Fuzzy One-phase Pull Diffusion for WSNs in Fading Channel

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***Abstract*—Using wireless sensor networks (WSNs) for a clinical purpose has many potential advantages. However, due to fading feature of wireless channel, providing an efficient and reliable communication is very challenging. In this paper, we propose FUZZ-OPP (FUZZy One-Phase Pull), a fuzzy logic based one-phase pull protocol. The protocol considers signal strength, inter-node distance and residual energy in the route selection. The protocol employs a fuzzy logic to consider these metrics jointly. Since the parameters and the rules used in the fuzzy logic are all reconfigurable, the proposed protocol can be used in any scenario by simple parameter tuning. We use computer simulations to evaluate the performance of the proposed protocol.**

I. Introduction

Wireless sensor networks (WSNs) provide wireless communications between sensor devices. In recent days, with the emergence of small and low-cost wireless devices, wireless sensor networks have been attracting the interest of many communities. In this research, we consider a wireless sensor network protocol for clinical usage in a hospital. For example, 24-hour recordings of electrocardiogram are important for the diagnoses of some patients. However, this is currently done by the patients writing down their moving history manually. This increases the stress level of a patient. Furthermore, the stress and carelessness behavior of a patient makes the recording inaccurate. Therefore, we want to realize 24-hour recordings in an accurate and efficient way. Fortunately, wireless sensor networks can provide a promising solution. Let us consider the following applications. Patients are equipped with wireless sensor devices. With the help of others wireless devices located in the hospital, a patient can communicate with clinical staffs and the hospital's data servers. Patients' information can be delivered to the central server periodically without any awareness of the patients. When a hospital staff requires the information of a patient, the staff just sends a query and the wireless sensor device of the patient sends back the information to the staff. By using wireless sensor networks, many kinds of monitoring can be done in an efficient way.

The monitoring interval and data length are different for different kinds of monitoring. A doctor may need the current status of a group of patients. However, it is difficult to use unique device identifiers (IP address or other addresses) in this case because grouping patients according to these device identifier is inefficient, especially when these device identifiers are dynamic. Therefore, a data-centric routing approach can be promising. When some information are required, the sink node (doctor) sends interests to specify required data and the sensor nodes (patients) send back the data automatically.

There have been some data-centric protocols proposed for wireless sensor networks [1], [2], [3]. In these protocols, one-phase pull protocol [2] is the most suitable one for the hospital application mentioned above due to the application requirement and the low overhead feature of one-phase pull. This is because one-phase pull is a subscriber based algorithm and it has a low overhead compared to two-phase pull [1]. However, one-phase pull only considers end-to-end delay in the route selection. As a result, the one-phase pull cannot work well in a fading environment. Due to the channel fading, a node can receive an interest message from a neighbor which is in a bad channel condition. If the node uses the neighbor node to deliver data, the data can be lost with a high probability. Fading conditions are different for different scenario and different radio frequencies. Therefore, we also need a flexible design for the protocol. One-phase pull also does not consider energy usage in the route selection, which is very important for battery limited sensor devices.

As mentioned above, the use of wireless sensor networks still presents many challenges to protocol designers. First, due to the limited battery power, an efficient data diffusion method is required. Second, fading feature of wireless channel should be considered. Third, the protocol should be flexible and easily reconfigurable. To satisfy these requirements, in this paper, we propose a FUZZy One-phase Pull diffusion (FUZZ-OPP). FUZZ-OPP derives the low overhead feature of One-phase Pull diffusion. By considering multiple metrics of signal strength, inter-node distance and residual battery in the route selection, FUZZ-OPP can work well in a fading environment. FUZZ-OPP can be reconfigured to use in any scenarios by changing parameters and rules with an external file. We evaluate FUZZ-OPP's performance using the network simulator ns-2 [4] and compare the protocol with original one-phase pull diffusion.

The remainder of the paper is organized as follows. In section II, we give a brief outline of related work. In section III, we give a detailed description of the proposed protocol. Next, we present simulation results in section IV. Finally, we present our conclusions and proposals for future work in Section V.

