

A Feedback-Based Distributed Phased Array Technique and Its Application To 60-GHz Wireless Sensor Network

Munkyo Seo, Mark Rodwell and Upamanyu Madhow

Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106-9560, Email: mkseo@ece.ucsb.edu

Abstract—A feedback-based approach is proposed to achieve phase-frequency synchronization among physically isolated sensors. This will enable forming a distributed phased array to significantly increase the communication range between energy-limited sensor fields and the central information collector. A three-element distributed phased array is prototyped based on a 60-GHz wireless sensor network. A 9.2 dB of distributed beamforming gain is demonstrated.

Index Terms—Phased array antenna, feedback, distributed beamforming, wireless sensor network.

I. INTRODUCTION

Wireless sensor networks continue to prove useful for robust and reliable information collection over a certain sensor field [1]. In such networks, wireless sensors are typically subject to severe energy constraint for the requirement of low maintenance, long battery life, small form factor, etc. This inevitably limits the sensor transmit power, making it impossible to transmit the sensor data over a very long distance.

An interesting possibility to extend the communication range is to group a number of neighboring sensors and adding up their transmit power [2], as shown in Fig. 1. In other words, a group of near-by sensors can form a *virtual antenna array*, or *distributed phased array* (as opposed to *regular* phased array in Fig. 2). If N sensors collaborate in this way, their aggregate transmit power will increase by a factor of N^2 , extending the communication range by N . The challenge in this approach is to make sure individual sensor RF carrier reach the receiver with the same frequency and phase.

In a regular phased array, this phase-frequency synchronization across the array is of no concern, because the entire array can easily share a common frequency standard. Further, the array's regular geometry makes it straightforward (at least in principle) to control the relative phase shift of each element. In a distributed phased array, however, not only the location of each sensor element is practically unknown, but also sharing a common local oscillator (LO) is not straightforward (broadcasting a frequency pilot is considered in [3] at the penalty of increased hardware complexity).

The concept of phase-conjugating array (or *self-phasing*, *self-steering*, etc) [4] is closely related to distributed

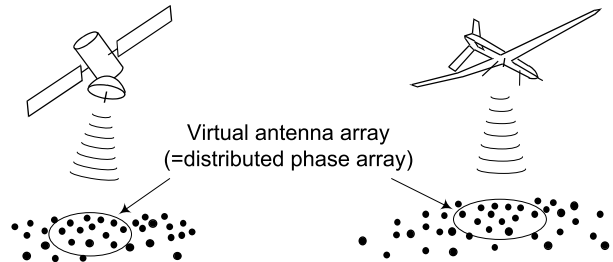


Fig. 1. Virtual sensor array for the sensor reachback problem

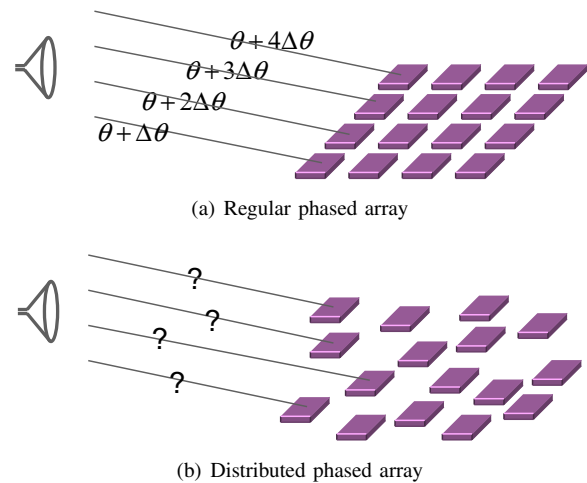


Fig. 2. Regular and *distributed* phased array

phased arrays, since it is capable of steering the reflected beam to the incident angle with no priori knowledge or no array regularity. The entire array, however, needs to use the same LO frequency to achieve phase conjugation.

In this paper, we present a feedback-based approach to the distributed phased array. In the next section, we describe the proposed method. Next, experimental results on a 3-element distributed phased array are discussed.

II. FEEDBACK-BASED PHASE-FREQUENCY SYNCH

The proposed method derives from a previously published technique [5], [6] where the phase of sensors are

gradually lined up (assuming no frequency error) in a random-walk fashion, but in a guidance of a feedback signal from the collector receiver. In this section, we extended the previous method to further synchronize sensor frequencies, as well as phases. This will require modification of the sensor hardware as well as overall signal processing.

