MA-LTRT : A Novel Method to Improve Network Connectivity and Power Consumption in Mobile Ad-hoc based Cyber-Physical Systems

---

Citation:

Yuichi Kawamoto, Hiroki Nishiyama, and Nei Kato, "MA-LTRT : A Novel Method to Improve Network Connectivity and Power Consumption in Mobile Ad-hoc based Cyber-Physical Systems," IEEE Transactions on Emerging Topics in Computing (TETC), vol. 1, no. 2, pp. 366-374, Dec. 2013.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6581865

MA-LTRT : A Novel Method to Improve Network Connectivity and Power Consumption in Mobile Ad-hoc based Cyber-Physical Systems

Yuichi Kawamoto, Hiroki Nishiyama, and Nei Kato
Graduate School of Information Sciences, Tohoku University, Sendai, Japan
E-mails: {youpsan, bigtree, and kato}@it.ecei.tohoku.ac.jp

Abstract—**Recently, the development in wireless devices has made it possible to connect numerous devices by constructing networks only amongst themselves. Cyber-Physical Systems (CPSs) are likely to emerge through such network environments to connect both humans and machines so that a "smart society" can evolve with remarkably convenient and yet foreseen pervasive communication. However, it is difficult to establish adequate network infrastructures anywhere and anytime. Therefore, a critical research issue is to formulate an effective method for constructing networks. To address this issue, we focus on mobile ad-hoc based CPSs, which is a network system consisting of mobile devices. Since it does not require any specific facility, the mobile ad-hoc based CPS may be considered to be a good candidate for realizing next generation CPSs. However, it presents two major research challenges, namely the difficulty to maintain high connectivity in the network constructed by only mobile nodes, and the need to reduce the power consumption of the nodes. For addressing these two challenges in the mobile ad-hoc based CPS, we propose a novel method called "Mobility Aware, Local Tree-based Reliable Topology" to construct the network with adequate network connectivity while ensuring a low level of power consumption.**

Index Terms—**Cyber-Physical Systems (CPSs), Mobile Ad-hoc based CPS, power consumption, and network connections redundancy.**

I. Introduction

In recent years, the concept of Cyber-Physical Systems (CPSs) has attracted a great deal of attention from researchers because they present an effective model to improve the interaction among different entities such as human-to-human, human-to-machine, and machine-to-machine communication [1]- [3]. The CPSs consist of networking equipment and machines such as sensors, smart phones, robots, and other wireless mobile devices [4]. Also, the vehicular CPS [5], [6] and ad-hoc based CPS [7] have emerged recently that exploit smart wireless devices. Researchers have shown that the utilization of both the cyber and physical components of a CPS can be improved in a synergistic manner by connecting these wireless devices with each other. The current trend also indicates that there is a wide spread of wireless devices, which also have mobility feature, to construct the CPSs. Therefore, it is essential to consider such CPS networks, which are often constructed by the ad-hoc connections amongst the mobile wireless devices. Hence, the focus of our paper is upon the mobile ad-hoc based CPSs.

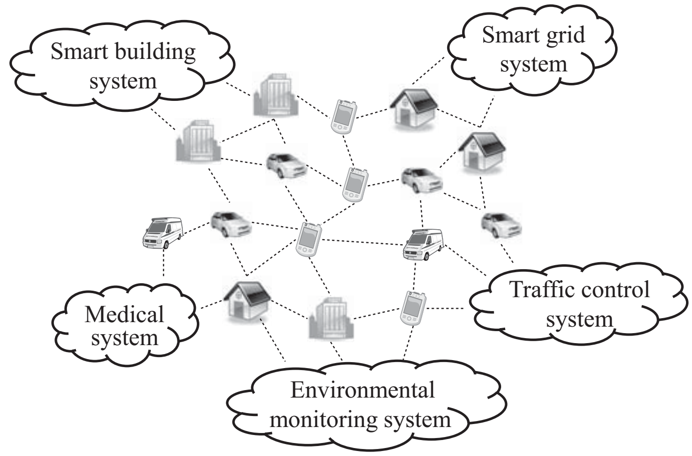

Fig. 1. An example of architecture of mobile ad-hoc based CPS

Fig. 1 depicts an example architecture of a mobile ad-hoc based CPS. In the mobile ad-hoc based CPS, wireless mobile devices are connected with one another to construct temporary communication networks. Note that these temporary networks could be connected with a number of different systems such as smart grid system, traffic control system, environmental monitoring system, medical system, and smart building system. By connecting the systems and the temporary networks, it becomes possible to achieve a more efficient connectivity between cyber and physical components of a CPS. However, since the network resources of the devices (e.g., battery life and bandwidth) are limited, it may be difficult to connect all the concerned devices at the same time [8]. Also, the power consumption of each device is a critical issues [9]. Furthermore, the mobility of the devices leads to network performance degradation since it is impossible to keep the fixed state (i.e., the same topology) of the network [10]. Therefore, an effective technique to control the mobile ad-hoc network topology (of the considered CPS) is imperative.

In the previously conducted research works, a number of topology control algorithms such as Local Minimum Spanning Tree (LMST) and Local Tree-based Reliable Topology (LTRT) were developed for Wireless Sensor Networks (WSNs). Although they exhibit certain advantages when used in fixed networks such as WSNs, their performance degrades substantially in scenarios involving moving nodes. This performance degradation occurs due to the fact that the network might be disconnected even if only a single link is broken. For use in mobile ad-hoc networks, the research conducted in [11] and [12] added improvements to the original LTRT method. Indeed, the improved version of LTRT could provide reliable communication in the mobile ad-hoc networks to an extent as it preserves a certain level of redundancy of network connectivity. However, in order to ensure high connectivity, it may often need reconstruction of topology in the situation where the mobility of nodes in the network is significantly high, which causes high power consumption. Hence, an adequate method, to set the interval of topology reconstruction to decrease power consumption while keeping a certain level of network redundancy, becomes essential. Therefore, in our paper, we analyze the impact of the interval of topology control and network redundancy on power consumption in the mobile ad-hoc based CPS by using the improved LTRT. In our analysis, the existence of optimal topology control interval and network redundancy are confirmed, respectively. Moreover, we propose an algorithm to adequately set the above mentioned parameters of the topology control method.

