Efficient Communication of Sensors Monitoring Overhead Transmission Lines

Yik-Chung Wu, Long-Fung Cheung, King-Shan Lui, and Philip W. T. Pong

***Abstract*—It is foreseen that a future smart grid has to handle more dynamic and distributed electricity supply and consumption. In that case, a robust automation system becomes essential. To monitor the status of the power system, a large amount of sensors are deployed in both the transmission grid and distribution grid. The sensors generate massive amount of data periodically for automation. This paper studies how the data measured on transmission lines can be delivered efficiently to substations. It has been demonstrated that the traditional way of data transmission is not sufficient and direct wireless links should be used to reduce the delay in information delivery. Furthermore, optimal placement of these direct wireless links is studied aiming at minimizing the delay in information delivery. The associated energy consumption in data transmission is also investigated.**

***Index Terms*—Delay-energy trade-off, information delivery, monitoring, overhead transmission lines.**

I. Introduction

BECAUSE OF THE use of renewable energy, power generation and usage in the future will be more dynamic and distributed [1]–[3]. To maintain the stability of power supply, digital technology will be heavily used to provide automation. It is anticipated that smart grid, the next generation electricity network, would be self-healing, fault tolerant, and can accommodate variation in generation, storage and consumption efficiently [4]–[6]. For the control center to master the status of the power system in real-time, sensors are put in various components in the whole power network [7], [8]. These sensors would take measurements every few milliseconds and generate a lot of information. How to deliver information to the control center becomes a necessary issue to be solved for building an intelligent smart grid [9]. This paper studies the wireless communication infrastructure for monitoring the overhead transmission lines. We propose a mathematical framework to understand the time delay in delivering data measured by sensors to the substations. We also demonstrate the trade-off between the energy spent in communication with the maximum delay. Our study provides guidelines on the design of information network in the transmission grid.

Due to the long distance between generation and consumption, extensive use of overhead transmission lines in the grid is required [10]. Besides the overhead transmission lines, there are substations monitoring and controlling the power transmission. Transmission poles/towers provide structural support for the overhead lines. The control center collects information from the substations every few seconds. Nowadays, the speed of communication links between the control center and the substation may be still slow [11], [12]. However, it is expected that more power companies will upgrade their existing communication links with higher bandwidth, lower latency communications lines (e.g., optical fiber), to form their backbone networks [13], [14]. More information can then be communicated between the control center and the substations to facilitate smart automation [15]. As a result, we need a cost effective communication network to deliver information of the transmission lines to the substations.

Although bandwidth abundant, wired network like optical fiber may not be appropriate in the transmission grid which is large in scale. A wireless solution is thus sought [16]. In [17], the concept of using wireless sensors to support substation automation is proposed. On the other hand, Yang *et al.* [18], [19] are known to be the first to extend the usage of wireless sensor network to monitor overhead transmission lines. Sensors are put on different positions on a transmission line. In this case, the conditions of the portion of the transmission line located far away from the substations can also be observed. Yang *et al.* further implement a prototype of the power line sensor to demonstrate its feasibility in [20], and predict the real-time overload capacity of the line locally in [21], [22]. Nevertheless, they did not study how the sensors are connected to each other but assume that an underlying network is present and is formed automatically for data forwarding.

To the best of our knowledge, Chen *et al.* [23] and Leon *et al.* [24] are the first to propose a network model tailor-made for supporting the overhead transmission lines monitoring applications. They suggest that each pole is equipped with a relay node, which has both short-range and long-range communication modules. Sensors deployed on the transmission line, which can only perform short-range communication, send their data to the relay node on the pole. The long-range communication in a relay node allows it to send the collected information to another relay on a nearby pole that is closer to the substations. In other words, the relay nodes form a *linear network* between the two substations sitting at the ends of the transmission lines (see Fig. 1). Our earlier studies [25] show that this linear network model is not sufficient in supporting speedy and extensive traffic requirement in smart grid. To reduce the delay in information delivery, some relay nodes should set up a direct wireless link to the control center.

