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Fuzzy Logic Based Improved Range Free Localization for Wireless Sensor Networks

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***Abstract*—**Wireless Sensor Networks (WSNs) are used to monitor/observe vast inaccessible regions through deployment of large number of sensor nodes in the sensing area. For majority of WSN applications, the collected data needs to be combined with geographic information of its origin to make it useful for the user; information received from remote Sensor Nodes (SNs) that are several hops away from base station/sink is meaningless without knowledge of its source. In addition to this, location information of SNs can also be used to propose/develop new network protocols for WSNs to improve their energy efficiency and lifetime. In this paper, range free localization protocols for WSNs have been proposed. The proposed protocols are based on weighted centroid localization technique, where the edge weights of SNs are decided by utilizing fuzzy logic inference for received signal strength and link quality between the nodes. The fuzzification is carried out using (i) Mamdani, (ii) Sugeno, and (iii) Combined Mamdani Sugeno fuzzy logic inference. Simulation results demonstrate that proposed protocols provide better accuracy in node localization compared to conventional centroid based localization protocols despite presence of unintentional radio frequency interference from radio frequency (RF) sources operating in same frequency band.

***Keywords*—**localization, range free, received signal strength, link quality indicator, Mamdani fuzzy logic inference, Sugeno fuzzy logic inference.

I. Introduction

LOCALIZATION of sensor nodes (SNs) in WSNs has gained importance due to advent of large number of location based applications and network protocols. However, localization of SNs is still a challenging task due to their large scale deployment and various constraints of size and cost. SNs in WSN can either be localized by installing Global Positioning System (GPS) on every SN or by manually positioning each SN at predefined location. Provisioning of GPS system on each SN is not a rational solution, as it adds to the cost and size of SN. Since, thousands of SNs are deployed in the sensing field; therefore, it may lead to exorbitantly high cost of WSN deployment. On the other hand, manual placement of SNs at known location is too complex or rather impossible in situations where nodes are deployed in inaccessible and hostile regions. To circumvent this problem, a number of localization protocols have been proposed in literature, where SNs are localized with the help of small number of location aware nodes deployed in the sensing field, known as anchor nodes (ANs) [1]-[4]. ANs may acquire their location information through GPS receiver or if feasible, by manual placement at known positions.

Depending on the application requirement, SNs may be localized in terms of (i) global or (ii) local coordinates [9]. Local coordinates may be defined by ANs in many applications like smart homes, hospitals, inventory management, etc.; where simple knowledge such as in which room a SN is located, is sufficient. Based on the mechanisms used for location estimation, localization protocols can be categorized into two classes; range based and range free. In former case, ranging is accomplished by absolute point to point distance estimates using Time of Arrival (ToA), Time Difference of Arrival (TDoA), or Angle of Arrival (AoA) measurements of radio frequency (RF) signals by using special ranging hardware installed on every SN [5]-[9]. Whereas, the latter localization technique does not require any special ranging hardware and simple transceiver is sufficient to achieve coarse grain localization. Range free localization derives location estimation of SNs from network connectivity or from the received signal strength (RSS), which can be directly obtained from RF transceivers section of the SN [10]. Location accuracy of range based localization protocols is better than range free protocols [9]. However, range free localization can be used as a cost effective alternative for those applications where coarse grain accuracy in node localization is sufficient. In this paper we have proposed range free localization protocols for WSN using improved Weighted Centroid Localization (WCL) algorithm which are based on fuzzy logic inference (FLI).

Rest of the paper is organized as per the following. Section II describes the background and fundamental terms/definitions essential for understanding the proposed protocol. Section III discusses about the FLI (Fuzzy Logic Inference) based WCL (Weighted Centroid Localization) scheme using received signal strength indicator (RSSI) and link quality indicator (LQI) dependent edge weights. Proposed node localization techniques are discussed in section IV. Performance of proposed schemes is simulated and evaluated in section V. Conclusions of the paper are drawn in section VI.

II. Background

The proposed localization protocol is based on improved weighted centroid localization, in which fuzzy logic inference

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model [17] has been used to calculate the edge weights of adjacent ANs. FLI calculates the edge weights based on the values of received signal strength and quality of link information obtained at the receiving SN. This section describes all relevant fundamental terms/definitions essential for understanding of the proposed localization protocol.