The remainder of this paper is organized as follows. The assumed network model and the way of topology control are introduced in Section II. In addition, the existing topology control methods and their shortcomings are presented in this section. Section III shows our proposed topology control method known as "Mobility Aware LTRT" (MA-LTRT). Additionally, some analyses on power consumption in mobile ad-hoc based CPS are also described in this section. In Section IV, we provide numerical results to verify the effectiveness of our proposed method. Finally, concluding remarks are presented in Section V.

II. An Overview of Topology control Methods

In this section, we introduce some of the topology control methods that exist in literature. In addition, we introduce the methodology of adopting an appropriate topology control for mobile ad-hoc networks based CPSs. Moreover, the shortcomings of these existing methods are delineated.

A. Existing topology control methods and their shortcomings

Topology control is a technique to reduce power consumption by removing redundant links and controlling the transmission range of each node in sensor or ad-hoc networks [13]- [16]. In the topology control method, at first, each node broadcasts a certain type of message called the *Hello Message* to neighboring nodes in its maximum transmission range. Each of the neighboring nodes, upon receiving the *Hello Message*, respond by returning the message including the node's information such as its position. Each node, after receiving these returned messages, decides the topology by using the neighbors' positions and reduces the transmission range according to the position of the farthest node in the topology. By reducing the transmission range, it achieves reduction in the power consumption and avoids interference. In the past, many topology control schemes were proposed in literature that aimed at determining the topology of the underlying network. Examples of prominent topology control methods include Cone-Based distributed Topology Control (CBTC), LMST, LTRT and so forth. Here, we introduce these prominent topology control methods, and also describe their shortcomings in case of applying them to the mobile ad-hoc networks based CPS.

CBTC is a topology control method which was developed by Li *et al.* [17]. In CBTC, each node sets its transmission range to connect its neighboring nodes, which are on the fan shaped area, having an angle of α [18]. In this method, each node can reduce its transmission range when the value of α is large because the probability that the neighboring node exists in the area increases with an increasing value of α. Additionally, it is proved that when $\alpha < 5\pi/6$, the network connectivity is ensured [19]. However, CBTC generates too many redundant links to construct the network topologies. As a consequence, this technique requires excessive power consumption.

On the other hand, LMST is the topology control method based on tree structure [20], [21]. In LMST, each node constructs the topology, which is based on the MST (Minimum Spanning Tree) [22] with the information from only the neighboring nodes that are one hop away. Each node calculates the MST by using the information including their position information, and uses the MST to construct topology. Although the topology made by this method is not entirely a tree structure, the topology becomes similar to the MST since it includes MST as a subgraph. However, since the topology, which is constructed by LMST, is a directed graph, additional messages are required to formulate the non-directed graph.

On the other hand, in LTRT [23], topologies are constructed based on LMST and Tree-based Reliable Topology (TRT) [24]. This method guarantees k-edge connectivity, i.e., the network connectivity cannot be lost if the number of broken links is smaller than k. Fig. 2 demonstrates an example whereby a node constructs a topology such that the redundancy of the topology is set to two in LTRT. In this method, the node broadcasts *Hello message* to all its neighboring nodes in its maximum transmission range that is the usual topology control. After that, by using the returned messages, the complete tree is constructed virtually. Fig. 2a shows the example of the complete tree constructed by six nodes. From the tree, the node chooses a first MST as shown in Fig. 2b, and stores the topology data at first. Secondly, the node chooses another MST from the tree such that the first MST is cut out from the complete tree. This is depicted in Fig. 2c. The second MST becomes totally different from the first one as described in Fig. 2d. In the case where the node constructs the topology having the redundancy equal to two, the links which were used in the first and the second MSTs, are utilized in the topology. Otherwise, the node repeats choosing different MSTs k times, and then decides the topology. After making the decision, the node adapts its transmission range to the furthest node in the topology. In this manner, the topology having the redundancy equal to k is constructed in LTRT. Since it is possible to control the value of k, it achieves an adequate tolerance to defection of nodes in the network.

