Energy Aware Distributed Estimator System over Wireless Sensor Networks with Ad-hoc On-Demand Distance Vector (AODV) Routing Algorithm

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***Abstract*—Wireless sensor networks (WSNs) have many applications such as environmental monitoring, industrial monitoring and control, structural health monitoring. WSNs have received considerable attention in recent years. The paper presents comparison of the performance of the combined centralized-decentralized Kalman filter with the centralized Kalman filter and the decentralized Kalman filter for state estimation over wireless sensor network. The wireless sensor network uses energy aware AODV routing algorithm to reduce energy consumption of sensors. In addition, the paper compares the energy consumption of each architecture and the difference between the energy aware and the regular AODV algorithm.**

***Index Terms*—AODV routing algorithms, Centralized, Decentralized, Estimator, Kalman Filter, Wireless Sensor Network (WSN).**

I. Introduction

A Wireless Sensor Networks (WSN) is a network that consists of many sensors connected wirelessly with limited memory unit, limited calculations and communication capabilities, and limited energy resources [1]. The progress of WSN has promoted multiple sensor fusion and state estimation as an important and emerging topic cover many application areas. A wireless sensor network (WSN) [2] is spatially distributed autonomous sensors to monitor (physical or environmental conditions, such as temperature, flow, sound, pressure, etc.) and to cooperatively pass their data through the network to a main location. Modern networks are bi-directional, also have enabling control of sensor activities.

The WSN consists of nodes, from one or two to several hundreds or thousands. Every node is linked to one sensor or a number of sensors. Each sensor network node comprises some parts such as a radio transceiver including an internal antenna or link to an external antenna, a microcontroller, an electronic device for interfacing with the sensors and an energy source from a battery or an energy harvesting form. The size of a sensor node might alter from that of a small box down to a grain. The cost of sensor nodes is also varied from a few to hundreds of dollars determined by the complexity of the peculiar sensor nodes. Constraints on size and cost of sensor nodes lead to limitations on properties of the nodes, for examples: energy supply, memory capacity, computational speed and bandwidth in communications.

In the WSNs, the topology can be designed from a simple star network to a complex multi-hop wireless mesh network. Routing or flooding is the transmission technique among the hops of the network [3][4]. A WSN might be a network that has flexible topology governed by a routing algorithm. One of the most popular routing algorithms is known as Ad-hoc On-Demand Distance Vector (AODV). Unfortunately, the algorithm does not account for energy efficiency. As energy is an essential part in wireless networks for the network lifetime, it is of interest to have an architecture and a network topology based on energy efficiency consideration [1][5][6].

The AODV (Ad-hoc On-Demand Distance Vector) routing protocol [7] is a reactive routing protocol based on some characteristics of practical routing protocols. In this protocol, routes are established on-demand, once established, a route is retained as long as it is required. On-demand (reactive) routing protocols locate a path between the source and the destination only when the path is required for data exchange. The routing method greatly reduces the routing expenses, but it may produce large delay from the moment the route is required to send a packet until the time the route is actually obtained.

In AODV, if there is no requirement of connections, the network remains silent. At that point in time, the network node that requires a connection announces a connection request. Other AODV nodes pass on this message and record the node, then making a sudden increase of temporary routes back to the needy node. When a node picks up such a message and already establishes a route to the desired node, it dispatches a message backwards through a provisional route to the requesting node. The needy node then begins using the route that has the least number of hops through other nodes. Vacant entries in the routing tables are reused afterwards. When a link breaks down, a routing error is returned to a transmitting node, and the

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process is repeated again. The AODV has advantages as it creates no extra traffic for communication along existing links, and the distance vector routing is simple, less memory requirement or calculation. Conversely, the AODV needs more time to begin a connection and has heavier initial communication to set up a route than other methods.

The estimators in WSN might have several architectures including centralized and decentralized architectures [8][9][10][11]. Estimator uses Kalman filter algorithm to combine sensor data and estimate the state of process. In this paper, the centralized and the decentralized architectures are combined in a WSN and use the energy-aware AODV routing algorithm in order to produce better performance WSN.