A. Centroid Localization (CL)

In case of CL, SNs compute their location as centroid of the positions of all connected ANs [1]. The anchor nodes broadcast periodic beacon message to SNs situated within their radio range. The beacon message comprises of anchor node id and location coordinates (x_i, y_i) of the AN. SN collects the position information of all connected ANs from received beacons and localizes itself to the region which coincides to the intersection of the connectivity regions of connected ANs. The estimated position of SN is given by centroid of ANs positions as:

$$(x_{est}, y_{est}) = \left(\frac{\sum_{i=1}^{N} x_i}{N}, \frac{\sum_{i=1}^{N} y_i}{N} \right) \tag{1}$$

where x_{est}, and y_{est} are estimated coordinates of SN. N is the number of adjacent connected ANs to the SN. Centroid localization method is quite simple and economic, but the location estimation results are poor and localization error is quite high, which is unacceptable in many applications.

B. Weighted Centroid Localization (WCL)

Weighted centroid localization (WCL) is an improved version of basic centroid localization method. This method introduced the quantification of the beacons, depending upon their distance towards localizing SN. The main aim of weighted centroid localization is to give more influence to those ANs which are near to the localizing SN. As received signal strength increases with decrease in distance between two nodes, received signal strength (RSS) is selected as an appropriate quantifier in [11]. Location of sensor node is calculated by using edge weights of ANs (based on proximity of nodes) connected to the sensor node, and each SN computes its position (x_{est}, y_{est}) by:

$$(x_{est}, y_{est}) = \left(\frac{w_1 x_1 + w_2 x_2 \ldots + w_n \cdot x_n}{\sum_{i=1}^{n} w_i}, \frac{w_1 y_1 + w_2 y_2 \ldots + w_n y_n}{\sum_{i=1}^{n} w_i} \right) \tag{2}$$

where, W_i is the edge weight of i^{th} AN connected to the SN. The edge weight is decided based on the proximity of SN to AN. Location accuracy of WCL method is highly dependent on the optimization of edge weights and their correlation to the distance between the nodes. Two basic measurements at receiving SN can be correlated to the distance between the nodes (1) Received Signal Strength Indicator (RSSI), and (2) Link Quality Indicator (LQI). In the next section we examine the correlation of these parameters to the distance between the wireless sensor nodes.

C. Received Signal Strength Indicator (RSSI)

Received signal strength can be correlated to the distance between two SNs. According to Friis' free space transmission equation, the received signal strength decreases with increase in distance between transmitter and receiver as per equation:

$$P_R = P_T \times G_T \times G_R \left(\frac{\lambda^2}{4\pi d^2} \right) \tag{3}$$

where P_T is transmission power of transmitter, P_R is power received at the receiver, G_T is gain of transmitter antenna, G_R is gain of receiver antenna, d is distance between transmitter and receiver, and λ is the wave length of RF signal [14].

In case of IEEE 802.15.4/Zigbee based SNs, the received signal power is usually converted to Received Signal Strength Indicator (RSSI), which is defined as the ratio of received power to the reference power (P_{ref}). Reference power is taken as 1mw and RSSI is given by:

$$RSSI = 10 \log \frac{P_R}{P_{ref}} \ dBm; \quad where\ P_{ref} = 1mw \tag{4}$$

RSS/RSSI can be precisely correlated to the distance between the nodes and can be used to decide the edge weight in case of WCL, provided the nodes are deployed in noise free and RF interference free environment. However, in real deployment scenario, WSNs operate in unlicensed ISM bands and share radio spectrum with several other devices. For example, in the 2.4 GHz frequency, WSNs might compete with the communications of WiFi and Bluetooth devices. Furthermore, a set of domestic appliances such as cordless phones and microwave ovens generate electromagnetic noise in same frequency band, which can significantly influence the signal power reception at receiver, rendering the poor RSSI and distance correlation [15], [16], [22]. Hence, RSSI based WCL protocols [11]-[13] which provide good localization results in absence of external RF interference and perform poorly in presence of RF interference [18].

D. Link Quality Indicator (LQI)

The link quality indicator (LQI) value reflects the link quality as seen from the receiver side and can be used as a measure of distance between transmitter and receiver. The LQI value correlates the expected and received data at receiver, reflecting the link quality between the transmitting and receiving node [19]. IEEE 802.15.4 has prescribed the LQI range between 0 and 255, where the highest value represents the maximum quality frames. LQI measurement is available at hardware level in IEEE 802.15.4 compliant RF transceivers, but its evaluation is vendor specific. For example, CC2420, which is the most widespread radio, calculates LQI value over 8 bits following the start frame delimiter (SFD). It provides a "chip error rate" that it uses in conjunction with the CRC OK/NOT OK, to estimate the LQI value. The LQI value read from the CC2420 ranges from 50-110 and is converted to the IEEE 802.15.4 range of 0-255 for comparison with other wireless motes [19]. Similar to RSSI, LQI can also be used to decide the edge weights of ANs for WCL [20]. In absence of noise, LQI decreases with increase in distance. However, LQI values may fluctuate in presence of noise and external RF interference, providing unrealistic distance estimation [18]-[19].

