

An Optimum Relay Sensor Placement Technique to Enhance the Connectivity of Wireless Sensor Network

Arifuzzaman Mohammad, Keping Yu, Sato Takuro

Abstract—In this paper, we have presented a novel algorithm of sensor deployment for re-establishing the connectivity of a disconnected sensor network. We also address the way of achieving k -connectivity which can provide the sensor network with some level of fault tolerance. We combine the concept of Voronoi diagram, Delaunay triangulation, Spanning tree and Steiner heuristic in order to achieve optimum solution. Our proposed algorithm can find optimum number of required relay sensors with reasonable running time complexity. The algorithm also finds the position where the relay nodes are to be place for repairing or enhancing the connectivity. The performance and complexity of our proposed algorithm are also analysed which is incorporate our simulation result.

Index Terms— Wireless sensor network; Relay sensor; Network connectivity; Steiner heuristic; Voronoi diagram; Delaunay triangulation;

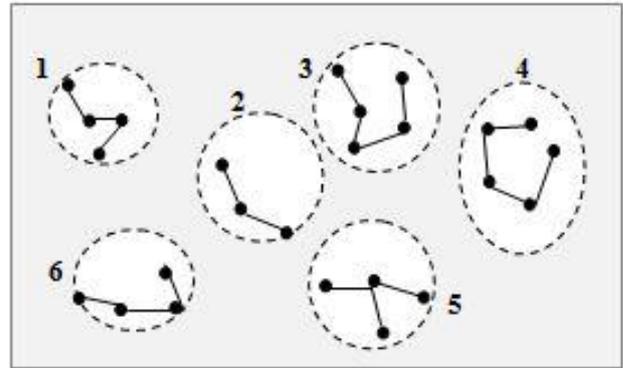


Figure 1. Disconnected components of sensor networks

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are emerging areas of research due to its wide range of applications in the last few years. Some of the applications are healthcare, fire detection in the forest and other commercial or military applications. WSN consists of a large number of wireless sensor nodes. The sensor nodes are typically small, and equipped with low-powered battery. Unlike other wireless networks, it is generally impractical to charge or replace the exhausted battery. Since prolonging lifetime of the sensor nodes is very important, energy efficiency becomes the most important attribute for WSNs [1]-[5]. Most of the cases, the sensor nodes are deployed randomly, therefore the networks might suffer from communication gaps in the deployed area, even in a high density networks. A group of sensors may also be damaged due to some external reasons which will create holes i.e. regions without enough sensor nodes. For these reasons the connectivity of the network can be decreased Unpredictable failure or run out of battery of sensor nodes also results disrupted connectivity. Figure 1 shows an example of disconnected sensor network, which consists of 6 components. Each circle represents a disconnected component of the network, within which sensor nodes are connected to each other. The sensor nodes are represented by dark dots and the transmission links are represented by line segments.

Additional deployment of sensor nodes, we call it relay nodes in this paper can heal the disconnected network. Again sometimes a certain level of connectivity is desired rather than merely connected one. Because such network has the desirable property that the losses of any single node or even some nodes will not partition the network. Furthermore, it affords multiple path redundancy between every pair of nodes enabling fault tolerance, load balancing or both. In this paper, we elaborate the technique for connecting a disconnected network which we call as 1-connectivity repair. We also propose a technique for making a k -connected network which we call as k -connectivity repair. The rest of the paper is organized as follows. Section II reviews the related works. In Section III, we will define the different terminology used in this paper and we will formulate the problems with necessary assumptions. In section IV, we will elaborate our proposed Optimum relay sensor placement algorithm (ORSP). Necessary calculations for the required relay node count and complexity of the algorithm are also analyzed in this section. In section V, we will describe our simulation results. And finally, we will conclude our paper in section VI with mentioning some guideline of the scope of future works.

II. RELATED WORK

As the connectivity is a major issue for throughput, delay and power consumption, so one critical mission is to find efficient algorithm for re-establishing a certain level of connectivity of sensor network. Understanding the importance of this particular issue, several researches have been conducted on this area in the recent years. Changing the communication radius of sensor nodes to improve connectivity is proposed in [6].

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* Correspondence Author (s)

Arifuzzaman Mohammad, is with the Graduate School of Global Information and Telecommunication Studies, Waseda University, Tokyo, Japan.

Keping Yu, is with the Graduate School of Global Information and Telecommunication Studies, Waseda University, Tokyo, Japan.

Takuro Sato, he is with the Graduate School of Global Information and Telecommunication Studies, Waseda University, Tokyo, Japan.

