디지털산업정보학회 논문지 제11권 제3호-2015년 9월
http://dx.doi.org/10.17662/ksdim.2015.11.3.079

Interactive Multipath Routing Protocol for Improving the Routing Performance in Wireless Sensor Networks

Jung Kwansoo*

<Abstract>

Multipath routing technique is recognized as one of the effective approaches to improve the reliability of data forwarding. However, the traditional multipath routing focuses only on how many paths are needed to ensure a desired reliability. For this purpose, the protocols construct additional paths and thus cause significant energy consumption. These problems have motivated the study for the energy-efficient and reliable data forwarding. Thus, this paper proposes an energy-efficient concurrent multipath routing protocol with a small number of paths based on interaction between paths. The interaction between paths helps to reinforce the multipath reliability by making efficient use of resources. The protocol selects several nodes located in the radio overlapped area between a pair of paths as bridge nodes for the path-interaction. In order to operate the bridge node efficiently, when the transmission failure has detected by overhearing at each path, it performs recovery transmission to recover the path failure. Simulation results show that proposed protocol is superior to the existing multipath protocols in terms of energy consumption and delivery reliability.

Key Words : Wireless Sensor Networks, Multipath Routing, Concurrent Routing, Energy Efficiency

Ⅰ. Introduction

Wireless sensor networks (WSNs) consist of a large number of sensor nodes randomly distributed and capable of computing, communicating, and sensing over a wide area. The usage of wireless sensor networks is almost unlimited with many industries and applications. The sensor nodes collect the physical or environmental information (temperature, pressure, proximity, vibration, sound, electromagnetic, etc.) and report the information to users. However, the limitations of sensor nodes, such as low computing power, weak communication capability, and unrechargeable battery, have motivated many researchers to develop effective routing protocols with the performance requirement of applications. Moreover, the routing protocols should be designed to consider both of reliability and energy efficiency in applications of environment monitoring, territorial

---

* Chungnam National University, Department of Computer Engineering Ph. D.

security, public protection, and disaster relief [1, 2].

However, since WSNs have the possibility of unforeseeable high channel error, it is difficult for the routing protocols to satisfy the high requirement performance of user [3]. In order to achieve the high reliability and low delay, one of the reliable and real-time routing schemes is the multipath routing. The traditional multipath routing protocols concurrently forward redundant data packets via multiple paths. However, the concurrent multipath routing causes collision and congestion due to the interference of each path. Additionally, hotspot problems could be frequently occurred because of shared resources between paths. Recently, to increase the robustness and efficiency of multiple paths, the whole or partial disjoint multipath routing protocols are proposed, considering the disjoint of node, link, or area. Although the multipath routing could provide more enhanced performance than the single path, it still causes the resource waste problem [2, 5].

Therefore, this paper proposes a novel energy-efficient multipath routing protocol with a small number of multiple paths. The proposed method is an Interactive Multipath Routing Protocol called IMRP. In the proposed protocol, the bridge nodes at the disjoint area between the paths check the forwarding status of each path via overhearing the data transmission and recover the data transmission in order to interact between paths. By checking the forwarding status, the nodes could be aware of failed transmission or delayed transmission and recover the transmission error of the paths. Namely, the bridge nodes could strengthen the reliability of the paths, increasing the reliability and reducing the energy consumption. Consequently, in the environment of high channel error, the proposed protocol with the bridge nodes provides the reliable and energy efficient multipath routing without increasing the number of paths. In dangerous terrain or hostile terrain, the sensor nodes might be randomly deployed due to the difficulty of planned deployment. Because of that, there might be an area where has a lower node density or a higher channel error than the average values. Moreover, the end-to-end reliability decreased according to the distance between a source and a sink in this area [3, 4]. For energy-efficient multipath routing in irregular network environment, the proposed protocol consists of the procedures: the flexible establishment of multiple paths and learning based path management. The proposed path establishment method makes an effort to satisfy the desired performance of applications by constructing a sub-path using the bridge nodes in the environment where it is difficult to construct multiple paths. The proposed path management maintains the reliability of multipath by reinforcing the path interaction based on the learning information in lossy networks. It also provides an immediate and localized path management. In summary, the proposed interactive multipath provides the energy efficient and reliable routing performance. Therefore, the proposed method can be useful on the variety of applications ranging from military to industry.

