Resource optimisation in a wireless sensor network with guaranteed estimator performance

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Abstract: New control paradigms are needed for large networks of wireless sensors and actuators in order to efficiently utilise system resources. In this study, the authors consider the problem of discrete-time state estimation over a wireless sensor network. Given a tree that represents the sensor communications with the fusion centre, the authors derive the optimal estimation algorithm at the fusion centre, and provide a closed-form expression for the steady-state error covariance matrix. They then present a tree reconfiguration algorithm that produces a sensor tree that has low overall energy consumption and guarantees a desired level of estimation quality at the fusion centre. The authors further propose a sensor tree construction and scheduling algorithm that leads to a longer network lifetime than the tree reconfiguration algorithm. Examples are provided throughout the paper to demonstrate the algorithms and theory developed.

1 Introduction

Wireless sensor networks (WSNs) have attracted much attention in the past decade, which can be used for environment and habitat monitoring, health care, home and office automation, traffic control and so on [1]. In WSN, there is an economic incentive towards using off-the-shelf sensors and standardised communication solutions. A consequence of this is that the individual hardware components might be of relatively low quality and that communication resources are quite limited. Thus a single sensor may not be enough to provide a desired level of estimation quality, and data fusion from multiple sensors is often required.

Estimation and control over such resource-constrained networks thus require new design paradigms beyond traditional sampled-data control. For example, consider the problem of state estimation over such a network using a Kalman filter. The Kalman filter [3] is a well-established methodology for model-based fusion of sensor data [4]. Kalman filtering under certain information constraints, such as decentralised implementation, has been extensively studied [5]. The interaction between Kalman filtering and how data are routed on a network seems to be less studied.

Another issue inherent with WSN is the limited energy resource available at each sensor node, which is typically battery powered. Periodically changing the battery is often difficult and expensive and sometimes even impossible. Thus any good design must fully consider the energy resource constraint and minimise the sensor energy consumption as much as possible.

Sensor network energy minimisation is typically done via efficient MAC protocol design [6], or via efficient scheduling of the sensor states [7]. A sensor transmitting
scheduling was suggested by Chen et al. [8], Lai et al. [9] proposed a scheme to divide the deployed sensors into disjoint subsets of sensors such that each subset can complete the mission, and then maximise the number of such disjoint subsets.

In this paper, we consider the problem of centralised state estimation while considering sensor energy constraint. The main contributions are summarised as follows:

1. Given a tree that represents the sensors' communications with the fusion centre, we derive the optimal estimation algorithm at the fusion centre, and we provide a closed-form expression on the steady-state error covariance matrix.

2. We present a tree reconfiguration algorithm that produces a sensor tree having low overall energy consumption and providing a desired level of estimation quality at the fusion centre.

3. We propose a sensor tree construction and scheduling algorithm that leads to a longer network lifetime than the tree reconfiguration algorithm.

Routing protocols have been widely investigated in the literature. The main efforts have concentrated towards defining protocols that discover routes on demand using local and scalable technique, while avoiding the overhead of storing routing tables or other expensive information such as link costs or topology changes. The main challenge in those works is in discovering paths that are both time and energy efficient, meaning that the information is delivered across the network in a reasonable amount of time and at the minimum cost. Some examples include energy-aware routing, attributed-based routing, rumour routing and directed diffusion. We refer the reader to [10] for a more detailed treatment. The focus of our paper is different since we want to simultaneously solve an estimation and energy minimisation problem. More specifically, we want to find the most efficient network topology given constraints on the estimation performance measured by the estimation error covariance matrix. Differently from the works mentioned above, our network topology is static and recovered once for all as the solution of an optimisation problem.

All algorithms have low complexity, which leads to efficient design and implementation in practice. Furthermore, the low complexity brings the plug-and-play feature to the network, that is, a new tree can be calculated and dynamically formed when new sensors join the network and existing sensors quit from the network, or when the performance requirement is time varying (e.g., see the example in Section 4.3).

The rest of the paper is organised as follows. In Section 2, we give the mathematical models of the considered problems, and provide some preliminary results on Kalman filtering to facilitate the analysis in remaining sections. In Section 3, we derive the optimal estimation algorithm at the fusion centre for a given sensor tree. In Section 4, we present the a sensor tree reconfiguration algorithm. Then in Section 5, we propose a sensor tree construction and scheduling algorithm that leads to a longer lifetime than the sensor tree reconfiguration algorithm. Concluding remarks as well as future work are given in the end.

## 2 Problem setup and preliminaries

### 2.1 Problem setup

Consider the problem of state estimation over a wireless sensor network (Fig. 1). The process dynamics is described by

$$x_{k+1} = Ax_k + \omega_k$$  (1)

A wireless sensor network consisting of $N$ sensors $\{S_1, \ldots, S_N\}$ is used to measure the state. When $S_i$ takes a measurement of the state in (1), it returns

$$y'_i = H_ix_k + \nu'_i \quad (i = 1, \ldots, N)$$  (2)

In (1) and (2), $x_k \in \mathbb{R}^n$ is the state vector in the real $n$-dimensional vector space, $y'_i \in \mathbb{R}^m$ is the observation vector at $S_i$, $\omega_k \in \mathbb{R}^m$ and $\nu'_i \in \mathbb{R}^m$ are zero-mean Gaussian random vectors with $E[\omega_k\omega'_k] = \delta_{ij}Q$, $Q \succeq 0$, $E[\nu'_i\nu'_{i'}] = \delta_{ij}R$, $R \succeq 0$, $E[\nu'_i\nu'_{i'}] = 0 \forall i, i'$, and $i \neq j$, otherwise. We assume that $(A, \sqrt{Q})$ is controllable, and $(A, C_{ub})$ is observable, where $C_{ub} = [H_1, \ldots, H_N]$, that is, the joint measurement matrix of all sensors.

