Testing Zero-Feedback Distributed Beamforming with a Low-Cost SDR Testbed

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Abstract*— Collaborative beamforming from distributed wireless transmitters has been envisioned as a means for range extension/connectivity enhancement if the signals transmitted from distributed terminals constructively add (i.e. in phase) at the destination receiver. The research community has mainly relied on feedback schemes from the final receiver towards the distributed transmitters, either in the form of pilot signals or explicit messages that coordinate the distributed transmissions and alleviate, to an extent, the frequency and time synchronization problems. This work assumes zero-feedback from destination towards the distributed transmitters, in sharp contrast to prior art. The frequency offsets among the distributed transmitters, typically undesired in classic beamforming schemes, are turned into an advantage and offer beamforming gains through signal alignment, i.e. when the transmitted signal-phasors align in time. The idea is validated in a custom, low-cost testbed, consisting of three embedded commodity radio transmitters with highly inaccurate, internal oscillators and a software-defined radio (SDR) receiver. This collaborative beamforming demonstration, perhaps the first of its kind on zero-feedback from the final destination, could potentially spark interest on relevant critical applications with ultra low complexity portable radios such as in *emergency radio*.

I. Introduction

Collaborative beamforming from distributed wireless transmitters has been envisioned as a means for range extension/connectivity enhancement if the signals transmitted from distributed terminals constructively add (i.e. in phase) at the destination receiver. By using the term “distributed” we imply independent single antenna terminals deployed in a random structure at different locations, in contrast with their uniform placement at traditional beamforming. However, the transmitting terminals are still controlled by a central source. In that case, constructive addition of collaborative transmitters offers beamforming gain. The problem becomes more difficult compared to classic phased-array systems with co-located antennas, given the fact that collaborative transmitters typically exhibit carrier frequency offsets, as well as time synchronization errors, due to their distributed nature.

The research community has mainly relied on feedback schemes from the final receiver towards the distributed transmitters, either in the form of pilot signals or explicit messages that coordinate the distributed transmissions and alleviate, to an extent, the frequency and time synchronization problems (e.g. see [1]- [5]). A few proposals assume knowledge of the spatial distribution among the collaborative transmitters (e.g. see [6]) or assume that number of transmitters is relatively large and study asymptotic performance (e.g. see [7] and references therein). The authors in [8] in an attempt to avoid channel state information (CSI), have relied on the idea of relay nodes, introducing this way a more distributed approach. However, the destination receiver still sends feedback which adaptively adjusts the relays’ weights. Related works in [9], [10] assume the same relay selection scheme, which is based in perfect knowledge of both receive and transmit instantaneous CSI at the intermediate nodes. A feedback connection from the receiver to the relay nodes is again assumed so as to determine beamformers’ weights that maximize the receiver’s signal-to-noise ratio (SNR). Zhang et al. in [11] propose an adaptive distributed antenna transmission strategy in order to find the number of optimal nodes to participate in the beamforming process. Nevertheless, the proposed scheme needs limited feedback on CSI from the receiver. A detailed overview of existing approaches on collaborative beamforming can be found at [12].

Recent work has mainly focused on improving the quality of beamforming in distributed networks by introducing more efficient algorithms for carrier synchronization. The authors in [2], [3] propose a master-slave network architecture, necessary for locking the carrier signals, while the receiver sends 1-bit feedback, information required for phase calibration and channel estimation. Implementation and evaluation of the proposed iterative scheme with commercial software defined radios are also provided. Research papers [14], [15] emphasize more on carrier synchronization methods either by using specialized hardware at each cooperating node or by employing a time division multiple access (TDMA) scheme for the transmitters respectively. Finally, Mudumbai et al. in [16] revisit the network architecture proposed in [2], [3] but this time they suggest to restrict the random search space for possible offsets to a specific probability distribution. The authors propose minimal feedback from the destination to the transmitting terminals that guarantees convergence time dependent on the number of terminals only.