In this paper, we develop a mathematical framework to understand the relation between transmission delay and the number

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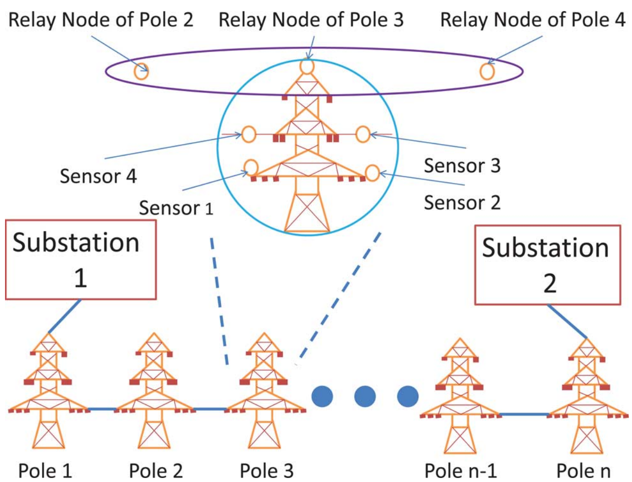

Fig. 1. Overhead transmission lines between two substations.

of direct links. We identify the optimal positions to establish direct links to minimize delay. We also find out that the improvement on delay is not linearly related to the number of links. Furthermore, to understand the energy used in these direct links, we carry out numerical computations based on realistic traffic and energy information [26], [27]. Our studies facilitate a better planning of the communication network in the transmission grid.

This paper is organized as follows. Section II explains how a direct link reduces the information delivery delay in more details. Then in Section III, we formulate the optimal direct link placement problem and collect energy profiles of cellular communications. In Section IV,we investigate the relationship between energy and traffic time. Finally, we conclude our work with some future directions in Section V.

II. Network Model

A. Description of Linear Network Model

Fig. 1 shows an example of how poles connect transmission lines between two substations. The distance between two substations can be as far as 50 km. On the other hand, the distance between two poles/towers can be 0.5–1 km depending on geographical constraints and actual needs. Therefore, there can be 20–100 poles/towers between two substations.

We follow the model in [23]–[25] that there is a relay node installed in each pole. The sensors placed on the transmission lines would send the information to the relay on the pole. For easy deployment, these sensors are usually put near the pole. Then, the distance between the sensor and the relay is less than 100 m, and a short-range communication technology, such as Bluetooth, suffices. After collecting information from the sensors, the relay should send the information to the substation. In the linear network model [23], [24], a relay not directly connected to the substation would send its information to its neighbor relay that is closer to the substation. For example, the relay on Pole 3 would send its data to Pole 2, which can then send its own data, together with the data from Pole 3 to Pole 1. Then Pole 1 sends all the collected information, together with its own information, to the substation. This is illustrated in Fig. 2.

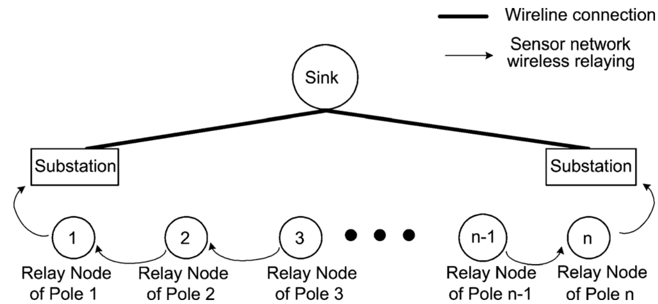

Fig. 2. Hop-by-hop relaying in linear network model.

TABLE I
Major Parameters for Computing the Delay in Linear Network Model

Number of poles	$n/2 = 50$
Message size per pole	S_d
Message size form Pole j to Pole $j-1$	$[n/2-(j-1)]S_d$
Interpole data relaying rate	R_i

B. Delay of Linear Network Model

In [25], we demonstrate that the linear network model cannot deliver information in a timely fashion. Consider the situation where there are $n = 100$ poles. Since there are substations at both sides of the network model, we only need to consider the data relaying on one side, i.e., from Pole 50 to Pole 1. In particular, the relay on Pole 50 sends its data to Pole 49. Pole 49 sends its own data and the data from Pole 50 to Pole 48. Suppose each relay collects S_d bytes of information from its sensors. Then, Pole 50 sends S_d Byte to Pole 49, Pole 49 sends $2S_d$ Bytes to Pole 48 and so on. It turns out that Pole 2 needs to send $49S_d$ Bytes of information to Pole 1. In general, the number of Byte sent from Pole j to Pole $j-1$ can be expressed as $[50-(j-1)]S_d$, where $1 \leq j \leq 50$. Let R_i be the data transmission rate between two poles, the total time for the data of Pole 50 to arrive at the substation is then given by

