accurate beamforming with low quantization lobes and minimum losses. To the best of our knowledge, this is the first time such a design is proposed and during the conference, the theoretical principles will be presented alongside simulations and measurements.