II. Problem Formulation

In this paper, it is considered a closed loop control system with measurement carried out via a sensor network system as illustrated in Fig. 1. The control system consists of the plant and N sensors. The paper only considers the problem of state estimation over the sensor network system of the closed loop control system. The process dynamics of the plant and the measurement equation of a sensor are given by a discrete time state space equation

$$x_k = Ax_{k-1} + w_{k-1} \quad (1)$$

$$y_k^i = C_i x_k + v_k^i \quad (2)$$

where $x_k \in \Re^n$ is the state, $y_k^i \in \Re^q$ is measurement output of a sensor i (i=1,2,…N). $w_k \in \Re^n$ and $v_k^i \in \Re^q$ are the process noise and the measurement noise for time step k. The noises are white Gaussian noise with zero mean and covariance matrix $Q \geq 0$ and $R > 0$ respectively.

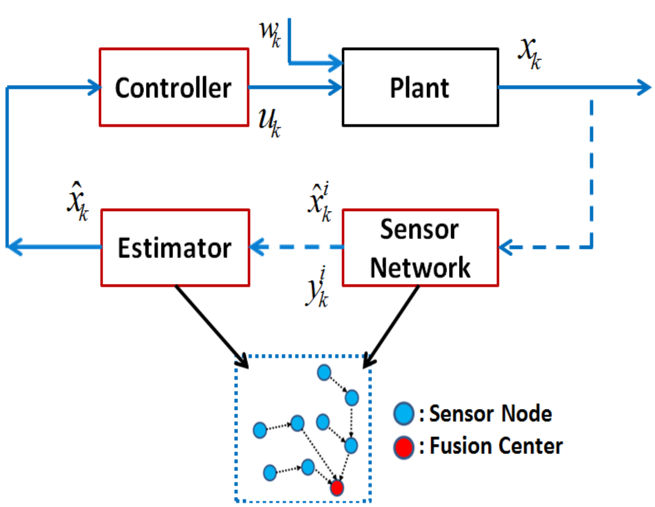

Fig. 1. A closed loop control system with a sensor network system

Estimators have several architectures such as centralization and decentralization. Both architectures have their advantages and disadvantages respectively. As it is possible to define the architecture easily over a large sensor network, in this paper, it is considered to combine the two architectures in the network. The performance of the combined architecture is then compared with the centralization and the decentralization architectures. In the control system, sensors transmit data measurement to an estimator or a fusion center. The estimator combines the data and computes the optimal state estimation. Filter Kalman and its variants are the well known optimal state estimation.

Data transmission route in the network is governed by a routing algorithm. The widely used routing algorithm is AODV routing algorithm [7]. AODV routing algorithm does not use energy parameter in the route discovery. Therefore, it is of interest to consider energy threshold in the routing algorithm. In this paper, the energy threshold is calculated by using Current Average Energy of The Network (CAEN) [12]. This considers other factors that may affect the performances of wireless communication instead of the excessive roaming activities considered in [13], action latency [14][15], stabilization and control network [15][16].

The difference in energy consumption between the energy aware and the regular AODV algorithm will be shown in the paper. The Filter Kalman estimator over WSN using the centralized-decentralized architecture with energy aware AODV routing algorithm is then simulated in order to show the effectiveness of the considered architectures over other architectures and routing algorithm. Kalman filter can be combined with other algorithms in order to improve its performance, such as discussed in [17].

III. Energy Aware AODV Routing Algorithm

An energy aware algorithm is an extension of the AODV algorithm with the addition of energy consideration in the route discovery. The AODV algorithm is modified by using the following steps.

A. *Revised Packets*

Hello packet: Hello packet is used to exchange information of remaining energy with neighboring sensors. The new data Remaining Energy (RE) will be added in order to store energy information. The new information is also added to local Remaining Energy Table (LRET) which records the remaining energy of all one hop neighbors.

RREQ packet: RREQ is also modified in order to obtain accumulation of local average remaining energy information. The information is denoted as E_{sum} and each intermediate sensor will update E_{sum} by cumulating its local average energy to it.

B. *Route Discovery Modification*

Route discovery process occurs when a source sensor needs to send data to a destination sensor. This process includes the operations at the source sensor and intermediate sensors.

