

# Distributed and Collaborative Tracking for Energy-Constrained Ad-hoc Wireless Sensor Networks

S. Balasubramanian, I. Elangovan, S. K. Jayaweera and K. R. Namuduri

Department of Electrical and Computer Engineering,  
Wichita State University, Wichita, KS 67260, USA.

Telephone: (316) 684 3837

Email: [sxbalasubramanian2@wichita.edu](mailto:sxbalasubramanian2@wichita.edu)

## Abstract

*An energy-aware, collaborative tracking algorithm is proposed for ad-hoc wireless sensor networks. The algorithm is implemented distributively by passing sensing and computation operations from one sensor to another. In order to maximize the life-time of the network, this active sensor is chosen by a high end sensor in order to minimize the cost function based on the total energy spent by the network at each time instant. Assuming a wireless ad-hoc sensor network in which low end sensors are randomly distributed with data gathering node as a high end sensor, a state-space model for a target motion and sensor measurement and a cost function based on energy requirements for communication and sensing has been derived. Simulation results for the performance of the proposed scheme have also been presented.*

## I. INTRODUCTION

Recently, there has been a great interest in wireless ad-hoc sensor networks. Such ad-hoc sensor networks find applications in military, animal tracking, environmental control etc. In these practical applications, they are expected to detect, track and classify objects [1]. For example, a set of sensors can be randomly distributed in an area where a target of interest is moving and expect to detect and track the target by self-forming a wireless ad-hoc sensor network.

A wireless ad-hoc network is a set of randomly distributed sensors that communicate with each other over a radio link. The sensor are assumed to have finite sensing radii. A moving target is assumed to be on the same plane on which the sensors

are located and only the active sensor will detect and track the target, whereas all other sensors will be in an idle mode. Throughout the paper we will assume that the sensor locations are fixed.

One of the important aspects of multisensor networks is collaborative signal and information processing; i.e , how to dynamically determine who should sense the target, what should be sensed and who should be the next leader to whom the information should be passed on to [2]. Most often sensor nodes of an ad-hoc wireless sensor network are powered by batteries with finite lifetime and hence they are subjected to energy constraints. These energy constraints impact both hardware operation and signal transmission associated with node operation [3]. Thus design of energy-aware collaborative signal processing algorithms is important in order to maximize the lifetime of such sensor networks [4].

In this paper, a collaborative tracking algorithm is developed for a wireless ad-hoc sensor network consisting of randomly distributed low end sensors. Every cluster of sensor will have a high end sensor as a data gathering node which will communicate with all the sensors in its cluster to collect the observation from them. Only this data gathering node is able to communicate with the base station. Sensor nodes are battery driven and hence operate on an extremely frugal energy budget [5], [6]. The distributed collaborative algorithm is based on the energy consumption of the sensor network, in which the next active sensor is decided by a data gathering node, in order to minimize the total energy spent by the network. Data gathering node decides the next active sensor based on a cost

function calculated by considering many factors such as energy requirements for communication and sensing.

The paper is organized as follows: In Section II, the proposed system model is presented. In Section III, the basic distributed tracking algorithm based on the Kalman filter is presented. Next, in Section IV, an energy aware, collaborative algorithm for deciding who is the next active sensor is described. Simulation results for target tracking with randomly distributed sensors are presented in Section V. Finally concluding remarks are given in Section VI.

## II. SYSTEM MODEL

We assume that the target movement can be modeled by a discrete-time, linear, dynamic system perturbed by additive noise.

Let  $\mathbf{x}(t - \frac{\tau(t)}{2})$  be the state at time  $t$  which consists of the position and velocity of the moving target (i.e.,  $\mathbf{x}(t - \frac{\tau(t)}{2}) = [x(t - \frac{\tau(t)}{2}), y(t - \frac{\tau(t)}{2}), \dot{x}(t - \frac{\tau(t)}{2}), \dot{y}(t - \frac{\tau(t)}{2})]^T$ ) where superscript T denotes the transpose. The state space model is given by (1) with  $T$  be the sampling time.