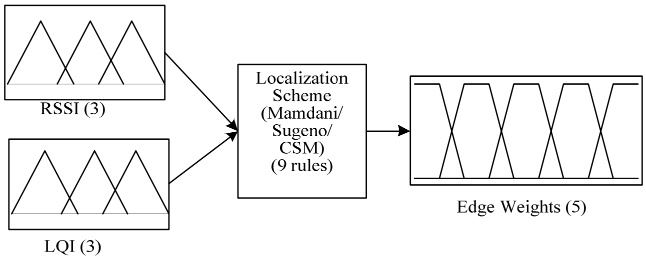


Fig. 1 Proposed TISO FLI

RSSI and LQI have different attenuation loss for varying distance between transmitter and receiver due to changes in signal intensity and channel interference; therefore, combination of RSSI and LQI can be a good indicator of distance between the nodes [20]. We have proposed to use combined value of RSSI and LQI to calculate the edge weights for WCL in order to improve the localization accuracy of SNs when WSN is deployed in environment infested with external RF interference. The proposed protocol does not require any special hardware on SN, as both measurements are already available on IEEE 802.15.4 compliant SNs. Fuzzy Logic Inference (FLI) can be used to decide the edge weights of ANs based on RSSI and LQI. Therefore, a two input single output (TISO) FLI system has been proposed to decide the edge weights of ANs, based on the RSSI and LQI values.

E. Fuzzy Logic Inference System

A fuzzy system is a computing framework based on the concepts of the theory of fuzzy sets, fuzzy rules, and fuzzy inference [21]. Fuzzy system has four main components; a knowledge base, a fuzzification block, an inference engine (decision making unit), and a defuzzification interface [22]. The knowledge base is defined in terms of fuzzy rules and a data base that contains the linguistic terms for each input and output variable. The fuzzification interface transforms the (crisp) input values into fuzzy values, by computing their membership to all linguistic terms defined in the corresponding input domain. The inference engine performs the fuzzy inference process, by computing the output of each rule. The defuzzification interface computes the (crisp) output values by combining the output of the rules and performing a specific transformation. Fuzzy systems can be classified in different categories, depending on the shape of the rules and the type of operators used for implementing the modules. The most widely used FLI models are the Mamdani and the Takagi Sugeno models. Both of these can be implemented as approximative or descriptive fuzzy systems. Both FLI can be modeled as single input single output (SISO), multi input single output (MISO) or multi input multi output (MIMO). In proposed protocol two input single output TISO FLI system is used with RSSI and LQI as input and edge weights as output.

III. FLI Based WCL Scheme Using RSSI and LQI Dependent Edge Weights

We have proposed to use FLI (Mamdani, Sugeno, and CMS) to decide the edge weights for WCL protocol. The scheme is based on connectivity and measurements of RSSI and LQI information, respectively. The localization procedure follows following steps:

- The connectivity based approach is used to find adjacent ANs connected to the SN which is to be localized.
- The RSSI and LQI based approach is used to find edge weights of ANs, using Mamdani/Sugeno/CMS FLI.
- Calculation of estimated location of sensor nodes is carried out using the weighted centroid formula.

A. Finding Adjacent Anchor Nodes Using Connectivity

The proposed localization scheme is based on adjacent connected ANs to a localizing SN. The SN can calculate its location based on the location of connected ANs. Therefore, first step is to find out the location information and number of connected ANs. This is achieved by transmitting periodic beacon containing the location information in terms of its x and y coordinates. On receiving the beacon signal, SN finds out the number of adjacent connected ANs along with their location information (x_1, y_1), (x_2, y_2), . . . (x_n, y_n), which could further be used for localization of SN.