A. System Model

Let $y_k(t)$ the k -th sensor transmit signal given as

$$y_k(t) = m_k(t)e^{j\omega_k t + \theta_k}, \quad (1)$$

where ω_k and θ_k are the frequency and phase of the k -th sensor LO. $m_k(t)$ is the k -th sensor's message to send to the collector. The collector receives all sensor signals, so its receive power is

$$r(t) = \sum_k^N h_k y_k(t), \quad (2)$$

where N is the number of sensors in the cluster which the collector is currently aimed at. h_k models the complex-valued gain of k -th sensor propagation channel. The phase of h_k is practically unknown, and may be even subject to time variation due to fading, atmospheric condition, sensor displacement, etc. The phase of h_k can be lumped to θ_k with no loss of generality.

B. Phase-Frequency Control by 1-Bit Feedback

We assume that a group of near-by sensors share the same message signal (i.e. baseband data. '1' or '0' in the simplest case) [2], [5]. In other words, sensor measurements are highly correlated within a certain vicinity. Therefore, $m_k(t) = m(t)$ for all sensors in the same cluster.

We also assume that there exists a common feedback channel with a low bit-rate (e.g. a few Kbps) from the collector to all sensors, whether the distributed array has achieved synchronization or not. This is believed realistic, because the central collector is, in general, not resource-limited.

The proposed feedback-based synchronization algorithm works in a feedback cycle with a period T_{fb} . The following steps constitute a single feedback cycle.

- 1) Each sensor makes an independent random adjustment to its LO phase θ_k ,

$$\theta_k[n] = \theta_k[n-1] \pm \Delta\theta, \quad (3)$$

where $\theta_k[n]$ is the LO phase at n -th feedback cycle. $\Delta\theta$ is a small constant ($\Delta\theta \ll 1$).

- 2) The collector measures the average power of $r(t)$ during the n -th cycle, $P_r[n]$,

$$P_r[n] = \frac{1}{T_{fb}} \int_{T_{fb}} |r(t)|^2 dt. \quad (4)$$

Then, it compares $P_r[n]$ with the previous measurement $P_r[n-1]$. A 1-bit signal $f[n]$ is generated depending on the comparison results,

$$f[n] = 1 \text{ if } P_r[n] > P_r[n-1]; 0 \text{ otherwise.} \quad (5)$$

This 1-bit signal is broadcast to all sensors.

- 3) If $f[n] > 1$, each sensor keeps the phase adjustment made earlier. Otherwise, it is discarded.
- 4) Finally, each sensor makes the following frequency adjustment.

$$\omega_k[n] = \omega_k[n-1] + \alpha(\theta_k[n] - \theta_k[n-1]), \quad (6)$$

which can be achieved by tuning a voltage-controlled oscillator (VCO).

Note that the feedback signal $f[n]$ is common to all sensors, not specific to each sensors. Important system parameters are $\Delta\theta$, α , and T_{fb} . Under appropriate choices of these parameters, the feedback loop will lead to phase-frequency equalization without creating instability. $\Delta\theta$ is a single step for each sensor's *random phase walk*. Simulation shows that $\Delta\theta = (1/20)\pi$ is a good trade-off between convergence speed and steady-state phase error. In general, α should be chosen sufficiently small. Otherwise, the loop may undergo instability. If the feedback rate is high (i.e. small T_{fb}), then, in general, the loop can compensate for a larger initial frequency errors. However, this will make the collector power measurement relatively noise under additive gaussian noise (due to a small integration interval in (4)). Simulation suggests that the overall convergence time is a strong function of the total number of sensors participating. A sample simulation results of a 10-sensor distributed phased array are presented in Fig. 3.

There are two major differences between the proposed and previous technique [5]: First, frequency synchronization is made possible by tuning a VCO based on a long-term observation of phase adjustment (6). It can be shown that (6) serves as an equivalent frequency error detector. Second, the 1-bit feedback signal is based on *differential* power measurement ((5)), rather than a comparison with the highest receive power in the past [5]. Differential power measurement substantially improves the loop performance in the presence of frequency error.

III. EXPERIMENTAL VERIFICATION

In this section, we present experimental verification of the proposed distributed phased array. The proposed distributed phased array technique is applied to the experimental 60-GHz wireless sensor network [7], [8].