II. Related works on data diffusion in wireless sensor networks

Data-centric protocols have been widely discussed in recent years [1], [2], [3]. In the data-centric protocols, a data packet is named by attribute-value pairs. Directed diffusion [1] is the first well-known data-centric protocol. In directed diffusion, a sink node requests data by disseminating interest messages in the network. Upon reception of an interest message, a source node sends exploratory event using multiple paths to the sink node. After the reception of these events, the sink node selects a particular path to drawn down real data. This approach is typically called two-phase pull. Since both interest propagation and exploratory event propagation use flooding, two-phase pull algorithm results a high overhead. J. Heidemann et al. [2] have designed push and one-phase pull algorithm which use only one-way flooding. Push algorithm only floods exploratory data. Since push algorithm uses a publisher based approach, the algorithm is not suitable for the applications considered in this paper. Contrast to push, one-phase pull only floods interest messages. One-phase pull is a subscriber based approach in which sink nodes send interest when sensing data are required. Upon reception of an interest, a source node uses the path (preferred gradient) which shows the shortest delay in the interest propagation. There also have been some protocols which aim to increase network reliability while conserving energy [3], [5], [6]. When multiple metrics are required to consider jointly, the optimization problem becomes complicated. Since fuzzy logic can handle approximate reasoning, some studies have used fuzzy logic to enhance routing in WSNs [7], [8].

However, all these protocols do not consider channel fading in the data propagation. In a wireless channel where fading exists, a source node can receive an interest message from a neighbor which is at a distance at which wireless communication can be unstable. If the source node uses such a neighbor node as a preferred gradient, the data may not be delivered to the neighbor node. Therefore, the channel fading should be considered in the route selection.

The effects of channel fading on wireless sensor networks have been studied recently [9], [10], [11]. However, these researches do not provide a solution how to select a reliable data propagation path in a fading wireless channel. Different application scenarios have different fading parameters. The fading conditions are also affected by human motion. Therefore, we require a flexible design which can be used in any kinds of wireless environment.

III. Proposed Protocol: FUZZ-OPP

FUZZ-OPP only floods interest messages. Therefore, the protocol exhibits a low control overhead. After reception of an interest message, a node sets up a gradient for the neighbor from which the node receives the interest message. In the gradient value calculation, the protocol uses a fuzzy logic to consider signal strength, inter-node distance and residual energy jointly. After receiving multiple copies of an interest message, a source node chooses the best neighbor node to propagate data messages. Similarly, the selected neighbor node also chooses its best neighbor node until the sink node is reached.

A. Interest propagation and route setup

As shown in Fig. 1, when sink node R requires data from sensor node S, the sink node floods interest messages. We assume every node knows its own position and residual energy. Before transmitting an interest message, a node (the sink node or other nodes) attaches these information to the interest message. Each node also calculates own maximum gradient

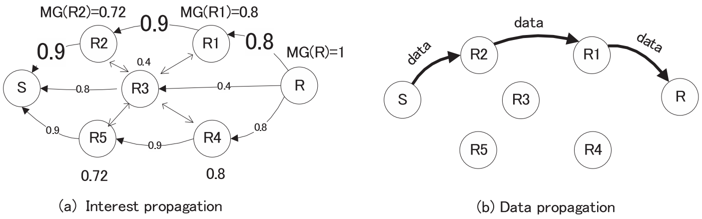

Fig. 1. Interest propagation and data propagation.

value and attaches this value to the interest message. This gradient value is used like a routing metric and it is used to avoid routing loop. Other node can use this value to determine whether to use the node as the next hop or not. The maximum gradient value of node a is calculated as

$$MG(a)=\begin{cases}1, & a\ is\ the\ sink\\ \max_{n\in N_a}[MG(n)\times ls(a,n)], & otherwise.\end{cases} \quad (1)$$

where where N_a denotes the set of neighbors of node a, and $ls(a,n)$ denotes the link status value of the link which connects a and n. For the sink node, the maximum gradient value is 1. Other nodes calculate the maximum gradient value based on the gradient value of the next hop and the link status value to the next hop. As shown in Fig. 1, $MG(R)$ is 1 because node R is the sink node. Since $ls(R1,R)$ is 0.8, $MG(R1)$ will be 0.8. Similarly, since $MG(R1)$ is 0.8 and $ls(R2,R1)$ is 0.9, $MG(R2)$ will be 0.72.

