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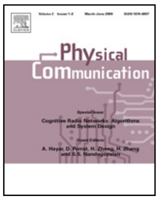

Full length article

A Distributed and Collaborative Beamforming algorithm for a self-organizing Wireless Sensor Network[☆]

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ABSTRACT

In this paper the scenario where sensors of a Wireless Sensor Network (WSN) are able to process and transmit monitored data to a far collector is considered. The far collector may be a Base Station (BS) that gathers data from a certain number of deployed WSNs, in applications such as earthquake, tsunami, or pollution monitoring. In this paper, the possible use of Distributed and Collaborative BeaMForming (DC-BMF) technique is analyzed, with the goal of enhancing the capability of a single sensor to communicate its data to the far collector. This technique considers nodes as elements of a phased array, where the phases of the signals at each antenna node are linearly combined in order to adjust the directional gain of the whole array. In particular, a novel self-localization technique for WSNs performing DC-BMF is studied, a closed form solution for beamforming gain degradation is derived and the evaluation of the power consumption of the proposed DC-BMF algorithm is provided.

1. Introduction

The advent of sensor network technology [1] is allowing tackling new applications, which had been considered unapproachable in the past. One such application involves a WSN with a certain number of sensor nodes randomly placed in the space, deployed to collect information from the environment. The nodes process sensed data, if necessary, and then send them to a far away point, for example a BS that collects data from a certain number of deployed WSNs. This information needs to travel over a relatively long distance, which may set heavy transmission gain requirements over the WSN. Furthermore, computational costs must typically be kept as low as possible and uniformly distributed in time and among nodes, in order to maximize the WSN lifetime [2], whose common definition is the shortest life among the nodes [3].

In this paper we examine the possibility of exploiting collaborative diversity [4] among the nodes to achieve a large transmission range, employing what we denote as Distributed and Collaborative BeaMForming (DC-BMF). This technique considers nodes as elements of a phased array, where the same data are synchronously transmitted by all the nodes, each employing a proper phase, tuned in order to shape the Array Factor (AF) and enhance the directional gain of the whole array [5]. We then discuss the practical details of its implementation and analyze its performance in the presence of non-idealities. Precise power consumption estimation and evaluation of the minimum number of nodes required to obtain a given beamforming gain are presented, proving the feasibility of the DC-BMF algorithm in a practical scenario. Furthermore, a novel solution for distance estimation is presented, based on the joint use of Carrier Phase Tracking (CPT) and range measurement techniques. Part of this paper was presented in our earlier conference paper [6], where the idea of

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Distributed Collaborative Beamforming was introduced within the framework of HAP applications.

Some prior art considers the problem of beamforming in a narrowband environment, with precisely known elements location and response, is well documented in the literature [5] [7]. In [8] it has been shown that randomly generated arrays with a large number of elements can form a good beam pattern with high probability, and in [9] the performance of a blind centralized beamforming algorithm operating on a randomly distributed sensor array has been investigated. The coordination of collaborating sensors is considered in [10] and [11], while in [12], Ochiai et al. analyze the achievable performance of a collaborative beamforming technique for randomly and uniformly distributed sensors in a two dimensional disk of given radius. A study on practical collaborative beamforming implementation is proposed in [13], while the problems of sensor localization and synchronization are discussed in [12] and [14]. Authors in [15] provide strategies for selecting the participating nodes in a DC-BMF scheme, while [16] considers the application of DC-BMF to WSNs, modeling the localization error of the sensor nodes with a Gaussian probability density function.

The rest of the paper is organized as follows. Section 2 provides a summary of the system model and some theoretical remarks on phased arrays. The two main sources of beamforming gain degradation, i.e. localization and time synchronization inaccuracies, are described in Sections 3 and 4. Furthermore, in Section 3 the novel self- localization technique based on the use of classic CPT and range measurement techniques is described. In Sections 5–9, the problems involved in the Distributed and Collaborative BeaMForming (DC-BMF) algorithm are described, such as the algorithm steps, the effects of the localization error and the consequent selection of the number and location of the collaborative nodes. Section 10 discusses the limitations on the maximum number of nodes and the relative achievable gain, Section 11 contains the power consumption evaluation, while the conclusions are drawn in Section 12.