A. System Setup Based On 60-GHz Wireless Sensor Network

Fig. 4 illustrates the overall system. Originally, this system is developed to demonstrate the imaging-based approach to wireless sensor network. Sensor data is collected

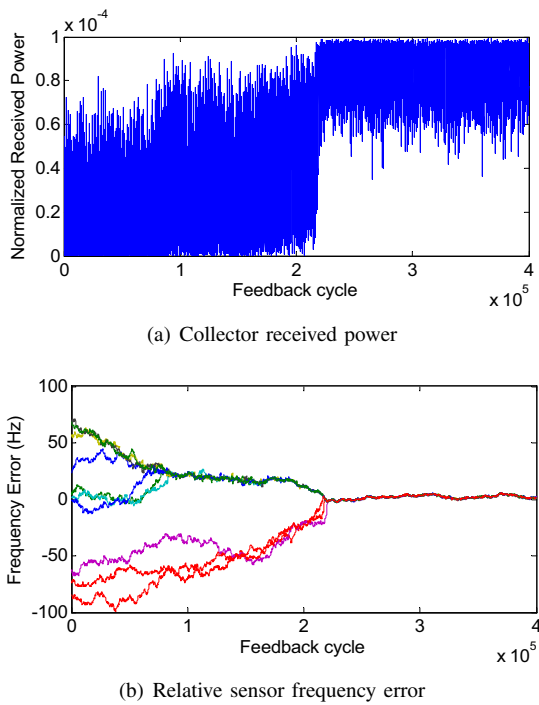


Fig. 3. A sample simulation results: $N=10$, $\Delta\theta = (1/20)\pi$, $\alpha = 0.05$, and $T_{fb} = 10^{-3}$. A phase-frequency synchronization is achieved after 22,000 feedback cycles. Initial frequency errors are uniformly distributed within $\pm 10\%$ of the feedback rate.

by *passive* reflection, similar to the RFID technology, and the 3-D location of sensors is identified by employing radar principle and matched filtering. For the present demonstration, several system modifications were necessary.

The operation of the overall system is summarized as follows: First, the collector transmits a 60-GHz single-tone signal toward a group of three sensors. Second, each sensor, upon receiving the 60-GHz beam, shifts its frequency by a 30 MHz LO, and re-transmit it back to the collector. Third, the collector receives a combined signal from all three sensors, and compares the current signal strength to the previous one. Then, a 1-bit feedback signal (at 2 KHz) is generated as a result, and sent to all three sensors. Finally, sensors use the feedback data to update their current estimate of the LO phase and frequency, as discussed in the earlier section.

See Fig. 5 for the sensor block diagram. Signal reception and re-transmission is achieved by a single open-slot antenna. A 30 MHz LO modulates a PIN diode bias, and this also changes the termination impedance seen by the antenna. The frequency of the reflected signal is, therefore, shifted by 30 MHz. This frequency shift allows the collector to selectively receive sensor signals by filtering out direct echoes from the environments. The feedback-based algorithm is implemented in a low-cost

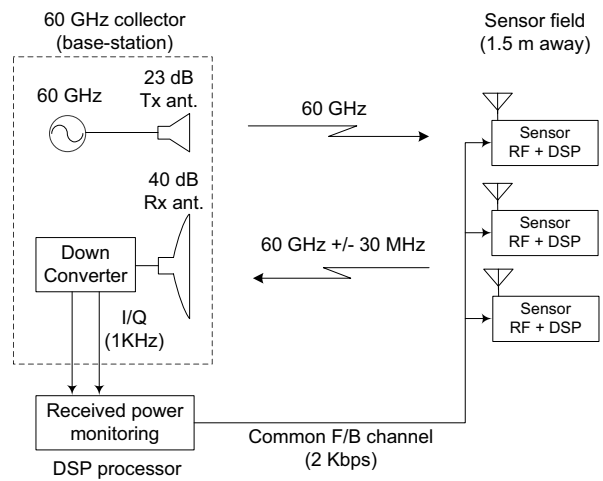


Fig. 4. Experimental system setup for the proposed distributed phased array.

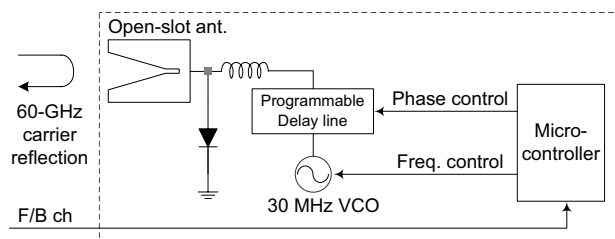


Fig. 5. Block diagram of each 60-GHz sensor with frequency-phase tuning capability.

microcontroller [9] to continuously adjust the frequency and relative phase of the 30 MHz LO.