B. Calculating the Edge Weights Using FLI System

The SN measures the received signal strength from periodic beacon transmitted by the ANs. The received signal strength is converted to RSSI as per (4). To determine the link quality between SN and AN, a periodic LINK_QUALITY signal is transmitted by the AN. This signal is known a priori to all SN. The SN correlates expected and received signal data and number of bits received successfully is used to ascertain the link quality. For simulation, LQI has been defined as:

$$LQI = \frac{255 \times (N_T - N_U)}{N_T} \tag{5}$$

where NT is total number of bits transmitted by AN and NU is number of bits received in error by the SN. LQI can have value between 255 and 0, depending upon the number of incorrect bits received at the receiver due to the noise present in the channel. However, the real SN can calculate the LQI value through hardware LQI measurement, specified in 802.15.4 protocol. The measured values of RSSI and LQI are correlated to the distance between the nodes by applying RSSI and LQI as input to TISO FLI system. The FLI system provides output in terms of edge weighs, which are subsequently used in proposed WCL algorithm for location estimation of the SN. The correlated value is used to calculate the edge weights to find estimated sensor node position using WCL. In proposed scheme, we have used two input single output (TISO) Mamdani/Sugeno/CMS FLI to obtain the edge weights as shown in Fig. 1.

C. Fuzzifying the Inputs

RSSI and LQI are used as input variable for TISO FLI. These variables can assume any value in the interval [0, $RSSI_{max}$] and [0, LQI_{max}] respectively, where $RSSI_{max}$ is the maximum RSSI value and LQI_{max} is the maximum LQI value. LQI value has been assumed to be in the interval [0, 255] as per IEEE 802.15.4 standard and RSSI value has been assumed in the interval [-50, -25] (in dBm), where, -50dBm is the minimum signal threshold of SN and -25dBm is maximum signal strength of SN. RSSI and LQI are defined as Low, Medium, and High. The output variable is the edge weight of each AN connected to a particular SN. It can assume any value in the interval [0, W_{max}], where W_{max} is the maximum weight. Its value has been defined in the interval [0, 1]. The output variable is defined as Very Low, Low, Medium, High, and Very High. The fuzzy rule base used for simulation is given in the Table I.

TABLE I
FUZZY RULES FOR FLI

RSSI	LQI	Edge Weight
Low	Low	Very Low
Low	Medium	Low
Low	High	Medium
Medium	Low	High
Medium	Medium	Medium
Medium	High	High
High	Low	Medium
High	Medium	High
High	High	Very High
RSSI	LQI	Edge Weight
Low	Low	Very Low
Low	Medium	Low

IV. NODE LOCALIZATION

Nodes present in the sensing field are localized using connectivity information of SNs with adjacent ANs and WCL method is used to estimate the coordinates of SNs based on edge weights obtained from Mamdani/Sugeno/CMS FLI.

A. Sugeno Node Localization

Nodes present in the sensing field are localized using connectivity information of SNs with adjacent ANs and WCL method is used to estimate the coordinates of SNs based on edge weights obtained from Sugeno FLI and as:

$$\left(x_{\text{est-Sug}}, y_{\text{est-Sug}}\right) = \left(\frac{w_{1(Sug)}x_1 + \ldots + w_{n(Sug)}x_n}{\sum_{i=1}^{n} w_{i(Sug)}}, \frac{w_{1(Sug)}y_1 + \ldots + w_{n(Sug)}y_n}{\sum_{i=1}^{n} w_{i(Sug)}} \right) \quad (6)$$

B. Mamdani Node localization

Nodes present in the sensing field are localized using connectivity information of SNs with adjacent ANs and WCL method is used to estimate the coordinates of SNs based on edge weights obtained from Mamdani FLI as:

$$\left(x_{est-Mam}, y_{est-Mam}\right) = \left(\frac{w_{1(Mam)}x_1 + \ldots + w_{n(Mam)}x_n}{\sum_{i=1}^{n} w_{i(Mam)}}, \frac{w_{1(Mam)}y_1 + \ldots + w_{n(Mam)}y_n}{\sum_{i=1}^{n} w_{i(Mam)}} \right) \quad (7)$$

C. Combined Mamdani Sugeno FLI Based WCL Scheme Using RSSI and LQI Dependent Edge Weights

In case of Combined Mamdani Sugeno Localization approach, edge weights for WCL are obtained by averaging the edge weights of Mamdani and Sugeno FLI systems If $\frac{\left(w_{(Sug)i} + w_{(Mam)i}\right)}{2} = w_{(avr)i}$, then final estimated node location coordinates ($x_{\text{est-final}}$, $y_{\text{est-final}}$) are calculated as:

$$\left(x_{\text{est-final}}, y_{\text{est-final}}\right) = \left(\frac{w_{(avr)1}x_1 + \ldots + w_{(avr)n}x_n}{\sum_{i=1}^{n} w_{(avr)i}}, \frac{w_{(avr)1}y_1 + \ldots + w_{(avr)n}y_n}{\sum_{i=1}^{n} w_{(avr)i}} \right) \quad (8)$$