Ⅱ. PROPOSED PROTOCOL

In this section, we introduce the detailed operations of multipath establishment and maintenance in IMRP.

2.1 Algorithm Analysis

This subsection analyses the difference between the algorithms of the traditional multipath routing protocol and the proposed multipath routing protocol, and describes the proposed protocol. In WSNs, the traditional multipath routing protocols forward packets via independent multiple paths. Therefore, the reliability of multipath is proportional to the number of paths and inversely proportional to the length of path. In the existing protocols [4], the number of paths needed is calculated by the following equation:

$$P = \frac{\log(1-DR)}{\log(1-(1-e)^{h})} \tag{1}$$

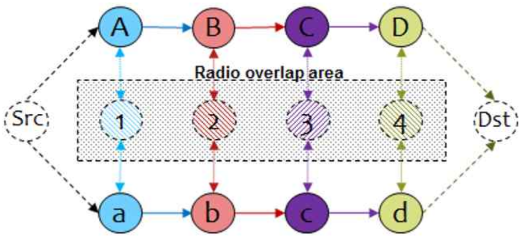
where P is the number of paths, DR is the desired reliability, e is the channel error rate of link, and h is the number of hops. By the equation (1), the tolerable failure rate of each path TF_{p} for satisfying the desired reliability in P paths could be calculated with the following equation (2):

$$TF_{p} \le 10^{\frac{\log(1-DR)}{P}} \tag{2}$$

In the environment of P multiple paths, the guarantee reliability GR_p for each path is calculated in the following equation (3):

$$GR_{p} = 1 - TF_{p} \ge 1 - 10^{\frac{\log(1-DR)}{P}} \tag{3}$$

The proposed protocol guarantees the reliability without additional paths in order to increase the reliability of multiple paths in resource-constrained networks. For this, the proposed protocol exploits mutually complementary localized recovery approach by the bridge nodes for interaction between paths in order to guarantee the desired reliability without adding paths. The figure 1 shows the example of disjoint multipath using bridge nodes.



<Figure 1> An example of the utilization of bridge nodes

In this paper, the bridge nodes are selected among the nodes at the radio overlapping area between a primary path and an adjacent sub-path. Any bridge node could detect the delayed or failed transmission of adjacent paths by overhearing and try to recover the data forwarding. Therefore, the reliability of the proposed protocol is increased by the number of the bridge nodes. The reliability of a path R_p is presented by the following equation (4): (if, $n \le h-1$, $P=2$)

$$R_p = \prod_{i=0}^{n} \left[1 - \left\{ \begin{matrix} \left(1 - S^{(\beta_i - \beta_{i-1})}\right) \\ \times \left(S^{((\beta_i + 2) - \beta_{i-1})} \right) \end{matrix} \right\} \right] \times S^{(h - \beta_n)} \tag{4}$$

where s is the communication success rate, *i* is the number of bridge node, and β_i is the hop distance of bridge node *i*. In the equation (4), if the number of bridge node is zero, the reliability of a path is same to that of the single path.

Consequently, the proposed protocol increases the reliability of each path as well as the reliability of multipath. Although the proposed protocol needs the additional resource for enhancing the reliability in the networks, the overhearing and caching operation of the bridge nodes consumes only insignificant energy. The recovery by caching data is done only when the transmission failure is occurred. Therefore, the energy overhead of the proposed protocol is insignificant in comparison with that of the existing protocols.