After reception of an interest message, a node calculates a link status value ($ls(a,n)$ in Eq. 4) based on the received interest message. This value is calculated by using fuzzy logic to jointly consider signal strength, inter-node distance and residual battery power (see III-B). Before sending a data packet, a node then calculates a gradient value for each neighbor n according to Eq. 2 (if the current node is a) and chooses the neighbor which has the maximum gradient value as the next hop.

$$gradient(n)=MG(n)\times ls(a,n). \quad (2)$$

After reception of the first interest message, a sensor waits for a short period of time before sending the data. This is to ensure all possible better route to be detected. Note that FUZZ-OPP may choose a suboptimal path. This is because in the interest propagation phase, each node sends interest message only once. Getting the best path is possible if we change interest propagation phase. For example, each node rebroadcasts an interest message when a better path is detected regardless of the message already having been broadcasted. However, this increases the number of interest messages. Therefore, FUZZ-OPP uses the same interest propagation method as the original one-phase pull.

B. Using Fuzzy Logic to Jointly Consider Multiple Metrics

1) Why Fuzzy Logic: Before sending a data packet, a node has to choose the next hop node which can provide reliable and efficient communication. If the node chooses a node in a very long distance, the selected node may not receive the data. If the node chooses a very near node, the selected node can receive the data but it is inefficient. The optimal distance can be different for different network environment. Therefore, the mathematical model of the optimal node selection problem is complex to derive and a solution based on it would be too expensive for practical application.

Fortunately, fuzzy logic can handle imprecise and uncertain information. Based on fuzzy set theory [12], fuzzy logic deals with the concept of approximate rather than precise factors. Since fuzzy logic can handle approximate reasoning which is similar to human reasoning, it has been widely accepted in industrial communities and used in many applications. In contrast to numerical values in mathematics, fuzzy logic uses non-numeric linguistic variables to express the facts. Fuzzy membership functions are used to represent the degrees of a numerical value belonging to linguistic variables. Fuzzy rules are used to achieve optimum results. By simply modifying fuzzy membership function and fuzzy rules, a fuzzy system can satisfy most applications' requirement. Therefore, a fuzzy logic based approach is flexible.

2) Procedure:

- Upon reception of an interest message from a neighbor, each node evaluates the link to the neighbor ($ls(a, n)$ in Eq. 4) in term of signal strength, inter-node distance and residual energy. For each neighbor, the calculation steps are as follows.
  - **Calculation of multiple factors** Calculate a Signal Strength Factor, Distance Factor and Residual Energy Factor for the neighbor.
  - **Fuzzification** Use predefined linguistic variables and membership functions to convert the Signal Strength Factor, Distance Factor and Residual Energy Factor to fuzzy values.
  - **Mapping and combination of IF/THEN rules** Map the fuzzy values to predefined IF/THEN rules and combine the rules to get the rank of the neighbor as a fuzzy value.
  - **Defuzzification** Use a predefined output membership function and defuzzification method to convert the fuzzy output value to a numerical value.
- After that each node calculates a gradient value for each neighbor as shown in Eq. 2, and selects the node that has the maximum gradient value to deliver the packet to the sink node.

3) Calculation of multiple factors: Upon reception of an interest message from a neighbor, a node calculates the following factors.