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In [7], the authors present algorithms for determining the critical transmission range for connectivity. In [8], approximation algorithm to place relay nodes to make the relay node network bi-connected is presented. The problem of exploiting the intersection between communication ranges to reduce the number of additional nodes needed to repair k -connectivity is studied in [9] and the authors proposed k -connectivity repair algorithms. In [10] Minimum Spanning Tree (MST) algorithm and Greedy Algorithm are proposed to improve the connectivity of Ad-Hoc network. In [11], authors propose an optimized relay node placement algorithm using a minimum Steiner tree on the convex hull. The algorithm identifies Steiner points in which relays are populated such that the segments can be connected with minimum number of relay nodes. The relay nodes deployment strategy of the algorithm is inwards from the periphery of the area identified by the convex hull. In [12], authors present a novel three-step algorithm (heuristics) which is based on steinerizing appropriate triangles. Each segment is represented by a terminal. Each subset of 3 terminals forms a triangle. Then authors simplified the problem as finding the optimal solution for a triangle. In [13], authors study the Steiner tree problem with minimum number of Steiner points and bounded edge-length, which asks for a tree interconnecting a given set of n terminal points and a minimum number of Steiner points such that the Euclidean length of each edge is no more than a given positive constant. Authors prove that this problem is NP-complete and present a polynomial time approximation algorithm. In [14], finding a Steiner tree that interconnects terminals (for n terminals in the Euclidean plane and a positive constant) with the minimum number of Steiner points such that the Euclidean length of each edge is no more than the given positive constant is studied. Authors found that the minimum spanning tree yields a polynomial-time approximation with performance ratio exactly 4. Besides the authors showed that there exists a polynomial time approximation with performance ratio 3, and there exists a polynomial-time approximation scheme under certain conditions. In [15], two versions of relay node placement problems are studied and polynomial time approximation algorithms are presented for each case. In the first version, authors consider the deployment of the minimum number of relay nodes so that, between each pair of sensor nodes, there is a connecting path consisting of relay and/or sensor nodes. In the second version, authors consider the deployment of the minimum number of relay nodes so that, between each pair of sensor nodes, there is a connecting path consisting solely of relay nodes. In [16], authors focus on network topology management techniques for tolerating/handling node failures in WSNs. Authors identified two broad categories of the existing techniques for restoring the overall network connectivity based on reactive and proactive methods. The problem of deploying or repairing a sensor network to guarantee a specified level of multipath connectivity (k -connectivity) between all nodes is considered in [17]. Authors design (and also analyze) the algorithms that place an almost-minimum number of additional sensors to augment an existing network into a k -connected network, for any desired parameter k . In [18] a relay sensor placement algorithm in order to maintain the connectivity of the network is proposed as the Steiner Minimum Tree with Minimum Number of Steiner Points (SMT-MSP). But the time complexity of the SMT-MSP algorithm is $O(n^3)$. In our previous work [19], we proposed an algorithm for connecting a Disconnected Sensor Network

with Deploying Additional Sensor Nodes. However, we didn't address the k -connectivity problem.

III. PRELIMINARY & PROBLEM FORMULATION

A. Problem Definition

Let the sensing area is in two dimension space, where the initially deployed sensor nodes, have been placed and a set of relay sensors are available to be added for connectivity enhancement of the network. Now the network is given as a set of locations of V , sensor nodes and transmission range R . Together these we get the network topology as an undirected graph, $G(V,E)$, where V is the set of vertices (set of sensor nodes) and E is the set of undirected edges (communication links). At this stage, we are ready to define following two problems.

Problem 1. We have to find a set of locations to place additional sensor nodes, i.e., relay nodes N with minimum cardinality such that the resulting graph becomes connected.

Problem 2. We have to find a set of locations to place relay nodes, N with minimum cardinality such that the resulting graph becomes k -connected.

B. Definitions

Definition #1: A component is a set of sensor nodes $C \subseteq V$ in a wireless sensor network iff for any two arbitrary subsets $C_1, C_2 \subseteq C$ and $C_1 \cup C_2 = C$ there exists at least one pair of nodes (u, v) , where $u \in C_1$, and $v \in C_2$ such that u is inside the communication range of v and v is also inside the communication range of u .

Definition #2: k -connectivity means, there exists at least k -node disjoint paths between every pair of nodes or, equivalently, there are no $k-1$ nodes whose failure would disconnect the network.

