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TRADEOFFS IN DETECTION AND LOCALISATION PERFORMANCE FOR MOBILE SENSOR SCANNING STRATEGIES

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ABSTRACT

Wireless sensor networks enjoy many advantages over wired networks due to their ability to be deployed easily and flexibly in many scenarios. However, they suffer from the drawback that the environment may be unknown and hence the sensor network cannot easily be optimised for it. Furthermore, state-of-the-art studies only consider the detection and localisation performance separately. The main novelty of this work is that we compare the theoretical properties of three scanning strategies both in terms of their detection and localisation performance. We consider: a) sequential scanning, where all sensors scan the channels in sequence, b) groupwise scanning, where the sensors are split into groups with each one performing a sequential scan, and c) random scanning, where each sensor is assigned a channel at random. We demonstrate the theoretical properties of the strategies and perform a numerical evaluation for a typical radio surveillance scenario. The tradeoffs of the methods between detection and localisation performance are demonstrated to be dependent on the detection and localisation accuracy with respect to the number of sensors. Approximate knowledge of those curves can aid in the design of an optimal sensor scanning strategy.

***Index Terms*—** sensor networks, sensor scanning, multiuser, detection, localisation

I. INTRODUCTION

A mobile sensor network (MSN) is a wireless sensor network with mobile nodes [1], [2]. MSNs have the advantage over static sensor networks that they can be deployed in a wide range of scenarios and cope with changing environmental conditions. MSNs can be used for applications such as radio surveillance, environment and health monitoring [3], [4].

The scanning strategy employed by sensors in a MSN is a crucial task especially in multi-user and multi-channel environments. The choice of a suitable sensor scanning method can greatly affect the user detection times as well as the detection and localisation performance [5], [6]. Furthermore, and in more general terms, a good scanning strategy should be efficient in its use of sensors, i.e. using no more sensors than required for the desired number of users performance, and also efficient in their utilisation [7], [8]; the sensors should not be used for more time than required.

The twin tasks of detection and localisation have been tackled separately in the sensor network literature. In [9], [10], [11], it is shown that increasing the number of sensing agents improves the detection performance and also provides more energy efficient solutions as in [8]. Similarly, according to [12], it is only necessary to use only a specific subset of sensors to achieve good performance. There are multiple applications where precise localisation of the transmiters is also of primary importance. In [13] compressive sensing is used for localisation after a brief training signal duration. A general review of localisation methods can be found in [14]. Joint spectrum sensing and localisation has been attempted in [15], [16], however, all the transmitters occupy the same band and no consideration is given to sensor management.

In this work, we consider three different scannning strategies and evaluate them both based on the detection and localisation performance for a multi-user and multi-channel scenario. We derive the statistical properties of each and provide results for a realistic radio surveillance scenario. Although we are considering a specific wireless signal scenario where its details are assumed to be known, the methodology is general enough and can be extended to many other applications including cognitive radio systems. In an attempt to cover the basic principles of scanning methodologies we consider a) sequential scanning where all the sensors scan a single channel per timeslot, b) groupwise scanning where the sensors are split into groups and c) random scanning where each sensor is randomly placed in a channel.

In Section II we describe the general setting of the sensors and the transmitters together with the basic evaluation metrics. Section III shows the theoretical properties of each of the scanning methods. In Sections IV, V and VI we describe the obtained results and put them into context.

II. SCENARIO DESCRIPTION

We consider a two dimensional scenario consisting of a square area of side length L, with K transmitters, and S sensors. There are N frequency channels to be monitored, with $K \leq N$, and a maximum of T timeslots for scanning as depicted in Fig 1. We assume each channel can be occupied by up to one transmitter and there is no spectral leakage. The propagation model of each of the transmitters is based on the rural scenario of the WINNER II model [17]. It is a statistical model where M path-loss multipath components and shadowing are generated for each transmitter to sensor link.

