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Design and Performance Evaluation of The Multi-Gateway Smart Grid NAN Networks For Maximizing Network Capacity

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Abstract

In recent years, lots of problems from the global climate change and energy depletion have been big issues, so research on the Smart Grid has been progressed significantly. The goal of the Smart Grid is to maximize energy efficiency by monitoring power information and controlling it with the help of Information and Communication Technology(ICT). The Smart Grid aims to fuse Green energy with the Information Communication technologies. In this paper, we pro-pose a design algorithm that improves the network utilization by performing path discovery and resource allocation simultaneously in the Neighbor Area Network (NAN) of the Smart Grid system. We propose the Joint Routing and Scheduling for Smart Grid (JRS-SG) algorithm in order to enhance traffic transmission rate. The proposed JRS-SG algorithm uses cross-layer design methods based on a numerical modeling to adaptively control data scheduling at the link layer and find a high data-rate path which has the least interference for each flow. We analyzed the optimal capacity using a numerical solution tool and verified that our proposed algorithm can improve the system capacity by distributing the gateway load efficiently and enhance system availability.

Keywords: Smart Grid, Wireless Mesh Networks, Joint Routing and Scheduling, Cross-layer Design, Convex Optimization

Introduction

The Smart Grid technology has been researched actively in recent years because lots of problems from global climate exchange and energy depletion have emerged. The goal of the Smart Grid is to fuse Green energy with the Information Communication technology, thus maximizing energy efficiency by monitoring the power information and controlling it with the help of Information and Communication Technology(ICT). The communication networks of the Smart Grid system can be classified as Wide

Area Network (WAN), Neighborhood Area Network (NAN) and Home Area Network(HAN) as shown in Fig. 1 [1]. The main traffic in the Smart Grid system is generated from smart meters in NAN [2].

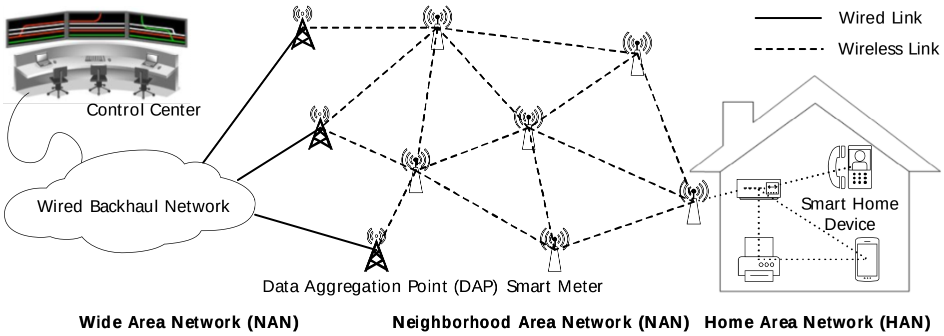

Figure 1: SmartGrid Communication Layer

To collect this bidirectional information between the power supplier and consumers efficiently, communication networks for a power distribution grid should be deployed. Various wired and wireless solutions have been studied for this network, but among them, a wireless mesh network is considered as a promising candidate between Data Concentration Units(DCU) and smart meters because of its low deployment cost and network scalability.

The general wireless mesh networks consist of mesh routers, mesh access points and mesh clients. Generally, wireless mesh routers in the wireless mesh networks are located in a fixed position for backbone networking and do not have power limitations. The mesh clients can access mesh networks by joining the mesh access point, and traffic can be delivered in a multi-hop manner via distributed mesh routers. These networks have increased reliability, low installation cost, large coverage area and automatic network connectivity as advantages [3]. These properties are suitable for SmartGrid applications.

In wireless mesh networks, the path of each flow is determined before the data transmission based on some routing strategies. At this moment, an important factor that should be considered is that the link capacity between mesh routers may be changed based on the current interference of the flow of other mesh router. In general, network availability is also influenced from the interference related to the other layers in the protocol stack [4].

This problem can be relieved in part by using multiple wireless interfaces and multiple wire-less channels. But, it cannot solve the problem completely, because the number of interference-free wireless channels for each flow is limited. Additionally, the channel assignment should be performed carefully to reduce interference, but it is very complicated [5].

Thus, the key point in the SmartGrid system using wireless mesh networks is to increase network capacity by selecting a path that has high data rate and less interference. Also, mesh routers should transmit packets simultaneously as much as possible by scheduling their transmission times based on the spatial reuse concept. This allows the system throughput to maximize by accepting as many flows as possible.