Definition #3: In a given triangle ΔABC with all angles less than $\frac{2\pi}{3}$, Torricelli point is the point, F which minimizes the sum of distances from A , B , and C .

C. Assumptions

As we take similar assumptions as stated in [9]. The assumptions are as follows:

- All sensor nodes have the same communication radius R . The nodes that we will deploy i.e., relay nodes also have the same communication radius R .
- Communication range and transmission range are same for all sensor nodes.
- Two nodes can communicate with each other, if they are within their mutual transmission range, R .
- The location of the all sensor nodes are recorded to a central server where computations take place.

IV. OPTIMUM RELAY SENSOR PLACEMENT ALGORITHM (ORSP)

A. Explanation of the Algorithm ORSP for 1-Connectivity Repair

Our proposed ORSP algorithm counts the number of the required relay sensor nodes and finds the position of their future placement in two steps.

In first step, the algorithm constructs the Voronoi diagram with considering each component as a vertex. The distance between two components is considered as the shortest distance. And by traversing the Voronoi edges each time the algorithm look for whether there exists any three neighbor components which can be connected by deploying a single sensor node. If such point is found then the node count is increased by one. And the intersection point of three edges is selected as the position for future sensor deployment. When no other such neighbor components exists then, algorithm *Voronoi_Count* of ORSP gives the remaining task of finding the position of placement of relay nodes and calculating the number of relay nodes to connect the sensor network to the algorithm *Delaunay_Count*. Then each time three component become connected by either in minimum Spanning tree fashion or exploiting the idea of Steiner tree for three points and the optimum one is chosen. Consequently, our ORSP algorithm minimizes the number of required relay sensors nodes for future deployment. The process is explained in Figure 2.

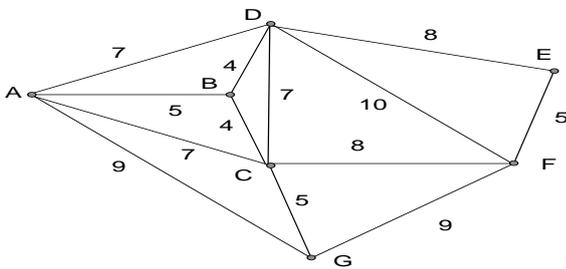


Figure 2. (a)

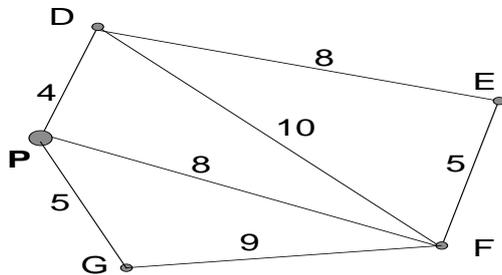


Figure 2. (b)

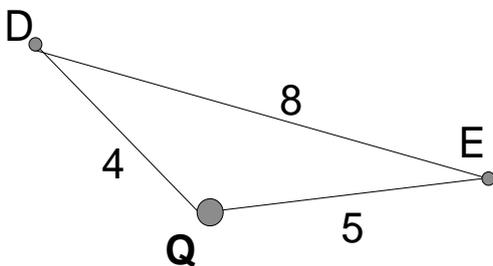


Figure 2. (c)

Figure 2. The Delaunay triangulation of 7 components (A, B, C, D, E, F, G) and the steps of the algorithm *Delaunay_Count* are realized. After merging the 3 component A, B, and C of figure (a) we get component, P of figure (b). And by merging components P, G, and F of

figure (b), component Q of figure (c) is generated. Each time the distance between components are recalculated. In figure 2 (a), we consider each disconnected component of a sensor network as a vertex. We assume there are 7 disconnected components (hence 7 vertices) namely A, B, C, D, E, F, G. The weight of edge of the graph between two vertices represents the unit of distance. For example, the distance between the component A and B is 5 units. Similarly, distance between A and D is 7. Now let us take the triangle ABC. From the triangle ABC, the shortest distance to the vertices D, G and F are 4, 5 and 8 respectively. Now let us contract the triangle ABC to a vertex P. So, in the new graph (Figure 2 b) the triangle ABC will be replaced by the point P and the distance from P to the vertices D, G and F will be 4, 5 and 8 respectively. In the next step, the triangle PGF is contracted to a single vertex Q. Between Triangle PGF and the point D there are two edges; one with weight 4 (edge PD) and the other with weight 10 (edge FD). So from Q to the D the distance will be 4 (in the graph 2c). Similarly distance from Q to the E will be 5 (in the graph 2c).