$$\mathbf{x}\left(t - \frac{\tau(t)}{2} + T\right) = \mathbf{A}\mathbf{x}\left(t - \frac{\tau(t)}{2}\right) + \mathbf{u}\left(t - \frac{\tau(t)}{2}\right), \quad (1)$$

where  $\mathbf{u}\left(t - \frac{\tau(t)}{2}\right)$  is the state noise which is assumed to be zero-mean with covariance matrix  $\mathbf{Q}$  and matrix  $\mathbf{A}$  is given by,

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2)$$

We assume an ad-hoc wireless network consisting of  $N$  sensors. The sensors are assumed to be active sensors with finite battery-life. Suppose that a signal  $E(t)$  is transmitted by a particular sensor at time  $t$ . The received signal reflected from the target is given by,

$$s_r(t) = \Re[A_r E(t - \tau(t)) e^{j\omega_c(t - \tau(t))}], \quad (3)$$

where  $A_r = \sqrt{2P_r}$ , ( $P_r$  includes the transmit power and the two-way propagation and reflection processes [7]),  $\omega_c$  is the carrier frequency and  $\tau(t)$  is round trip delay of the transmitted wave between the sensor and the target.

The delay  $\tau(t)$  is given by,

$$\tau(t) = \tau_0 - \frac{2v_{rad}}{c}t, \quad (4)$$

where  $\tau_0$  is the reference delay and  $v_{rad}$  is the radial velocity of the target. Substituting  $\tau(t)$  in (3), we get

$$s_r(t) = \Re \left[ A_r E \left( t - \tau_0 + \frac{2v_{rad}}{c}t \right) e^{j\omega_c(t - \tau_0 + \frac{2v_{rad}}{c}t)} \right]. \quad (5)$$

From (5), we note that the doppler frequency shift  $f_D$  of the received signal is,

$$f_D = \frac{2f_c}{c}v_{rad}. \quad (6)$$

Referring to Fig.1(a), the time delay  $\tau(t)$  is given by,

$$\tau(t) = \frac{2}{c} \sqrt{\left(x\left(t - \frac{\tau(t)}{2}\right) - x_s\right)^2 + \left(y\left(t - \frac{\tau(t)}{2}\right) - y_s\right)^2},$$

where  $(x_s, y_s)$  represents the sensor location.

Linearizing the above equation around  $(x_{t-1}, y_{t-1})$ , where  $(x_{t-1}, y_{t-1})$  is the previous location of the target, we have

$$\tau(t) = \frac{2}{c} \left[ \left(\frac{x_{t-1} - x_s}{R_{t-1}}\right) x\left(t - \frac{\tau(t)}{2}\right) + \left(\frac{y_{t-1} - y_s}{R_{t-1}}\right) y\left(t - \frac{\tau(t)}{2}\right) \right]. \quad (7)$$

Suppose that the target is moving with a velocity  $v$  as shown in Fig. 1(b). Then, the radial component of the velocity is given by,

$$v_{rad} = \dot{x}\left(t - \frac{\tau(t)}{2}\right) \cos(\varphi) + \dot{y}\left(t - \frac{\tau(t)}{2}\right) \sin(\varphi), \quad (8)$$

where angle  $\varphi$  represents the orientation of the line connecting the target and sensor.

Substituting equation (8) in (6) we see that,

$$f_D(t) = \frac{2f_c}{c} \left[ \dot{x}\left(t - \frac{\tau(t)}{2}\right) \cos(\varphi) + \dot{y}\left(t - \frac{\tau(t)}{2}\right) \sin(\varphi) \right]. \quad (9)$$

Defining the observation vector as  $\mathbf{y}\left(t - \frac{\tau(t)}{2}\right) = [\tau(t), f_D(t)]^T$ , the measurement equation can be given by,

$$\mathbf{y}\left(t - \frac{\tau(t)}{2}\right) = \mathbf{C}\mathbf{x}\left(t - \frac{\tau(t)}{2}\right) + \mathbf{v}\left(t - \frac{\tau(t)}{2}\right), \quad (10)$$

where  $\mathbf{v}\left(t - \frac{\tau(t)}{2}\right)$  is a random disturbance vector of zero-mean Gaussian noise with covariance matrix  $\mathbf{R}$  and  $\mathbf{C}$  is the observation matrix defined as,

$$\mathbf{C} = \begin{bmatrix} \frac{2}{c} \left[ \frac{x(t-1) - x_s}{R(t-1)} \right] & \frac{2}{c} \left[ \frac{y(t-1) - y_s}{R(t-1)} \right] & 0 & 0 \\ 0 & 0 & \frac{2f_c}{c} \cos(\varphi) & \frac{2f_c}{c} \sin(\varphi) \end{bmatrix}.$$