Each sensor can potentially communicate via a single-hop connection with a subset of all the sensors by adjusting its transmission power. We assume that the communication links are perfect in this paper in the sense that data packets travelling on the links will not be dropped. Thus, we will not consider the effect of interference or fading and so on. Let us introduce a fusion centre, which we denote as $S_0$, and consider a tree $T$ with root $S_0$ (Fig. 2). We suppose that there is a non-zero single-hop communication delay, therefore, from the fusion centre to the sensors, we get the following equation:

$$x_k = H_ix_k + \nu'_i \quad (i = 1, \ldots, N)$$  (3)

![Figure 1 State estimation using a wireless sensor network](image-url)
which is smaller than the sampling time of the process. All sensors are synchronised in time, so the data packet transmitted from $S_i$ to $S_0$ is delayed one sample when compared with the parent node of $S_i$. We also assume that $S_i$ aggregates the previous time data packets from all its child nodes with its current time measurement into a single data packet. Therefore only one data packet is sent from $S_i$ to its parent node at each time $k$.

### 2.2 Problems of interest

We are interested in the following problems. The first one is how should the fusion centre process the measurement data from the sensors that arrive at different times (due to the multi-hop communications) such that the estimation error is minimised?

The second problem is related to the energy constraint on the sensor nodes. Apparently, to minimise the energy consumption, sensors should only use minimum transmission energy and communicate with their nearby neighbours; on the other hand, the many short-hop communications introduce many delays when delivering the data to the fusion centre. As delays deteriorate the estimation quality, there is a clear trade-off between how much energy the sensors should spend and how good the estimation quality is at the fusion centre. We are thus interested in seeking a low-energy sensor tree, which still guarantees a desired level of estimation quality at the fusion centre.

When all sensors need to participate in the estimation, minimising the total energy consumption might not lead to a longer lifetime of the network as demonstrated by the example in Section 5.3. Therefore we are also interested in schemes that can maximise the network lifetime.

In Sections 3–5, we provide answers to the above three problems, respectively. Before we present the main result of the paper, we briefly introduce the standard Kalman filtering upon which our optimal estimation algorithm for solving the first problem relies.

### 2.3 Kalman filtering preliminaries

Consider the process in (1) with the following single-sensor measurement equation

$$y_k = C_k x_k + v_k$$

where $v_k$ is zero-mean Gaussian random vectors with $E[v_k v_k'] = R_k$, $R_k > 0$ and $E[w_k w_k'] = 0$ for $j, k$. Note that we consider time-varying $C_k$ and $R_k$ here. The Kalman filter in its most general form can assume time-varying $A$ and $Q$. The special form we look at here suffices for deriving the optimal estimation algorithms in later sections.

Assume a linear estimator receives $y_k$ and computes the optimal state estimate at each time $k$. Let $Y_k$ denote all measurements available at the estimator at time $k$. Further define

$$\hat{x}_k \triangleq E[x_k | Y_k]$$

$$P_k \triangleq E[(x_k - \hat{x}_k)(x_k - \hat{x}_k)' | Y_k]$$

$$P \triangleq \lim_{k \to \infty} P_k$$

If the limit exists

$$\langle \hat{x}_k, P_k \rangle = KF(\hat{x}_{k-1}, P_{k-1}, y_k, C_k, R_k)$$

where $KF$ denotes the Kalman filter, which consists of the following update equations at time $k$

$$\hat{x}_k = \hat{x}_{k-1} + A \hat{x}_{k-1}$$

$$P_k = AP_{k-1}A' + Q$$

$$K_k = P_k C_k' [C_k P_k C_k' + R_k]^{-1}$$

$$\hat{x}_k = \hat{x}_{k-1} + K_k (y_k - C_k \hat{x}_k)$$

$$P_k = (I - K_k C_k)P_k$$

Let $\mathbb{S}_+$ be the set of $n$ by $n$ positive semi-definite matrices. For functions $f_1, f_2 : \mathbb{S}_+ \to \mathbb{S}_+$, define $f_1 \circ f_2$ as

$$f_1 \circ f_2(X) \triangleq f_1(f_2(X))$$

Further define the functions $h, \tilde{g} : \mathbb{S}_+ \to \mathbb{S}_+$ as

$$h(X) \triangleq AXA' + Q$$

$$\tilde{g}(C, R)(X) \triangleq X - XC' [CXC' + R]^{-1} CX$$

We write $g(C, R)(X)$ and $\tilde{g}(C, R)(X)$ as $g_C$ and $\tilde{g}_C$ if there is no confusion on the underlying parameters $R$.
3 State estimation over a sensor tree

Let us define the following state estimate and other quantities at the fusion centre $x_0$. For a given tree $T$ rooted at $x_0$, define $\hat{x}_k(T), P_k(T), \mathcal{P}(T)$ at $x_0$ similar as in (4)–(6). We write $\hat{x}_k(T)$ as $\hat{x}_k$, and so on, if there is no confusion on the underlying tree $T$. In this section, we shall compute $\hat{x}_k$ and $P_k$ for a given $T$.

Assume the tree $T$ has depth $D$. Define $\mathcal{Y}_j^{k-i}$ as the set of all measurements available at the fusion centre for time $k-i$ at time $k$, $i = 0, \ldots, D-1$. Let $S_i$ be the sensor node, that is $j$ hops away from the fusion centre. Define

$$\Gamma_j \triangleq [H_j, H_2, \ldots], \quad j = 1, \ldots, D$$

$$C_i \triangleq [\Gamma_1, \ldots, \Gamma_j], \quad i = 1, \ldots, D$$

$$Y_j \triangleq \text{diag}(\Pi_1, \Pi_2, \ldots), \quad j = 1, \ldots, D$$

$$R_i \triangleq \text{diag}(Y_1, \ldots, Y_j), \quad i = 1, \ldots, D$$

Then the following theorem presents the optimal estimation algorithm over a sensor tree and characterises the steady-state error covariance matrices in closed-form expression.