$$\sum_{j=1}^{50} \frac{(51-j)S_d}{R_i} = \sum_{j=1}^{50} \frac{jS_d}{R_i} = \frac{\frac{50\times 51 S_d}{2}}{R_i}, \quad (1)$$

where j is the summation index. Table I summarizes the major system parameters in the above calculation. To get a sense of the delay, suppose ZigBee[1] with a data rate of 31.25 kBytes/s [20] is used for the communications between poles, and $S_d = 4$ kBytes [25]. It takes $50 \times 51 \times 4/(2 \times 31.25) = 163.2$ s for the information collected at Pole 50 to reach the substation.

Notice that the above simple calculation does not include the relaying channel access time, which occurs because wireless channel is a shared medium. One device may have to wait if the channel has already been occupied by other devices, in order to avoid data packet collision. The most common medium access mechanism is *channel sense medium access/collision avoidance* (CSMA/CA), and for a typical sensor network, CSMA/CA time is around 41 ms [28], [29]. The inclusion of wireless channel access time would further add 50×41 ms $= 2$ s, giving the total information delivery time 165.2 s, which is far longer than

[1]Although standard Zigbee only covers several hundred meters of transmission range, more advanced version of wireless sensor transceiver can support transmission range up to 1.5 km [20]

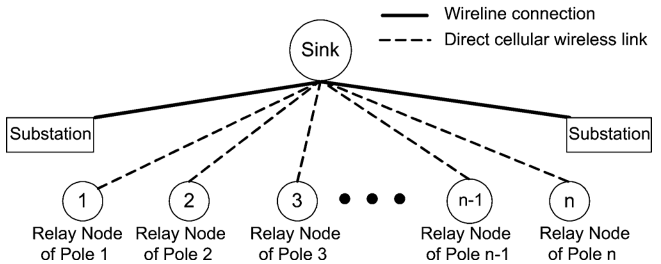

Fig. 3. All relay nodes transmit their information through direct wireless links.

the duration that the Supervisory Control and Data Acquisition (SCADA) system gathers data [15].

C. Beyond Simple Interpole Relaying

Apart from the delay issue, the linear network model also suffers from imbalance of workload that the relays closer to the substations have to handle a lot more traffic than those sitting farther away. As a result, it is necessary to identify a more efficient way to deliver the collected sensor data. We propose to establish some direct links between the pole relays and the control center to solve the problem [25]. In this way, the data collected at these relays can be sent to the control center directly, without relying on neighbor relays. Fig. 3 presents the network abstraction when all relays are directly connected to the control center, represented as the sink node. Because the control center may be several kilometers away from the pole, the direct link between them should rely on cellular technology. For example, the data rate of GSM is around 8 kBytes/s [30], [31], the time to send information to the control center is significantly reduced to $4/8 = 0.5$ s. Delay can be further reduced if we use 3G wireless connection instead of GSM.

Definitely, by setting up a direct link on each pole, the delay will be minimized and the workload among relays will be the most balanced. Nevertheless, this arrangement is expensive in terms of equipment cost and extra energy consumption of the direct cellular wireless links. To strike a balance, we should select only some relays to establish direct links. Relays that are not directly connected to the control center should send their data to one of those relays that have a direct link. Nevertheless, it is not clear how many links we should set up to achieve a certain delay requirement. Besides, the positions of the direct links would affect the delay as well. For example, it is probably not very beneficial if we set up a direct link at Pole 2 as the information collected at Pole 50 still need to travel a long way before reaching a direct link. To the best of our knowledge, there is no study on the optimal arrangement of direct links in monitoring of transmission grid. In the next section, we present the theoretical analysis on the issue.

