Framework of Joint Communications and Sensing Using Two Phased Antenna Arrays

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***Abstract*—Joint communications and sensing (JCAS) receives strong interest and is promising for many emerging platforms such as unmanned aerial vehicles and smart cars. Setting up transceivers and antennas to meet the requirements for both communications and sensing is very challenging. In this paper, we propose a system architecture which allows seamless operation of JCAS and flexible configurations of transceivers and antennas, based on the use of two phased antenna arrays. The signal processing required by JCAS for the proposed system is also briefly discussed.**

I. Introduction

There are increasing demands for systems having both communications and sensing capabilities, on emerging platforms such as unmanned aerial vehicles and smart cars [1]. Sensing techniques are evolving towards advanced pattern analysis and information retrieval, based on estimating the position and speed of objects in surrounding environment. Instead of having two separate systems, it is possible to have them integrated in one system by sharing hardware and signal processing modules, and achieve immediate benefits of reduced cost, size, weight, and better spectrum efficiency. An integrated system will also benefit from mutual sharing of information for improved performance, e.g., using sensed environment knowledge to assist beamforming design [2].

Among many technical challenges for joint communications and sensing (JCAS) [3], a basic problem is how to set up transceivers and antennas to meet the requirements for both communications and sensing. An array with steerable beamforming and narrow beamwidth is typically required for sensing. However, communications require fixed and accurately-pointed beams to achieve large beamforming gain.

In this paper, we present a scheme which allows seamless operation of JCAS, while enabling flexible array configurations. We consider a system with two phased antenna arrays.Using two arrays can not only reduce leakage signal from transmitter to receiver, which is essential for making sensing work efficiently, but also provide great flexibility in designing beamforming and operation modes. Instead of generating simple single beam, we will propose a system architecture and protocol which exploits arrays' multibeam capacity, and investigate how to configure beams to meet and balance the different requirements by sensing and communications.

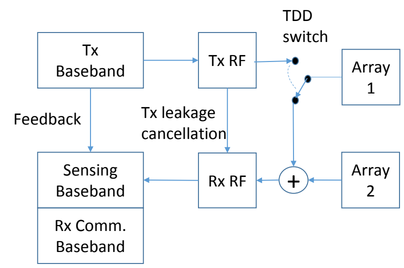

Fig. 1. Block diagram of the proposed transceiver.

II. Proposed Scheme

The system is based on time division duplex (TDD) for two-way communications. It uses two steerable antenna arrays. One is dedicated to the receiver, the other is shared by transmitter and receiver through time division. Although the proposed system is not limited to any communication schemes, we consider orthogonal frequency division multiplexing (OFDM) for its popularity in modern communication systems, and its strong potential for sensing [4].

Fig. 1 shows the block diagram of the proposed transceiver. The transmitter baseband module is common to communications and sensing. The generated baseband signal is sent to the transmitter radio frontage (RF). A TDD switch controls the time of connecting Array 1 to transmitter or receiver. The transmitter RF signal after power amplifier can also be optionally fed to the receiver RF for cancelling leakage signal from the transmitter.

At the receiver, Array 2 is always connected to the RF, and Array 1 is only connected when it is receiving signal from the other node. Although two separate receiver RF branches can also be used to connect to each array, we consider a lower-cost option where the signals from the two arrays are added together by a combiner before the RF module. Sensing and communications at the receiver baseband share some processings such as channel estimation, but are largely different. The receiver baseband also accepts feedback from the transmitter baseband, mainly for the purpose of sensing.

Fig. 2 illustrates the proposed procedure of JCAS between two nodes A and B. From a receiver's viewpoint, one complete cycle for each node includes two stages: *active sensing* (AS), and *communications and Passive Sensing* (C&PS). We refer active and passive sensing to the cases where sensing signal is

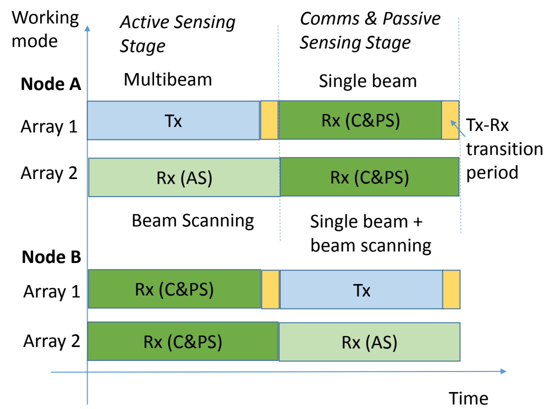

Fig. 2. Procedure of communications and sensing in a point-to-point scenario.

transmitted by the node itself and by other nodes, respectively. The major difference between them is that the transmitted signal is known in the former while it is typically unknown, but may be decoded, in the latter. In addition, the sensed environment could be different due to different propagations. The two nodes communicate in the TDD mode, and the transmitted signal from one node is used for AS by itself and for C&PS by the other node. Using Node A as an example, we describe the detailed implementations in the two stages below.