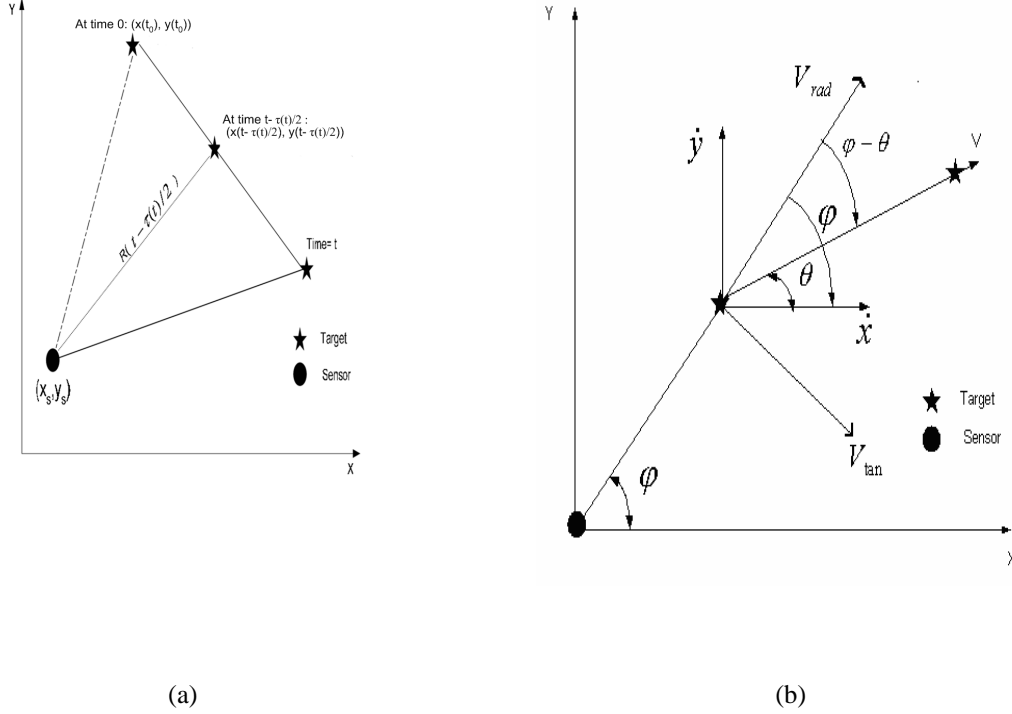


Fig. 1. (a) The Orientation of Sensor and Target for Computing Delay and Doppler. (b) Velocity Components of the Target.

### III. TRACKING ALGORITHM FOR SENSOR NETWORK

In this section, we propose a distributed tracking algorithm based on the Kalman filter [8], [9]. Based on the model (1) and (10) Kalman filter recursively updates the estimate of the state of the vector by processing successive measurements.

The predicted state before update and its corresponding error covariance matrix, denoted by  $\hat{\mathbf{x}}(t+1|t)$  and  $\mathbf{P}(t+1|t)$  are given by,

$$\hat{\mathbf{x}}(t+1|t) = \mathbf{A}\hat{\mathbf{x}}(t|t) \quad (11)$$

$$\mathbf{P}(t+1|t) = \mathbf{A}\mathbf{P}(t|t)\mathbf{A}^T + \mathbf{Q}. \quad (12)$$

The filtered estimate  $\hat{\mathbf{x}}(t+1|t+1)$  is then given by

$$\hat{\mathbf{x}}(t+1|t+1) = \hat{\mathbf{x}}(t+1|t) + \mathbf{K}(t+1)\mathbf{y}(t+1) - \mathbf{C}(t+1)\hat{\mathbf{x}}(t+1|t) \quad (13)$$

where the kalman gain is

$$\mathbf{K}(t+1) = \mathbf{P}(t+1|t)\mathbf{C}^T(t+1) (\mathbf{C}(t+1)\mathbf{P}(t+1|t)\mathbf{C}^T(t+1) + \mathbf{R})^{-1}. \quad (14)$$