Source Sensor: When a source sensor would like to communicate with a destination sensor and no route is available, the source sensor then broadcasts RREQ. As the first sensor on the route, the source sensor initiates E_{sum} with its local average energy defined as [12]:

$$E_{sum} = E_l^s = \frac{E_r^s + \sum_{k=1}^{n} E_r^k}{n+1} \quad (3)$$

where E_r^s denotes the remaining energy of the source sensor, E_r^k denotes the remaining energy of its 1-hop neighbor sensors and n denotes the number of neighbors.

Intermediate Sensor: Once sensor receives RREQ, an intermediate sensor decides its own response to the RREQ received by comparing its remaining energy with energy threshold which is described as follows.

Following the same procedures as that in the source sensor, the intermediate sensor i calculates its local average energy using the following equation [12]:

$$E_l^i = \frac{E_t^i}{n+1} \quad (4)$$

Where E_t^i is the total remaining energy of sensor i and its neighbors, the number of which is defined as n. There is a new parameter called Current Average Energy of The Network (CAEN), which can be calculated as:[12]

$$E_c^i = \frac{E_{sum} + E_l^i}{i} \quad (5)$$

Where i is the number of nodes along the backward path, and E_{sum} is accumulation of local average energy on route.

Given CAEN, the energy threshold can be calculated:[12]

$$E_{thres}^i = \alpha E_c^i \quad (6)$$

where α is system parameter, $0 < \alpha < 1$.

When the remaining energy of intermediate sensors is greater than the energy threshold, it is considered that the sensors have enough energy. These sensors then accumulate their local average energy to E_{sum} and continue to broadcast RREQ. Otherwise, the sensors should wait for a while and determine whether to forward RREQ or drop RREQ based on the number of identical RREQ received during the delay period.

IV. Estimator

In this paper, we consider Kalman filter algorithm to estimate the state variables and to combine data measurement from sensors. Kalman filter is designed to have multiple architectures such as centralized and decentralized.

A. Centralized Kalman Filter

In the centralized Kalman filter (Fig. 2), the sensor measurement is sent directly to the fusion center through communication lines. The fusion center is used to combine the data measurement from sensors and to estimate the states. The transmitted data are the measurement received from sensors.

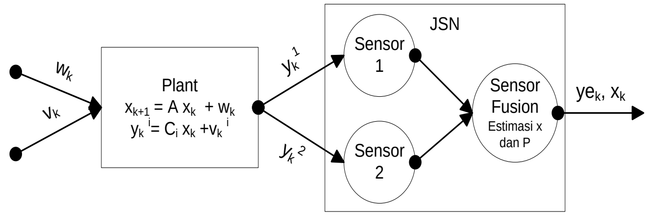

Fig. 2. Centralized Kalman Filter

The advantage of centralized architecture is each sensor may not have computing capabilities because sensors only measure the variable and then transmit data to the fusion center. The energy consumption and bandwidth are also relatively small compared to the decentralized architecture. However, the centralized Kalman filter calculates all of the process in the fusion center. This is the main weakness in case of failure in the centralized Kalman filter.

Kalman filter algorithm for centralized can be formulated as follows: [9]

$$x_k^- = A x_{k-1} \quad (7)$$

$$P_k^- = A P_{k-1} A^T + Q \quad (8)$$

$$K_k^i = P_k^- (C^i)^T (C^i P_k^- (C^i)^T + R)^{-1} \quad (9)$$

$$e^i = y^i - C^i x_k^- \quad (10)$$

$$x_k = x_k^- + \frac{1}{N}\left(\sum_{i=1}^{N} K_k^i e^i\right) \quad (11)$$

$$P_k = [I - \frac{1}{N}\left(\sum_{i=1}^{N} K_k^i C^i\right)] P_k^- \quad (12)$$

The variable i indicates the i-th sensor.

B. Decentralized Kalman Filter

In this architecture (Fig. 3), the filter has two kinds of filter which are local filter and global filter. The local filter is in each sensor while the global filter can occur in each sensor or in the fusion center. Because sensors have the local filter and the global filter separately, there is no point of failure.