III. Optimal Arrangement

In this section, we study the problem that given a number of direct wireless links, where should we put these links so that the delay of data delivery is minimized. We develop a relation between the number of direct wireless links and the maximum delay in information delivery. System administrators can determine how many direct links they need based on their delay requirement. We first demonstrate our idea using a simple case

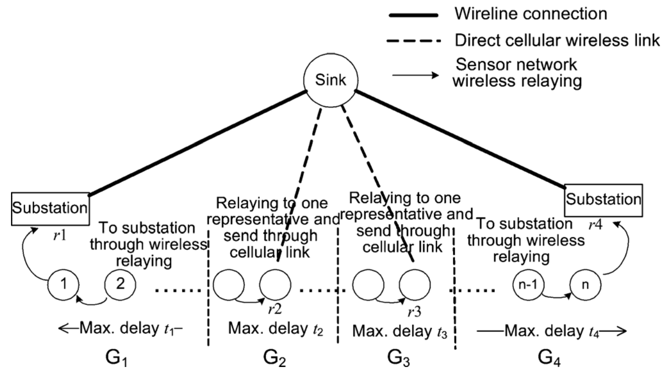

Fig. 4. Network with two wireless direct links. expressions for t_2 and t_1 are given by (2) and (3), respectively.

where there are only two direct wireless links. We then extend our idea to the general situation.

A. Simple Situation

For the ease of discussion, we call a node that connects directly, with or without a wire, to the sink node (control center) as *representative*. Note that the two substations on both sides are always representatives because they directly connect to the sink through Ethernet or other wireline technology. A node that does not connect directly to the sink node should send its information in a hop-by-hop manner to one of the representatives. We divide all the nodes into different groups where each group contains the nodes that send information to the same representative. Suppose there are two direct wireless links, then there are four groups: G_1, G_2, G_3, and G_4, as shown in Fig. 4. We let the four representatives in the four group be $r1$, $r2$, $r3$, and $r4$.

Each node i should select the representative that can deliver its information to the sink node using the minimum time. The time needed involves the hop-by-hop travel from node i to the representative and the transmission time from the representative to the sink node through the direct wireless link. We assume that each node would forward its information and the information from other nodes that it has to relay together. Therefore, if nodes i and $i+2$ select the same representative, node $i+1$ would select the same representative as well (see Fig. 4). Within the same group, the node sitting at the end would suffer the largest delay in sending information to the control center. We refer this delay as *maximum delay* and denote the maximum delay of group G_i as t_i. Our goal is to minimize $\max\{t_i\}$ by selecting the size of each group and the appropriate $r2$ and $r3$.

To minimize $\max\{t_i\}$, the maximum delays of the groups should be the same. Therefore, we have $t_1 = t_2 = t_3 = t_4$, which implies a symmetric structure in the topology. Under the assumption that each relay collects the same amount of data from its sensors, this is equivalent to the number of nodes in G_1 should be the same as that in G_4. Furthermore, the number of nodes in G_2 should be the same to that in G_3. This reduces to the problem of putting $n/2$ nodes in two groups only such that $t_1 = t_2$.

Notice that in each group using a direct wireless link, there are two components in the delay. The first one is relaying all the data in a group to the representative, and then the representative node sends all the collected data through the direct link. Since the total amount of data in a group is fixed no matter where to put the representative node, it is the first factor that affects the placement of representative node in a group. In a linear network model, each node receives data from an adjacent node, appends its own data and then forwards the whole data to the next node, it is obvious that the smaller number of nodes the data go through, the faster the data reaches the destination. Therefore, t_2 will be minimized if we select the middle node in the group to be the representative.

To compute the optimal number of nodes to be put in G_1 and G_2, let the number of nodes in G_2 be $2k+1$, i.e., k nodes on each side of $r2$. Further, let t_{MA} be the average channel access time, and R_d be the transmission data rate for the direct wireless link from $r2$ to the control center. In G_2, for the first $k-1$ hops on each side of $r2$, the data can be relayed at the same time without collision, and it takes the delay $t_{MA}(k-1)+S_d(1+2+\cdots k-1)/R_i$. On the other hand, in the last hop relaying from both sides to $r2$, they should be performed one after another; otherwise, there would be collision at $r2$. The time required for the last hop of relaying is therefore $2(t_{MA}+S_d k/R_i)$. Together with the transmission delay from $r2$ to the sink, the total delay is

$$t_2 = t_{MA}\times(k+1)+\frac{S_d(1+2+\cdots k)}{R_i}+\frac{S_d k}{R_i}+\frac{S_d(2k+1)}{R_d}. \tag{2}$$