The corresponding error covariance matrix is,

$$\mathbf{P}(t+1|t+1) = \mathbf{P}(t+1|t) - \mathbf{K}(t+1)\mathbf{C}(t+1)\mathbf{P}(t+1|t). \quad (15)$$

### IV. MULTISENSOR COLLABORATION

In this section we develop an energy-aware collaborative tracking algorithm for a wireless ad-hoc sensor network. In our setup there are two types of sensors: *high-end* and *low-end sensors*. Ad-hoc sensor network is divided into many cluster and each cluster will have one data gathering sensor which is assumed to be high end sensor. This data gathering node is able to communicate with all the sensors in its cluster and also with the base station. The other sensors which are randomly distributed are low-end sensors which are just capable of sensing the environment to produce measurements and then pass the information to data gathering sensor over a wireless link.

#### A. Cost Associated with each sensor

We assume that the sensing cost depends on the distance between the sensor and the target, i.e, larger the distance

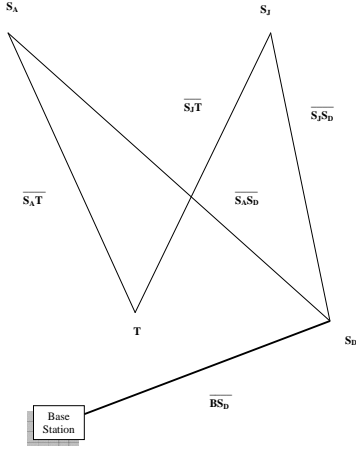


Fig. 2. Geometric Arrangement of Sensors with Respect to Target, Data Gathering Sensor and Base Station

to the target, more energy is required for a reliable sensor measurement. Let  $P_s$  be the sensor transmit power. The sensor received power can be written as,

$$P_L = \frac{P_s}{|\overline{S_A T}|^\beta} r \frac{1}{|\overline{S_A T}|^\beta}, \quad (16)$$

where  $|\overline{S_A T}|$  is the distance between the active sensor and the target as shown in the Fig. 2,  $r$  is the reflection coefficient and  $\beta$  is the attenuation factor. From (16), the required transmit power for sensing will be given by

$$P_s = \frac{P_L |\overline{S_A T}|^{2\beta}}{r} \quad (17)$$

The communication cost depends on distance between the sensor and the data gathering node, i.e., larger the distance between them, more energy will be needed for reliable communication. Let  $P_c$  be the transmit power at current active sensor ( $S_A$ ) communicating with data gathering sensor ( $S_D$ ). The received power at data gathering sensor ( $S_D$ ) is given by,

$$P_D = \frac{P_c}{|\overline{S_A S_D}|^\alpha} \quad (18)$$

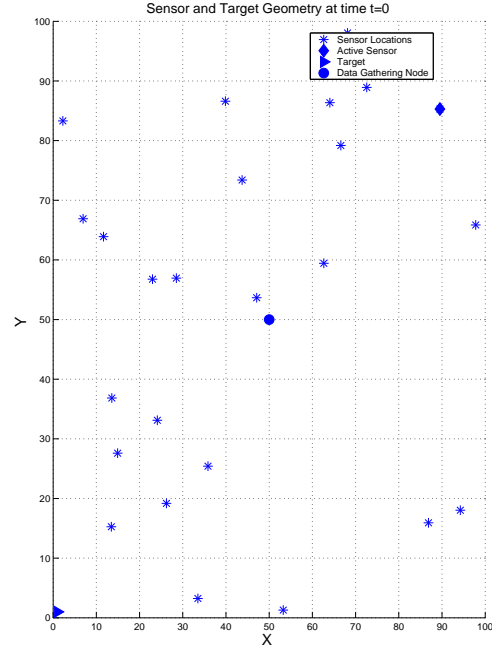


Fig. 3. Initial Location of Sensors and the Target

where  $|\overline{S_A S_D}|$  is distance between  $S_A$  and  $S_D$  and  $\alpha$  is an attenuation factor. From (18), the required transmit power for successful communication will be,

$$P_c = P_D |\overline{S_A S_D}|^\alpha \quad (19)$$

### B. Active Sensors

The *Data Gathering Sensor* decides which sensor needs to be the active sensor so that the total energy spent by the whole network is minimized.