Signal Strength Factor: upon reception of an interest message from a neighbor X, a node calculates a Received Signal Strength Indication Factor ($RSSIF$) as in Eq.3. In Eq.3, $RxPr$ is the received signal power, $RXThresh$ is the reception threshold. The value of $RXThresh$ is defined based on received power. Generally, an interest message cannot be received when the received power is lower than this value. $RSSIF$ indicates the average signal strength of the neighbor node.

$$RSSIF(X) = \begin{cases} 1 - \frac{RXThresh}{RxPr}, & RXThresh < RxPr \\ 0, & otherwise. \end{cases} \quad (3)$$

Distance Factor: upon reception of an interest message from a neighbor X, a node calculates a Distance Factor (DF) as in Eq.4. In Eq.4, $d(X)$ is the distance between the current node and node X. R is the maximum distance over which stable communications can be provided. Here we assume that every node has the same transmission power and that the transmission power is constant.

$$DF(X) = \begin{cases} \frac{d(X)}{R}, & d(X) <= R \\ 1, & d(X) > R. \end{cases} \quad (4)$$

Energy Factor : a node also calculates a Energy Factor (EF) as in Eq.5 where Maximum energy means the maximum possible energy of the node after battery charge. We assume all sensor nodes have the same maximum possible energy. EF indicates the residual energy level of the node. When the node has a external power supply the EF is 1.

$$EF(X) = \begin{cases} 1, & \frac{\text{Residual energy}}{\text{Maximum energy}} >= 1 \\ \frac{\text{Residual energy}}{\text{Maximum energy}}, & otherwise. \end{cases} \quad (5)$$

4) Fuzzification: The process of converting a numerical value to a fuzzy value using a fuzzy membership function is called "fuzzification." The fuzzy membership function of the RSSI factor is defined as in Fig. 2. The sender node uses the membership function and the RSSI factor to calculate which degree the RSSI factor belongs to {Good, Medium, Bad}.

The fuzzy membership function of the distance factor is defined as in Fig. 3. The sender node uses the membership function and the distance factor to calculate which degree the distance factor belongs to {Good, Medium, Bad}.

The fuzzy membership function of the energy factor is defined as in Fig. 4. The sender node uses the energy membership function and the energy factor to calculate which degree the energy factor belongs to {High, Medium, Low}.

5) Mapping and combination of IF/THEN rules: Once the fuzzy values of RSSI factor, distance factor and energy factor have been calculated, the sender node uses the IF/THEN rules (as defined in Table I) to calculate the rank of the neighbor node. The linguistic variables of the rank are defined as {Perfect, Good, Acceptable, NotAcceptable, Bad, VeryBad}. For example, in Table I, Rule1 may be expressed as follows.

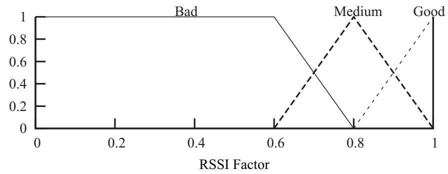

Fig. 2. Signal strength membership function.

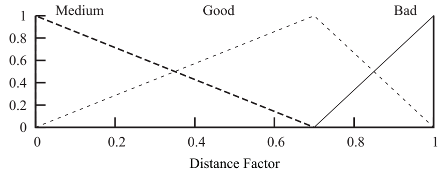

Fig. 3. Distance membership function.

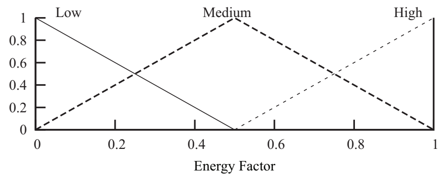

Fig. 4. Energy membership function.

TABLE I
RULE BASE

	Signal Strength	Distance	Energy	Rank
Rule1	Good	Good	High	Perfect
Rule2	Medium	Good	High	Good
Rule3	Bad	Good	High	NotAcceptable
Rule4	Good	Good	Medium	Good
Rule5	Medium	Good	Medium	Acceptable
Rule6	Bad	Good	Medium	Bad
Rule7	Good	Good	Low	NotAcceptable
Rule8	Medium	Good	Low	Bad
Rule9	Bad	Good	Low	VeryBad
Rule10	Good	Medium	High	Good
Rule11	Medium	Medium	High	Acceptable
Rule12	Bad	Medium	High	Bad
Rule13	Good	Medium	Medium	Acceptable
Rule14	Medium	Medium	Medium	NotAcceptable
Rule15	Bad	Medium	Medium	Bad
Rule16	Good	Medium	Low	Bad
Rule17	Medium	Medium	Low	Bad
Rule18	Bad	Medium	Low	VeryBad
Rule19	Good	Bad	High	NotAcceptable
Rule20	Medium	Bad	High	Bad
Rule21	Bad	Bad	High	VeryBad
Rule22	Good	Bad	Medium	Bad
Rule23	Medium	Bad	Medium	Bad
Rule24	Bad	Bad	Medium	VeryBad
Rule25	Good	Bad	Low	Bad
Rule26	Medium	Bad	Low	VeryBad
Rule27	Bad	Bad	Low	VeryBad