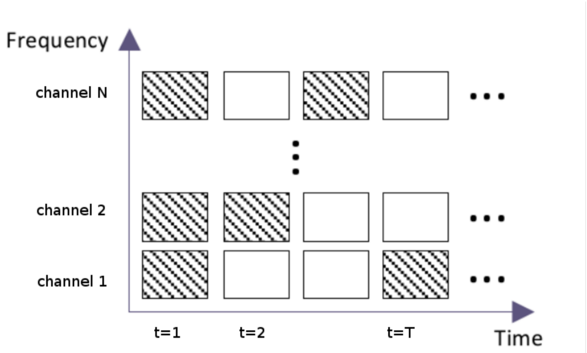

Fig. 1. *Time-frequency plot for the N channel and T timeslots used by the sensors. Shaded and blank boxes indicative the duty cycle of transmission.*

II-A. Detection performance

We assume that each of the transmitters is using orthogonal frequency division multiplexing to transmit in one channel with known cyclic prefix time duration. This is utilised by the sensors in order to detect its presence [18]. The probability of detection for a sensor is then given by [18]:

$$Pd = (1/2)Q(\sqrt{M}((\theta - \rho)./(1 - \rho.^2))) \tag{1}$$

where M is the autocorrelation size, $Q()$ is the normal quantile function, $\theta = (1/\sqrt{M})(Q^{-1}(2P_{fa}))$ is the threshold obtained for a specific probability of false alarm (P_{fa}) and $\rho = (T_c/(T_d+T_c))(SNR./(1+SNR))$. SNR is the signal-to-noise-ratio at the sensor level and T_d, T_c being the time duration of the cyclic prefix and one symbol respectively. The SNR is calculated using the sum of the powers of all multipath components and considering setting the noise figure of the receivers to -9dBW. We assume that each sensor communicates with a fusion centre. The fusion center then performs sensor fusion by having only the best sensor report a signal (the one with the highest SNR) for detection. Therefore we consider $P_d(S)$ as the resulting detection performance of the best sensor out of S sensors. In order to facilitate efficient communication of the signal from only the best sensor, the sensors may delay their transmission to the fusion centre in inverse proportion to the SNR. A high SNR detection would be communicated to the fusion centre quickly; conversely, a lower SNR detection would incur a higher delay before being transmitted. If the other sensors overhear a detection transmission for the channel they are scanning, they may decide not to communicate their own detection to the fusion centre. This scheme is inspired by a similar idea for selecting the best relay for data transmission proposed in [19].

II-B. Localisation performance

The localisation performance is evaluated by computing the Cramer-Rao Lower Bound (CRLB) of the localisation error for time difference of arrival (TDOA) estimation. We assume that the network is synchronised e.g. through the use of GPS signals. We consider a successful localisation if a group of sensors achieves a lower localisation bound than some predefined threshold. The computation of the CRLB is based on [20] (Eq. 4 and 5).

III. SCANNING STRATEGIES

In this paper we evaluate three different scanning strategies in terms of both detection and localisation performance.

III-A. Sequential scanning

In the sequential scanning strategy each channel is scanned sequentially by all S sensors. The fraction of occupied channels is:

$$F_{occ} = \frac{KD}{N} \tag{2}$$

where K is the number of transmitters and D is the duty cycle of the transmitter. The average number of detections up to timeslot t is given by:

$$E\{d^{seq}(t)\} = tF_{occ}P_d(S) \tag{3}$$

where $P_d(S)$ is the probability of detection for S sensors. This quantity is a composite measure of the chance that the sensors occupy the same channel as a transmitter and the probability of detection according to the scenario under consideration.

The localisation accuracy for sequential scanning is given by the fraction of cases that achieve a lower localisation error than some predefined threshold η:

$$P_{loc}(S, \eta) = \frac{\sum_i CRLB(S) < \eta}{M} \tag{4}$$

where M is the number of different radio environments generated by the WINNER II channel model during the Monte-Carlo simulation.

III-B. Groupwise scanning

This scanning strategy splits the S sensors into G groups. Each group consists of S/G sensors which are used in a sequential scanning fashion. No two groups will scan the same channel within the same timeslot. The average number of detections up to timeslot t is given by:

$$\mathbb{E}\{d^{gr}(G, t)\} = tGF_{occ}P_d(S/G) \tag{5}$$

where $F_{occ} = \frac{KD}{N}$ again denotes the fraction of occupied channels.

Similar to the sequential case, the localisation accuracy for random scanning is given by $P_{loc}(S/G, \eta)$.

III-C. Random scanning

Random scanning entails allocating sensors into the N channels randomly with the constraint that the occupied channels have at least 4 sensors for 3D localization using time difference of arrival (TDOA) methods. The allocation is performed according to the following procedure (a) Place each sensor to a channel with probability $\frac{1}{N}$ and (b) redistribute sequentially the sensors in channels with 1,2, and 3 sensors. This algorithm, termed random scanning, results in a random number $\{0, 4, ..., S\}$ of sensors per channel. The F_{occ} is now the proportion of channels that have at least 4 sensors. The average number of detections is:

$$\mathbb{E}\{d^{rnd}(t)\} = tF_{occ} \sum_{i=4}^{S} P_r(i)P_d(i) \tag{6}$$

where P_r is the discrete probability distribution of the number of sensors in a channel. The probability distribution is computed numerically.

