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Brief paper

Co-design of jump estimators and transmission policies for wireless multi-hop networks with fading channels☆

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ABSTRACT

We study transmission power budget minimization of battery-powered nodes in a remote state estimation problem over multi-hop wireless networks. Communication links between nodes are subject to fading, thereby generating random dropouts. Relay nodes help to transmit measurements from distributed sensors to an estimator node. Hopping through each relay node introduces a unit delay. Motivated by the need for estimators with low computational and implementation cost, we propose a jump estimator whose modes depend on a Markovian parameter that describes measurement transmission outcomes over a finite interval. It is well known that transmission power helps to increase the reliability of measurement transmissions, at the expense of reducing the life-time of the nodes' battery. Motivated by this, we derive a tractable iterative procedure, based on semi-definite programming, to design a finite set of filter gains, and associated power control laws to minimize the energy budget while guaranteeing an estimation performance level. This procedure allows us to tradeoff the complexity of the filter implementation with performance and energy use.

1. Introduction

Wireless communication technologies have considerably improved in recent years in terms of reliability and transmission rates, favoring their use for control and estimation purposes (Chen, Johansson, Olariu, Paschalidis, & Stojmenovic, 2011). However, wireless links are subject to channel fading that may lead to time-varying delays and packet dropouts (Hespanha, Naghshtabrizi, & Xu, 2007) that must be taken into account when designing networked control systems.

Considering remote estimation over networks, Kalman filter (KF) approaches (with time-varying gains) may yield optimal performance (for linear dynamical systems), but possibly at the expense of notable implementation and computational complexity (e.g. Schenato, 2008). Motivated by alleviating the computing requirements, we extend the proposal in Smith and Seiler (2003) that used a jump linear estimator whose gains depend on the history of measurement transmission outcomes for a system with one sensor and without delays. Our approach was initially presented in Dolz, Quevedo, Peñarrocha and Sanchis (2014). Here, we extend it for its use in multisensor schemes with delays, and show the feasibility conditions and a design procedure to reduce the complexity of the filter.

A higher transmission power leads to lower dropout probabilities, which improves estimation performance but shorten battery life-time, what encourages to design both the estimator and the transmission policy (Nourian, Leong, & Dey, 2014; Quevedo, Ahlén, Leong, & Dey, 2012; Shi & Xie, 2012). These works present methodologies to minimize the estimation error using a KF while limiting the energy use considering only the sensor and estimator nodes.

In this work, we focus on multi-hop wireless networks where some nodes (relays) consciously help to transmit the information from the source to the final destination, and where node data broadcasts are more likely to be acquired from nearby nodes, a more general topology than the two-hop network presented in Shi, Jia, Mo, and Sinopoli (2011). In our recent articles (Leong & Quevedo, 2013; Quevedo, Østergaard, & Ahlén, 2014), we studied

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the KF estimation and power control problem through multi-hop fading networks. In the current work, we will assume that hopping through each relay introduces an additional unit delay on the data, an effect that was neglected in the previous works.

In this paper, we study the transmission power budget minimization of wireless self-powered nodes in a remote state estimation problem for multi-sensor systems over multi-hop networks. Wireless links are subject to fading leading to random dropouts; hopping through each intermediate node introduces an additional unit delay. We describe this via a finite measurement outcome parameter taken as a finite Markov chain and, based on the network average behavior, we propose a jump linear filter structure. As a difference w.r.t. Smith and Seiler (2003), we use convex optimization in the design of the filter, which allows us to include constraints to fix the number of gains of the jump filter, leading to a trade-off between filter complexity and estimation performance. We characterize this compromise and give some insights on how to reduce the filter complexity via Lagrange multipliers. We study the co-design problem of minimizing the power budget while guaranteeing a prescribed estimation performance. Since this optimization is non-linear, we derive a greedy algorithm that solves iteratively semi-definite programming problems in order to obtain the set of filter gains and the power transmission laws.

2. Remote estimation over a multi-hop network

We consider a LTI discrete-time system defined by

$$x[k+1] = A\,x[k] + B\,w[k], \qquad y_s[k] = c_s\,x[k] + v_s[k], \tag{1}$$

where $x[k] \in \mathbb{R}^n$ is the system state, $y_s[k] \in \mathbb{R}$ is the sth measured output ($s = 1, \dots, n_y$), $w[k] \in \mathbb{R}^{n_w}$ is the state disturbance assumed to be a Gaussian signal of zero mean and (known) covariance $\mathbf{E}\{w[k]\,w[k]^T\} = W$, and $v_s[k] \in \mathbb{R}$ is the sth sensor's measurement noise considered as an independent zero mean Gaussian signal with (known) variance $\mathbf{E}\{v_s[k]^2\} = \sigma_s^2$. For further reference, we define $y[k] \triangleq [y_1[k] \ \dots \ y_{n_y}[k]]^T$. Also, we assume the pair (A, C) to be detectable, where $C = [c_1^T \ \dots \ c_{n_y}^T]^T$.