IF *Signal Strength* is Good, *Distance* is Good, and *Energy* is High **THEN** *Rank* is Perfect.

In a rule, the IF part is called the "antecedent" and the THEN part is called the "consequent." Since there are multiple rules applying at the same time, we have to combine their evaluation results. Here we use the Min-Max method. In the Min-Max method, for each rule, the minimal value of the antecedent is used as the final degree. When combining different rules, the maximal value of the consequents is used.

For example, we assume a neighbor's RSSI factors, distance, energy belong to the corresponding linguistic variables as {Good:0.5, Medium:0.5, Bad:0}, {Good:1, Medium:0, Bad:0} and {High:0.75, Medium:0.25, Low:0} respectively. In this case, these fuzzy sets would match Rule1, Rule2, Rule4 and Rule5 as shown in Table II. For Rule1, the degree for {Good} (Signal Strength) is 0.5, the degree for {Good} (Distance) is 1 and the degree for {High} (Energy) is 0.75. In the Min-Max method, we take the minimal value of antecedent members and therefore the degree of the antecedent will be 0.5 (Rank Perfect). Similarly, the degrees of the antecedents for Rule2, Rule4 and Rule5 will be 0.5, 0.25 and 0.25 respectively. As both Rule2 and Rule4 lead to the Rank Good, we take the maximal value of their consequents and therefore the degree of the Rank Good will be 0.5. In this way, all rules are combined to give a fuzzy result ({Perfect:0.5, Good:0.5, Acceptable:0.25}).

TABLE II
RULE MATCHING

	Signal Strength	Rank	Distance	Energy
Rule1	Good (0.5)	Good (1)	High (0.75)	Perfect (0.5)
Rule2	Medium (0.5)	Good (1)	High (0.75)	Good (0.5)
Rule4	Good (0.5)	Good (1)	Medium (0.25)	Good (0.25)
Rule5	Medium (0.5)	Good (1)	Medium (0.25)	Acceptable (0.25)

6) Defuzzification: Defuzzification is the process of producing a numeric result based on an output membership function and corresponding membership degrees. The output membership function is defined as in Fig. 5. Here we use the Center of Gravity (COG) method to defuzzify the fuzzy result. More specifically, we cut the output membership function (Fig. 5) with a straight horizontal line according to the corresponding degree, and remove the top portion. For the example given above, the degree for Rank {Acceptable} is 0.25, the degree for Rank {Good} is 0.5 and the degree for Rank {Perfect} is 0.5 and consequently the result function will form a shape as shown in Fig. 5. Then, we calculate the centroid of this shape. The x coordinate of the centroid will be the defuzzified value.

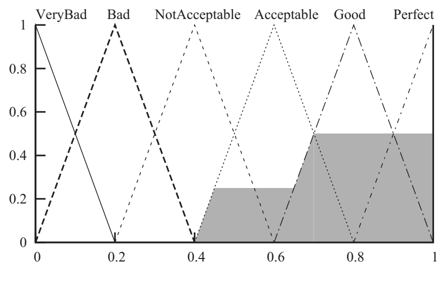

Fig. 5. Output membership function and an example of $\mu(x)$.

If we use $\mu(x)$ to denote the result function and use x to denote the X-axis, the center of gravity will be

$$COG = \frac{\int \mu(x)xdx}{\int \mu(x)dx}. \tag{6}$$

Here COG represents the evaluation value of the link which connects the current node and the neighbor node ($ls(a,n)$ in Eq. 4). The higher the value is, the better the link will be.