As mentioned above, each method has its respective ad-

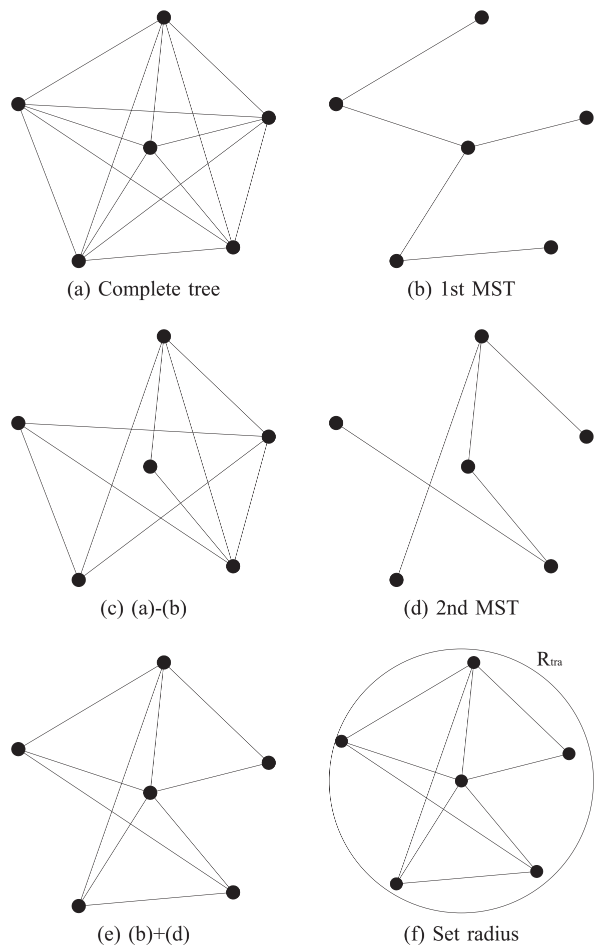

Fig. 2. An example of proceeding to construct a topology in LTRT

vantages. In particular, amongst the afore-mentioned methods, LTRT is considered as a good candidate to be utilized in the mobile ad-hoc based CPS, where each node moves randomly. The reason behind choosing LTRT for such a CPS is due to LTRT's ability to control "redundancy" (i.e., redundant network connectivity) adequately. Therefore, in the remainder of our paper, we focus on adapting LTRT to mobile ad-hoc networks by considering its redundancy.

B. Adapting topology control methods to mobile ad-hoc network based CPS

Since each node moves randomly in the mobile ad-hoc based CPS, the topologies need to have a certain level of redundancy to keep the connectivity. In [11], a method to dynamically change the value of k in LTRT to ensure high connectivity was proposed. In this method, each node chooses an appropriate value of k for each local graph based on local movements. As a result, it achieves a certain level of connectivity. However, since the topology reconstruction interval in the method is set to a constant value, the connectivity decreases dramatically when the average moving speed of nodes is high. For example, if the nodes near the edge of the transmission range of the center node C (which controls the topology) move in a direction away from C, they are not able to keep the connection with C any more. Furthermore, the power consumption of the nodes is not taken into account much in [11]. In the mobile ad-hoc network based CPS, the nodes may be quite small-sized and not equipped with large enough battery. Thus, the power consumption is a critical parameter, which requires careful consideration. Therefore, we analyze the impact of these parameters (i.e., both redundant network connections and power consumption) on the topology control in mobile ad-hoc network based CPS and propose a method to set them adequately.

III. Envisioned Mobile Aware LTRT (MA-LTRT) Method

In this section, we propose a new topology control method called Mobile Aware LTRT (MA-LTRT) to improve the connectivity in mobile ad-hoc network based CPS by dynamically using the redundant transmission range. Additionally, we analyze the relationship between the power consumption and reconstruction interval of topology with some mathematical expressions, and minimize the power consumption in the proposed MA-LTRT method by controlling the reconstruction interval of the topology. In addition, we consider LTRT to be the base policy to construct topology in our proposal.

A. Dynamic utilization of the redundant transmission range

In our proposed MA-LTRT, we aim at utilizing the redundant transmission range dynamically for topology control. As mentioned in the preceding section, the edge node of the transmission range of the center node which controls the topology results in the decrease of the connectivity in the mobile ad-hoc network based CPS. Thus, in this proposed MA-LTRT method, redundant transmission range is utilized to keep a certain level of redundancy of the topology. Fig. 3 demonstrates an example of the utilization of the redundant transmission range. Here, we define the maximum transmission range and the transmission range which is set by the basic LTRT as R_{max} and R_{tra}, respectively. In our proposal, we focus on moving of the center node which controls the topology and the edge node of the transmission range, and define the moving speed of these two nodes as v_{c} and v_{e}, respectively. To keep connectivity with the edge node at any time until the next reconstruction of the topology, the redundant transmission range is determined by considering the worst situation where the center and edge nodes move in the opposing directions. By considering the worst situation in determining the level of redundancy, the center node will be able to keep connection with the edge node regardless of the moving direction. Thus, we set the redundant transmission range, R_{red}, with the topology reconstruction interval, Δt, as follows.

$$R_{\mathrm{red}} = R_{\mathrm{tra}} + (v_{\mathrm{c}} + v_{\mathrm{e}}) \cdot \Delta t. \tag{1}$$

By using the redundant transmission range, it is possible to keep the link between the center and edge nodes of the transmission range during the time of the topology reconstruction interval. Thus, it improves the reliability to maintain the topology. From Eq. 1, it is understood that R_{red} is controlled by the value of Δt in this method because R_{tra}, v_{c}, and v_{e}

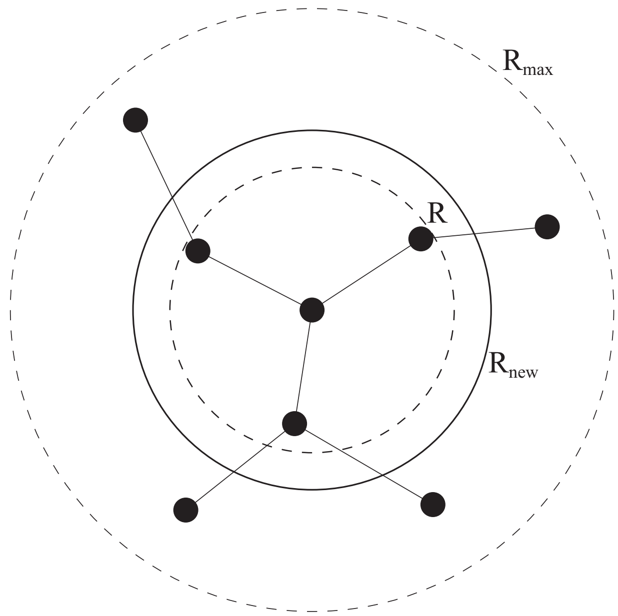

Fig. 3. Utilizing redundant transmission range.

are decided by the placement and moving speed of each node. Thus, it is needed to determine the value of Δt to utilize an adequate value of R_{red}.