On the other hand, the maximum delay for G_1 is

$$t_1 = t_{MA}\times[\ell-(2k+1)]+\frac{S_d\{1+2+\cdots[\ell-(2k+1)]\}}{R_i} \tag{3}$$

with $\ell = n/2$ represents the index of the last node in G_2. In order to minimize the maximum delay, we want $t_1 = t_2$, and we obtain a quadratic equation

$$t_{MA}\times(\ell-3k-2) + \frac{S_d[3k^2-(1+4\ell)k+(\ell^2-\ell)]}{2R_i} - \frac{S_d(2k+1)}{R_d} = 0. \tag{4}$$

Putting into a standard quadratic form, we have

$$\left(\frac{3S_d}{2R_i}\right)k^2 - \left(\frac{S_d(1+4\ell)}{2R_i}+3t_{MA}+\frac{2S_d}{R_d}\right)k + \left(\frac{S_d(\ell^2-\ell)}{2R_i}+(\ell-2)t_{MA}-\frac{S_d}{R_d}\right) = 0. \tag{5}$$

Of course, k can only be integer, and the left hand side of the above equation will likely not be exactly zero. So strictly speaking, we have to employ exhaustive search to minimize the left hand side of the above equation. On the other hand, in order to save computation, we can relax the constraint of k being an integer and approximately solve the above equation using solution for quadratic equation.

Putting $\ell = 50$, $S_d = 4$ kBytes, $R_i = 31.25$ kBytes/s, $t_{MA} = 41$ ms, $R_d = 8$ kBytes/s (corresponds to GSM transmission), we can obtain $k = 14.2$ and 57.9. Since k must be smaller than 50, we take the first solution. Furthermore, since k is an integer, k should be either 14 or 15. When $k = 14$, $t_1 = 30.429$ s and $t_2 = 28.514$ s. Similarly, we can also compute t_1 and t_2 for $k = 15$. It turns out that $k = 14$ is the optimal solution, and $\max\{t_i\}$ is 30.429 s.

After knowing k, we can determine the positions of $r2$ and $r3$. Since k represents the number of nodes on either left or right of $r2$, we can calculate group size of G_2 by $2k+1$. In the above case, G_2 has 29 nodes. Then G_1 has $50-29=21$ nodes. Obviously, $r2$ is Node $(21+14+1)=36$. Also, $r3$ can be obtained in a similar way.

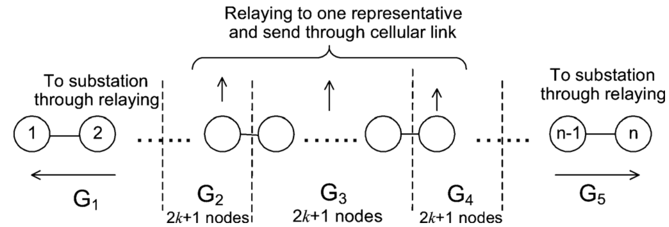

Fig. 5. Network with more wireless groups.

B. General Situation

We can extend the idea to more than two relay nodes establishing direct wireless links. For example, for three nodes being used as representative nodes to employ the direct wireless links, we have the scenario in Fig. 5. Due to symmetry, G_2, G_3, and G_4 will have the same number of nodes and denoted by $2k+1$. Also, within each of G_2, G_3, and G_4, the representative node lies in the middle. If we focus on G_1 and G_2 in Fig. 5, it is obvious that this problem is the same as that formulated with two representative relays. However, the index of the last node of G_2 is given by

$$\ell = \frac{n-g(2k+1)}{2}+(2k+1) = \frac{n-(g-2)(2k+1)}{2} \tag{6}$$

where $g \geq 2$ is the total number of groups using direct links. It is obvious that ℓ now depends on k, and we have to solve (7). Putting (6) into (7), after some tedious but straightforward manipulations, we have

$$\left(\frac{S_d(g^2-1)}{2R_i}\right)k^2 + \left(\frac{S_d[g(g-n-1)-3]}{2R_i}-(g+1)t_{MA}-\frac{2S_d}{R_d}\right)k + \left(\frac{S_d(n-g)(n-g+2)}{8R_i}+\frac{(n-g-2)t_{MA}}{2}-\frac{S_d}{R_d}\right) = 0, \tag{7}$$

and we can solve for k using the solution of quadratic equation as before. For example, for $n = 100$, $g = 4$, ZigBee for inter-pole relaying (i.e., $R_i = 31.25$ kBytes/s), and the direct wireless link is a GSM link with $R_d = 8$ kBytes/s, the k obtained from solving the quadratic equation is 8.4489 (the other solution is 18.7397, which is impossible as this would lead to more than 100 nodes). Then we check $k = 8$ and $k = 9$ to see which one gives a smaller maximum delay. It turns out that $k = 9$ is the optimal solution with $t_1 = 10.476$ s, and $t_2 = 15.629$ s. In this case, the $\max\{t_i\}$ is 15.629 s.