7) Next hop node selection: Based on the link status value calculated above, a sender node calculates a gradient value for each neighbor node (as in Eq. 2) and then selects the neighbor node which has the maximum gradient value. Note that all membership functions and fuzzy rules given above are all reconfigurable and users can tune them according to their requirements.

IV. Simulation Results

We used Network Simulator 2 (ns-2.34) to conduct simulations. Simulation parameters are shown in Table III. We generated a network which has 20 mobile nodes and other many static nodes. We generated random movement for the mobile nodes and the maximum velocity was 2 m/s. We used the Nakagami propagation model to simulate a fading channel. The parameters of the Nakagami model are shown in Table IV. These parameters result a reception probability as shown in Fig. 6.

Other simulation parameters were the default settings of ns-2.34. We launched simulations with 50 different node deployments and different node movements, and analyzed the average value of the results. The proposed protocol was compared with original one-phase pull algorithm [2]. In the following simulation results, the error bars indicate the 95% confidence intervals.

TABLE III
Simulation Environment

Topology	100m × 500m
Number of nodes	100 to 300
Mobility generation	Random waypoint model (0 – 2 m/s)
Number of sinks and sources	5 and 10
Number of packets	200 packets at each source
Packet size	512 bytes
Data sent interval	5 s
Interest interval	30 s
Power consumption rate	Tx:0.66W, Rx:0.359W and Idle:0.035W
MAC	IEEE 802.11 MAC (2Mbps)
Propagation model	Nakagami model
Simulation time	1000 s

TABLE IV
Parameters of Nakagami Model

gamma0_	gamma1_	gamma2_	d0_gamma_	d1_gamma_
1.8	2	2	80	100
m0_	m1_	m2_	d0_m_	d1_m_
1.2	1.1	1	80	100

A. Packet Reception ratio

Fig. 7 shows that the original one-phase pull cannot provide enough packet reception ratio. Choosing the lowest delay path

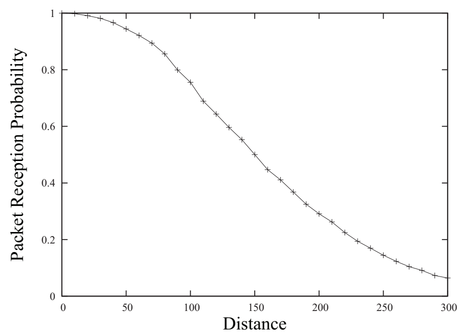

Fig. 6. Packet reception probability for various distances.

is totally unreliable in a fading environment. The lowest delay path is always the shortest (the number of hops) path. A shorter path means a larger inter-node distance. However, in a fading channel, a large inter-node distance results a low packet reception ratio. That is why the lowest delay path cannot provide a high packet reception ratio. With the increase of the node density, the packet reception rate decreases. This is because with the increase of the node density, the number of paths increases, making the lowest delay path becomes more shorter. In a hospital sensor network which requires reliable delivery of data, if a sink node cannot receive a data packet, the sink node has to flood interest again. This incurs a high message overhead in a high density network.

FUZZ-OPP shows a high packet reception ratio (above 95%) regardless of node density. In FUZZ-OPP, a source node chooses the next hop node considering the received signal strength. As a result, FUZZ-OPP can choose a reliable path to deliver data packet. In a fading channel, the received signal strength can be time varying. However, FUZZ-OPP also works well in this case because it also considers inter-node distance in the route selection. As we can see from Fig. 7, FUZZ-OPP outperforms the original one-phase pull significantly by jointly considering the received signal strength and inter-node distance.

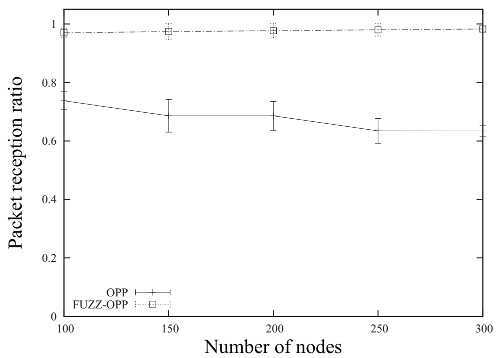

Fig. 7. Packet reception ratio for various numbers of nodes.