**Theorem 1 [2]:** Consider a sensor tree $T$ with depth $D$ that is rooted at the fusion centre. Then

1. $\hat{x}_k$ and $P_k$ can be computed from $D$ Kalman filters in sequence as

$$\hat{x}_{k-D+1}, P_{k-D+1} = \text{KF}(\hat{x}_{k-D}, P_{k-D}, \mathcal{Y}_{k-D+1}, C_D, R_D)$$

$$\vdots$$

$$\hat{x}_{k-1}, P_{k-1} = \text{KF}(\hat{x}_{k-2}, P_{k-2}, \mathcal{Y}_{k-1}, C_2, R_2)$$

$$\hat{x}_k, P_k = \text{KF}(\hat{x}_{k-1}, P_{k-1}, \mathcal{Y}_k, C_1, R_1)$$

2. Furthermore, the steady-state error covariance matrix $\mathcal{P}$ satisfies

$$\mathcal{P} = \mathcal{G}_{C_1} \circ \mathcal{G}_{C_2} \circ \cdots \circ \mathcal{G}_{C_D}(P_0)$$

(16)

where $P_0$ is the unique solution to $\mathcal{G}_{C_1}(P_0) = P_0$.

4 Minimum-energy sensor tree

In this section, we seek a low-energy sensor tree that guarantees a desired level of estimation quality at the fusion centre. The following definition are used in the remaining of the paper. Define Node($T$) as all the nodes of $T$, Fam$_T(S_i)$ as the subtree of $T$ that is rooted at $S_i$, Par$_T(S_i)$ as the parent node of $S_i$ in $T$ and Edge($T$) as the edges of $T$, that is

$$\text{Edge}(T) \triangleq \{(S_i, S_j) : S_i \in \text{Node}(T), S_j = \text{Par}_T(S_i)\}$$

We sometimes omit the subscript $T$ if there is no confusion on the underlying tree $T$, as for example, we write Fam$_T(S_i)$ simply as Fam($S_i$).

We assume to have an energy sensor model regulating the amount of energy expenditure for transmission and reception. Further assume that the total energy used by two sensors (one sending and the other receiving) increases as the distance between the two sensors increases [11]. Since at each time, each sensor sends and/or receives fixed number of data packets, without loss of generality, let $e_{i_s}(T)$ be the energy cost for $S_i$, sending a measurement packet to Par$_T(S_i)$ and $e_{i_r}(T)$ as the energy cost for $S_i$, receiving measurement packets from its children. The total energy cost of $T$ per time is then given by

$$e(T) = \sum_{S_i \in T} e_{i_s}(T) + e_{i_r}(T)$$

(17)

Denote $T_{\text{all}}$ as the set of all sensor trees and let $P_{\text{desired}} \in S_{\text{all}}^+$ be given. Since the sensors operate on batteries, it is natural to let the network operate at an energy level that is as low as possible. Thus we are interested in the following problem:

**Problem 1:** How can we choose the sensor tree that has the least overall energy consumption yet still provides certain desired level of estimation quality? that is

$$\min_{T \in T_{\text{all}}} e(T)$$

subject to

$$\mathcal{P}(T) \leq P_{\text{desired}}$$

where the inequality is in the matrix sense, that is, $P_{\text{desired}} - \mathcal{P}(T)$ is positive semi-definite. Cayley [12] showed that the number of all possible trees is $N^{N-2}$, thus solving Problem 4.1 via exhaustive search is intractable when $N$ is large. It is also non-convex, thus finding the global optimal solution is in general difficult. To approximate the global optimal solution, we present the following tree reconfiguration algorithm.

4.1 Tree reconfiguration algorithm

The proposed tree reconfiguration algorithm (Fig. 3) consists of three subroutines. The first one is the tree initialisation algorithm, which forms an initial tree $T_0$ (the top rectangular block). Depending on whether $T_0$ provides the required estimation quality, the switching tree topology algorithm (the middle-right rectangular block) and the minimum-energy subtree algorithm (the bottom rectangular block) are executed, respectively. These algorithms are presented in detail next.
Tree initialisation algorithm: The idea contained in the tree initialisation algorithm is that the fusion center $S_0$ first establishes direct connections with its neighbour sensors using minimum transmission power level $D_e$. After that, its neighbour sensors establish further connections with their own neighbour sensors also using minimum transmission power level $D_e$. This process continues until a tree of depth $D$ is formed. As a result, the complexity of the algorithm is $O(D)$. The algorithm is presented graphically in Fig. 4.

Switching tree topology algorithm: For a given tree $T$, if $P(T) \neq P_{\text{desired}}$, the tree needs to be adjusted in a way that the estimation quality is improved. The switching tree topology algorithm provides such a way (Fig. 5). The idea is that a sensor node in $T$ that is two-hops away from the fusion centre is reconfigured to directly connect with it, hence becomes only one-hop away from the fusion centre. As we prove shortly, this reconfiguration always improves the estimation quality at the fusion centre.

The algorithm is given as Fig. 6, where $\text{Tr}(X)$ denotes the trace of the matrix $X$.

Minimum energy subtree algorithm: For a given tree $T$ with $P(T) \leq P_{\text{desired}}$, the minimum energy subtree algorithm finds the subtree $T'$ rooted at $S_0$ with the property that $P(T') \leq P_{\text{desired}}$, and $\epsilon(T') \leq \epsilon(T)$ for any subtree $\tilde{T}$ of $T$ rooted at $S_0$. The idea is that all possible subtrees $\tilde{T}$ rooted at $S_0$ and satisfying

$$P(\tilde{T}) \leq P_{\text{desired}}$$

are found in an efficient way utilising the structure of $T$. Then the subtree $T'$, which has the least overall energy cost is returned. The details are as follows.

To make the presentation clear and easy to follow, we divide the algorithm into several key steps and provide an example to illustrate each step. Before introducing the algorithm, let us define $S(i_1, i_2, \ldots, i_p)$ as the subtree that consists of the sensor nodes $\{S_{i_1}, S_{i_2}, \ldots, S_{i_p}\}$. We further define $\Omega(i_1, i_2, \ldots, i_p)$ as the complementary tree of $S(i_1, i_2, \ldots, i_p)$ in $T$, that is

$$\Omega(i_1, i_2, \ldots, i_p) = T \setminus S(i_1, i_2, \ldots, i_p)$$

We assume $i_1 \leq i_2 \leq \cdots \leq i_p$. The following example is provided to illustrate the algorithm.
Step 1:

1. \( \mathcal{P}(T) \leq P_{\text{desired}} \), that is, \( T \) provides the desired estimation quality.