Similar to the sequential case, the localisation accuracy for random scanning is given by $P_{loc}(s, \eta)$ where s is the random number of sensors in a channel.

III-D. Comparison

In groupwise scanning, increasing the number of groups will increase the number of detections per timeslot as long as the increase in G is larger than the decrease in $P(S/G)$. In other words the quantity to examine is whether:

$$\frac{G'}{G} <> \frac{P_d(S/G)}{P_d(S/G')} \tag{7}$$

For a specific application if the form of $P_d(x)$ is approximately known the choice of G can be made during network configuration. In terms of localisation, decreasing the number of sensors will increase the error for all scanning methods (note there should be a minimum of four sensors for localisation). The design choice for the number of groups for a specific application is then whether the increase in $\mathbb{E}\{d^{gr}(G, t)\}$ justifies the decrease in $P_{loc}(S/G, \eta)$.

IV. RESULTS

We consider a scenario with $N = 25$ channels, $T = 25$ timeslots, $K = 15$ transmitters and $S = 100$ sensors. Transmitters are randomly placed following a uniform distribution in a square area of 2000 m × 2000 m. The sensors are placed in fixed locations following a uniformly spaced, square-grid pattern over the same square area. All transmitters have a duty cycle of $D = 1$ with transmit power $P = -33$ dbW. Results in this section are averaged over 500 Monte-Carlo runs for transmitter locations.

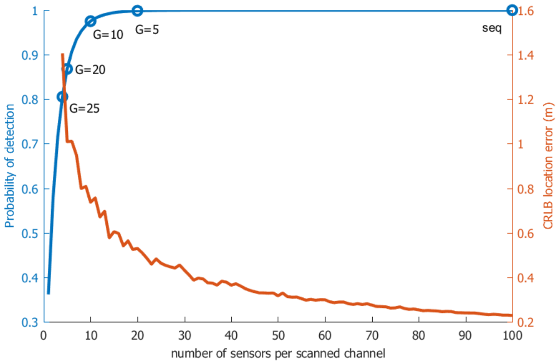

Fig. 2. *Probability of detection (left-axis) and CRLB (right-axis) against the number of sensors that scan a channel. The total number of sensors is fixed to $S = 100$ and the different points indicate the number of groups that are used for scanning in G channels. Each group uses (S/G) sensors.*

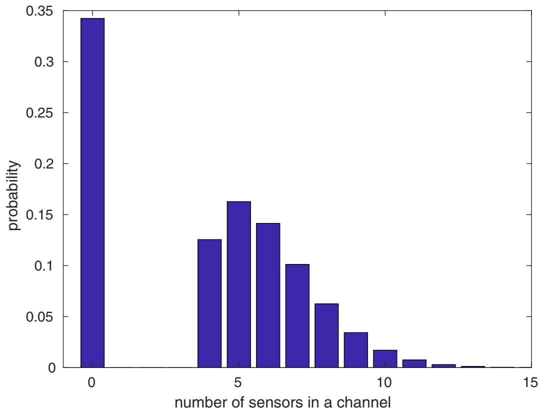

Fig. 3. *Discrete probability distribution of the number of sensors per channel for the specific scenario. The total average number of sensors is 4.*

Firstly, we show the obtained curves for the probability of detection and the CRLB on localisation error with respect to the number of sensors per scanned channel in Fig 2. As expected, the metrics improve as the number of sensors on one channel increase. In Fig 3 we show the numerical evaluation of the probability distribution of the number of sensors in a channel. The evaluation is performed using 10000 runs on the random scanning algorithm described in Section III-C.