B. Dynamic utilization of the topology reconstruction interval

In order to decide an adequate redundant transmission range, we focus on the relationship between the power consumption and topology reconstruction interval. If the interval is set to a small value, each node needs to broadcast the *Hello Message* quite frequently. Since the message is sent to the entire area covered by the maximum transmission range, the increase of number of times to send the message causes the increase of power consumption. On the other hand, from Eq. 1, a large value of Δt causes a large value of R_{red}. If the value of the redundant transmission range is set to a large value, each node sends its data to longer distance than the case where the value of redundant transmission range is set to small. It also causes the increase of power consumption. Thus, there is a trade-off relationship between the value of topology reconstruction interval and power consumption.

To analyze the afore-mentioned tradeoff relationship, we formulate the amount of power which is consumed when each node broadcasts the *Hello message* and sends data during the topology reconstruction interval, respectively. Here, we consider the power consumed for a certain period of time to measure the power consumption, T. Additionally, we define the power consumption to broadcast the *Hello message* during the time, T, as P_{hello}, and the power consumption to send data during the time, T, as P_{data}. Thus, in the case where the topology reconstruction is executed n times during the time, T, P_{hello} is formulated with the required power consumption to send a unit amount of data within the bound of maximum transmission range one time, p_{d}, and the data size of the *Hello message*, d_{hello}, as follows.

$$P_{\mathrm{hello}} = n \cdot p_{\mathrm{d}} \cdot d_{\mathrm{hello}}. \tag{2}$$

On the other hand, we define the average size of data which is sent during a topology reconstruction interval as d_{data}. Thus, since the power consumption decreases with the fourth order of the transmission range, the power consumption to send data during the topology control reconstruction interval during the time, T, is expressed as follows.

$$\begin{aligned} P_{\mathrm{data}} = \; & n \cdot \Delta t \cdot p_{\mathrm{d}} \cdot d_{\mathrm{data}} \\ & \cdot \left\{ \frac{R_{\mathrm{tra}} + (v_{\mathrm{c}} + v_{\mathrm{e}}) \cdot \Delta t}{R_{\max}} \right\}^4 . \end{aligned} \tag{3}$$

Therefore, the total power consumption, P_{total}, which is defined as the sum of P_{hello} and P_{data}, is expressed as follows.

$$P_{\mathrm{total}} = P_{\mathrm{hello}} + P_{\mathrm{data}}. \tag{4}$$

Additionally, the number of topology reconstruction during the time of T is expressed with the topology reconstruction interval and the time of T as follows.

$$n = \frac{T}{\Delta t}. \tag{5}$$

Therefore, from Eqs. 2, 3, 4, and 5, the total power consumption may be expressed as follows.

$$\begin{aligned} P_{\mathrm{total}} = \; & \frac{p_{\mathrm{d}} \cdot d_{\mathrm{hello}} \cdot T}{\Delta t} \\ + \; & p_{\mathrm{d}} \cdot d_{\mathrm{data}} \cdot T \cdot \left\{ \frac{R_{\mathrm{tra}} + (v_{\mathrm{c}} + v_{\mathrm{e}}) \cdot \Delta t}{R_{\max}} \right\}^4 . \end{aligned} \tag{6}$$

From the right side of Eq. 6, it is understood that the first term decreases and the second term increases with the increase of the topology reconstruction interval. Thus, P_{total} is considered to be a convex function of the interval. Therefore, there is an optimal number of the interval to minimize the power consumption. We define the optimal topology reconstruction interval as Δt_{opt}. Δt, which minimizes the right side of Eq. 6, is obtained when the differentiated equation of the right side of Eq. 6 equals zero. Thus, it is obtained as Δt which satisfies the next equation.

$$\frac{d}{d\Delta t} \left[\frac{d_{\mathrm{hello}}}{\Delta t} + d_{\mathrm{data}} \cdot \left\{ \frac{R_{\mathrm{tra}} + (v_{\mathrm{c}} + v_{\mathrm{e}}) \cdot \Delta t}{R_{\max}} \right\}^4 \right] = 0. \tag{7}$$

From Eq. 7, the optimal topology reconstruction interval to minimize the power consumption is expressed as follows.

$$\Delta t_{\mathrm{opt}} = \arg\min_{\Delta t} P_{\mathrm{total}}. \tag{8}$$

Therefore, from Eqs. 6 and 8, the power consumption, when the proposed method is utilized, is calculated as follows.

$$\begin{aligned} P_{\mathrm{opt}} = \; & \frac{p_{\mathrm{d}} \cdot d_{\mathrm{hello}} \cdot T}{\Delta t_{\mathrm{opt}}} \\ + \; & p_{\mathrm{d}} \cdot d_{\mathrm{data}} \cdot T \cdot \left\{ \frac{R_{\mathrm{tra}} + (v_{\mathrm{c}} + v_{\mathrm{e}}) \Delta t_{\mathrm{opt}}}{R_{\max}} \right\}^4 . \end{aligned} \tag{9}$$

TABLE I
A LIST OF NOTATIONS DEFINED AND USED IN OUR ANALYSIS.

R_{red}	Radius of redundant transmission range which is set by proposed method
R_{tra}	Radius of transmission range which is set by LTRT
$R_{\max}$	Radius of maximum transmission range
v_{c}	Moving speed of center node of its topology
v_{e}	Moving speed of edge node of its topology
Δt	Topology reconstruction interval
Δt_{opt}	Optimal value of topology reconstruction interval
P_{hello}	Power consumption to broadcast *Hello message* during the time T
P_{data}	Power consumption to send data during the time T
P_{total}	Total power consumption
P_{opt}	Optimal total power consumption
$P_{\max}$	Amount of energy consumption when all nodes utilize the maximum transmission range
p_{d}	Power consumption to send unit amount of data within the bound of maximum transmission range
n	Number of times to reconstruct topology during the time T
d_{hello}	Data size of *Hello message*
d_{data}	Average size of data which is sent during a topology reconstruction interval
T	Certain period of time to measure the power consumption