2. \( \mathcal{P}(S(i)) \neq P_{\text{desired}} \) for \( i = 1, 2, 3, 4 \), that is, no single sensor provides the desired estimation quality.

3. \( \mathcal{P}(S(i)) \leq P_{\text{desired}} \) if \( \{i, j\} \in \{1, 2, 3, 4\} \), that is, among the two sensor pairs, only \( \{S_1, S_3\} \) can provide the desired estimation quality.

4. \( \mathcal{P}(\Omega(i)) \leq P_{\text{desired}} \) for \( i = 2, 3, 4 \), that is, any three sensors except \( \{S_2, S_3, S_4\} \) can provide the desired estimation quality.

5. The energy cost of a single-hop communication in \( T \) is \( \Delta e \).

By the above assumptions, it is easy to see that the minimum energy subtree \( T' \) is given by \( T' \) with \( \epsilon(T') = 2\Delta e \).

Let us examine the case when we take \( T \) as an input to the minimum energy subtree algorithm, which consists of the following key steps.

Step 1:

- Init: \( T \)

- Compute \( S_i = \arg \min \{ Tr(\mathcal{P}(T, S_i)) \} \).

- Return \( T' := \pi(T, S_i) \).

Step 2:

- \( i := i + 1 \), \( D_i := D_{i-1} \)

- \( \forall S_i \in D_{i-1} \) with \( \mathcal{P}(\Omega(i)) \leq P_{\text{desired}} \) and \( \forall q > p \), \( S_q \in \text{Fam}(S_p) \), if \( \mathcal{P}(\Omega(i,p,q)) \leq P_{\text{desired}} \), \( D_i := D_i \cup S(i,p,q) \).

In this step, \( D_1 \) holds all single-sensor or two-sensor pairs without which the remaining sensors still satisfy the estimation quality constraint. The third line of Step 2 eliminates the redundancy in listing the subtrees as \( S(i,p,q) = S(i,p) \), and if \( S_q \) is removed from a tree, so is \( \text{Fam}(S_p) \). Therefore in Example 1, \( D_1 = \{S_2, S_3, S_4, S(23)\} \).

Step 3:

- \( i := i + 1 \), \( D_i := D_{i-1} \)

- \( \forall S(i,j) \in D_{i-1} \) with \( \mathcal{P}(\Omega(i,j)) \leq P_{\text{desired}} \) and \( \forall q > p \) and \( S_q \notin \text{Fam}(S_p) \), if \( \mathcal{P}(\Omega(i,p,q)) \leq P_{\text{desired}} \), \( D_i := D_i \cup S(i,p,q) \).

Similar to Step 3, \( D_2 \) holds all single-sensor, two-sensor pairs or three sensors without which the remaining sensors still satisfy the estimation quality constraint. The algorithm continues in this way until \( D_r = D_{r-1} \) at some step \( r \leq D \).

Step 4

- Return \( T' = \arg \min_{\Omega(i) \in D} \epsilon(\Omega(i)) \).

In Example 1, \( D_2 = \{S_2, S_3, S_4, S(23)\} = D_1 \). Hence, the algorithm stops and returns \( T' = \Omega(23) = S(14) = T_4 \) with \( \mathcal{P}(T') \leq P_{\text{desired}} \) and \( \epsilon(T') = 2\Delta e \).

Remark 1: In general, the global minimum energy tree depends on the initial tree that we start with. The particular initial tree that we choose is certainly arbitrary but has a low-energy consumption. Star tree (e.g. all sensor nodes connect to the fusion centre directly) could be another choice, which provides the least estimation error. However, it is unlikely to be the minimum energy tree. A better approach may be that start from a few random initial trees and run the algorithms simultaneously. In the end, choose the minimum energy tree from all outcomes of the algorithms. This will be the essential idea in the next section when we consider maximising network lifetime.
4.2 Performance analysis of the algorithms

The performance of the previous algorithms are summarised in the following algorithm.

**Theorem 2 [2]:**
1. Given a tree $T_t$, the switching tree topology algorithm returns $T_{t+1} \in \mathcal{T}$ such that
   $$\mathcal{P}(T_{t+1}) \leq \mathcal{P}(T_t)$$
2. Given a tree $T$ with $\mathcal{P}(T) \leq \mathcal{P}_{\text{desired}}$, the minimum energy subtree algorithm returns $T' \in T$ rooted at $S_0$ such that $\mathcal{P}(T') \leq \mathcal{P}_{\text{desired}}$ and $\mathcal{e}(T') \leq \mathcal{e}(T)$ for any other $\tilde{T} \in T$ that is rooted at $S_0$.
3. If $\exists T \in \mathcal{T}$ such that $\mathcal{P}(T) \leq \mathcal{P}_{\text{desired}}$, then the output $T'$ from the tree reconfiguration algorithm satisfies $\mathcal{P}(T') \leq \mathcal{P}_{\text{desired}}$.

4.3 Example

In this section, we provide an example to demonstrate the use of the tree reconfiguration algorithm. Consider the following process with three sensors. The dynamics of the process and sensor measurement equations are as follows:

$$
x_k = 0.9x_{k-1} + \omega_k
$$
$$
y^1_k = x_k + \nu^1_k
$$
$$
y^2_k = x_k + \nu^2_k
$$
$$
y^3_k = x_k + \nu^3_k
$$

with $Q = 1$, $\Pi_1 = 1.5$, $\Pi_2 = 1$ and $\Pi_3 = 0.5$.