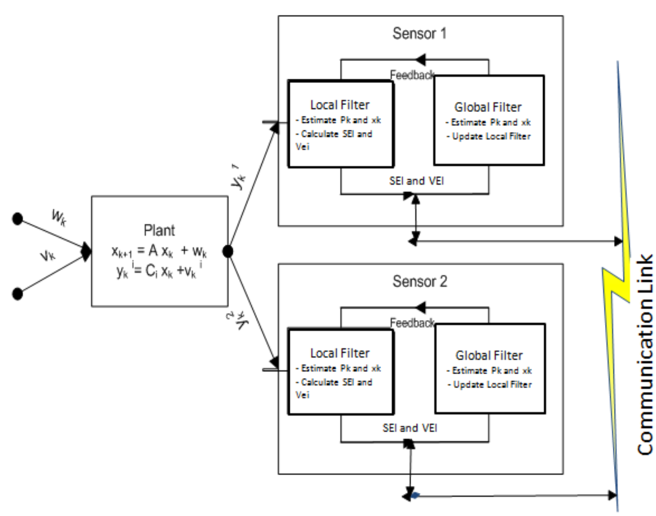

Fig. 3 Decentralized Kalman Filter

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The local filter at each sensor uses its measurement to obtain estimation of the local state, x and the error covariance, P. Both of these data are then transmitted to a global filter in surrounding sensors. The global filter combines the data. The data received in the global filter are State Error Information (SEI) and Variance Error Information (VEI). Once these data received by each sensor, the global filter estimates the new state and the error covariance. The results are then used to update the data in the local filter on each sensor.

At the local filter, Kalman filter algorithm is added with SEI and VEI as follows: [9]

$$x_k^- = Ax_{k-1} \tag{13}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{14}$$

$$K_k = P_k^- C^T (CP_k^- C^T + R)^{-1} \tag{15}$$

$$x_k = x_k^- + K_k (y - Cx_k^-) \tag{16}$$

$$P_k = (I - K_k C)P_k^- \tag{17}$$

$$SEI^i = x_k P_k^{-1} - x_{k-1} P_{k-1}^{-1} \tag{18}$$

$$VEI^i = P_k^{-1} - P_{k-1}^{-1} \tag{19}$$

The algorithm in the global filter is given by: [9]

$$P_k^{-1} = P_{k-1}^{-1} + \frac{1}{N}(\textstyle\sum_{i=1}^{N} VEI^i) \tag{20}$$

$$x_k = P_k (x_{k-1} P_k^{-1} + \frac{1}{N}(\textstyle\sum_{i=1}^{N} SEI^i)) \tag{21}$$

$$P_{k+1} = AP_k A^T + Q \tag{22}$$

$$x_{k+1} = Ax_k \tag{23}$$

C. *Centralized-Decentralized Kalman Filter*

In the centralized-decentralized architecture (Fig. 4), the sensors are divided into several areas. Each area has its own fusion center. The local filter in fusion center has the same algorithm with the regular Kalman filter algorithm with addition SEI and VEI calculation. The result of this local filter is then transmitted to another fusion center and processed in a global filter. The result of the global filter (state estimation and error covariance) is used to update the data in the local filter at each fusion center.

The Kalman filter algorithm is the same as the local filter algorithm in Equation (7)-(12), and Equation (18)-(19). The algorithm in the global filter is same with Equation (20)-(23).

V. Estimator Design in WSN

In the paper, the main considered architecture is described by the centralized-decentralized architecture using energy aware AODV routing algorithm to organize the topology of WSN.

The algorithm is described as follow:

1. Sensors receive measurement data.
2. Energy aware AODV routing algorithm initiates according to the logic as follow:
   a. If sensors have a route to the fusion center, the measurement data will be sent. If sensors do not have a route, then sensors will broadcast RREQ.
   b. If sensors are not a fusion center, sensors that received RREQ will calculate the energy threshold in Equation (3)-(6).
   c. If the energy threshold is less than the energy battery, sensors will broadcast RREQ to other sensors. Otherwise, sensors will wait whether to continue or to drop the RREQ which is based on the number of identical RREQ received by sensor.
   d. If sensors are fusion center, sensors will send an RREP to the source sensor.
   e. When the source sensor received RREP, route has been obtained.
3. Sensors will transmit measurement data after the route is obtained.
4. Fusion center receives measurement data from the sensor and processes the data in the local filter.
5. The results of the local filter (SEI and VEI) are sent to another fusion center.
6. Fusion center receives SEI and VEI from another fusion center and then processes the data on the global filter.
7. The results of global filter then will be used to update the data in the local filter at the fusion center.