Next, we show the obtained number of detections per timeslot for the different strategies in Fig 4. It can be observed that the larger the number of groups the less time is required to fully detect the 15 transmitters. Also note that the random scanning results almost coincide with $G = 10$. Fig 5 shows the probability of correct localisation

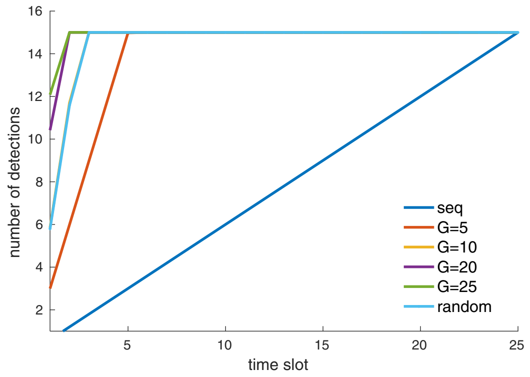

Fig. 4. *Average number of detections with respect to the time slot for the different strategies evaluated in this work.*

against different thresholds as described in Section II-B. In contrast to detection, the sequential method obtains the best performance while the groupwise methods have diminishing performance with increasing number of groups. This is because more sensors are used for localisation. Finally, in Fig 6 we show the tradeoff between the time it takes to detect all 15 transmitters and the probability of correct localisation for the different strategies. The time to detect all transmitters corresponds to the timeslot where the expected number of detections equals the number of transmitters. Each point in the graph represents the performance of a different scanning method. The localisation threshold is set at $1m$. The larger the number of groups the less time it takes to detect all transmitters with the downside of reduced localisation performance. Random scanning is shown as a point and provides a good performance tradeoff.

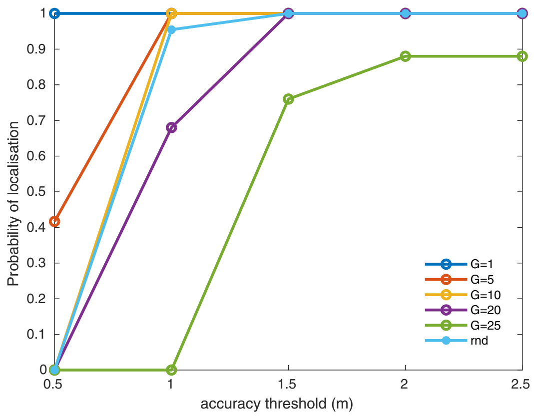

Fig. 5. *Probability of localisation against the detection threshold evaluated by the CRLB.*

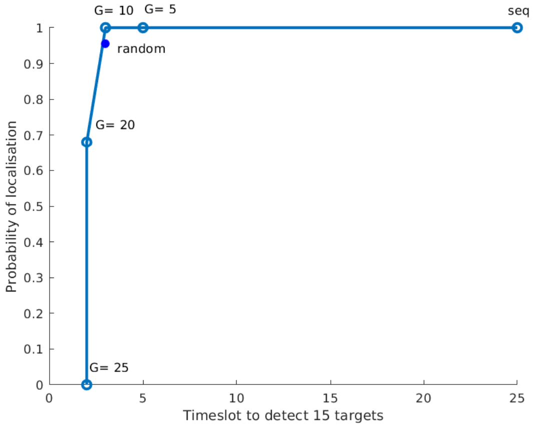

Fig. 6. *Probability of localisation against the time slot where all transmitters where detected for a threshold of* $1m$. *The labelled points in the graph represent the different methods used. This figure showcases the tradeoff between localisation accuracy and detection accuracy.*

V. DISCUSSION

The performance of the three methods in terms of detected transmitters per timeslot can be seen in Fig 4. For our example scenario, increasing the number of groups increases the number of detected transmitters for a given number of timeslots. On the other hand, increasing the number of groups decreases the localisation acccuracy as observed in Fig 5. The choice of the scanning method can be made prior to the scanning if the curves of detection and localisation error are available as seen in Fig 2.

In our case, the optimal choice is to split the sensors into 10 groups providing reduced detection time and optimal localisation accuracy as compared to the sequential method. This can be observed in Fig 6 where the tradeoff between localisation and detection is showcased for the different methods used in this paper. Each point in Fig 6 shows the probability of localisation against the time to detect all transmitters for the different scanning methods described in this paper. Two interesting observations arise; firstly, for $G < 10$ the sensors are underutilised resulting in large detection times with no benefit in localisation. Secondly, the case of $G = 25$ exhibits the same detection time as $G = 20$ for worse localisation performance. If in our scenario the P_d and $CRLB$ were approximately known (Fig 2), an optimal choice could be made regarding the scanning strategy. If not, random scanning exhibits good performance for both detection and localisation.

VI. CONCLUSIONS

The scanning strategy used in sensor networks can be crucial to the success of the algorithm. In this work, we compared sequential, groupwise and random scanning in