The sensors positions are illustrated in Fig. 8. Assume that if $S_i$ is connected to $S_{i-1}$, $i = 1, 2, 3$, the energy of communication is $\Delta e$; if $S_i$ is connected to $S_{i-2}$, $i = 2, 3$, the energy is $4\Delta e$ and if $S_3$ is connected to $S_0$, the energy is $8\Delta e$. Without loss of generality, for the remaining examples, we only calculate the total transmission energy.

Suppose the following performance specification is received by the fusion centre

$$
\mathcal{P} \leq 0.75, \quad 1 \leq k \leq 100
$$
$$
\mathcal{P} \leq 0.25, \quad 101 \leq k \leq 200
$$
$$
\mathcal{P} \leq 1.0, \quad 201 \leq k \leq 300
$$
$$
\mathcal{P} \leq 0.75, \quad 301 \leq k \leq 500
$$

Then the fusion centre can find the corresponding minimum energy tree that fulfills the performance requirement. Fig. 9 shows the simulation result when the fusion centre uses the same tree $(T_0 \setminus S_3)$ all the time, and Fig. 10 shows when it reconfigures the trees according to the performance specification. It is easy to see that when $101 \leq k \leq 200$, the total energy usage increases from $2\Delta e$ to $13\Delta e$. However, the error becomes much smaller; when $201 \leq k \leq 300$, the total energy usage reduces to just $2\Delta e$. Although in this case, the error becomes much larger, the performance specification is still satisfied.

5 Towards maximising sensor network lifetime

We say the sensor network is functioning if there are sufficient number of sensors that can provide the estimation equality, that is, $\mathcal{P} \leq \mathcal{P}_{\text{desired}}$. We define the network...
lifetime as the first time that the sensor network stops functioning, that is, after some sensors die because of running out of battery, the remaining sensors cannot provide the estimation equality.

In some applications, all sensors might be needed (or some high-quality sensors are always needed) for guaranteeing the estimation quality at the fusion centre. In those scenarios, although the tree configuration algorithm in the previous section minimises the total energy consumption of the sensor nodes, it may not maximise the lifetime of the network, which is given by in this case the first time that a sensor dies because of running out of battery.

For example, consider a network that consists of two sensors (Fig. 11). Assume both $T_1$ and $T_2$ in Fig. 11 satisfy

$$P(T_i) \leq P_{\text{desired}}, \quad i = 1, 2$$

Further assume that

$$P(S) \neq P_{\text{desired}}, \quad i = 1, 2$$

Let $c_{ij}$ be the total energy cost for $S_i$ in $T_j$, $i, j = 1, 2$, and let $E_i$ be the initial energy for $S_i$. Consider the following parameters

$$E = [c_{ij}] = \begin{bmatrix} 10 & 1 \\ 1 & 10 \end{bmatrix}, \quad E_1 = E_2 = 1000$$

Denote the lifetime of the network as $L$. It is easy to verify that $L = 100$ when the tree reconfiguration algorithm is executed, as $T_1$ is the only tree used.

It turns out that we can increase $L$ by mixing the use of $T_1$ and $T_2$. Let $0 \leq \alpha \leq 1$ denote the portion of times that $T_1$ is used, we can show that if $0 < \alpha < 1$, then $L > 100$. It is also easy to verify that $L$ attains its maximum value at $\alpha = 0.5$.

From this example, we see that simply minimising the total energy consumption of the sensors may not maximise the network lifetime, which is the focus of this section.

We point out in Section 4 that the set of all possible trees has cardinality $N^{N-2}$. Thus optimal scheduling on the $N^{N-2}$ trees is intractable when $N$ is large. We therefore restrict our attention to a set of $M << N^{N-2}$ trees, and optimally schedule those $M$ trees instead. It turns out that choosing a set of $M$ trees that maximises the lifetime is NP-complete. The complete proof is provided in Section 9.1 in the Appendix. We therefore propose a tree construction algorithm that generates a set of $M$ trees followed by a scheduling algorithm on the $M$ trees. We show that these algorithms lead to a longer lifetime than the previous tree reconfiguration algorithm.

### 5.1 Tree construction algorithm

The proposed tree construction algorithm consists of three main subroutines, which are the random initialisation algorithm, the topology improvement algorithm, and the tree reconfiguration algorithm from Section 4. The overall algorithm is presented in Fig. 12.

**Random initialisation algorithm:** For a given $T$ that is rooted at $S_0$, define $S'(T)$ as

$$S'(T) = \{S_j; S_i \text{ is not in } T\}$$

The intuitive idea of the random initialisation algorithm is that $S_{j-beg}, j = 1, \ldots, D$, defined in (18), are randomly determined in sequence until all $S_i$’s are included in the tree.

After the execution of the random initialisation algorithm, an initial tree of depth $D$ is constructed with $|S_{j-beg}| = n_j, j = 1, \ldots, D$ and $\sum_{j=1}^{D} n_j = N$. 
Remark 2: If \( n_1 = N \), then the algorithm returns \( T^* \), that is, all sensor nodes connect to \( S_0 \) directly.

**Topology improvement algorithm:** Since the previous algorithm randomly constructs the initial tree, some sensor communication paths may be established inefficiently, that is, some sensors use more energy yet need more hops to communicate with \( S_0 \). The topology improvement algorithm aims to remove this inefficiency.

When \( S_i \) is connected to \( S_p \), we define \( t_i,p \) as the number of hops between \( S_i \) and the fusion centre \( S_0 \), and \( e_i,p \) as the transmission energy cost of \( S_i \). We further define \( t_0 \) and \( e_0 \) for \( S_i \) in the initial tree constructed by the random initialisation algorithm.

We consider modifying the path of \( S_i \) in the initial tree, where \( S_i \in S_{j-hop}^1 \geq 2 \), only if there exists \( S_j \) in the same tree and \( S_j \in S_{j-hop} \leq t_0 - 1 \) such that either \( e_{j,p} < e_0 \) or \( e_{j,p} = e_0 \) and \( t_{j,p} < t_0 \). In these cases, \( S_i \) is connected to \( S_p \). The first condition corresponds to reducing the energy cost of \( S_i \) yet not making the hops between \( S_i \) and \( S_0 \) larger; the second condition corresponds to making the hops between \( S_i \) and \( S_0 \) smaller yet not increasing its energy cost. Define \( F_i \) as the indicator function for \( S_i \), and \( F_i = 1 \) means that \( S_i \) has already been examined for possible improvement and \( F_i = 0 \) otherwise. The full algorithm is presented in Fig. 13.