2. System model and phased arrays theory

In Fig. 1 the reference system scenario is depicted [12]. The WSN nodes are supposed to lie on the x–y plane and the far away target location is given in spherical coordinates (A_0, ϕ_0, θ_0). Each sensor-node location is expressed in polar coordinates [17]: the kth node has coordinates (r_k, α_κ). Furthermore, $\theta \in [0, \pi]$ represents the latitude of a point, while $\phi \in [-\pi, \pi]$ represents its longitude.

The same assumptions as [12], are considered, i.e. the location of each node is chosen randomly, following a uniform distribution within a disk of radius $R_{\max}$, the channel is assumed quasi-stationary, with known attenuation during the localization and beamforming processes, each node is supposed equipped with a single ideal isotropic antenna, and mutual coupling effects among antennas belonging to different nodes are supposed negligible due to their distance.

A transmitting phased array is a system able to coordinate a certain number of sensors to simultaneously transmit a signal (each sensor adding a specific phase offset) in order to obtain the effect of electronically steering the overall beam of the array toward an *a priori* known direction. The target, toward which the array shapes the beam, ideally receives a linear combination of all the signals transmitted by the array.

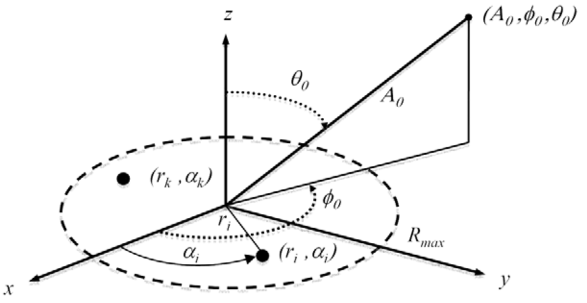

Fig. 1. System model.

The AF, previously cited, is defined in [12] as

$$F(\phi, \theta|\underline{r}, \underline{\psi}) = \frac{1}{N}\sum_{k=1}^{N} e^{j\psi_k} e^{j\frac{2\pi}{\lambda} d_k(\phi,\theta)} = \frac{1}{N}\sum_{k=1}^{N} e^{j\frac{2\pi}{\lambda}[d_k(\phi,\theta)-d_k(\phi_0,\theta_0)]} \tag{1}$$

where

$$\psi_k = -\frac{2\pi}{\lambda} d_k(\phi_0, \theta_0) \tag{2}$$

is the initial phase of the kth node, $\underline{r} = [r_1, \dots, r_N]$, $\underline{\psi} = [\psi_1, \dots, \psi_N]$, and

$$d_k(\phi, \theta) = \sqrt{A_0^2 + r_k^2 - 2A_0 r_k \sin(\theta)\cos(\phi - \alpha_k)} \tag{3}$$

is the Euclidean distance between the kth node and the target location (A_0, ϕ_0, θ_0), λ is the wavelength of the radiofrequency carrier and N is the number of nodes of the array.

Another assumption is that the well known far field approximation $A_0 \gg r_k$ holds. Furthermore, we do not loose generality if we consider $\theta = \pi/2$. Given these hypotheses, we can rewrite (3) and (1), as

$$d_k(\phi, \theta = \pi/2) \approx A_0 - r_k\cos(\phi - \alpha_k) \tag{4}$$

$$\tilde{F}(\phi \mid \underline{r}, \underline{\psi}) = \frac{1}{N}\sum_{k=1}^{N} \exp\left(j\frac{2\pi}{\lambda} r_k[\cos(\phi_0 - \alpha_k) - \cos(\phi - \alpha_k)]\right) \tag{5}$$

where $\tilde{F}(\phi \mid \underline{r}, \underline{\psi})$ is the approximated version of the AF that will be considered in the following.

3. Self-localization

In a WSN, self-organization capabilities are important because they provide the network with the ability to collect, share and exploit all the external information to perform its task autonomously. In our framework the