Algorithm 1 Algorithm to adapt proposed method

```
1: loop
2:     Calculate moving speed.
3:     Broadcast Hello message to the maximum transmission range.
4:     Construct topology using LTRT with a given value of k.
5:     Calculate Δt_opt by using Eq. 8.
6:     Calculate redundant transmission range by using Eq. 1.
7:     Set the transmission range to R_red.
8:     Keep the transmission range during the time equal to Δt_opt.
9: end loop
```

C. Algorithm to adapt the proposed MA-LTRT method

In the remainder of this section, we introduce an algorithm to apply our proposed MA-LTRT method to decide the redundant transmission range of each node. Algorithm 1 shows a flow, using which a node constructs the network topology. In other words, each node uses this algorithm to construct the topology. In our algorithm, at first, each node sends the Hello message including its moving speed and the position to the neighboring nodes in the area of its maximum transmission range. This part is similar to the existing topology control method (refer to the basic LTRT). Secondly, after receiving the returned message including the information of the node such as the position and the moving speed from the neighbors, the topology based on LTRT is constructed according to the neighbors' information with the given initial value of k.

After that, the optimal topology reconstruction interval and the redundant transmission range are calculated by using Eqs. 8 and 1, respectively. Then, each node sets its transmission range to R_{red}, and keeps the transmission range during the time equal to Δt_{opt}. All the notations used in our analysis are summarized in Table I.

IV. Performance Evaluation

In this section, we verify the correctness of our analysis and evaluate the proposed method with numerical calculation. In this evaluation, we confirm the relationship between the energy consumption and the topology reconstruction interval and the change of the interval when the average moving speed of the nodes changes. Additionally, the energy expanded ratio is measured to confirm the effectiveness of the proposed method. Moreover, we show the change of the average number of surrounding nodes within one node's transmission range to confirm the effectiveness of our proposed method in reducing the interference.

A. Parameter settings

The parameter settings of our considered numerical calculation environment are summarized in Table II. In this evaluation, 100 nodes are placed uniformly in an area of 1000m $\times$ 1000m and we set the certain period of time (to measure the power consumption) to 10,000s. Additionally, we

TABLE II
PARAMETER SETTINGS

Simulation area	1,000m × 1,000m
Number of nodes	100
Average transmission range	125m
Maximum transmission range	250m
Average moving speed	12.5m/s
Average size of data	3kB
Data size of *Hello message*	1kB

suppose that the average transmission range set by the basic LTRT and the maximum transmission range of a given node are set to 50m and 250m, respectively. Moreover, to evaluate normalized value of power consumption, we set the power consumption required to send a unit amount of data as 1 and the average size of data which is sent during a topology reconstruction interval as 3kB. Also, the data size of the *Hello message* is set to 1kB. Note that in our proposed method, $R_{\rm red}$ and $\Delta t_{\rm opt}$ can be calculated regardless of the given value of k. They only depend on moving speed of nodes and the transmission range calculated after applying the basic LTRT algorithm. Therefore, in order to evaluate the performance of our proposed method, we only take into account the average moving speed of nodes and the given average transmission range calculated after applying the basic LTRT algorithm..

B. Numerical results

At first, to confirm the correctness of our mathematical analysis, we evaluate the power consumption when the redundant transmission range is utilized by substituting some numerical values to Eq. 6. Fig. 4 demonstrates the change of the total power consumption when the topology reconstruction interval changes from 0s to 10s in the case where the average moving speed of nodes is different. From Fig. 4, it is understood that the total power consumption is a convex function of the topology reconstruction interval. Thus, we confirm that there is an optimal interval to minimize the power consumption.

Secondly, we confirm the change of the optimal topology reconstruction interval by using Eq. 8. Fig. 5 represents the change of the optimal topology reconstruction interval when the average moving speed of the nodes vary from 0m/s to 25m/s, and the average size of data which are sent during a topology reconstruction interval is different. From the result, we can see that the topology reconstruction interval should be set to a shorter value to minimize the power consumption when the average moving speed of the nodes is higher. Moreover, when the average size of data which are sent during a topology reconstruction interval is large, the optimal topology reconstruction interval becomes short. Moreover, when the average size of data which are sent during a topology reconstruction interval is set to a significantly large value, the optimal value of the topology reconstruction interval becomes short. This is because that the required power consumption to increase the transmission range becomes large when the value

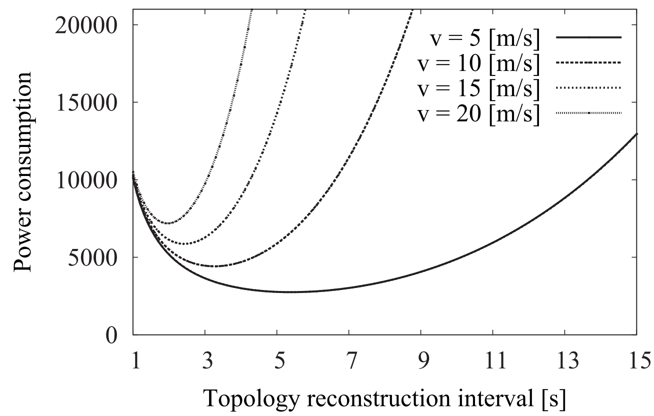

Fig. 4. The change of power consumption when the value of topology reconstruction interval changes in each case where the average moving speed is different.

