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Some aspects of DOA estimation using a network of blind sensors

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ABSTRACT

Recently, the DOA (direction of arrival) estimation of an acoustic wavefront has been considered in a setting where the inference task is performed by a wireless sensor network (WSN) made of isotropic (hence individually useless) sensors. The WSN was designed according to the SENMA (SEnsor Network with Mobile Agents) architecture with a mobile agent (MA) that successively queries the sensors lying inside its field of view. In this paper the ideal assumption previously made that the visibility of individual sensors is governed by deterministic laws is relaxed; this yields, interestingly, simpler analytical formulas. Both fast/simple and optimal DOA-estimation schemes are proposed, and an optimization of the MA's observation management is also carried out, with the surprising finding that the MA ought to orient itself at an oblique angle to the expected DOA, rather than directly toward it. The extension to multiple sources is also considered; intriguingly, per-source DOA accuracy is higher when there is more than one source. In all cases, performance is investigated by simulation and compared, when appropriate, with asymptotic bounds; these latter are usually met after a moderate number of MA dwells.

1. Introduction

The direction of arrival (DOA) estimation is a key topic in statistical signal processing, with relevant practical impact and well established approaches and methodologies, see e.g., [1–6] and therein references for useful entry points to that literature. Some recent papers [7–10], however, addressed the issue in a specific and relatively new scenario whose main features are: (i) the estimation system consists of a wireless sensor network (WSN) [11–18] with a SENMA (SEnsor Network with Mobile Agents) architecture [19–22]; (ii) sensors (also referred to as *nodes*) are isotropic, hence completely blind to DOA, and they are only capable of sensing the incoming signal and of recording the impinging time instant; (iii) the mobile agent (MA) does not know the number nor the position of the nodes, i.e., sensors are unlabeled and disseminated at random; (iv) nodes have very limited communication capabilities, since they can only recognize a wake-up signal to switch from sleep to working mode and, when operating in this latter modality, they can transmit short beeps; (v) the sought DOA refers to an acoustic (plane) wavefront, while beeps are electromagnetic. We can summarize this setting by saying that the acoustic-wave DOA estimation must be accomplished by a network of *dumb beepers*.

As to the choice of the SENMA, we stress that the recent growing interest in this paradigm is mainly motivated by some key advantages over alternative architectures (such as multi-hop protocols) in terms of energy savings and scalability [19–22]. In addition, the SENMA scheme is particularly suited to applications where it may be not safe or not convenient to deliver informations towards a fusion center (or exchanging informations among sensors) while the system is sensing the environment. In these cases, separating the environmental monitoring from the estimation stage can

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be in fact a necessity. In the SENMA, the MA (think of a wheeled rover or an aircraft, for instance) travels across the surveyed area and repeatedly polls the sensors lying inside its field of view (FOV). As shown in [7–10], a viable DOA estimation strategy may be accordingly conceived: when polled, each sensor transmits a periodic train of beeps and the aggregate of these signals is what the MA observes. Based on this information, after an appropriate number of network polls, the MA can estimate the sought DOA.

While we borrow the scenario and the basic ideas from [7–10], the main contribution of this paper is to relax some of the over-idealized assumptions made in these earlier works, and to address some related new issues not considered before:

- A more physically appealing model for the FOV is introduced (shaded FOV). Using that, we first propose a very simple DOA estimation method based on the empirical spread of the data. Then, the maximum likelihood (ML) estimator is investigated (we loosely call it the *optimal* estimator) and its asymptotic performances (Fisher information) are analytically derived. We are able to find a closed-form result based on a Gaussian FOV model; despite the relaxation of assumptions, the expressions are simpler than those previously reported.
- We formulate and solve the problem of optimizing the MA's path (actually, orientation) while polling. We find significant performance enhancement from a rover FOV that is *squinted* near, but not at, the current DOA estimate.
- The problem of possible inaccuracies in determining the wavefront hitting time is also briefly discussed. Under the assumption of Gaussian timing errors, we still derive the ML estimator and the Fisher information. The pertinent formulas admit a straightforward interpretation, in the light of those found without accounting for timing inaccuracies.
- We then consider the multiple-source problem in which the correlations arising from the interaction of the planar wavefronts from different sources with the network's sensors are properly exploited. This requires a slightly more sophisticated communication protocol with respect to the previous approach, but the estimation performances can be significantly improved. An appealing result here is that the accuracy is actually *enhanced*: the DOA of each of two sources is more closely estimated than it would be if it were the only source.

The reference scenario is depicted in Fig. 1, where some symbolisms and notations are also introduced: $\theta_i \in (0, \pi)$, $i = 1, 2$, are the DOAs of the acoustic waves that impinge at different and arbitrary times on the sensor network; later on, a MA polls the sensors within its FOV. The model of this latter implies that sensors closer to the MA have larger probability of being seen, with respect to farther nodes. At each snapshot the MA's FOV has a different and arbitrary orientation $\phi_s \in (0, 2\pi)$, with $s = 1, 2, \ldots,$ the snapshot index. It is convenient to model such a sequence $\{\phi_s\}_{s=1}^{\infty}$ as independent realizations of a random variable uniformly distributed in $(0, 2\pi)$, an assumption that we relax in Section 2.4. In any case we assume that successive

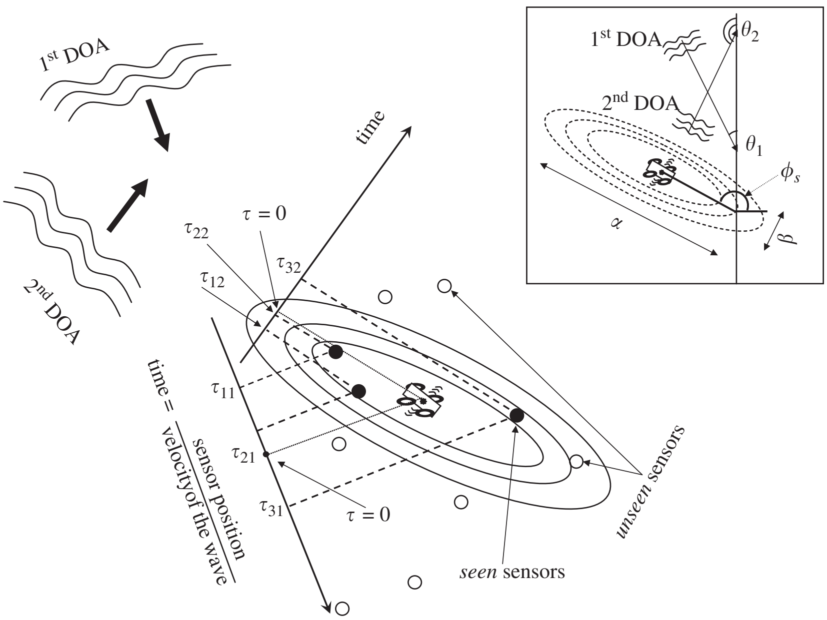

Fig. 1. The reference scenario. The MA is depicted as a rover and its field of view as a family of ellipses where the probability that a sensor is seen stays constant. (Farther sensors have smaller probability of being seen.) In this example two sources with different DOAs impinge the network at arbitrary times prior of the MA visit. Note how the ordering and the relative delays of the impinging times depend upon the DOA. The separate box introduces some definitions: α and β measure the ellipses' major and minor axes, respectively; θ_i, $i = 1, 2$ represent the two DOAs; and ϕ_s is the MA orientation at current snapshot s.