2.2 Construction of multiple paths

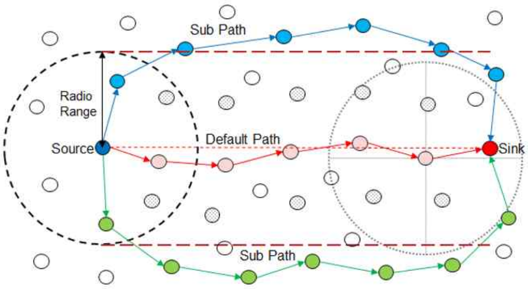
The proposed protocol constructs a pair of radio-disjoint paths that has a low inter-path interference. Namely, each path has no common nodes except the source and the destination. But the number of the multipath is flexibly set according to the node density, energy, radio status and the end-to-end distance. In the following, we describe a construction method for the proposed radio-disjointed multipath in detail.

2.2.1 The disjoint multipath in dense network

The construction procedure of multipath is composed of the route discovery and establishment. Based on the idea of the directed diffusion [6] the sink node starts the multiple paths discovery phase to create a set of edges that able to forward data towards the sink from the source node. At the initialization phase, in order to route discovery, the sink floods the RREQ (Route Request) message to whole networks, which includes the interest and requirement information of users. Every node adds the collected metric information into the RREQ message and forwards the message to next-hop node. In this procedure, whole sensor nodes store the metrics of 1-hop neighbor nodes. The metrics are the followings: link (hop) latency, route latency and hop distance to sink, remained battery and SNR (Signal-Noise Rate) of neighbors. The metrics are updated by the message transmission or the periodical management. After the sink flooding, the source node, which detects an event and have to report the event, forwards an RREP (Route Reply) message to sink for constructing paths between itself to the sink. In order efficiently to make radio-disjoint multiple paths, the paths are sequentially constructed. The source node selects the best route as the default path and constructs the secondary path as the sub-path. The basic rule for establish a path is to select next-hop nodes to provide the best routing performance. The priority to select next-hop node is as followings: the latency to sink, hop distance to sink, link latency, remained battery, and SNR.

First, the default route is established with the selected nodes to provide the best routing performance. The nodes, overhearing the RREP message, cache the path information about the forwarding nodes. The source node constructs the sub-path by forwarding the second RREP message. The selection rule for the sub-path is based on the basic rule for the default path. The nodes for sub-path are selected among nodes, not receiving or overhearing the first RREP. The nodes, overhearing the first and second RREP message, cache the path information about the forwarding nodes, and then they notify their metric information and that they are candidates of bridge node by one-hop broadcasting. By this procedure, the radio-disjoint multipath is constructed.

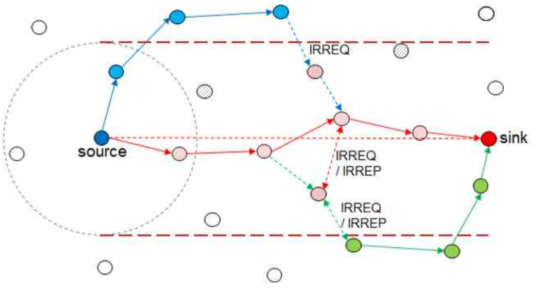
According to the requirement of application or the network environment, an optional third path as the sub path might be needed. Only in this case, we constructs the third path needed. In the following last step, when the selection process of bridge node is terminated, the establishment of the multipath also is completed. The selection method of the bridge node will be described in detail later on. The figure 2 shows the example of the multipath established.