- *The active sensor remains the same*

If the active sensor remains the same at the next time instant, then the total cost for the network would be the sensing cost and the communication cost to communicate with data gathering sensor, which is given by,

$$C_{T,A} = \frac{P_L}{r} |\overline{S_A T}|^{2\beta} + P_D |\overline{S_A S_D}|^\alpha \quad (20)$$

where T is the target location and  $C_{T,A}$  is the total cost spent by the active sensor.

- *The active sensor changes*

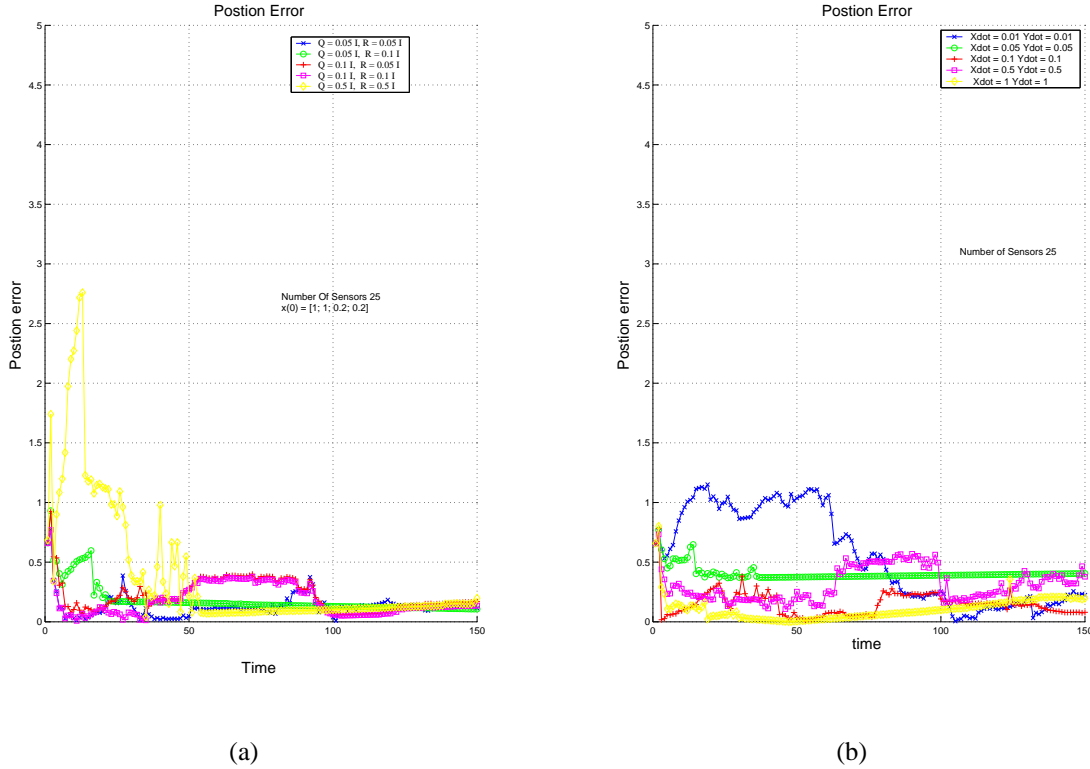


Fig. 4. (a) Position Error for Various Values of Q and R of the Distributed Collaborative Tracking Algorithm for Wireless Ad-hoc Sensor Network. (b) Position Error for Various Initial Velocities of the Distributed Collaborative Tracking Algorithm for Wireless Ad-hoc Sensor Network.

If the active sensor is changed, then the total cost for the network would consist of sensing cost of the next active sensor and communication cost for the next active sensor to communicate with data gathering sensor, which is given by,

$$C_{T,J} = \frac{P_L}{r} |\overline{S_J T}|^{2\beta} + P_D |\overline{S_D S_J}|^\alpha \quad (21)$$

Thus, if  $S_A$  is the current active sensor, then the next active is chosen to be  $S_J$ , where

$$J = \arg \min_{j=\{1,\dots,N\}} \left( \lambda |\overline{S_J T}|^{2\beta} + (1 - \lambda) |\overline{S_D S_J}|^\alpha \right)$$

where  $0 \leq \lambda \leq 1$ .