V. PERFORMANCE EVALUATION

In this section we evaluate the performance of proposed range free localization approaches (1) Mamdani FLI based weighted centroid localization scheme using RSSI and LQI dependent edge weights, (2) Sugeno FLI based weighted centroid localization scheme using RSSI and LQI dependent edge weights, and (3) Combined Mamdani Sugeno FLI based weighted centroid localization scheme using RSSI and LQI dependent edge weights. MATLAB has been used as a simulation tool for performance evaluation of the proposed schemes. The simulations have been carried out number of times and average results of simulations are used for performance evaluation. The proposed schemes have been compared with (1) Centroid Localization, (2) Mamdani FLI Localization using RSSI dependent edge weights, and (3) Sugeno FLI Localization using RSSI dependent edge weights. Two scenarios are used for performance evaluation through simulation. In first scenario, the nodes are assumed to be deployed in AWGN environment and second scenario assumes the deployment of sensor nodes in environments having AWGN alongwith external RF interference noise sources. For further discussion in the paper, these scenarios are referred as scenario-one and scenario-two, respectively. The parameters used for simulation are given in Table II.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Total number of nodes in the sensing field	200
Number of Anchor nodes	121
Area of sensing field	$100 \times 100 m^2$
Transmission range of nodes	10m
Frequency of operation	914 MHz
Minimum RSSI threshold of receiver	-50dBm
Maximum transmission power of node	-2dBm

LQI range	0-255
Path loss exponent (β)	2
AWGN mean (μ) and variance (σ)	0, 1
External interference noise power, PI (max)	-30dBm

A. Performance Metrics

For evaluating the performance of proposed protocols with existing localization methods following two performance metrics have been considered:

- Instantaneous localization error: it is defined as the difference between estimated position and instantaneous actual position of a sensor node. It is given as:

$$\text{Instantaneous localization error} = \sqrt{\left(x_{est} - x_a\right)^2 + \left(y_{est} - y_a\right)^2}$$

where (x_{est}, y_{est}) is the estimated position of sensor node, while (x_a, y_a) is the instantaneous actual position of the SN.

- Average location error: it is the average of difference between the estimated position and the actual position of all sensor nodes present in the sensing field. It is calculated as:

$$\text{Average localization error} = \frac{\sum\sqrt{\left(x_{est} - x_a\right)^2 + \left(y_{est} - y_a\right)^2}}{\text{Number of sensor nodes}}$$

B. Centroid Localization (CL)

In this setup, the CL protocol is used for localization estimation of SNs and estimated location of a SN is calculated using (1). Simulation result for instantaneous location estimate of each SN present in the sensing field is shown in Fig. 2. Since, the localization accuracy of SN for CL solely depends on the location coordinates of adjacent ANs, which are in range of localizing SN, hence, it is least affected by the presence of noise and external RF interference, provided the coordinate information of ANs is correctly discerned by the SN. However, simulation results demonstrate that localization accuracy for CL protocol is not very good. It is due to the fact that localization accuracy in CL protocol depends on the number of adjacent ANs used by a SN for its localization. Each SN cannot get localized by achieving requisite degree of connectivity to the ANs because of random deployment of SNs in the sensing field. This amounts to poor localization results for CL. In our simulation setup the results obtained for CL are (i) maximum and minimum instantaneous localization error of 3.570m and 0.213m respectively, and (ii) average localization error of 1.68m.

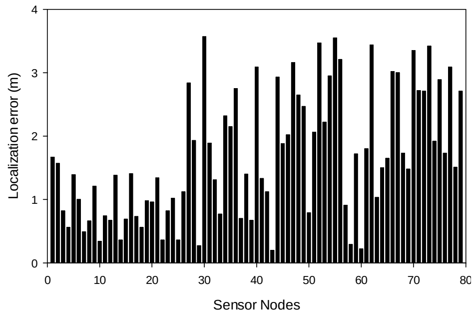
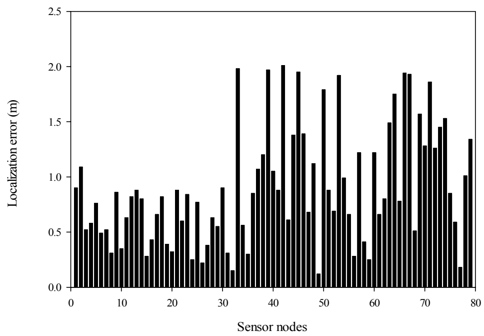
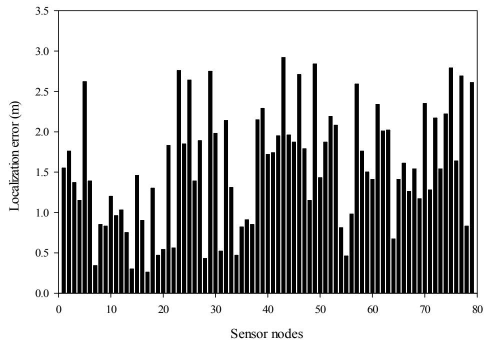


