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A multi-model sequential Monte Carlo methodology for indoor tracking: Algorithms and experimental results

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ABSTRACT

In this paper we address the problem of indoor tracking using received signal strength (RSS) as a position-dependent data measurement. Since RSS is highly influenced by multipath propagation, it turns out very hard to adequately model the correspondence between the received power and the transmitter-to-receiver distance. Although various models have been proposed in the literature, they often require the use of very large collections of data in order to fit them and display great sensitivity to changes in the radio propagation environment. In this work we advocate the use of switching multiple models that account for different classes of target dynamics and propagation environments and propose a flexible probabilistic switching scheme. The resulting state-space structure is termed a generalized switching multiple model (GSMM) system. Within this framework, we investigate two types of models for the RSS data: polynomial models and classical logarithmic path-loss representation. The first model is more accurate however it demands an offline model fitting step. The second one is less precise but it can be fitted in an online procedure. We have designed two tracking algorithms built around a Rao-Blackwellized particle filter, tailored to the GSMM structure and assessed its performances both with synthetic and experimental measurements.

1. Introduction

The problem of indoor tracking has recently received a great deal of attention. The reasons obviously include its many practical applications (e.g., security, guidance, tourism, healthcare, etc. [1–6]) but also the availability of ubiquitous existing communication network infrastructures that can be used for the positioning of mobile terminals. In particular, most current wireless communication networks (WiFi, ZigBee or even cellular networks) provide radio signal strength (RSS) measurements for each radio transmission. The RSS depends on the transmitter–receiver distance and, therefore, it can be used as ranging data for positioning if a suitable model of this dependence is available.

Unfortunately, the construction of such models is far from trivial [7,8]. Indeed, the RSS is strongly affected by radio propagation phenomena such as scattering or multipath. As a result, RSS measurements are very unstable in practical scenarios. Some authors approach this problem using a class of methods known as fingerprinting [7,9]. These methods are based on the construction of a radio map that associates directly the RSS measurements to positions on the area of interest. When tracking is performed, new measurements are compared against the RSS values stored in the database, the closest match is selected and the position in the map associated to this match is chosen as the estimate of the target position.

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These methods require a costly and lengthy calibration procedure and are strongly linked to the specific physical environment. Therefore, if the scenario changes a whole new radio map has to be built.

In order to avoid this burden, other approaches aim at fitting a mathematical model of the data that yields an explicit expression of the RSS measurements as a function of the transmitter–receiver distance. In this case, the usual choice is the classical log-normal path-loss model with attenuation factors that depend on the building floors or building materials [10]. However it has also been shown that the distribution of the RSS measurements can be non-Gaussian, left-skewed, device-dependent and even multimodal depending on the physical environment [11]. Overall, there is a need for flexible models that can be easily adapted to various kinds of indoor scenarios and handle the effect of scattering or multipath propagation properly.

The design of efficient target tracking algorithms not only requires a proper selection of the model for the observed data, but also the dynamics (i.e. the type of motion) of the target needs to be adequately dealt with [12,13]. Of special interest in this context is the combination of multiple motion models that has been proposed and investigated in connection with the problem of maneuvering target tracking (see, e.g., [14,15] and references therein). This type of representation of the target motion has a characteristic switching structure, where a random sequence of indices determines the dynamic regime adopted by the target at every time step [16]. One class of state-space dynamic systems that enables the incorporation of multiple models both for the target motion and the collected observations is the family of so-called jump Markov Systems (JMS) [17,18]. In JMS, the random model indices are assumed to form a Markov chain and every index value determines a model for the target dynamics and an associated model for the observed data.

The assumption of multiple models for the dynamics of the target has an important impact on the design of the tracking algorithm. Interacting multiple model (IMM) algorithms [19] compute a set of estimates of the target state, each one associated to a different dynamic model, and then merge them with appropriate weights in order to obtain a global estimate. Often, the estimates corresponding to each dynamic model are computed using Kalman filters [15,20]. Recently, however, the sequential Monte Carlo (SMC) methodology (particle filtering) [21–24] has received considerable attention. In [25], an IMM particle filter is proposed to track a non-Markovian jump system. Other multiple model particle filters have also been proposed in the literature in order to track switching state-space systems. In [26], for instance, each particle is propagated across all possible dynamic models, the importance weights are computed and resampling is performed to (randomly) select the fittest particles and keep their number fixed. A particle filter, for switching observation models has been recently proposed in [27] and exemplified with an outdoor navigation application. Having a "ready-to-use" description of the different physical environments where the tracker has to operate can be advantageous compared to estimating any necessary parameters online. When the environment can be described by sub-models and those are a priori available, the tracking algorithm only has to detect that the physical scenario has changed and quickly switch to the most useful sub-model. This is in contrast with parameter-estimation based, online techniques, where the adaptation of the parameters involves possibly long transients and also convergence issues.[1]

In this paper, we propose a novel scheme for indoor tracking using RSS that relies on

(a) the representation of both the mobile target dynamics and the resulting RSS observations by means of multiple switching sub-models,
(b) a Rao-Blackwellized particle filter to recursively compute Bayesian estimates of the target position and velocity and
(c) the construction of accurate observation sub-models using experimental data collected by the wireless sensor network (WSN) to be employed for tracking the target.

As for the structure of the state-space system, we introduce a generalized switching multiple model (GSMM) framework in order to adequately handle the uncertainty in both the dynamics of the target and the RSS observations from the sensors *separately*, in an indoor environment. In particular, we allow the representation of the target motion and the RSS measurements at any time to be drawn from two independent collections of candidate sub-models according to two different indicator random processes (possibly multivariate). Although, strictly speaking, a JMS can be used to represent the same system, using a single indicator to determine the pair of motion and observation models, we advocate the scheme in this paper, with independent indicators, because it is a better fit with our physical intuition (the measurements of the RSS are not necessarily dependent on the type of motion).

The main advantage of the GSMM scheme is that it is flexible enough to encompass a broad range of indoor scenarios. Its main drawback is the need to track the target in a higher dimensional state space (its actual dimension depending on the number of switching sub-models used). We show, however, that the SMC methodology is powerful enough to numerically compute accurate state estimates within this setup. In particular, we propose a Rao-Blackwellized particle filtering (RBPF) algorithm [12,29] in which a subset of the state variables, including the observation indicator variables, is integrated out to improve the tracking accuracy. We also propose an implementation of the RBPF algorithm that uses auxiliary variables, in the vein of [30], to sample new particles conditional on the most recent data. The computational complexity of the auxiliary RBPF is only marginally higher than that of the RBPF with prior importance

[1] See [28], Section 4 for a discussion of parameter estimation in the context of particle filtering.