In this work, we study the remote estimation of the system states (1) where the received measurements at the estimator node arrive through an unreliable multi-hop wireless network with fading channels and known topology. We assume that multiple sensors sample the system outputs synchronously and send them independently through the network to a centralized estimator. We assume that nodes cannot send and receive at the same time and there is no interference between them. Moreover, we assume that nodes are time-driven and synchronized. Here, we consider multi-hop wireless networks that can be described via an acyclic directed graph. We denote the set of network nodes by $\mathcal{N} = \{N_1, \dots, N_M, N_{M+1}\}$ with $M > n_y$ being the number of transmitter nodes. N_1 to N_{n_y} are the sensor nodes, N_{n_y+1} to N_M are the relay nodes and N_{M+1} refers to the estimator node. While relay nodes are used to retransmit data, sensors can only send their own samples. The network topology is classified and ordered by layers depending on the maximum number of hops (longest path) for a transmission to arrive at the estimator from each node. We assume that the number of different layers is bounded by $\bar{d} + 2$ and thus, the maximum number of hops is $\bar{d} + 1$. The set of nodes in the d-layer is denoted by $\mathcal{N}_d \triangleq \{N_a \in \mathcal{N}_d : |(N_a, N_{M+1})| = d\} \subset \mathcal{N}$ where $|(N_a, N_{M+1})|$ stands for the maximum number of hops from N_a to the estimator node. The 0-layer contains only the estimator node, the $(\bar{d} + 1)$-layer includes only sensor nodes, and all other layers may comprise either relay nodes (intermediate nodes that help to retransmit the data) or sensors.

At each instant k, a set of nodes (that transmit in different frequency bands) aggregate all their available measurements in a single time-stamped packet and broadcast it once (without retransmissions) at the same time. Only nodes within a lower layer will accept the transmission (i.e., from d_1-layer to d_2-layer with $d_1 > d_2$), establishing wireless links. The rest of the nodes in the same or higher layers ignore the reception. Thus, a node may receive multiple measurement packets from higher layer nodes and may forward this information to various lower layer nodes. We denote the entire set of wireless links as $\mathcal{L}$, and a single link as $(N_a, N_l) \in \mathcal{L}$. When the dedicated transmission time slot is over, the following set of nodes starts to transmit. After all nodes have attempted to communicate (and before the sampling period has passed), the estimator uses all the received information at instant k to run the state estimation algorithm to be presented in Section 4. While each sensor transmits the current sampled output, each relay node transmits at instant k only the acquired data at $k - 1$.

The transmission protocol implies that communicating through each relay layer introduces an additional unit delay. Direct transmissions to the estimator node do not introduce delays. Thus, a measurement being transmitted at time k by sensor node $N_s \in \mathcal{N}_{d+1}$ may arrive at the estimator node with an end-to-end delay of up to d time steps, depending on the number of intermediate layers visited. The estimator node discards measurements already received.

3. Transmission outcome model

To model the unreliable transmission through the available wireless links $(N_a, N_l) \in \mathcal{L}$, we introduce the binary variable $\gamma_{a,l}[k]$ that takes value 1 if N_l receives a packet from N_a at k and 0 otherwise. Throughout the first part of this work, we assume that each $\gamma_{a,l}[k]$ is an i.i.d. stochastic process. The probability of successfully acquiring a transmitted packet is given by

$$\beta_{a,l} \triangleq \mathbf{Pr}\{\gamma_{a,l}[k] = 1\}, \quad a, l \in \{1, \dots, \}. \tag{2}$$

We denote by $\tau_s[k] \in \mathbb{N}$ the delay experienced by the kth measurement from sensor s when accepted at the estimator node. Thus, $\tau_s[k] = d$ means that $y_s[k]$ is accepted, i.e., for the first time received by the estimator at time $k + d$. The instance $\tau_s[k] > d$ states that the measurement may still be acquired with an induced delay greater than d. Since the number of hops is bounded by $\bar{d} + 1$, the maximum possible end-to-end delay is $\bar{d}$, i.e., $\tau_s[k] \in \{0, 1, \dots, \bar{d}\}$. Thus, $\tau_s[k] > \bar{d}$ means that $y_s[k]$ is lost.

Let us use $\Gamma_{s,d}^k$ to enumerate the Boolean combinations (logical "and" and "or" operations) of variables $\gamma_{a,l}$ that define the possible paths a measurement from sensor N_s sent at time k may take to reach and be accepted by the estimator node with a given delay d, i.e., with $\tau_s[k] = d$. The possible node-to-node transmission outcomes leading to $\tau_s[k] > d$ are denoted by $\daleth_{s,d}^k$ and can be obtained by the negation of the disjunction of the corresponding $\Gamma_{s,d}^k$, i.e., $\daleth_{s,d}^k = \neg\left(\bigvee_{\delta=0}^{d} \Gamma_{s,\delta}^k\right)$.

Considering the network model described above, the available information at the estimator node at time k are the pairs $(m_{s,d}[k], \alpha_{s,d}[k])$ for all $s = 1, \dots, n_y$ and $d = 0, \dots, \bar{d}$, where $m_{s,d}[k] = \alpha_{s,d}[k]\,y_s[k-d]$ and $\alpha_{s,d}[k]$ is a binary variable that takes value 1 if $y_s[k-d]$ is received at time k, and 0 otherwise. When $\alpha_{s,d}[k] = 1$, the measurement sent at time $k - d$ from sensor N_s has experienced a delay of $\tau_s[k-d] = d$. If $y_s[k-d]$ has not yet arrived at time k, then $m_{s,d}[k] = 0$. Since delayed copies (already received measurements with a higher delay) are discarded, $\alpha_{s,d}[k]$ is equal to zero if $\alpha_{s,d-\delta}[k-\delta] = 1$ for some integer $\delta \in \{1, \dots, d\}$.

Let us now introduce a vector $\theta_{s,d}[k]$ which models the successful reception of $y_s[k-d]$ during the interval $\{k-d, k-d+1, \dots, k\}$:

$$\theta_{s,d}[k] = \begin{bmatrix}\alpha_{s,0}[k-d] & \alpha_{s,1}[k-d+1] & \cdots & \alpha_{s,d}[k]\end{bmatrix}. \tag{3}$$