Fig. 2 Localization error of SNs for Centroid Localization (CL)

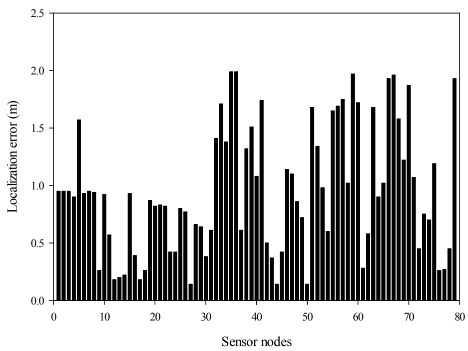


(a)

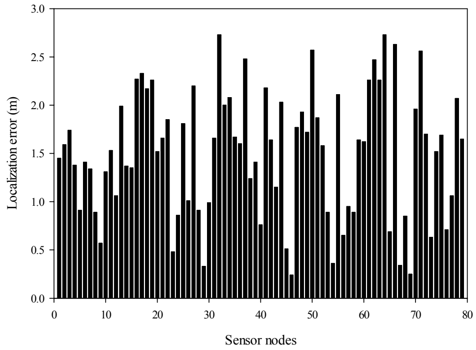


(b)

Fig. 3 Node localization error for Mamdani FLI based WCL using RSSI dependent edge weights in (a) AWGN environment, and (b) environment having AWGN and external RF interference



(a)



(b)

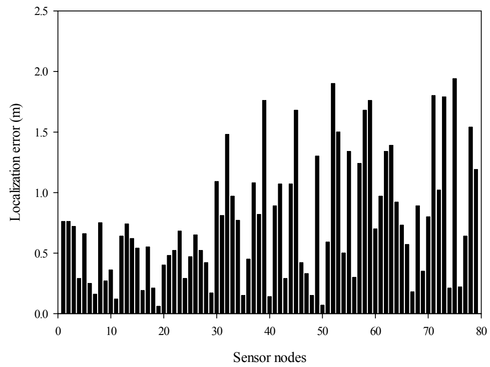
Fig. 4 Node localization error for Sugeno FLI based WCL using RSSI dependent edge weights in (a) AWGN environment (b) environment having AWGN and external RF interference

C. Mamdani FLI Based WCL Using RSSI Dependent Edge Weights

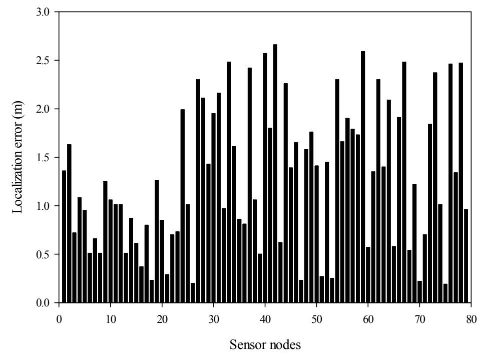
In this simulation setup, Mamdani FLI is used to decide the edge weights for WCL, which are RSSI dependent. Estimated location of SN is calculated using (7). Simulation results for instantaneous location estimate of each SN present in the sensing field for scenario-one and scenario-two are shown in Fig. 3. The protocol results in improvement of location estimation for SN in scenario-one, as RSSI dependent weights are assigned to each adjacent AN, which is directly proportional to the distance between the nodes. However, in scenario-two, the RSSI fluctuates due to presence of RF interference signals and is no longer proportional to the distance between the nodes. For example, in the presence of very high RF interference, RSSI obtained at the SN is always high, even if the transmitting AN is situated at large distance from the SN. In such situation, RSSI based edge weight always assumes high value of edge weights depicting smaller distance between the nodes. This amounts to large error in location estimation of the SN. Therefore, in presence of RF interference (scenario-two), localization estimation of RSSI based system is quite poor. In our simulation setup for scenario-one, average localization error, maximum and minimum localization error is obtained as 0.895m, 2.012m, and 0.12m respectively, which are better than the CL; whereas, for scenario-two, the average localization error, maximum and minimum localization error escalates to 1.55m, 2.92m, and 0.26m respectively. Simulation results demonstrate that node localization of RSSI based Mamdani FLI are quite poor in scenario-two.