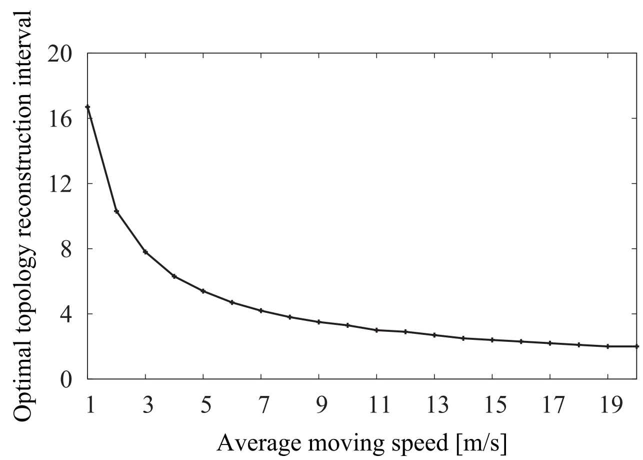

Fig. 5. The change of optimal topology reconstruction interval when the average moving speed changes.

of the average size of data which are sent during a topology reconstruction interval is set to large.

Thirdly, we evaluate the energy expanded ratio to confirm the effectiveness of our proposed MA-LTRT method. The energy expanded ratio is calculated as the fraction of the power consumption in two cases. The first is the case where our MA-LTRT method is applied. The second is the case where all the nodes utilize the maximum transmission range to send their data. We define this amount of power consumption when the maximum transmission range is utilized as $P_{\max}$. Thus, the energy expanded ratio, denoted by EER, is expressed as follows.

$$EER = \frac{P_{\rm opt}}{P_{\max}}. \tag{10}$$

On the other hand, the amount of power consumption when the maximum transmission range is utilized is expressed below.

$$P_{\max} = p_{\rm d} \cdot T \cdot (d_{\rm hello} + d_{\rm data}). \tag{11}$$

Therefore, the enegy expanded ratio is calculated by using

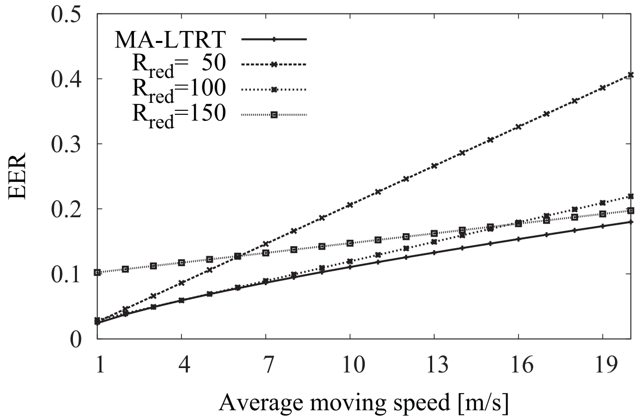

Fig. 6. The change in EER for different values of the average moving speed in case of the proposed MA-LTRT method and the basic LTRT method with different values of the redundant transmission range.

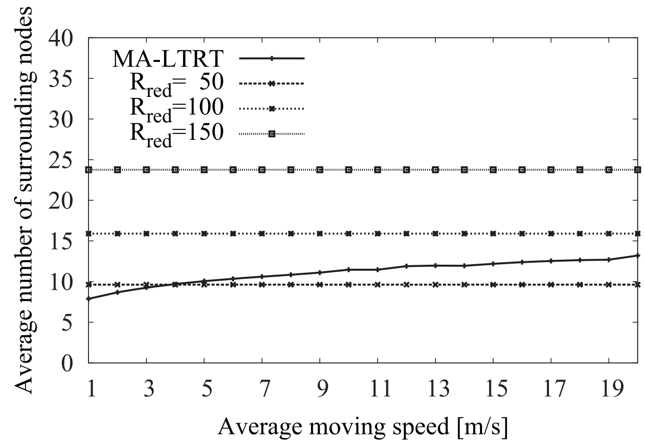

Fig. 7. The change in the average number of surrounding nodes within one node's transmission range with the different values of the average moving speed in case of the proposed MA-LTRT method and the basic LTRT method with different values of the redundant transmission range.

Eqs. 9, 10, and 11.

$$EER = \frac{1}{d_{\text{hello}} + d_{\text{data}}} \cdot \left[\frac{d_{\text{hello}}}{\Delta t_{\text{opt}}} + d_{\text{data}} \cdot \left\{ \frac{R_{\text{tra}} + (v_{\text{c}} + v_{\text{e}}) \cdot \Delta t_{\text{opt}}}{R_{\max}} \right\}^4 \right]. \quad (12)$$

Since $P_{\max}$ represents the maximum power consumption, EER always takes the value of from 0 to 1. Additionally, the lower value of EER shows the effectiveness of the proposed MA-LTRT method.

Fig. 6 demonstrates the change of the values of EER with the change of the average moving speed of the nodes while LTRT sets the transmission range to 50m, 100m, and 150m, respectively. From the obtained results, it is evident that the EER of our proposed MA-LTRT is always smaller than the other case where the redundant transmission range is different. It means that our MA-LTRT becomes successful in reducing the power consumption by setting an adequate transmission range.

Finally, in order to confirm the effectiveness of our proposed method in reducing the interference, we show the change of the average number of surrounding nodes within one node's transmission range when the average moving speed changes. The large number of nodes surrounding one node implies that the node causes interference to many other nodes. From Fig. 7, it is understood that our proposed method achieves lower interference than the basic LTRT method when the redundant transmission range is set to 100m or 150m. Additionally, although the number of surrounding nodes within one node's transmission range becomes higher when the redundant transmission range of the basic LTRT is set to 50m and the average transmission range is high, the power consumption in the case of the basic LTRT becomes drastically high at that time as shown in Fig. 6. Therefore, it can be considered that the proposed method MA-LTRT achieves lower power consumption and interference.