After determining the number of nodes in each group, it can be easily shown that the position of r_a is the $(n-g(2k+1)/2+(a-2)(2k+1)+k+1)^{\text{th}}$ node, where $2 \leq a \leq g+1$. In practice, the system administrator should first determine the number of direct links based on the delay requirement of the system. Locations of the direct links can be computed using (7) deterministically in the substation, or a centralized server of the whole system. Representatives can then be informed by hop-by-hop relaying. That is, substation puts the representative information in a message and sends it to Pole 1. Pole 1 can then send it to Pole 2, and so on. Once all representatives are informed, the system can start monitoring the transmission grid. Furthermore, in normal operation, there is no need to re-assign representatives unless the system administrator wants to change the number of groups or there is a node failure. The former case can be handled by relaying the new information among the poles. In case of node failure, the two neighbor poles of the failed node should be the first to notice it. They should turn on their direct links and inform the substation immediately. The substation can then determine how groups should be formed and inform the poles.

Finally, we notice that there is a physical constraint on how many nodes can be put into a group that uses a direct wireless link. Since data is periodically generated, the data rate of the direct wireless link should be faster than the data generation rate within a group. Otherwise, data will be backlogged and overflow at buffer will occur. More specifically, we need

$$R_d \times t_r > (2k+1)S_d \tag{8}$$

where t_r is the time interval between two adjacent reporting. On the other hand, for the two groups G_1 and G_{g+2}, the corresponding constraint on the data rate is

$$R_i \times t_r > \frac{n - g(2k+1)}{2} S_d. \tag{9}$$

Equations (8) and (9) form the constraints on the feasible set of (k, g).

For example, if we use GSM as the direct wireless link, reporting frequency is every 4 s, $S_d = 4\ \mathrm{kBytes}$, then the constraint on k is $k < 3.5$ (or equivalently each group using direct wireless link can have at most 7 nodes). Putting $k = 3$ into (9), the corresponding constraint on g is $g > 5.3$. These constraints reduce the flexibility of choosing a trade-off between number of groups and maximum delay. If we want to have more choices in choosing the number of nodes in a group, we can use a wireless technology with higher data rate. For example, if we use 3G network, $R_d = 48\ \mathrm{kBytes/s}$ [32]. This translates to the maximum supported k to be 18 (or equivalently each group using a single direct wireless link can have at most 37 nodes), and the constraint on g is $g > 1.01$. The constraints become less stringent. Of course, we can choose to reduce the reporting frequency or reduce the amount of data to be reported to make (8) and (9) satisfied. However, these may not be the available options in some situations.

C. Energy Consumption Analysis

The energy used in transmission can be divided into two parts. The first part is the energy in interpole relaying, and the second part is direct wireless link transmission energy. For the interpole relaying, assuming there are g groups using direct wireless links, the total data size in relaying for these g group is $2S_d g(1+2+\cdots+k) = S_d gk(k+1)$. On the other hand, the total data size relayed in the two groups directly attached to the substations is $2S_d(1+2+\cdots+[\ell-(2k+1)]) = S_d(\ell-2k-1)(\ell-2k)$, where ℓ is defined in (6). Therefore, for one round of reporting, the total energy spent in relaying is

$$S_d[gk(k+1) + (\ell-2k-1)(\ell-2k)] \times E_{IP} \tag{10}$$

where E_{IP} is the energy per byte for interpole relaying, including transmission and reception. For example, for the XBee-PRO (S2B) [27], the energy consumption for transmitting and receiving one byte of data can be computed to be $17.3184\ \mu\mathrm{J}$ (3.3 V, operating current during Tx is 117 mA, current during Rx is 47 mA, 250 Kbps PHY rate).