D. Sugeno FLI Based WCL Using RSSI Dependent Edge Weights

Here, Sugeno based FLI model is used to decide the RSSI dependent edge weights for WCL. Simulation results for instantaneous node localization error of nodes, as obtained in this protocol for SN deployment in both the scenario are shown in Fig. 4. Similar to the RSSI based Mamdani FLI; simulation results for SN localization error in scenario-one are better than that of CL and are almost comparable to the RSSI based Mamdani FLI. However, localization error of this protocol for scenario-two is poor due to the reason that only RSSI is used to decide the edge weights of ANs and in presence of external RF interference, its correlation to the distance between nodes may be poor. For simulation setup under scenario-one average localization error, maximum and minimum localization error for simulation is 0.946m, 1.96m, and 0.14m respectively, which are better than the CL and comparable to Mamdani FLI; Whereas, for simulation under scenario-two the average localization error, maximum and minimum localization error escalate 1.50m, 2.72m, and 0.241m respectively.



(a)



(b)

Fig. 5 Node localization error for Combined Mamdani-Sugeno FLI based WCL using RSSI dependent edge weights in (a) AWGN environment (b) environment having AWGN and external RF interference

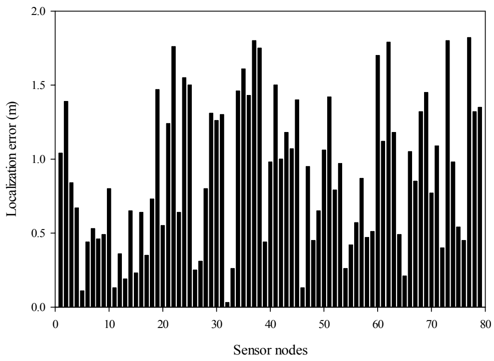


Fig. 6 Node localization error for Mamdani FLI based WCL using RSSI and LQI dependent edge weights in the environment having AWGN and external RF interference

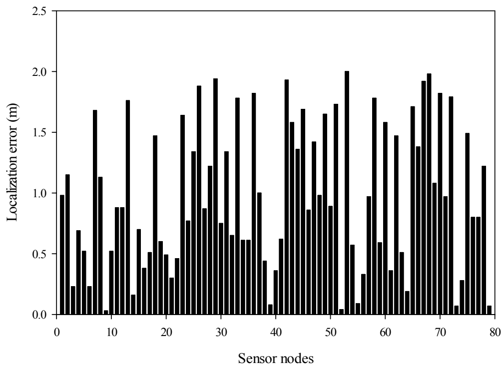


Fig. 7 Node localization error for Sugeno FLI based WCL using RSSI and LQI dependent edge weights in the environment having AWGN and external RF interference

E. Combined Mamdani-Sugeno (CMS) FLI Based WCL Using RSSI Dependent Edge Weights

In our proposed localization scheme, average values of edge weights obtained from Mamdani and Sugeno FLI are used todecide final edge weights for WCL protocol. The edge weights are assumed to be dependent of RSSI. Instantaneous node localization error of SNs for their deployment in scenario-one and scenario-two is shown in Fig. 5. Simulation results of localization error for CMS WCL in scenario-one are much better than CL and the results are better than Mamdani or Sugeno FLI. However, location estimation becomes poor for node deployment under scenario-two. Simulation results of node localization for scenario-one i.e. average, maximum and minimum localization error is 0.761m, 1.94m, and 0.062m respectively, which are better than the CL, Mamdani or Sugeno FLI. Whereas, in scenario-two the average localization error, maximum and minimum localization error become 1.31m, 2.64m, and 0.191m respectively.

TABLE III
SIMULATION RESULTS FOR NON-COOPERATIVE LOCALIZATION PROTOCOLS

Localization Protocol	Deployment Scenario	Max. error (m)	Min. error (m)	Average error (m)
Centroid Localization (CS)	Scenario-two	3.570	0.213	1.68
Mamdani FLI based WCL using RSSI dependent edge weights	Scenario-one	2.012	0.12	0.895
	Scenario-two	2.92	0.26	1.55
Sugeno FLI based WCL using RSSI dependent edge weights	Scenario-one	1.96	0.14	0.946
	Scenario-two	2.72	0.24	1.50
Combined Mamdani-Sugeno FLI based WCL using RSSI dependent edge weights	Scenario-one	1.94	0.062	0.761
	Scenario-two	2.64	0.191	1.31
Mamdani FLI based WCL using RSSI and LQI dependent edge weights	Scenario-two	1.82	0.291	0.89
Sugeno FLI based WCL using RSSI and LQI dependent edge weights	Scenario-two	1.96	0.2	0.971
Combined Mamdani-Sugeno FLI based WCL using RSSI and LQI dependent edge weights	Scenario-two	1.38	0.015	0.781