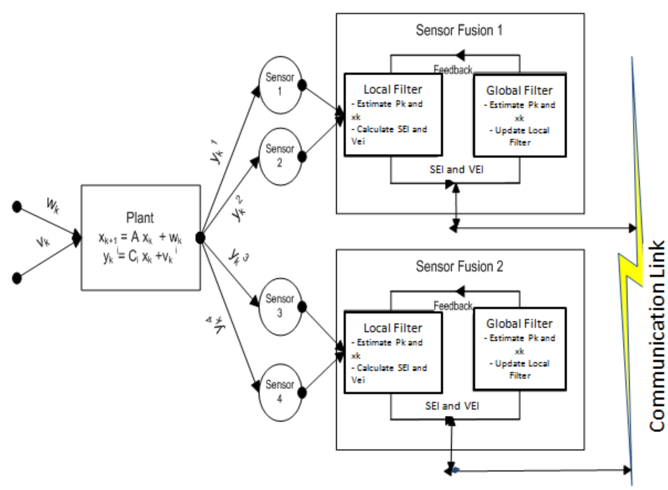

Fig. 4. Centralized-Decentralized Kalman Filter

VI. Simulation

As an example, the considered system is a heat transfer system in a closed room with the following partial differential equation:

$$\frac{\partial u}{\partial t} = \alpha(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) \tag{24}$$

with boundary conditions described as follow:

$$\left.\frac{\partial u}{\partial x}\right|_{t,0,y} = \left.\frac{\partial u}{\partial x}\right|_{t,l,y} = \left.\frac{\partial u}{\partial y}\right|_{t,x,0} = \left.\frac{\partial u}{\partial y}\right|_{t,x,l} = 0 \quad (25)$$

where x and y are the coordinates of the area, $u(t,x,y)$ indicates the temperature at time t at location (x,y), and α is the speed of diffusion process. Equation (24) is converted into discrete form using a finite difference method. The area is assumed to be a rectangular with length l meters and discretized with $N \times N$ grid with grid size $h = l/(N-1)$. By use of the finite difference method, the equation (24) becomes:

$$u(k+1,i,j) - u(k,i,j) = \alpha / h^2 [u(k,i-1,j) + u(k,i,j-1) + u(k,i+1,j) + u(k,i,j+1) - 4u(k,i,j)] \quad (26)$$

where $u(k,i,j)$ denotes the temperature at time k at location (ih,ij).

If all temperatures at k are combined into a vector $U_k = [u(k,0,0),..u(k,N-1,N-1)]$, we will obtain the discrete equation where the matrix A can be calculated from Equation (26). By introducing process noise, w, the equation will be same as Equation (1).

For the simulation, the following parameters are selected:

- α = 10 m^2/s.
- l = 420 m and N = 4 therefore h = 140 m.
- We use 12 sensors: 9 sensors for measurement and 3 sensors for fusion center.
- The placement of sensors is shown in Fig. 5.

The considered architectures are simulated by using the defined system and the energy-aware AODV routing algorithm. In the simulation, only the centralized-decentralized architecture will use two kinds of routing algorithm (i.e. energy-aware and regular AODV). Results from the simulation are then compared between the AODV routing algorithm and the energy-aware AODV routing algorithm.