This work assumes zero-feedback from destination towards the distributed transmitters, in sharp contrast to prior art. Moreover, no carrier frequency or phase synchronization method is applied among the transmitters, assuming that we have to deal with simple commodity radio transceivers. The frequency offsets among the distributed transmitters, typically undesired in classic beamforming schemes, are turned into an advantage and offer beamforming gains through signal alignment, i.e. when the transmitted signal-phasors align in time. Repetition coding is utilized in conjunction with message passing from a local coordinator, the maestro, only close to the transmitters and not the receiver, alleviating the time synchronization problem. The idea is validated in a custom, low-cost testbed, consisting of three embedded transmitters with highly inaccurate, internal oscillators and a software defined radio (SDR) receiver. We are motivated by both low-power and low-cost sensor networks, where ultra low-complexity commodity transceivers take part; no access to the local oscillator subsystem (e.g. phased-lock loop) is assumed to be feasible. This collaborative beamforming demonstration, perhaps the first of its kind on zero-feedback from the final destination, could potentially spark interest on relevant critical applications with low-complexity portable radios (e.g. emergency radio, environmental, low-complexity wireless sensor networks).

Section II provides the basic idea of zero-feedback collaborative beamforming that exploits lack of carrier synchronization among distributed transmitters. Extensive theoretical analysis of the proposed scheme can be found in [17]. This work offers a practical demonstration. Section III describes the custom testbed used for experimental validations, while Section IV discusses the experimental findings. Finally, Section V provides the conclusion.

II. Zero-Feedback Distributed Beamforming Idea

Denoting with T_s the sampling period and assuming a flat fading model, the received baseband signal $y(nT_s) \triangleq y[n]$ at the destination receiver when M distributed terminals desire to transmit can be expressed as [17]:

$$\begin{aligned} y[n] &= \sum_{i=1}^{M} h_i \; e^{+j2\pi\Delta f_i n T_s} \; x[n] + w[n] \\ &= \underbrace{x[n] \sum_{i=1}^{M} A_i \exp\left\{+j\left(2\pi\Delta f_i n T_s + \phi_i\right)\right\}}_{\widetilde{x[n]}} + w[n] \\ &= \widetilde{x[n]} + w[n], \end{aligned} \tag{1}$$

where $h_i = A_i e^{j\phi_i}, \Delta f_i$ is the wireless channel coefficient and carrier frequency offset between transmitter i and receiver, respectively, $x[n]$ corresponds to the transmitted data symbol and finally, $\{w[n]\}$ correspond to samples from a zero-mean additive white Gaussian noise (AWGN) process, with variance N_0.

The basic idea behind zero-feedback beamforming is that the existence of carrier frequency offsets among distributed transmitters and receiver can be turned to an advantage [17]; the transmitted signals by the distributed transmitters can be viewed as phasors $A_i \exp\{+j2\pi\Delta f_i n T_s + \phi_i\}$ that rotate with different rotating speeds (depending on the different carrier frequency offsets $\{\Delta f_i\}, \; i \in \{1, 2, \ldots, M\}$. Thus, there are time instants where the signals align (within an angular sector) as time progresses, offering beamforming gains and assuming that everything else remains constant. Work in [17] exploited repetition coding (so that transmitted symbol spans more than one symbol period) and quantified for given channel coherence time (so that channel does not change), the probability of signal alignment as a function of number of distributed transmitters M, as well as expected number of symbols where such zero-feedback beamforming gains occur. Such scheme can extend range and coverage, even though NO software or hardware manipulation of carrier frequencies is required. Therefore, the scheme could be used with low-cost radios, even in scenarios where reliable feedback from destination cannot be assumed.