F. Mamdani FLI Based WCL Using RSSI and LQI Dependent Edge Weights

We have proposed to use combined value of RSSI and LQI to decide the edge weights of WCL using Mamdani FLI in present strategy. The simulation for proposed strategy is carried out for scenario-two only. Instantaneous node localization error of nodes for their deployment in scenario-two is shown in Fig. 6. The proposed localization protocol provides better node localization even in presence of external RF interference. For simulation setup of proposed protocol under scenario-two, average localization error, maximum and minimum localization error are obtained as 0.89m, 1.82m, and 0.291m respectively. Simulation results demonstrate that the localization accuracy for proposed protocol is better than conventional RSSI based Mamdani, Sugeno, and CMS FLI in presence of noise and RF interference.

G. Sugeno FLI Based WCL Using RSSI and LQI Dependent Edge Weights

In this proposed protocol, Sugeno FLI is used to decide the edge weights for WCL, which are RSSI and LQI dependent. Instantaneous node localization error of nodes for their deployment for scenario-two i.e. environment having AWGN along with external RF interference is shown in Fig. 7. This protocol provides node localization comparable to RSSI and LQI dependent Mamdani FLI in presence of external RF interference. The average localization error, maximum and minimum localization error as obtained for simulation of proposed protocol under scenario-two are 0.971m, 1.96m, and 0.20m respectively.

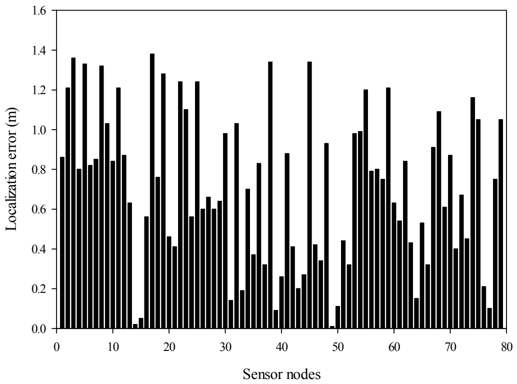


Fig. 8 Node localization error for CMS FLI based WCL using RSSI and LQI dependent edge weights in the environment having AWGN and external RF interference

H.Combined Mamdani-Sugeno FLI Based WCL Using RSSI and LQI Dependent Edge Weights

In proposed localization protocol, edge weights for WCL are calculated by averaging the edge weights obtained from Mamdani and Sugeno FLI. RSSI and LQI values are used to decide the edge weights for Mamdani and Sugeno FLI. Instantaneous node localization error of SNs for their deployment in the environment having AWGN along with external interference is shown in Fig. 8. Simulation results for average localization error, maximum and minimum localization error for proposed protocol as obtained under scenario-two are 0.781m, 1.38m, and 0.015m respectively. The simulation results demonstrate that proposed localization protocol provides better results for SN localization compared to RSSI based Mamdani, Sugeno, CMS FLI or RSSI and LQI dependent Mamdani and Sugeno FLI when SNs are deployed under scenario-two. Although, this protocol is having more Mamdani as well as Sugeno FLI system; however it is a good localization option for applications requiring fine grain localization accuracy. The simulation results of average, minimum, and maximum localization error for all above localization protocols are summarized in the Table III.

VI. Conclusion

This paper presents new range free localization protocols for WSN, based on improved WCL. The edge weights for proposed WCL protocols are obtained through TISO FLI system; the magnitude of edge weights is based on RSSI and LQI values of received signal, measured at the localizing SN. Simulation results demonstrate that combination of RSSI and LQI results in better correlation between WCL edge weights and node distance in presence of external RF interference. This makes the proposed protocols a suitable localization option for SNs in realistic deployment scenario, where SNs need to operate in presence of various external RF sources sharing same frequency band. The inclusion of LQI for edge weight calculation does not require any additional hardware implementation on the SN, as this measurement is already available along with RSSI for IEEE 802.15.4 compliant SNs.

In proposed protocol, edge weights are decided by TISO FLI system. RSSI and LQI are given as input to the FLI system. TISO FLI is implemented and simulated using (i) Mamdani, (ii) Sugeno, and (iii) combined Mamdani-Sugeno FLI models. Simulation results demonstrate that proposed protocols provide better localization accuracy compared to conventional RSSI based WCL protocols proposed in literature.

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