## V. SIMULATION RESULTS

We simulate an ad-hoc wireless network consisting of  $N = 25$  randomly distributed sensors in one cluster and we have one data gathering sensor in that cluster. It is assumed that at each time instant only the active sensor in the network will measure the time delay and the doppler shift corresponding to

the target. Initially, one of the sensors is randomly chosen as the active sensor. Figure 3 shows a typical distribution of initial locations of sensors and the target. The sampling interval  $T$  is set to 1.

Figure 4(a) corresponds to the position estimate error at the lead sensor. Note that in this figure the initial target velocity was set to  $\dot{x} = 0.2$  and  $\dot{y} = 0.2$ . The covariance matrix  $\mathbf{Q}$  and  $\mathbf{R}$  is given by  $\sigma_s^2 I$  and  $\sigma_o^2 I$  respectively. Figure 4(a) is a parametric plot of the position error for different values of  $\sigma_s^2$  and  $\sigma_o^2$ . From Fig. 4(a), we can observe that the proposed energy-aware collaborative tracking algorithm can achieve sufficiently small error values.

Figure 4(b) also shows the position estimate for fixed values of  $\sigma_s^2 = 0.05$  and  $\sigma_o^2 = 0.05$  and when the initial velocity of the target is varied between 0.01 and 1. We observe that usually the algorithm converges faster when the velocity is high, but there are large fluctuation in the final error due to high velocity of the target.

## VI. CONCLUSION

In this paper, we presented a distributed collaborative tracking algorithm for an energy constrained wireless ad-hoc sensor network. We derived a state space model for an ad-hoc wireless sensor network with active sensors that measure the time delay and doppler shift of a target. The proposed energy-aware distributed tracking algorithm attempts to optimize the total energy consumption of the network (as against that of a particular sensor) in order to maximize the life time of the total network. From the simulation results, we observe that this collaborative algorithm performs well providing sufficiently small estimation errors. Energy requirement for communications and sensing at the sensors are taken into account for computing the cost associated in deciding the next active sensor. In future, it is expected to modify the cost function by including other energy terms, multiple active sensors and also by including multitarget scenarios in the analysis.

## ACKNOWLEDGEMENT

This research was supported in part by Kansas NASA EP-SCoR program under grant KUCR ‡ FED33144/KAN33145.

## REFERENCES

- [1] D. McErlean and S. Narayanan, "Distributed Detection and Tracking in Sensor Networks," *Proc. 36<sup>th</sup> Asilomar Conf. on Signal, Systems and Computers*, pp. 1174-1178, Nov. 2002.
- [2] F. Zhao, J. Shin and J. Reich, "Information-driven dynamic sensor collaboration for tracking applications," *IEEE Sig. Pro. Mag.*, pp. 61-72, Mar. 2002.
- [3] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Commun.*, pp. 8-27, Aug. 2002.
- [4] A. Wang and A. Chandrakasan, "Energy-Efficient DSPs for Wireless Sensor Networks," *IEEE Sig. Pro. Mag.*, pp. 68-78, July 2002.
- [5] V. Raghunathan, C. Schurgers, S. Park and M. B. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Sig. Pro. Mag.*, pp. 40-50, Mar. 2002.
- [6] R. Min, M. Bhardwaj, S. Cho, N. Ickes, E. Shih, A. Sinha, A. Wang and A. Chandrakasan, "Energy-centric enabling technologies for wireless sensor networks," *IEEE Wireless Commun.*, pp. 28-39, Aug. 2002.
- [7] M. I. Skolnik, *Introduction to Radar Systems, Second Edition*, McGraw-Hill Book Company, New York, USA, 1980.
- [8] K. V. Ramachandra, *Kalman Filtering Techniques for Radar Tracking*, Marcel Dekker, Inc, New York, USA, 2000.
- [9] H. V. Poor, *An Introduction to Signal Detection and Estimation, Second Edition*, Springer-Verlag, New York, USA, 1994.