Notice that \( F_i \) is set to be 1 for all \( S_j \in S_{j-hop} \leq 1 \), as for those sensor nodes that are one hop away from \( S_0 \), no improvement can be made that further reduces the energy cost (and maintains the same hop numbers) or reduces the hop numbers.

At this step, we have constructed a set of \( M \) randomised initial trees. We then use them as input to the tree

\[
\begin{align*}
D & := 0 \\
T & := \{S_p, \emptyset\} \\
\forall j \ S_{j-hop} & := \emptyset \\
S^* & := \{S_1, \ldots, S_N\} \\
\text{while} \ (S^* \neq \emptyset) \text{ do} \\
D & := D + 1 \\
\text{Pick} \ u_D \text{ from } (1, |S^*|) \text{ uniformly randomly.} \\
l & := 1 \\
\text{while} \ (l \leq n_D) \text{ do} \\
\text{Pick any } S_p \in S^* \text{ and any } S_j \in S_{(D-1)-hop} \text{ uniformly randomly.} \\
\text{Connect } S_p \text{ to } S_j, \\
S^* & := S^* \setminus \{S_p\} \\
T & := T \cup \{S_p, (S_p, S_j)\} \\
S_{D-hop} & := S_{D-hop} \cup \{S_p\} \\
l & := l + 1 \\
\text{end while} \\
\text{end while}
\end{align*}
\]

**Figure 13 Random initialisation**

reconfiguration algorithm from Section 4.1 (ignoring its tree initialisation algorithm subroutine) to make sure that each tree provides the desired estimation quality.

**Remark 3:** The randomised algorithm here to a certain extent guarantees that the constructed \( M \) trees will have different energy cost of the individual sensor nodes, hence through the scheduling algorithm presented in the next section, the overall lifetime of the network is maximised in Fig. 14.

### 5.2 Tree scheduling algorithm

Up to now, we have constructed a set of trees \( T \) and for each \( T_j \in T \)

\[
\overline{P}(T_j) \leq P_{desired}
\]

Let \( T_j \) be the low-energy tree from the tree reconfiguration algorithm in Section 4. Denote \( \theta \) as a scheduling policy on \( T \cup \{T_0\} \), and \( t_j(\theta) \) as the time that \( T_j \) is used for the policy \( \theta \). Then the network lifetime \( L(\theta) \) can be computed as

\[
L(\theta) = \sum_{j=0}^{M} t_j(\theta)
\]

Consider the following optimisation problem

**Problem 2:**

\[
\max_{0 \leq t_j \leq T} \sum_{j=0}^{M} t_j
\]
\( \forall i \quad F_i := 0 \)
\( \forall S_i \in S_{j-hop}, j \leq 1, \quad F_i := 1 \)

while \( \exists F_i = 0 \) do

\( F_i := 1 \)
\( \Sigma := \{ S_p : S_p \in S_{j-hop}, j \leq \tau_0 - 1, \quad e_{i,p} \leq e_0 \} \)

if \( \Sigma \neq \emptyset \) then

\( \tau_{i,q} := \min \{ \tau_{i,p} : S_p \in \Sigma \} \)

if \( e_{i,q} < e_0 \) or \( (e_{i,q} = e_0 \text{ and } \tau_{i,q} < \tau_0) \) then

reconnect \( S_i \) to \( S_q \)

update \( S_{j-hop}, j \leq \tau_0 \)
end if

end if

end while

Problem 2 can be solved efficiently via linear programming, as both the objective function and constraints are linear functions of the variables. We also have the following result which shows that the tree construction and scheduling algorithm leads to a longer lifetime than using the tree reconfiguration algorithm.

**Lemma 1:** Let the lifetime of the network via solving Problem 2 be \( L^* \), and via \( T_0 \) alone be \( L(T_0) \). Then

\( L(T_0) \leq L^* \)

with \( L(T_0) = L^* \) iff \( t_j^* = 0 \) for all \( j = 1, \ldots, M \).

**Proof:** Assume \( L(T_0) > L^* \). Then setting \( t_j^* = 0 \) for all \( j = 1, \ldots, M \) leads to a better solution than \( L^* \), that is, \( L(T_0) \). This violates the optimality assumption of \( L^* \). \( \square \)

### 5.3 Example

In this section, we provide an example to demonstrate the theory and algorithms developed so far. We start by describing the process and sensor models.

**Process and sensor models:** We consider the process in (1) with

\[
A = \begin{bmatrix}
1 & 0.1 & 0.05 & 0.0002 \\
0 & 1 & 0.1 & 0.05 \\
0 & 0 & 1 & 0.1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

and \( Q = 0.1I \). There are three sensors available. The measurement equations are given by

\[
y_1^1 = [1 \quad 0 \quad 0 \quad 0]x_k + v_1^1
\]
\[
y_2^2 = [0 \quad 1 \quad 0 \quad 0]x_k + v_2^2
\]
\[
y_3^3 = [1 \quad 0 \quad 1 \quad 0]x_k + v_3^3
\]

with \( \Pi_1 = 0.5, \Pi_2 = 0.25 \) and \( \Pi_3 = 0.1 \). Assume the sensors are placed in a line (Fig. 15) with relative distance

\[
d_{1,0} = 2, \quad d_{2,1} = 1, \quad d_{3,2} = 1
\]

where \( d_{p,q} \) is the distance between \( S_p \) and \( S_q \).