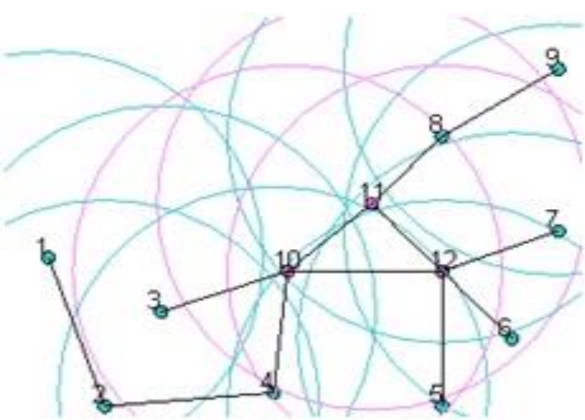

Fig. 5 Topology of centralized-decentralized

The simulation result for the centralized-decentralized architecture in sensor 4 is shown in Fig. 6. This figure shows that the state estimation approaches the true value of measurement data.

The MSE comparison between the architecture is summarized in Table 1. The simulation result shows that the centralized-decentralized yields the best MSE value than the other architectures.

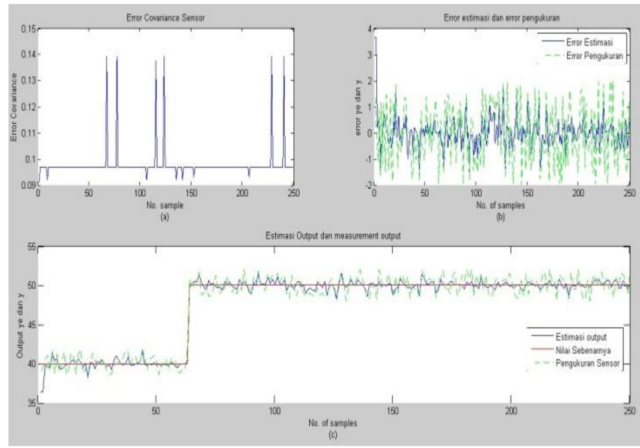

Fig. 6 Centralized-Decentralized Sensor 4

TABLE 1. MSE Comparison between Architecture

MSE	Sensor	Centralized	Decentralized	Centralized-Decentralized	
				Energy Aware AODV	Regular AODV
Before filtering	4	1.2013	1.2013	1.2013	1.2013
	5	1.3784	1.3784	1.3784	-
After Filtering	4	0.3689	0.7188	0.3619	0.3658
	5	0.3689	0.9304	0.3618	-

The centralized architecture has better performance than the decentralized architecture. This is caused by the measurement data from all the sensors can be combined into one in order to provide better accuracy. In the decentralized architecture, the data are only sent to neighboring sensors. This causes the MSE value is higher than the centralized.

Comparison on the energy consumption of the architectures is given in Table 2. This table shows that the largest energy consumption is taken by the decentralized architecture. This architecture did not use AODV routing algorithm to determine the network topology. Topology in this architecture is determined by neighboring sensors. The decentralized architecture will broadcast its data to all sensors within its range. If there are a lot of sensors within its range, the energy consumption will be large. The biggest energy consumption in WSN is due to data transmission.

Table 2 also shows the difference between the energy-aware AODV routing algorithm and the regular AODV routing algorithm. The energy consumption in the energy-aware AODV routing algorithm is smaller than the regular AODV. This is because of in the regular AODV, sensor 3 will not be included in the route discovery if there is another route.

However, if the sensor 3 is the only route then it will be included into the route discovery.

TABLE 2. Comparison of Energy Consumption

Sensor	Centralized	Decentralized	Centralized-Decentralized Energy Aware AODV	Centralized-Decentralized Regular AODV
3	-2.4608×10^{-6}	-2.9496×10^{-6}	-2.1495×10^{-6}	-2.2365×10^{-6}
4	-2.6173×10^{-6}	-3.0781×10^{-6}	-2.2696×10^{-6}	-2.3069×10^{-6}

VII. CONCLUSION

The paper considered a centralized-decentralized architecture in a wireless sensor network. The simulation results showed that the combined architecture yielded the best performance. The worst performance was produced by the decentralized. The centralized architecture had similar performance with the centralized-decentralized but it had the point of failure in the fusion center. A Wireless Sensor Network is a network that promotes energy efficiency. The simulation results showed that the smallest energy consumption was obtained by using the centralized-decentralized architecture with the energy-aware AODV routing algorithm. The energy-aware AODV routing algorithm can be used as a way to reduce energy consumption in the wireless sensor networks.

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