More specifically, channel *coherence time* spans τ_c samples, i.e. $\{h_i\}$ remain constant within τ_c samples. The received signal power per symbol for any $n \in [1, \tau_c]$ is calculated as:

$$\begin{aligned} \left|\widetilde{x[n]}\right|^2 &= |x[n]|^2 \Bigg\{ \sum_{i=1}^{M} A_i^2 + \\ &+2 \sum_{i \neq m} A_i A_m \cos\big(\underbrace{2\pi\Delta f_i n T_s + \phi_i}_{\widetilde{\phi_i}[n]} - \underbrace{2\pi\Delta f_m n T_s - \phi_m}_{\widetilde{\phi_m}[n]}\big) \Bigg\} \\ &= |x[n]|^2 \left\{ \sum_{i=1}^{M} A_i^2 + 2 \sum_{i \neq m} A_i A_m \cos\left(\widetilde{\phi_i}[n] - \widetilde{\phi_m}[n]\right) \right\}. \end{aligned} \tag{2}$$

Denoting $\mathcal{P}_T = \mathbb{E}\left\{|x[n]|^2\right\}$ the transmitted power per individual terminal - $M\mathcal{P}_T$ is the total transmitted power by all terminals - the SNR at the destination can be written as:

$$\begin{aligned} \mathsf{SNR}[n] &\triangleq \frac{\mathbb{E}\left\{\left|\widetilde{x[n]}\right|^2\right\}}{\mathbb{E}\left\{|w[n]|^2\right\}} \\ &= \frac{\mathcal{P}_T}{N_0} \left\{ \sum_{i=1}^{M} A_i^2 + 2 \sum_{i \neq m} A_i A_m \cos\left(\widetilde{\phi_i}[n] - \widetilde{\phi_m}[n]\right) \right\}, \\ &= \frac{\mathcal{P}_T}{N_0} \Bigg\{ \sum_{i=1}^{M} A_i^2 + \\ &+2 \sum_{i \neq m} A_i A_m \cos\left(2\pi(\Delta f_i - \Delta f_m) n T_s + \phi_i - \phi_m\right) \Bigg\}, \\ &= \frac{\mathcal{P}_T}{N_0} \; \mathsf{L}_{\mathsf{BF}}[n], \end{aligned} \tag{3}$$

where $\mathsf{L}_{\mathsf{BF}}[n]$ is the observed *beamforming gain* factor at sample n. Notice that this factor can be in principle close to zero, when signals add destructively and cancel each other. Work in [17] calculated the expected number of symbols where such alignment offers *strictly positive* beamforming gains.

III. Experimental Setup

In this section the low-cost experimental testbed of this work is described. Fig. 1 and Fig. 2 depict three custom embedded, software-defined radio (SDR) transceivers, used as part of the distributed transmitter, as well as a commercial SDR, used as the destination receiver.

(a) Custom beamforming transmitters (iCube).

(b) Destination receiver.

Fig. 1. Experimental setup. Beamforming transmitters along with maestro deployed and commercial SDR USRP-based destination receiver from left to right.

(a) Transmitter schematic. Maestro achieving packet synchronization.

(b) Receiver schematic.

Fig. 2. Transmitter (left) and receiver schematics (right).

A. Distributed Transmitters: Low-cost, Custom, Embedded SDR Transceiver

Each low-cost embedded transceiver consists of a $\mathrm{Chipcon/TICC2500}$ radio transceiver module, interfaced to a Silabs $\mathrm{C8051F321}$ micro-controller unit (MCU). The developed board is part of a larger infrastructure utilized for telecommunication research as well as sensor network applications and was named *iCube* [18]. That version of iCube can operate at the 2.4GHz band with maximum transmit power of $+1$dBm, programmable rates up to 0.5Mbps and various modulation schemes (OOK, FSK, GMSK, MSK); in this work, simple On-Off Keying was adopted.

Fig. 1-(a) illustrates the experimental setup of $M = 2$ beamforming iCube transmitters. Basic *transmit* and *receive* functionalities have been implemented in plain C. A third node, called maestro is also depicted in Fig. 1-(a), and performed the role of transmission coordinator.

In order to achieve packet synchronization (i.e. *synchronized distributed transmission*), one of the iCube transmitters was utilized as a maestro node. That node was responsible for transmitting a common pilot signal to $M = 2$ transmitters (Fig. 2-(a)), directing initiation of their symbol transmission. More analytically, the beamforming transmitters were initiated in “rx” state. If valid packet reception occurred, both transceivers entered “tx” state and started synchronized transmission. Such operation is feasible due to the relatively small switching time between receive and transmit operation of iCubes.