B. Battery Usage

Fig. 8 shows the energy consumption per data packet delivered for various numbers of nodes. FUZZ-OPP consumes lower energy than the original one-phase pull for successfully delivering a data packet. Although the chosen path is not the shortest path, FUZZ-OPP is more efficient because it can result a high packet reception ratio.

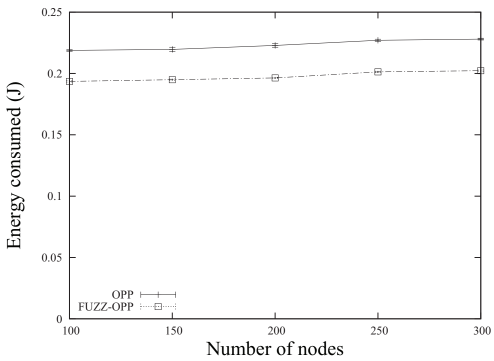

Fig. 8. Energy consumption per data packet delivered for various numbers of nodes.

Fig. 9 shows probability density function of residual energy after the 1000 s simulation. Since FUZZ-OPP chooses the route considering the residual energy, FUZZ-OPP results a more fair energy distribution among all nodes than one-phase pull. The average residual energy of FUZZ-OPP is lower than one-phase pull because FUZZ-OPP delivers more packets.

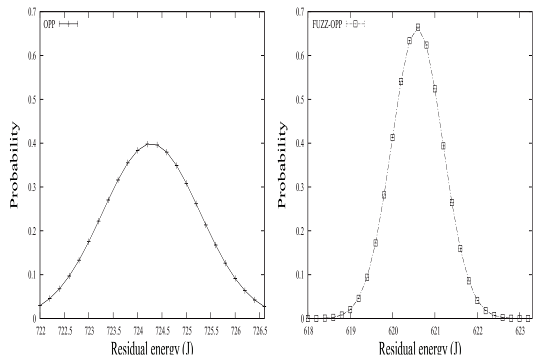

Fig. 9. Probability density function of residual energy after 1000 s simulation.

C. End-to-end Delay

Fig. 10 shows end-to-end delay for various numbers of nodes. In the delay calculation, we only considered the successfully delivered packets. Although FUZZ-OPP may choose a longer path, it shows a very comparable delay to the original one-phase pull. In some applications, if a date packet is lost, the packet has to be retransmitted. In this case, one-phase pull may incur a higher delay. FUZZ-OPP does not incur too much this kind of retransmission delay because FUZZ-OPP results a high packet delivery ratio. Therefore, we can know that end-to-end delay of FUZZ-OPP is totally acceptable.

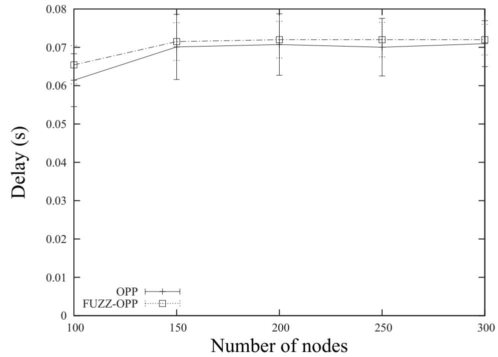

Fig. 10. End-to-end delay for various numbers of nodes.

V. Conclusions and Future Works

We have proposed FUZZ-OPP, a fuzzy logic based one-phase pull diffusion method for wireless sensor networks with fading channel. FUZZ-OPP employs a fuzzy logic to evaluate a neighbor considering signal strength, inter-node distance and residual battery power. Through computer simulations, we have confirmed that FUZZ-OPP results a high packet delivery ratio and an efficient use of buttery power as compared to one-phase pull method. We intend to improve our protocol by using adaptive interest propagation interval and data aggregation. Implementing FUZZ-OPP on IRIS sensor nodes is also considered as a future work.

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