<Figure 2> An idealized example of proposed multipath

2.2.2 The disjoint multipath in sparse network

Sometimes, in the hostile area or dangerous area, the node density might be very low. As network operation time goes on, the number of sensor nodes could be reduced because of energy exhaustion or failure of node. In the sparse network like these environments, the multiple paths could not be constructed or the inefficient multipath could be constructed to provide the low routing performance. This phenomenon causes the waste of the network resource and makes the network lifetime shorten. Therefore, the multipath routing protocol should consider a flexible construction method of the multipath to satisfy the required performance of applications with the energy efficiency in the irregular network environment. In the sparse network, we propose a partial radio-disjoint multipath routing protocol for achieving the original goal of the protocol. First, the proposed method for the sparse network is same to the above-described method to construct the default path in the dense network. However, due to the lack of the network resource, the sub-path construction might be impossible with the above-mentioned selection rule of the forwarding node for the sub-path. Therefore, the method constructs an incomplete sub-path with some forwarding nodes for the sub-path for the interaction between the paths. In the procedure for construction of the sub-path, if the network could not select next-hop forwarding node, the data-holding node finds a forwarding node and forwards an IRREQ (Incomplete Route Request) message via the default path. The nodes in the default path re-forward the message to the candidate of the neighboring bridge node. The candidates of the bridge node, receiving the message, find the forwarding node to satisfy the selection rule and relay the IRREQ message. The forwarding node, receiving the IRREQ message, replies the IRREP (Incomplete Route Reply) message and then it continues the route establishment.



<Figure 3> An example of proposed incomplete multipath

In case of the success of the message, the candidates are selected as the bridge node. Otherwise, the IRREQ message is forwarded via the default path to the next-hop forwarding node. The try for establishment of the sub-path is repeated to the sink. The example of the establishment of incomplete sub-path is showed in the figure 3.

2.2.3 Selection of Bridge Node

After the complete establishment of the radio-disjoint multiple paths, the protocol forwards the R2REQ (Route Reinforcement Request) message in order to choose the bridge nodes among the candidates of bridge node via the default path. The mission of the bridge node is to check whether the transmission of the packet is successful or not and to forward the data packet for recovery transmission. Although the usage of the bridge nodes could increase the reliability of the multipath routing, it needs additional resource consumption. Thus, unnecessary selection and usage of the bridge nodes might cause the path interference and the resource waste. In order to prevent this problem, the bridge nodes should be located at the optimized area and be used for only the essential situation for recovery. The proposed protocol exploits the GR_p to find the optimized location for enhancing the path reliability. To guarantee the desired reliability of users, every forwarding node in the multipath should have the data receiving rate greater than the GR_p. The forwarding nodes could calculate the expected delivery rate with the collected metric information like the equation (5). The nodes that have the expected delivery rate less than the GR_p find the proper bridge node among the neighboring candidates. The selected bridge nodes provide the interaction between paths and the increased expected delivery rate greater than GR_p.

$$Er_i = (1-e)^i = Dr_{i-1} \times (1-e) \tag{5}$$

where the Er is the expected delivery rate, the Dr is the delivery rate, the i is the hop distance of node from source, and the e is the channel error rate of link.

Since enhancing the path reliability by the bridge nodes makes the change of the expected delivery rate, the equation (5) is not proper to the forwarding node of the proposed multipath. Accordingly, we apply the equation (6) to more correctly calculate the delivery rate considering the delivery rate of the previous node and the bridge nodes. The expected delivery rate of the forwarding node is sequentially calculated from the source node.

$$Er_i = 1 - \left[\left\{ 1 - \left(Dr_{i-1} \times (1-e) \right) \right\} \times B_f \right] \tag{6}$$

$$B_f = 1 - \left\{ Dr_{k-1} \times (1-e)^3 \right\} \tag{7}$$

where j and k is the forwarding nodes of the adjacent sub-path, n is the number of bridge nodes, and B_f is the bridge node failure rate. If there is no bridge node with adjacent path, the Dr value of the bridge node is zero.

In summary, the forwarding nodes on the default path calculate their own expected delivery rate when they receive the R2REQ message. After that, if enhancing the path reliability is needed, the protocol finds the bridge nodes, re-calculates the expected delivery rate, and forwards the information the next-forwarding node.