However, iCubes highly unstable MCU clocks initially provided some timing errors, which were eliminated by repetitively transmitting each data symbol. As a result, synchronized operation among the transmitting nodes was accomplished without employing an explicit time synchronization protocol. Instead, careful maestro’s coordination, along with the use of repetition coding at the beamforming transmitters offered a simple and viable solution to the symbol/time synchronization problem among the distributed collaborative transmitters.

The packet sent from each transmitter adopted the following format:

<preamble><syncword><lengthfield><datafield><CRC>

while each field’s length is programmable.

iCubes were selected mainly due to their fast frequency hopping capability, small radio switch time between receive and transmit, low cost and plethora of different controllable parameters such as: carrier frequency, type of modulation, transmission power, receiver filter bandwidth, number of preamble bits used for bit-level synchronization, cyclic redundancy check (CRC), automatic gain control (AGC) and receive signal strength indication (RSSI). As a consequence, we have chosen simple low-cost commodity radios for the transmitting part of our testbed, as no sophisticated carrier synchronization or physical layer processing is required for proving the concept of the proposed zero-feedback scheme.

B. Receiver: Low-cost, Commercial SDR

The Universal Software Radio Peripheral (USRP) was utilized as a low-cost Software Defined Radio (SDR) receiver. USRP consists of a motherboard containing four 12-bit analog-to-digital converters (ADCs), four 14-bit digital-to-analog converters (DACs), a programmable Cypress FX2 USB 2.0 controller, an Altera FPGA for high rate signal processing and daughtercards which implement front end functionality. Flex2400 cards which operate at 2300-2700MHz frequencies were used for our experiments. The USRP also provides data buffers both in the FX2 and FPGA. The FX2 provides 2KB each for TX and RX, and the FPGA provides an additional 4KB each.

Furthermore, USRPs follow a direct conversion (homodyne) receiver architecture, producing two baseband signals, the inphase (I) and quadrature (Q) component, with the help of a decimation filter implemented at the FPGA part of the board (Fig. 2-(b)). The typical I/O stream is 32 bits of I/Q samples. The USB2 rate is 60MB/sec and the USRP can theoretically transfer 15 Msamples/sec. The physical layer processing is carried out on the PC that hosts the device, by using the GNU Radio framework. However, the USRP uses a single FIFO which collects streams of received data. As a result, we developed a simple energy-based packetizer, in order to discern packet boundaries and make individual processing.

IV. Experimental Proof-of-Concept Results

In the experimental implementation of this work, beamforming transmitters were set to operate at $f_c = 2.436$GHz while they used $f_c = 2.438$GHz in order to communicate with the *maestro* node. Both frequencies were chosen after careful RF background measurements with a spectrum analyzer, to avoid interference from other RF sources. Symbol rate (baud rate) was set to 2000 symbols per second, sampling period duration at the receiver was $T_s = 4$ μsec and repetition of 10 consecutive symbols of the same data was exploited. Furthermore, the *average* frequency skew of the iCubes' radio module clock crystals was found ~ 20 parts per million (ppm) according to radio module manual.

Fig. 3-(a) provides the energy of the received signal as a function of time, when $M = 1$ or $M = 2$ transmitters operate (in the latter case, with zero-feedback beamforming). From Section II it can be easily seen [17] that beamforming factor $\mathsf{L}_{\mathsf{BF}}[n]$ is lower-bounded by:

$$\mathsf{L}_{\mathsf{BF}}[n] \geq \left\{ \sum_{i=1}^{M} A_i^2 + 2a \sum_{i \neq m} A_i A_m \right\} = \\ = \mathcal{O}\left(M + 2a \binom{M}{2} \right) = \mathcal{O}\left(M[1 + a(M-1)] \right),$$

where $\mathcal{O}(\cdot)$ is the mathematical symbol for order of magnitude and $0 < \alpha < 1$ is an alignment parameter (where 1 means that phasors are perfectly aligned and 0 corresponds to the case of destructive alignment). The upper bound of the beamforming gain can be at best, a factor of M^2.