For transmission using direct wireless link, the energy consumption depends on the particular wireless technology one employs. For example, for a GSM device, the energy consumption (obtained from measurement) is [26]

$$0.036(x) + 0.25 \min\left(6, t_r - \left(\frac{x}{R_d}\right)^+\right) + 0.03t_r, \tag{11}$$

where $(a)^+ = \max(0, a)$, $x = (2k+1)S_d/1000$ is the data size in kilobyte in each transmission, and $\max(a.b)/\min(a,b)$ takes the maximum/minimum among a and b. The first term in (11) represents the actual energy for transmitting the data. The second term represents the ramp-down energy after transmission, while the third term is the maintenance energy for a transmitter. On the other hand, for 3G standard, the energy consumption is found to be

$$0.025(x) + 0.62 \min\left(12.5, \left(\frac{t_r - x}{R_d}\right)^+\right) + 0.02t_r, \tag{12}$$

where the three terms in (12) hold the same meanings as that in (11).

IV. Numerical Results

Fig. 6 shows the maximum delay time $\max\{t_i\}$ versus the number of groups g using direct wireless link. Total number of node is 100, the amount of data per report for each pole is 4 kBytes, and the reporting interval is 4 s. ZigBee is used for interpole relaying, and both GSM and 3G are considered for the direct wireless link. From the figure, it is obvious that increasing the number of groups reduces the $\max\{t_i\}$. However, the trend of $\max\{t_i\}$ shows a diminishing return. When the number of group is larger than 10, the potential improvement in $\max\{t_i\}$ is small. Furthermore, for the same number of groups, 3G network shows a significantly smaller $\max\{t_i\}$ than that of GSM. This is because the data rate for 3G transmission is much higher than that of GSM.

On the other hand, if we also consider the energy consumption, GSM demonstrates advantages. This is illustrated in Fig. 7, which shows the total energy consumption in each round of reporting versus $\max\{t_i\}$. From Fig. 7, it is clear that, in general, for the same $\max\{t_i\}$, the total energy spent by using GSM cellular link is smaller than that of 3G link. More interestingly, for both GSM and 3G wireless links, the curves show a V shape and have clear minimum points in terms of total energy consumption. This is because although energy in transmitting a unit of data in wireless sensor network is smaller than that in cellular links, in relaying, each node is spending a large amount of energy to help its neighboring nodes to forward data, thus

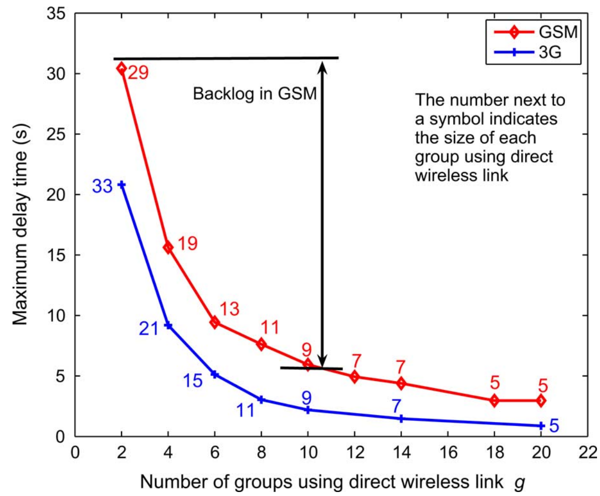

Fig. 6. Maximum delay time versus number of groups using direct wireless link.

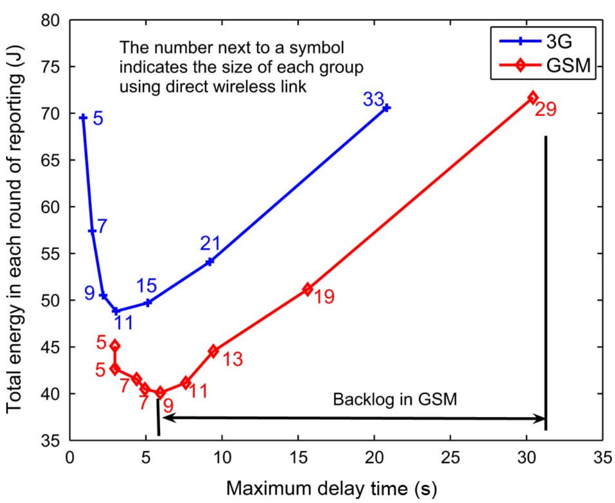

Fig. 7. Energy versus maximum delay time.

dominating the total energy consumption. When we increase the number of groups, the amount of data in relaying decreases, but the increase in energy due to more direct wireless links is moderate, thus both delay and total energy consumption decrease. However, if we are having too many groups, the high energy consumption of cellular links would start to dominate the total energy. This result clearly shows a trade-off between total energy consumption and delay of the system.