2.2.4 Data Transmission

This paper focuses on only the concurrent multipath routing for data transmission, not a load-balancing and a bandwidth aggregation. After completing the multipath construction, the source node transmits the data packets via the multipath. In data forwarding process, the bridge nodes also detect the transmission failure and recover the failure with caching data. For this mission, the bridge nodes overhear the transmission of corresponding path and cache the overheard data. The overheard data packet is maintained in a certain time until the redundant data packet is overheard by other path. However, if the bridge nodes could not overhear the redundant data packet, the node regards the transmission failure and transmits the caching data to next-hop node for recovery. If the next-hop node has received the data packet redundantly, the node drops the redundant packet. With this scheme, the proposed protocol increases the data transmission possibility and stabilizes the end-to-end latency.

2.2.5 Learning-based Path Management

In order to guarantee the efficient routing performance, the path management, such as the modification or reconfiguration of the path and selection of the bridge node, should be done in the routing protocol. Therefore we propose a learning-based path management. In the proposed learning-based path management, the path and routing informations are managed locally and the informations could be modified and re-configured by the local decision. This subsection describes the path management by the status learning and local decision.

The every forwarding node could learn the path status by sharing the information about the path and routing performance. The learned information by the nodes are the link status, the average receiving possibility and delay time of the whole path, and the link quality and link delay. It also is accumulated and then utilized for the localized path management. With the accumulated information, every sensor node checks regionally its own status in the multipath. If the result of checking cannot be satisfied the requirement of user, the node determines that it is the inefficient path and modifies the path. If several forwarding nodes fails or transmission failure is occurred frequently in the certain area, our method can find the failure area by the neighboring path. The node, located at the front of the frequent failure area, modify the partial failure path. If it is difficult to modify the path or the path is destroyed, the proposed method also notifies to the source node and then the source node re-establishes a new path or the multipath.

The management of bridge nodes maintains the routing performance via additional selecting or releasing the bridge node. If higher reliability is required by user, the bridge nodes are added until the desired reliability is ensured. After adding the bridge nodes, the location adjustment of the bridge node might be needed due to the changed delivery rate of the node. The location adjustment of the bridge node is done with forwarding data and updating the routing information. Then, it is gradually and local progressed. By the modification and re-establishment of path, partial or whole bridge node could be selected newly. Therefore, the learning-based path management could guarantee the stable routing performance of the multipath.

Ⅲ. SIMULATION

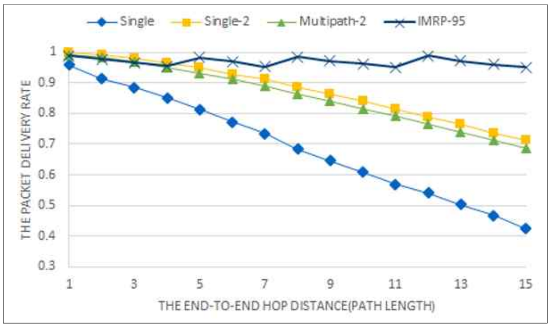
In this section, we evaluate the performance of IMRP in terms of the packet delivery rate and the average energy consumption.

3.1 Simulation Environment

We used Qualnet 4.3 [7] simulator to simulate three protocols. The simulation parameters and model are based on the characteristics of Mica 2 [8]. The simulated network is composed of 300 static nodes deployed uniformly randomly within a 500m by 500m area. We also adopt the IEEE 802.11 MAC layer protocol [9] and the transmit range of each node is set to 50m. A source node transmits the data packet at a speed of 64 bytes/sec. The energy consumption of the node is configured as follows: reception is 15mA, and transmission is 25mA. All the simulation time is 600 seconds and the simulation is performed 10 times.