For $M = 2$ and perfect alignment, received SNR and energy should be improved by a factor of 4. From Fig. 3-(a) it can be seen that indeed, the received signal energy improvement does not exceed the above factor (from approximately 350 is increased to approximately 1250 units, thus the improvement ratio is below 4).

The fact that received SNR is improved (by no more than a factor of $M^2 = 4$ or 6 dB in a logarithmic scale) can be also seen at Fig. 3-(b), where a different experiment is run; the SNR is estimated after processing of the received signal and is plotted as a function of received signal symbol index. Again, it can be seen that zero-feedback collaborative beamforming, as experimentally tested with the ultra-low complexity transceivers of this work, improves received SNR, compared to single-node, non-collaborative transmission.

In contrast to the ideal distributed beamformer where the SNR performance improvement would be on the order of $M^2 \rightarrow 6$dB, the evaluation of the proposed scheme for $M = 2$ distributed transmitters gives us almost ~ 1.5dB less than the ideal case. Nevertheless, apart from the increase in signal-to-noise ratio at the receiver, we gain connectivity between our transmitters and the destination comparing to the non-beamforming case of $M = 1$ transmitter.

V. Conclusion

Zero-feedback collaborative beamforming feasibility was demonstrated with a low-cost testbed, exploiting lack of carrier synchronization among distributed transmitters. By turning into an advantage the frequency skew that every commodity radio transceiver experiences and without demanding any type of feedback from the destination we validated experimentally an increase in both energy and received signal-to-noise ratio. In that way, we proved that there is no need for perfect CSI knowledge or explicit carrier synchronization (specialized hardware) between the transmitting terminals so as to achieve beamforming gains. The proposed implementation can also apply in sensor networks where distributed clustering schemes have been proposed in order to fuse information throughout the network, when a single node is not able to directly communicate with the final destination, i.e. in scenarios where feedback is not an option.

Future work will focus on the design and deployment of a non-coherent receiver for the proposed scenario. Moreover, undergoing work is done over appropriate synchronization and detection techniques in order to evaluate the system's performance and compare it with scenarios where different number of transmitters M collaborate or more efficient detection and coding schemes (other than repetition) are employed.

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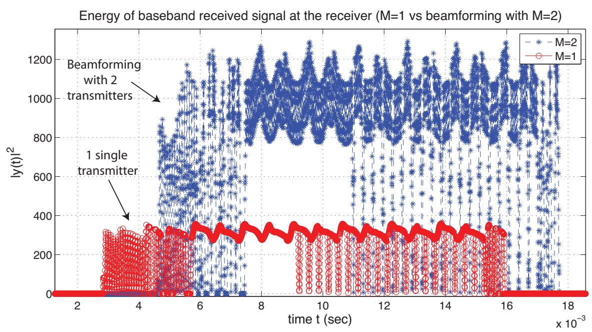
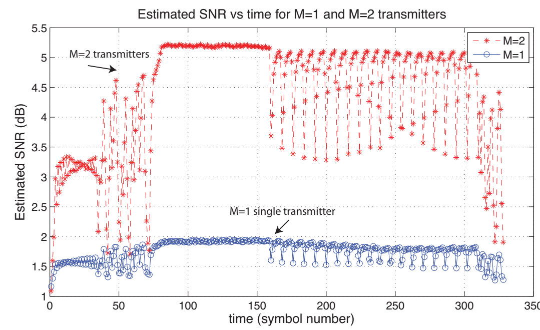


(a) Energy received at the USRP: 1 transmitter vs 2 transmitters with proposed, zero-feedback beamforming.



(b) Signal to Noise ratio as a funtion of time with $M = 2$ versus $M = 1$ transmitters.

Fig. 3. Energy received at the USRP and Signal to Noise ratio: $M = 1$ transmitter vs $M = 2$ beamforming transmitters from left to right.

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