B. Explanation of the Algorithm ORSP for k-Connectivity Repair

B.1. Intra Component k-connectivity repair

Within a component for establishing k-connectivity we follow the algorithm to establish k-connectivity based on finding the minimum k-connected sub-graph [17]. We add relay nodes on the position of the already deployed sensor nodes in order to augment connectivity for achieving k-connectivity with in a component.

B.2. Inter Component k-connectivity repair

Algorithm *Add_Relay_Sensor* describes how we repair 1-connectivity of a disconnected sensor network. After running the algorithm if we place more (k-1) relay sensors on the same positions that found by the algorithm, then the inter component k-connectivity is established. We can also do it by directly placing k relay sensor nodes instead of the 1 relay sensor for achieving k-connectivity during execution of *Add_Relay_Sensor* algorithm.

Algorithm Add_Relay_Sensor (Graph S)

[S: a Set of sensor nodes after deployment]

1. Construct a graph V where each vertex of V corresponds to a disconnected component of S
2. *Voronoi_Count*(V)
3. *Delaunay_Count*(V)
4. $Total_relaynodes_needed = v_node_count + d_node_count$

Algorithm Voronoi_Count (Graph S)

1. Compute the component of S.
2. If component == 1, return v_node_count
3. Construct graph V where each vertex of V corresponds to a component of S
4. Construct Voronoi diagram of V and Put the weight of the edges of the Voronoi diagram as distance of two component by which the edge was constructed.
5. Traverse each edges of the Voronoi diagram and Find the intersection point, P of edges whose distance ≤ R from at least 3 components
6. If no such point found return v_node_count
 Else Put a relay node on the point, P
 Merge the three component to one,
 v_node_count= (v_node_count++) +
 Voronoi_Count (V)

Algorithm Delaunay_Count (Graph S)

1. Compute the connected component of S.
2. If component == 1 return d_node_count
3. Construct graph V where each vertex of V corresponds to a component of S
4. Construct Delaunay triangulation of V and Put the weight of the triangle edge (as the minimum distance of two component by which the edge was constructed.)
5. Take a triangle which is constructed in step 4.
6. If there is no angle ≥ 120 degree
 d_node_count = d_node_count + (l₁ + l₂ + l₃)/R
 [line l₁, l₂ and l₃ connect the Torricelli point of triangle with the vertices of the triangle]
 Put relay nodes on the line l₁, l₂ and l₃
 Else d_node_count = d_node_count + (e₁ + e₂)/R
 [e₁, e₂ and e₃ are edges of triangle, provided that e₃ > e₁ & e₃ > e₂]
 Put relay nodes on the line e₁, and e₂
7. Merge the three vertices of triangle i.e., three components, in order to form one component.
8. Update the weight of edges of the corresponding Delaunay triangle
9. Delaunay_Count(V)

B.3. Mathematical Analysis for counting the required Relay nodes

Let, total number of disconnected components in the sensor network is n and there are r components every three of which can be connected by a single sensor node. Therefore, by placing one sensor node the number of disconnected components from r will be decreased to r/3. So, it can be easily shown that the number of disconnected components, r will be decreased with the placement of relay nodes and it will be in the fashion of the following series:

$$\frac{r}{3} + \frac{r}{3^2} + \frac{r}{3^3} + \frac{r}{3^4} + \dots \text{-----} (I)$$

So, number of nodes found by Algorithm Vornoi_Count

$$= \frac{n \times \frac{1}{3} \times \left\{ 1 - \left(\frac{1}{3} \right)^{\log_3 r} \right\}}{1 - \frac{1}{3}}$$

$$= \left[\frac{n}{2} \times \left(1 - 3^{-\lceil \log_3 r \rceil} \right) \right] \text{-----} (II)$$

Now, If there are r' components, r' of which are such that every three of them can be connected by adding relay sensor nodes through the lines connecting to the Torricelli point and the vertices of the triangle. And let, the remaining disconnected components are r'₂, every three of which are connected by placing the relay nodes on the line of minimum spanning tree edges. Therefore,

Delaunay_Count

$$= \sum \frac{\text{distance of torricelli point of } \Delta, \text{ from each corner}}{R}$$

$$+ \sum \frac{\text{Length of MST}}{R} \text{-----} (III)$$

So, by summing up the equation (II) and (III) we get the total number of relay nodes required to be deployed for connecting the disconnected sensor network. We can calculate the number of required relay nodes for achieving k-connectivity in the similar fashion by using the concept described in section 4.2.1 and 4.2.2 of this paper.