Let \( e_{sa}(S_p, S_q) \) be the energy cost for \( S_p \) transmitting a packet to \( S_q \), and \( e_{sr}(S_p, S_q) \) be the energy cost for \( S_q \) receiving such a packet from \( S_p \). We use the following simplified energy model

\[
e_{sa}(S_p, S_q) = 1, \quad e_{sr}(S_p, S_q) = d_{p,q}^2
\]

\( \forall 1 \leq p, \quad q \leq 3, \quad p \neq q \)

Assume the initial energy \( E_i \) available at \( S_i \) is known and given by

\[
E_1 = E_2 = E_3 = 2000
\]

Let the performance specification at the fusion centre be

\[
\text{Tr}(P(T_k)) \leq 1.75, \quad \forall k
\]

It is easy to verify that

\[
\text{Tr}(P(T \setminus S_2)) = 2.7062, \quad \text{Tr}(P(T \setminus S_3)) = 3.1110
\]

and \( (A, [H_2; H_3]) \) is not observable. Therefore all three sensors are needed in order to satisfy the estimation quality constraint.

**Tree construction algorithm:** Initially, we run the tree reconfiguration algorithm, which returns the initial tree \( T_0 \) as seen from Fig. 16. It is easy to verify that
\( \text{Tr}(\mathcal{P}(T_0)) = 1.5752, \) which satisfies the estimation quality constraint.

We further construct three trees, that is, \( M = 3 \) here. Figs. 17–19 demonstrate the use of the tree construction algorithm. As a result

\( \mathcal{T} = \{T_1, T_2, T_3\} \)

is returned with \( \text{Tr}(\mathcal{P}(T_1)) = 1.6773, \) \( \text{Tr}(\mathcal{P}(T_2)) = 1.3777, \) \( \text{Tr}(\mathcal{P}(T_3)) = 1.5023, \) and energy cost

\[
E = [e_{ij}] = \begin{bmatrix}
4 & 1 & 0 & 5 \\
10 & 11 & 9 & 1 \\
1 & 1 & 16 & 16
\end{bmatrix}
\]

where \( i = 1, 2, 3 \) and \( j = 0, 1, 2, 3. \) Note that during the construction of \( T_1 \) to \( T_3, \) only the topology improvement algorithm modifies the input tree.

**Tree scheduling algorithm:** Let \( t_j \) be the time that \( T_j \) will be used. In order to maximise the lifetime of the network, we solve the following scheduling problem

\[
\max_{t_0, \ldots, t_3} \sum_{j=0}^{3} t_j \\
\text{subject to} \\
\sum_{j=0}^{3} t_j e_{ij} \leq 2000, \quad i = 1, 2, 3 \\
t_j \geq 0, \quad j = 0, 1, 2, 3
\]
Solving the above problem via standard LP toolbox gives the following optimal value

\[ t^* = [186 \ 0 \ 0 \ 131] \]

Therefore only \( T_0 \) and \( T_3 \) will be used, and the maximum network lifetime \( L^* \) is given by

\[ L^* = \sum_{j=0}^{3} t_j = t_0 + t_3 = 301 \]

It is also to compute that

\[ L(T_0) = 200, \quad L(T_1) = 181, \quad L(T_2) = 222, \quad L(T_3) = 125 \]

Hence the network lifetime is indeed increased.

6 Conclusions

In this paper, we consider the problem of discrete-time state estimation over a wireless sensor network. We first study the problem of optimal estimation over a sensor tree, and showed that the optimal estimator is a chain of Kalman filters and the length of the chain corresponds to the depth of the tree. Closed-form expression on the steady-state error covariance is obtained, which suggests how much each sensor contributes to the overall estimation quality. Then we present a tree reconfiguration algorithm to establish a sensor tree that has low overall sensor energy consumption and also guarantees a desired level of estimation quality. After that, we propose a tree construction and scheduling algorithm, that has a longer lifetime compared with the tree reconfiguration algorithm. The idea is that a set of low-energy trees with different energy cost of individual sensors are constructed, and those trees are then scheduled in a way that the network lifetime is maximised.

There are many interesting directions along the line of the current work that will be pursued in the future.

We have assumed the communication links are perfect in the current paper in the sense that data packets travelling on the links will not be dropped. However, in many cases, especially in wireless communications, packet drops are often seen, for example, due to interference, fading and so on. We have studied the tradeoffs between measurement communication and estimate communication for a fixed sensor tree subject to random packet drops on the communication links in [13]. We will further take a look at the tradeoff between the estimation quality, the underlying graph that represents the sensor communication, the quality of the communication link and the energy cost of the sensors. We assumed synchronisation of all sensor nodes in the current work and we plan to relax this assumption in the future work. For the algorithms presented in the paper, we will give bounds on how far the solution obtained is from the global optimal solution, and also look for better algorithms. Closing the loop using the estimation algorithms developed in the paper is also interesting.

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8 References


Before formalising the problem of interest, we introduce some notation. Given a set $S = \{s_1, \ldots, s_M\}$ of vertices, let us denote by $T$ the family of all trees having $S$ as vertex set. For any given integer $M$, we denote by $F_M$ the family of all subfamilies consisting of $M$ trees, with each tree belonging to $T$. Formally speaking

$$F_M = \{G_i : G_i \subset T, |G_i| = M\}$$

Let $f: 2^T \to \mathbb{R}^+$, where $2^T$ denotes the power set of $T$. Moreover, let us denote by $(F_M, f_M)$ the family $F_M$ endowed with the function $f_M$, which is obtained projecting $f$ on $F_M$, meaning restricting the domain of $f$ to $F_M$.

We now have all ingredients needed to formalise our optimisation problem of interest:

Problem 2: Given $(F_M, f_M)$, where $f_M(G)$ is computable in polynomial time for any $G_i \in F_M$, find

$$\max \{ f_M(G_i) : G_i \in F_M \}$$

Before proceeding with the proof of the NP-completeness, we want to relate the formal problem (2) to our original problem (1) of interest. The correspondence is as follows

$S \to$ sensors of the network

$T \to$ set of possible trees of sensors

$f_M(G_i) \to$ LP($G_i$)

where LP($G_i$) is the solution of the linear programming problem applied to the family $G_i$ of sensor trees, which is computable in polynomial time using, for example, the ellipsoid method. Using the correspondence given in (21), it is straightforward to check that problem (2) is the formalisation of problem (1). We next proceed with the proof of the NP-completeness. Since NP-completeness deals with decision problems, we reformulate problem (2) as the following decision problem.