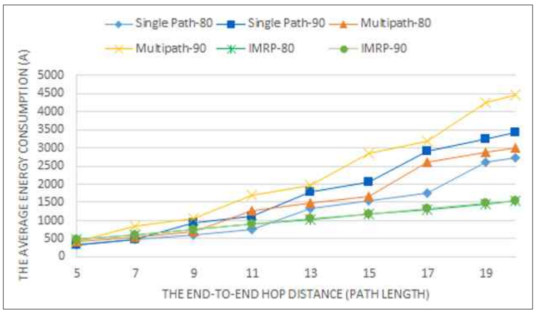
3.2 Simulation Result

The first simulation shows the packet delivery reliability of each routing techniques according to increase of the end-to-end hop distance. For this simulation, the communication channel error rate is set uniformly to 5%. In order to compare only the routing performance of transport protocol, we also have not used other reliability routing techniques such as ARQ (automatic repeat request). Figure 4 shows the routing reliability attained for single forwarding and two redundancy forwarding over single path, simultaneous transmit over the multipath (two paths) and interactive multipath forwarding at desired reliability of 95%. The performance evaluation results are as follows. First, the reliability provided by single path forwarding is significantly decreased. Next, the reliability provided by redundancy forwarding over single path and traditional multipath forwarding show a similar decrease rate. Commonly, these results, decreasing delivery reliability in proportion to the hop distance, are predictable. In contrast, a proposed method ensures the highly reliability than 95%. Although we have used slightly more resources than other methods, the amount of used resources is negligible. This reason can be verified in the next simulation result. As a result, IMRP provides the superior routing performance than other protocols, although the path length is increased.



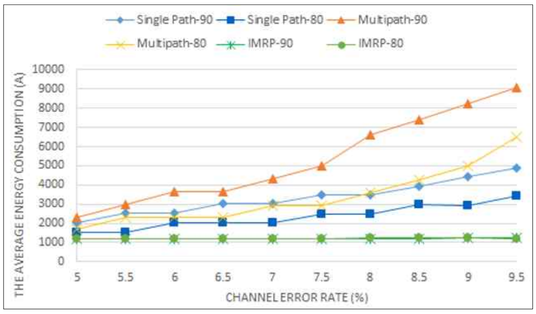
<Figure 4> The packet delivery rate for the path length

The second simulation shows the impact of increasing the average energy consumption to ensure the desired reliability of applications. For this simulation, the communication channel error rate is set uniformly to 5%. The hop distance also is increased from 5 to 20. Figure 5 shows the average energy consumed for redundancy forwarding over single path, simultaneous transmit over the multipath and interactive multipath forwarding at desired reliability of 80% and 90% respectively. The performance evaluation results are that single path redundancy forwarding and traditional multipath forwarding require more higher the energy consumption due to the increasing the number of transmit or the number of multipath in proportion to the hop distance and desired reliability. In contrast, the rate of average energy consumption increase of IMRP is very insignificant rather than other protocols. This reason is that our protocol has not required more redundant transmission and additional sub-path due to the use of bridge node that perform mutual cooperation between paths. Even, the results of IMRP for desired reliability 80% and 90% are very similar. As a result, we could be verified that IMRP provides more energy-efficient routing than existing routing techniques in large-scale WSNs.



<Figure 5> The energy consumption for the path length

The last simulation shows the impact of changing the average energy consumption according to the channel error rate. For this simulation, the end-to-end hop distance is set uniformly to 15 hops. The communication channel error rate is increased from 5% to 9. 5%. Figure 6 shows the average energy consumed for redundancy forwarding over single path, simultaneous transmit over the multipath and interactive multipath forwarding at desired reliability of 80% and 90% respectively. In this simulation, the proposed method shows the stable average energy consumption for the increasing channel error rate. Therefore, the performance evaluation results, in common with the results of previous evaluation, are that IMRP provides more energy-efficient routing than other protocols in poor wireless channel environment.



<Figure 6> The energy consumption for the channel state

Consequentially, we have verified a superior routing performance of IMRP through above performance evaluation. IMRP provides the energy efficient as well as reliable data forwarding than other routing techniques due to the fact that IMRP does not require the additional paths or the additional redundant forwarding that could be increased exponentially in the average energy consumption, even if the error and hop distance is increased.