B.4. Complexity of the proposed Algorithm

The best known complexity for the generation of the Voronoi diagram or Delaunay triangle is O(n log n). The conversion of graphs and weight assignments can be accomplished in O(n) time. But we use the O(n) repetition in our algorithm. So the overall running time or complexity of our proposed algorithm is O(n²).

V. RESULTS AND DISCUSSION

In this section, the numerical results of our proposed algorithm ORSP for 1-connectivity, 2-connectivity and 3-connectivity repair have been shown. We compare the efficiency of our proposed ORSP algorithm against two other algorithms namely Greedy Minimum Spanning Tree, G-MST(k) algorithm presented in [9] and the algorithm to establish k-connectivity based on finding the minimum k-connected sub graph proposed in [17]. And for the case of 1-connectivity we consider Minimum Spanning Tree algorithm as well. We use cost per node as the performance metric to evaluate our proposed ORSP algorithm. The cost per node defined as the number of relay nodes added divides by number of original sensor nodes.



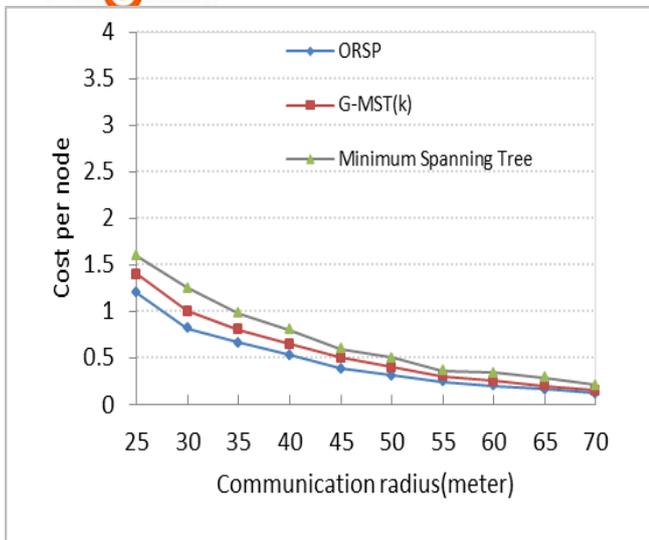


Figure 3. (a) The Average Cost per Node for 1-Connectivity Repair

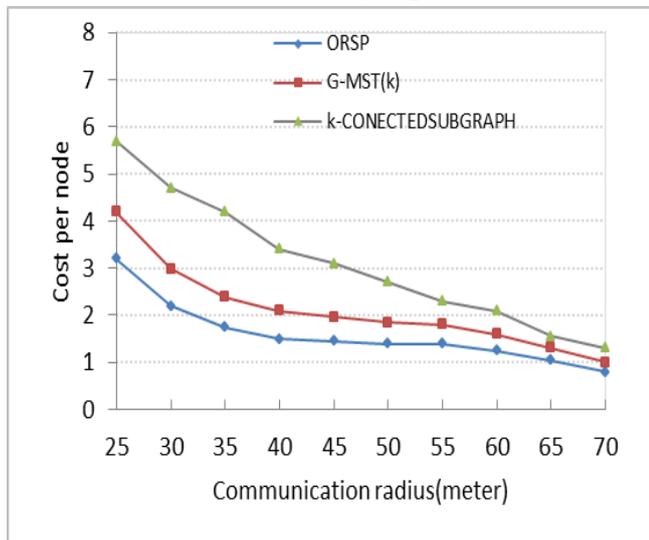


Figure 3. (b) The Average Cost per Node for 2-Connectivity Repair

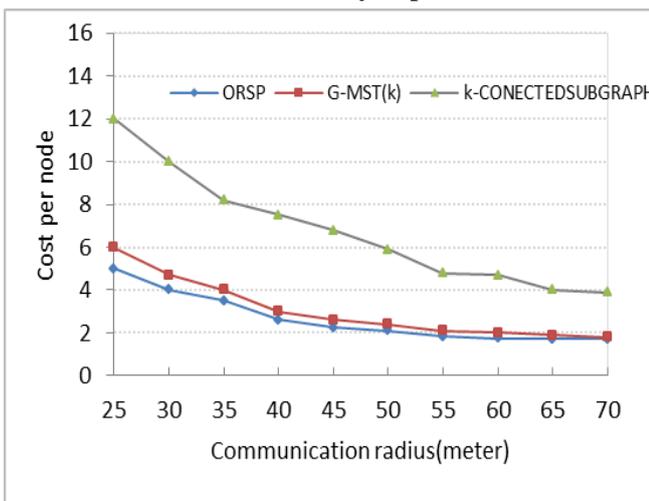


Figure 3. (c) The Average Cost per Node for 3-Connectivity Repair

In Figure 3(a), (b) and (c) we see that the performance of ORSP algorithm is better than other two existing algorithm. It is because, our proposed ORSP algorithm minimizing the required relay nodes by considering coinciding corners of the Voronoi cells, the minimum spanning tree edge and the lines connecting the vertices of the Delaunay triangle through the