V. Conclusion

A technique to provide network environment anytime and anywhere is required to realize the next generation CPSs. However, existing network infrastructures are not adequate to provide the necessary CPS network environment due to the limitation of place and cost to prepare the infrastructure. To overcome this challenge, in this paper, we focused on mobile ad-hoc network based CPS as a method to connect many kinds of wireless mobile devices for facilitating the next generation CPSs. Since the mobile ad-hoc network based CPS consists of only mobile devices, they can construct network environment without special facilities. However, to construct a reliable network with mobile nodes is difficult, and the power consumption of the nodes is essential issue in the mobile ad-hoc network based CPS. Therefore, we proposed a mobility aware LTRT (MA-LTRT) method to construct the network with a certain level of redundancy and low power consumption. In our proposal, each node sets the reconstruction interval of its topology dynamically to increase the connectivity and to reduce the power consumption. Additionally, by controlling the redundancy of the topology, it also achieves to prevent ineffectual increase of the power consumption while keeping high network connectivity. Moreover, the results obtained from our conducted numerical calculation demonstrated the effectiveness of our proposed MA-LTRT method in terms of significant improvement in the network connectivity and power consumption.

References

[1] L. Shao-Yu, C. Shin-Ming, S. Sung-Yin, and C. Kwang-Cheng, "Radio Resource Management for QoS Guarantees in Cyber-Physical Systems," *Parallel and Distributed Systems, IEEE Transactions on,* vol. 23, no. 9, pp. 1752–1761, Sep. 2012.

[2] C. Xianghui, C. Peng, C. Jiming, S. Youxian, "An Online Optimization Approach for Control and Communication Codesign in Networked Cyber-Physical Systems," *Industrial Informatics, IEEE Transactions on,* vol. 9, no. 1, pp. 439–450, Feb. 2013.

[3] Q. Fengzhong, W. Fei-Yue, and Y. Liuqing, "Intelligent transportation spaces: vehicles, traffic, communications, and beyond," *Communications Magazine, IEEE,* vol. 48, no. 11, pp. 136–142, Nov. 2010.

[4] L. Husheng, L. Lifeng Lai, and H. V. Poor, "Multicast Routing for Decentralized Control of Cyber Physical Systems with an Application in Smart Grid," *Selected Areas in Communications, IEEE Journal on,* vol. 30, no. 6, pp. 1097–1107, Jul. 2012.

[5] L. Xu, Q. Chunming, Y. Xuegang, A. Wagh, R. Sudhaakar, and S. Addepalli, "Toward Effective Service Scheduling for Human Drivers in Vehicular Cyber-Physical Systems," *Parallel and Distributed Systems, IEEE Transactions on ,* vol. 23, no. 9, pp. 1775–1789, Sep. 2012.

[6] A. Miloslavov and M. Veeraraghavan, "Sensor Data Fusion Algorithms for Vehicular Cyber-Physical Systems," *Parallel and Distributed Systems, IEEE Transactions on,* vol. 23, no. 9, pp. 1762–1774, Sep. 2012.

[7] Li Xiaobo and Zhang Xu, "The Design of Simulation Platform for Ad Hoc Based Cyber-Physical System," *Mobile Ad-hoc and Sensor Networks (MSN), 2011 Seventh International Conference on,* pp. 350–353, Dec. 2011.

[8] L. Zhang, L. Cai, and J. Pan, "Connectivity in Two-Dimensional Lattice Networks," *IEEE Infocom'13,* Turin, Italy, Apr. 2013.

[9] T. T. P. Luong, T. H. Nguyen, W. Jin, L. Sungyoung, and L. Young-Koo "Energy Efficiency Based on Quality of Data for Cyber Physical Systems," *Internet of Things (iThings/CPSCom), 2011 International Conference on and 4th International Conference on Cyber, Physical and Social Computing,* pp. 232–241, Oct. 2011.

[10] J. Fink, A. Ribeiro, and V. Kumar, "Robust Control for Mobility and Wireless Communication in Cyber??Physical Systems With Application to Robot Teams," *Proceedings of the IEEE,* vol. 100, no. 1, pp. 164–178, Jan. 2012.

[11] H. Nishiyama, T. Ngo, N. Ansari, and N. Kato, "On Minimizing the Impact of Mobility on Topology Control in Mobile Ad Hoc Networks," *IEEE Transactions on Wireless Communications,* vol. 11, no. 3, pp. 1158–1166, Mar. 2012.

[12] N. Thuan, H. Nishiyama, N. Ansari, and N. Kato, "On Performance Evaluation of Reliable Topology Control Algorithms in Mobile Ad Hoc Networks," *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd,* pp.1–5, Sep. 2010.

[13] Jie Wu and Fei Dai, "Mobility-sensitive topology control in mobile ad hoc networks," *Parallel and Distributed Systems, IEEE Transactions on,* vol. 17, no. 6, pp. 522–535, Jun. 2006.

[14] J. B. D. Cabrera, R. Ramanathan, C. Gutierrez, and R. K. Mehra, "Stable Topology Control for Mobile Ad-Hoc Networks," *Communications Letters, IEEE,* vol. 11, no. 7, pp. 574–576, Jul. 2007.

[15] G. Quansheng, F. R. Yu, J. Shengming, and W. Gang, "Prediction-Based Topology Control and Routing in Cognitive Radio Mobile Ad Hoc Networks," *Vehicular Technology, IEEE Transactions on,* vol. 59, no. 9, pp. 4443–4452, Nov. 2010.

[16] N. Li and J. C. Hou, "Localized falut-tolerant topology control in wireless ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 4, pp. 307–320, Apr. 2006.

[17] L. Li, J. Y. Halpern, P. Bahl, Y. Wang, and R. Wattenhofer, "Analysis of a cone-based distributed topology control algorithm for wireless multihop networks," *Proceedings of Twentieth ACM Symposium on Principles of Distributed Computing (PODC 2001)*, pp. 264–273, Aug. 2001.

[18] R. Wattenhofer, L. Li, P. Bahl, and U. M. Wan, "Distributed topology control for power efficient operation in multihop wireless ad hoc netwroks," *Proceedings of Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies (INFO-COM 2001)*," vol. 3, pp. 1388–1397, Apr. 2001.