$\Pi_{\text{scheduling}}$: Given $(F_M, f_M)$ where $f_M(G_i)$ is computable in polynomial time for any $G_i \in F_M$, and a real number $k$, where $k \geq 0$, is

$$\{ f_M(G_i) : G_i \in F_M \} \geq k?$$

If $G_i \in F_M$ is such that $f_M(G_i) \geq k$, then we say that $G_i$ satisfies the decision problem $\Pi_{\text{scheduling}}$.

We briefly recall the definition of NP-completeness and refer the reader to [14] for more details. We start with the following definitions:

Definition 1: Let $\Pi$ be a decision problem. Then $\Pi$ is said to belong to the class $NP$ if, given a candidate solution $s$ for the problem $\Pi$, it is possible to verify in polynomial time that $s$ satisfies the decision problem $\Pi$. 

9 Appendix

9.1 Optimal scheduling is NP-complete

In this section, we prove the following.

Problem 1: Show that finding the family, which maximises the network lifetime, among all families consisting of $M$ trees, is NP-complete.


Definition 2: Let $\Pi_1$ and $\Pi_2$ be two decision problems. We say that $\Pi_1$ is polynomially reducible to $\Pi_2$ (notation: $\Pi_1 \leq_p \Pi_2$), whenever any instance $I_1$ of $\Pi_1$ can be transformed in polynomial time to an instance $I_2$ of $\Pi_2$ such that $I_2$ satisfies $\Pi_1$ if and only if $I_2$ satisfies $\Pi_2$.

Roughly speaking, Definition 2 says that $\Pi_1$ is a special case of $\Pi_2$. Thus, if $\Pi_1 \leq_p \Pi_2$, then there exists a polynomial time algorithm that transforms an instance for $\Pi_1$ into an instance for $\Pi_2$, that does not change the outcome.

A decision problem $\Pi$ is said to be NP-complete if the following holds:

(a) $\Pi$ is in NP

(b) $\Pi_1 \leq_p \Pi$ for any decision problem $\Pi_1$ in NP.

We first establish (a), that is that $\Pi_{\text{scheduling}}$ is in NP. Suppose that we are given a candidate solution, let us call it $G_{sol}$ consisting of $n$ variables, all of which have been assigned to some time $t$. Then we can verify in polynomial time whether the boolean formula $\phi(s)$ corresponds to the constructed family $G_{sol}$.

We next prove (b). We will show that the satisfiability problem can be reduced to $\Pi_{\text{scheduling}}$ in polynomial time. This will directly imply (b) since the satisfiability problem is well known to be NP-complete, therefore for any decision problem $\Pi_1$ in NP, we would have

$$\Pi_1 \leq_p \Pi_{\text{scheduling}}, \quad \forall \Pi_1 \in \text{NP}$$

which clearly implies

$$\Pi_1 \leq_p \Pi_{\text{scheduling}}^*, \quad \forall \Pi_1 \in \text{NP}$$

The satisfiability decision problem.

Definition (SAT): Given the boolean formula $\psi$ consisting of $n$ literals $x_1, x_2, \ldots, x_N$, find an assignment $y \in \{0, 1\}^N$ such that $\psi(y) = 1$.

Next, we show that we can map an instance of SAT to an instance of $\Pi_{\text{scheduling}}$ as follows.

Cayley [12] proved that the number of spanning trees of a complete simple graph with $n$ vertices is $n^{n-2}$. We use the result by Prüfer [15] who noticed the fact that $n^{n-2}$ is the number of ways to write down a string of length $n-2$ from a set $S$ of $n$ numbers and constructed a code (called Prüfer’s code) that maps polynomially such strings to labelled trees in a one-to-one correspondence.

Let $s \in \{0, 1\}^{(n-2)M}$ be a string, with $s = s_1s_2 \ldots s_M$, that is, $s$ is obtained concatenating $M$ strings, each having length $(n-2)$. We can associate to any string $s_i$ its corresponding tree $T_i := \phi(s_i)$ given by the Prufer code. This gives us a family of trees of size $M$ defined as

$$G_s = \{\phi(s_1), \phi(s_2), \ldots, \phi(s_M)\}$$

Since the time required to construct the Prüfer’s code for each substring, $s_i$, $i = 1 \ldots M$, is polynomial in the length $n$ of the substring, it follows that the above construction is polynomial in $n$. The function $f_M$ associated to the constructed family $G_i$ would be

$$f_M(G_i) = \psi(i)$$

where $\psi(i)$ indicates the output of the evaluation of the boolean formula $\psi$ on the string $s_i$. Since evaluating a boolean formula of $n$ literals can be done polynomially, any instance $s$ of SAT can be polynomially reduced to an instance $(G_s, f_M(G_s))$ of $\Pi_{\text{scheduling}}$. We set the decision boundary $k$ in $\Pi_{\text{scheduling}}$ to 1.

In order to complete the proof, we need to show that a string instance $s$ satisfies SAT if and only if the corresponding instance $G_i$ satisfies $\Pi_{\text{scheduling}}$. Assume first that a string instance $s$ satisfies SAT. Then $\psi(s) = 1$. Since $f_M(G_i) = \psi(s)$ by construction and since the decision boundary $k = 1$, we would have that $G_i$ satisfies $\Pi_{\text{scheduling}}$. Assume now that $G_i$ satisfies $\Pi_{\text{scheduling}}$. This means that $f_M(G_i) = 1$. Since $f_M(G_i) = \psi(s)$ by construction, we would have that the boolean formula $\psi$ in SAT evaluates to one on the string instance $s$, thus it is satisfiable.

Having proven both (a) and (b), we can conclude that $\Pi_{\text{scheduling}}$ is NP-complete.