Torricelli points and take the optimum value. The time complexity of our proposed algorithm is $O(n^2)$. The time complexity of the Minimum Spanning Tree algorithm is $O(n \log n)$ and for the case of Greedy algorithm the complexity is $O(n^2)$. Here n , represents the number of sensor nodes that are already deployed. So with a reasonable running time our proposed algorithm can minimize the number of required relay sensor nodes for enhancing the connectivity of sensor network.

VI. CONCLUSION AND FUTURE WORK

We have developed a novel Optimum relay sensor placement algorithm (ORSP) for enhancing the connectivity of wireless sensor network by deploying additional relay sensors. With a reasonable complexity our algorithm can be used for re-establishing the connectivity of a disconnected sensor network provided that the sensor nodes are homogenous in terms of transmission radii. The algorithm is also applicable for achieving higher level of connectivity to support fault tolerance of the network. As a future work, the problem of deploying optimum relay sensor nodes for achieving higher level of network connectivity will be studied for the heterogeneous sensor networks, where sensor nodes possess different transmission radii. There is also scope of considering the three dimensional scenarios for the similar problem. Besides, since the connectivity and the coverage are much related issue, the concept of this paper of connectivity can be enhanced to apply in the coverage problem of sensor networks.

VII. ACKNOWLEDGEMENT

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Mohammad Arifuzzaman, received the B.Sc. degree in Computer Science & Engineering from Bangladesh University of Engineering and Technology (BUET) in 2001. He worked as an Assistant professor at IBAIS University, Dhaka, Bangladesh from 2001 to 2005. After that he joined in the Bangladesh Civil Service in 2006 and worked as an Assistant secretary to the Government of the People's Republic of Bangladesh till 2010. He has completed Masters in Global Information and Telecommunication Studies from Waseda University, Tokyo, Japan in 2012. Now he is a PhD candidate at GITS of Waseda University. He received many awards including the best paper award in the ITU Kaleidoscope Conference, Cape Town, South Africa, 12-14 December 2011. His research interests lie in the area of Communication protocols, wireless ad-hoc and sensor networks, Next Generation Mobile communication systems and Future Internet Architecture. He is a student member of IEEE.



Keping Yu, was born in China, on January 1988. He received his B.E. and B.Admin. degree from Sichuan Normal University, Sichuan, China in 2010 and University of Electronic Science and Technology of China, Sichuan, China in 2010, respectively. He received his M.Sc. degree in Wireless Communication from Waseda University, Tokyo, Japan in 2012. Currently, he is a Ph.D. candidate at Graduate School of Global Information and Telecommunication Studies (GITS), Waseda University, Tokyo, Japan. He is a student member of IEEE. His research interests include smart grid, content-centric networking and their information security.



Takuro Sato, received the B.E. and Ph.D. degrees in Electronics Engineering from Niigata University in 1973 and 1993 respectively. He joined the Research and Development Laboratories of OKI Electric Industry Co., Ltd., Tokyo, Japan in 1973 and he has been engaged in research on PCM transmission equipment, mobile communications, data transmission technology and digital signal processing technology. He developed wideband CDMA system for personal communications system and joined the PCS standardization committee in

USA and Japan. He contributed in high speed cellular modem standardization for ITU, 2.4GHz PCS standardization for ITA and wireless LAN standardization for IEEE 802.11. He was a Senior Research Manager and Research Director in Communication Systems Laboratory of OKI Electric Industry Co., Ltd. He served as a professor of Niigata Institute of Technology from 1995 and he researched on CDMA, OFDM, personal communication systems and related area. In 2004, he joined as a professor of GITS at Waseda University and currently serving as a Dean of the Graduate School of Global Information and Telecommunication Studies (GITS), Waseda University. His current research interests include Wireless Sensor Network, Mobile IP Network, ICT in Smart Grid, 4G mobile communication systems. He is senior member of IEICE and IEEE Fellow.