In the current prototype, the feedback channel is implemented as a wire for easy system construction. Implementing wireless feedback is, however, entirely feasible with no major technical difficulty. Fig. 6 shows the photo of the entire system setup.

The following loop parameters are chosen: $\Delta\theta = (1/20)\pi$, $\alpha \simeq 10^{-2}$, and $T_{fb} = 1/2\text{KHz} = 0.5$ ms. The sensitivity of the sensor VCO (Fig. 5) is approximately 300 Hz/V.

B. $N=3$ Distributed Phased Array: Measured Beamforming Gain

Now, our goal is to form a virtual phased array of three entirely isolated sensors, each running off an independent 30 MHz LO. The initial frequency error among three LO's, before closing the feedback loop, is measured approximately 100 Hz (≈ 3 ppm of 30 MHz or 5% of the feedback rate). Once the loop is closed and convergence achieved, the reflected 60 GHz signals from each sensor will arrive at the collector receive antenna with the same frequency

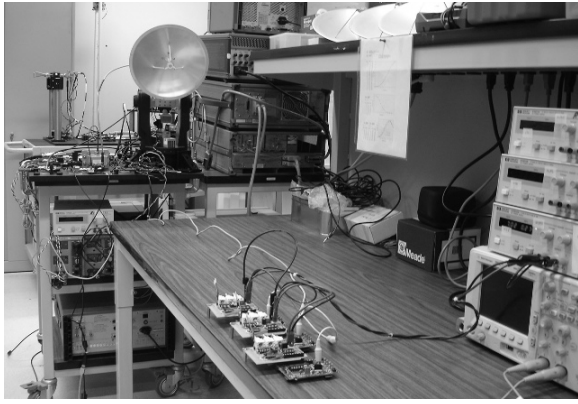


Fig. 6. System setup photograph. A cluster of three sensors (bottom) are 1.5 m away from the base station (top left).

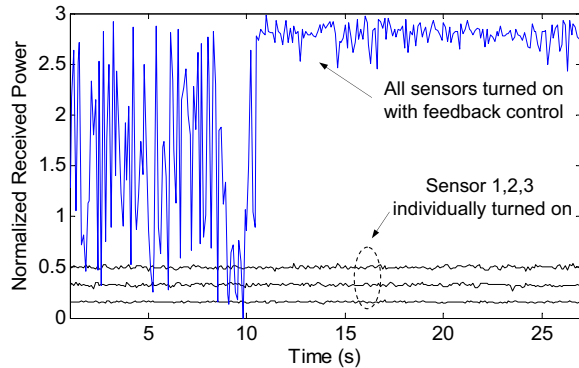


Fig. 7. Measured collector receive power. Although the actual measurement rate is 2 KHz (i.e., feedback rate), only one sample out of 200 was sent to a computer (i.e. 10 Hz) to reduce computational burden of the DSP processor.

and phase. Note that, other than the initial LO frequency error, only a slight change in sensor location will produce significant phase change ($\lambda_{\text{freespace}} = 5 \text{ mm}$ at 60 GHz).

First, the collector receive power is measured with sensors individually turned on. Measurement shows that each sensor produces 0.325, 0.158, and 0.50 of normalized power at the collector receiver (lower traces on Fig. 7). Assuming perfect phase and frequency control, the total power of the distributed phased array is expected to be

$$P_{\text{array}} = \left(\sqrt{P_1} + \sqrt{P_2} + \sqrt{P_3} \right)^2 = 2.802, \quad (7)$$

where P_k is the collector power due to the k -th sensor alone. Next, the feedback loop is closed, and the total receiver power was monitored and plotted against the time in Fig. 7. The initial nonzero frequency error results in periodic fluctuation of the measured power. After 11 seconds, however, synchronization is achieved among sensors, producing 2.747 of (time-averaged) normalized power. This is close to the prediction (7), and amounts to

9.2 dB of array gain (theoretical power gain of a *uniform* 3-element array is equal to $20\log_{10}3 = 9.5 \text{ dB}$). Similar results were obtained with two-sensor configurations.

IV. CONCLUSION

A feedback-based approach is proposed to achieve phase-frequency synchronization among isolated wireless sensors. Experimental verification is also presented based on 60 GHz wireless sensor network. Three-sensor distributed array experimentally achieved 9.2 dB of beamforming power gain. To the best of authors' knowledge, this paper is the first proposal and demonstration of the distributed phased array accounting for sensor frequency error, as well as static phase misalignment. Analysis of the nonlinear loop behaviors is currently under investigation.

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