[19] M. Bahramgirim, M. Hajiaghayi, and V. S. Mirrokni, "Fault-tolerant and 3-dimensional distributed topology control algorithms in wireless multi-hop networks," *Wireless Networks*, pp. 179–188, Mar. 2006.

[20] N. Li, J. Hou, C. Sha, and L. Sha, "Design and analysis of an MST-based topology control algorithm," *IEEE Transactions on Wireless Communications*, vol. 4, no. 3, pp. 1195–1206, May. 2005.

[21] X. Y. Li, Y. Wang, and W. Z. Song, "Applications of k-local mst for topology control and broadcasting in wireless ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 15, no. 12, pp. 1057–1069, Dec. 2004.

[22] N. Li, J. C. Hou, and L. Sha, "Design and analysis of an MST-based topology control algorithm," *in Proc. of IEEE INFOCOM*, San Francisco, USA, Apr. 2003.

[23] K. Miyao, H. Nakayama, N. Ansari, and N. Kato, "LTRT: An Efficient and Reliable Topology Control Algorithm for Ad-Hoc Networks," *IEEE Transactions on Wireless Communications*, vol. 8, no, 12, pp. 6050–6058, Dec. 2009.

[24] N. Ansari, G. Cheng, and R. N. Krishnan, "Efficient and reliable link state information dissemination," *IEEE Communications Letters*, vol. 8, no. 5, pp. 317–319, May 2004.

Yuichi Kawamoto received his B.E. in Information Engineering from Tohoku University, Japan, in 2011. Currently, he is pursuing M.S. degree in the Graduate School of Information Science (GSIS) at Tohoku University. He was awarded the Satellite Communications Research Award in the fiscal year of 2011 from the Institute of Electronics, Information and Communication Engineers (IEICE). He is recipient of Japan Society for the Promotion of Science (JSPS) in 2013. His research interests are in the areas of satellite networks and sensor networks. He is a student member of IEEE.

Hiroki Nishiyama received his M.S. and Ph.D. in Information Science from Tohoku University, Japan, in 2007 and 2008, respectively. He was a Research Fellow of the prestigious Japan Society for the Promotion of Science (JSPS) until the completion of his PhD, following which he went on to become an Assistant Professor at the Graduate School of Information Sciences (GSIS) at Tohoku University. He was promoted to his current position of an Associate Professor at GSIS in 2012, when he was just 29 years old. He was acclaimed with the Best Paper Awards in many international conferences including IEEE's flagship events, namely the IEEE Wireless Communications and Networking Conference in 2012 (WCNC'12) and the IEEE Global Communications Conference in 2010 (GLOBECOM'10). He is a young yet already prominent researcher in his field as evident from his valuable contributions in terms of many quality publications in prestigious IEEE journals and conferences. He was also a recipient of the IEICE Communications Society Academic Encouragement Award 2011 and the 2009 FUNAI Foundation's Research Incentive Award for Information Technology. He received the Best Student Award and Excellent Research Award from Tohoku University for his phenomenal performance during the undergraduate and master course study, respectively. His research covers a wide range of areas including traffic engineering, congestion control, satellite communications, ad hoc and sensor networks, and network security. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), and he is also an IEEE senior member.

Nei Kato (A'03-M'04-SM'05-F'13) received his Bachelor Degree from Polytechnic University, Japan in 1986, M.S. and Ph.D. Degrees in information engineering from Tohoku University, Japan, in 1988 and 1991, respectively. He joined Computer Center of Tohoku University at 1991, and has been a full professor with the Graduate School of Information Sciences since 2003. He became Special Assistant to the President of Tohoku University since 2013. He has been engaged in research on satellite communications, computer networking, wireless mobile communications, smart grid, image processing, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as the Vice Chair of IEEE Ad Hoc and Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the steering committee member of WCNC and a voting member of GITC, an editor of IEEE Wireless Communications (2006-), IEEE Wireless Communications (2006-), IEEE Network Magazine (2012-), IEEE Transactions on Wireless Communications (2008-), IEEE Transactions on Vehicular Technology (2010-), and IEEE Trans. on Parallel and Distributed Systems (TPDS). From 2013, he also serves as an Associate Editor-in-Chief of TPDS. He has served as the Chair of IEEE Satellite and Space Communications Technical Committee (2010-2012), the Chair of IEICE Satellite Communications Technical Committee (2011-2012), guest-editor of many IEEE transactions/journals/magazines, a symposium co-chair of GLOBECOM'07, ICC'10, ICC'11, ICC'12, Vice Chair of IEEE WCNC'10, WCNC'11, ChinaCom'08, ChinaCom'09, Symposia co-chair of GLOBECOM'12, ICC'14, and workshop co-chair of VTC2010. His awards include Minoru Ishida Foundation Research Encouragement Prize (2003), Distinguished Contributions to Satellite Communications Award from the IEEE Communications Society, Satellite and Space Communications Technical Committee (2005), the FUNAI information Science Award (2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion (2008), the IEICE Network System Research Award (2009), the IEICE Satellite Communications Research Award (2011), the KDDI Foundation Excellent Research Award (2012), IEICE Communications Society Distinguished Service Award (2012), IEEE GLOBECOM Best Paper Award (twice), IEEE WCNC Best Paper Award, and IEICE Communications Society Best Paper Award (2012). Besides his academic activities, he also serves on the expert committee of Telecommunications Council, Ministry of Internal Affairs and Communications, and as the chairperson of ITU-R SG4 and SG7, Japan. Nei Kato is a Distinguished Lecturer of IEEE Communications Society (2012-2014) and the co-PI of A3 Foresight Program (2011-2014) funded by Japan Society for the Promotion of Sciences (JSPS), NSFC of China, and NRF of Korea. He is a fellow of IEEE and IEICE.