In the AS stage of Node A, when Node B is in the C&PS stage, the transmitter uses Array 1 to form multiple beams, with one beam pointing to Node B and other beams adapting to the sensing requirement. Array 2 of Node A is used for AS only. It typically forms a narrow single-beam and scans the environment. In the end of the AS stage, there is a short transition period between transmission and reception, as usually exists in a TDD transceiver. This period also serves as a guarding interval for Array 2, such that the reflected signals from its own transmitter will be separated from the received signals from Node B's transmitter in the coming C&PS period.

In the C&PS stage when Node B is in the AS stage, both Arrays 1 and 2 of Node A work in the receiving mode, and their signals are combined and processed, primarily for communications, and optionally for sensing. Sensing in this case uses transmitted signal from Node B. The two arrays in this stage can be treated equally, and optimized jointly to achieve best results for either communications only or JCAS. The channel variation due to combined beamforming variation, however, needs to be known to the receiver for successful demodulation in communications.

III. Beamforming Design and Signal Processing

For a transmitted signal $s(t)$, the general noise-free received signal after a L-path multipath channel, for both sensing and communications, can be represented as

$$r(t) = \sum_{0}^{L-1} b_\ell(t) s(t-\tau_\ell) e^{j2\pi f_{D,\ell} t}, \tag{1}$$

where τ_ℓ is the multipath delay, $f_{D,\ell}$ is the associated Doppler frequency with the ℓ-th multipath, $b_\ell(t)$ is the combined complex channel coefficient.

Consider a simple uniform linear antenna array with only phase shifters. For planar incoming signals, $b_\ell(t)$ for this array is given by

$$b_\ell(t) = a_\ell \sum_{m=0}^{M-1} e^{j(2\pi m \sin(\theta_\ell) d/\lambda - \phi_m(t))}, \tag{2}$$

where a_ℓ and θ_ℓ are the coefficient and the angle of the signal arriving at the first antenna element, respectively, M is the number of antenna elements and d is the distance between them, λ is the wavelength corresponding to the central frequency, and $\phi_m(t)$ is the applied phase shifting value. For combined signal output from two arrays, it will be the weighted sum of two terms with similar expressions to (2), with complex weights accounting for attenuation and initial phase differences in array hardware.

The basic task in sensing is to determine range, direction, and speed of environmental objects from received signals. The signal in (1) can be converted to frequency domain for estimating τ_ℓ and $f_{D,\ell}$, across subcarriers and OFDM symbols, respectively [4]. Spectrum analysis techniques such as periodogram and ESPRIT [4] are typically applied. The direction can be determined by using narrow scanning beams. The proposed system also provides great flexibilities for developing advanced sensing algorithms by exploiting beamforming vectors and techniques such as compressive sensing [5].

For sensing using OFDM signals, the phase shifting values in the receiver array need to be fixed during at least one OFDM-symbol period T_s. This results in the capability of varying beams for hundreds of times within one cycle, which shall be sufficient for a good sensing. For example, consider a system with a central carrier frequency of 24 GHz and symbol period of 2.56 us. One cycle of 1 ms can contain about 400 OFDM symbols, when the moving distance is only 4 mm for a relative speed of 40m/s.

Optimization of beam generation is a challenging task. A suboptimal and simple approach is to group phase shifters. Consider an example of generating two beams in the transmitter array. One beam is for communications and the other is for sensing. The first step is to determine the number of antenna elements allocated for each function according to their gain requirements. The total arrays can then be divided into two groups, with adjacent elements in one group. One group generates a single beam accurately pointing to the other node, primarily for communications. The other group generates a beam covering the desired area of space for sensing, taking into consideration of constructive addition to the primary beam for communications. Both beams are generally fixed over one frame period such that the other node can successfully demodulate the signal. The shape of the overall transmit beamforming needs to be considered by its receiver for scanning and sensing. Detailed design and results are omitted due to page limits, but will be presented in the conference if the paper is accepted.

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