Ⅳ. CONCLUSION

This paper proposes an interactive multipath routing protocol in order to solve the energy-inefficiency of the traditional multipath routing protocols. In the proposed protocol, the bridge nodes for communication between the paths are used in order to increase the routing performance of the radio disjoint multipath. By the bridge nodes, we could achieve the desired reliability, reducing the number of paths. In the protocol, reducing the number of paths makes the energy consumption more efficient than the existing protocols. We consider the environment where it is difficult to establish the multiple paths. In the environment, we guarantee the desired reliability by the incomplete and radio-disjoint sub-path. The protocol operates the path management based on local decision with the learning-based path information. For learning this information, the forwarding nodes on the multipath share the routing metrics; check the status of each path; modify or re-configure the multipath. The proposed path management helps to provide the reliable and stable routing performance. As a result, the proposed protocol could guarantee the packet transmission rate required by applications, as well as provide energy-efficient multipath routing in irregular network environment. Therefore, the proposed protocol can be useful on the variety of applications ranging from military to industry. However, the proposed method should be further studied in order to overcome protocol's weakness and compensate for practicality. The simulation results show that our protocol is superior to the existing studies.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, Vol. 38, No. 4, 2002, pp. 393-422.

[2] M. Radi, B. Dezfouli, K. Abu Bakar, and M. Lee, "Multipath Routing in Wireless Sensor Networks: Survey and Research Challenges," *Sensors*, Vol. 12, No. 1, Basel, Switzerland, 2012, pp. 650-658.

[3] Douglas S. J. De Couto, D. Aguayo, J. Bicket, R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wireless Networks*, Vol. 11, No. 4, 2005, pp. 419-434.

[4] Deb, Budhaditya, Sudeept Bhatnagar, and Badri Nath, "ReInForM: Reliable information forwarding using multiple paths in sensor networks," Local Computer Networks, IEEE, 2003, pp. 406-415.

[5] Wang, Zijian, Eyuphan Bulut, and Boleslaw K. Szymanski, "Energy efficient collision aware multipath routing for wireless sensor networks," ICC'09. International Communications Conference on. IEEE, 2009, pp. 1-5.

[6] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks," Proceedings of the 6th annual international conference on Mobile computing and networking. ACM, 2000, pp. 55-67.

[7] Scalable Network Technologies, Qualnet, Retrieved Oct., 30, 2013, http://www. scalable-networks. com.

[8] V. Shnayder, M. Hempstead, M. -R. Chen, G. W. Allen, and M. Welsh, "Simulating the power consumption of large-scale sensor network applications," in Proc. ACM Embedded Networked Sensor Syst. (SenSys), Baltimore, U. S. A, 2004, pp. 188-200.

[9] IEEE, Wireless LAN Medium Access Protocol (MAC) and Physical Layer (PHY) Specification, IEEE Std. 2012, 802.11-2012.

[10] H. Yang, "A Study on Share Group Configuration Technique for Improving Data Transmission Performance," *Journal of Korea society of digital industry and information management*, Vol. 11, No. 1, 2015, pp. 89-96.

[11] J. S. Kim, "A New Scheme for Maximizing Network Lifetime in Wireless Sensor Networks," *Journal of Korea society of digital industry and information management*, Vol. 10, No. 2, 2014, pp. 47-59.

■ 저자소개 ■

정 관 수
(Jung Kwansoo)

2015년 2월 충남대학교 컴퓨터과학과
(공학박사)
2007년 2월 충남대학교 컴퓨터공학과
(공학석사)
2005년 2월 충남대학교 컴퓨터공학과(공학사)

관심분야 : 5G, D2D, WSN, Routing, Security.
E-mail : ksjung79@gmail.com

논문접수일: 2015년 8월 27일
수 정 일: 2015년 9월 5일
게재확정일: 2015년 9월 8일