As a reference, if the system does not employ cellular link, the total energy consumption in relaying can be easily obtained from (10), by putting $g = 0$ and $k = 0$. With the same parameters as those for generating Fig. 7, it turns out that the energy consumption in each round of reporting is 169.72 J. This unfavorable configuration corresponds to very large delay (165.2 s as calculated in Section II-C) and large energy consumption. On the other extreme, if all of the nodes employ direct GSM links to transmit data, the total energy consumption in each round of reporting would be 126.38 J, and the delay is only 0.5 s.

It is noticed that there are some configurations of GSM that are not valid because they do not satisfy (8) and (9). In general, how many configurations are invalid highly depends on the reporting interval and the amount of data reported by each sensor.

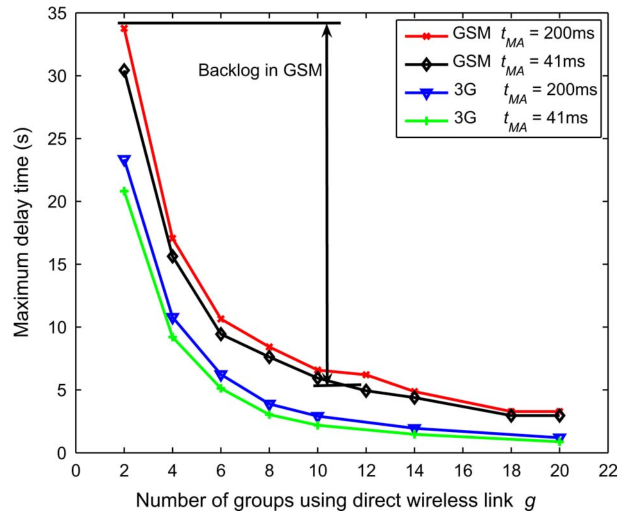

Fig. 8. Comparison of maximum delay performance of the proposed scheme between $t_{MA} = 41$ ms and $t_{MA} = 200$ ms.

For example, if the reporting interval is doubled, only the configurations with group sizes 19 and 29 are invalid. Furthermore, since 3G has a high data rate, there is no invalid configuration for the system setting we considered.

Finally, as the multiple access time varies with network topology and channel contention protocol, Fig. 8 compares the case of $t_{MA} = 41$ ms and $t_{MA} = 200$ ms on maximum delay performance. It can be seen that except the maximum delays are increased slightly due to the increased multiple access time, the case of $t_{MA} = 200$ ms basically exhibits the same behavior as the case of $t_{MA} = 41$ ms. Thus, it can be concluded that the exact value of t_{MA} has a relatively small effect on the overall system performance.

V. Conclusions and Future Work

In this paper, the reconfigurable network model currently proposed in the literature was revisited. It was shown that the performance of this model can be further improved by careful choice of the position of direct wireless links and communication mode. To further investigate this issue, an optimization problem was formulated such that the configuration of the network minimizing the maximum delay can be determined. The network delay improvement made by the proposed solution with direct wireless link was shown to be significant. Furthermore, trade-off between energy consumption and delay performance was also studied. It was found that while increasing the number of groups would reduce the delay, too many groups is not beneficial in terms of energy consumption. The result of this paper help developers of future smart grid to balance performance and cost constraints. In the future, we plan to carry out site implementation of the model as well as continuous performance study of this newly proposed network model against some other realistic data traffics.

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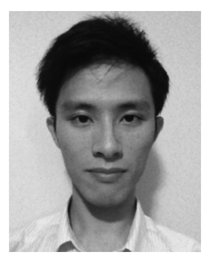

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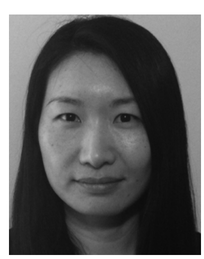

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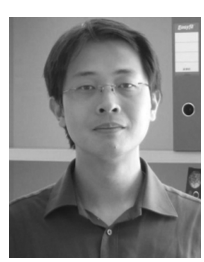

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