One of routing strategies usually used in mesh networks is the shortest-path. If this scheme is applied to the SmartGrid system and link scheduling for data transmission along the determined path is applied, then the current available link capacity is not considered and the overall network cannot be fully utilized. Thus, a routing strategy considering the current available link capacity needs to be proposed. At this moment, one important factor is that the link capacity can be varied depending on how we assign link the capacity between mesh routers. That means, if we assign more resources(slots, frequencies, etc.) to one node, then the other nodes within the interference range cannot use same resource. Consequently, the link capacity will be reduced. So, route discovery and resource scheduling should be considered at the same time by the cross-layer design technique. Many optimization solutions using the cross-layer design have been actively suggested to improve the system capacity for the wireless mesh networks.

In this paper, we consider multi-gateway wireless mesh networks [6] for a SmartGrid NAN and propose a new JRS-SG algorithm which utilizes both route discovery and resource allocation at the same time in order to maximize network capacity under these multi-gateway wireless mesh networks. The proposed algorithm uses a cross-layer design method based on the numerical modeling in order to control data scheduling adaptively at the link layer and find a high data-rate path with minimum interference for each flow at the network layer. We analyzed the optimal capacity using a numerical solution tool and verified that our proposed algorithm can improve the system capacity by distributing a gateway load efficiently and enhance the system availability.

This paper consists of five sections. In Section II, we review previous works on optimization solutions in the wireless mesh networks using a cross-layer design and capacity enhancement methods. The system model we consider is explained in Section III, and the proposed algorithm and its numerical modeling by considering both the route discovery at the network layer and scheduling at the data link layer in spatial reuse TDMA protocol are described in detail in Section IV. In Section V, the numerical analysis results of the load distribution and the increased system capacity are shown. Finally, Section VI comes to a conclusion and further study areas.

Related Works

Candidate Wireless Mesh Networks Technologies for SmartGrid NAN

In the SmartGrid system, power information is delivered between the suppliers and customers, and the power system is remotely controlled and monitored in real time. So, the traffic capacity of multi-hop transmission is very important. Recently, the SmartGrid service using Institute of Electrical and Electronics Engineers(IEEE) wireless technologies has been actively proposed. Thus, the SmartGrid networks based on IEEE 802.15.4 ZigBee [7], IEEE 802.11e [8], IEEE 802.11s [9] and IEEE 802.11ah [10] technologies have been actively researched.

In [7], the system capacity of a routing algorithm in a ZigBee-based wireless mesh system is analyzed using the mathematical analysis model. It enhances the capacity of wireless mesh networks by reducing the number of the average transmission hops in a multi-hop system. In [8], the problem of the 'Flow Fairness' which resulted in performance degradation was solved. This problem occurred because the fair bandwidth allocation cannot be guaranteed. So, [8] proposed a resource allocation scheme based on the real traffic of each queue by extending IEEE 802.11e MAC protocol, Enhanced Distributed Coordination Access(EDCA). This scheme prevents a specific flow from monopolizing a queue and enables the capacity of a queue be partitioned based on the number of flows and the required bandwidth. The study in [9] showed why the SmartGrid system needs high data-rate capacity and a Quality of Service(QoS) guarantee, such as high bandwidth and low latency, in a 802.11s-based SmartGrid system. Also, the authors of [9] analyzed some vital problems of the IEEE 802.11s default routing protocol(HWMP) from the perspective of transfer reliability; they proposed the appropriate solution with a new routing method called HWMP-reliability enhancement; this method improved the routing reliability of 802.11s-based SmartGrid mesh networking.

All of the previous works use the existing IEEE wireless LAN standards, but recently new IEEE 802.11ah has been standardized for SmartGrid applications. The IEEE 802.11ah [10] is designed based on the down-clocked operation of IEEE 802.11ac's and uses the new PHY and MAC designs that operate in the sub-one-gigahertz(900 MHz) band. These lead to the extended transmission range compared to IEEE 802.11 WLAN operating at 2.4 GHz and 5 GHz bands, as shown in Fig. 2. The IEEE 802.11ah considers a use case having 100 kbps data rate in the SmartGrid NAN networks, as shown in Fig. 3 [11].

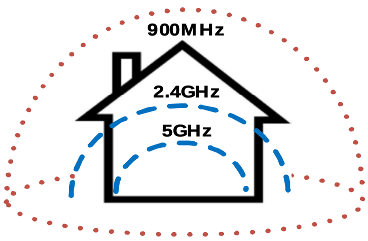

Figure 2: IEEE 802.11ah for Power Efficiency and Long Range

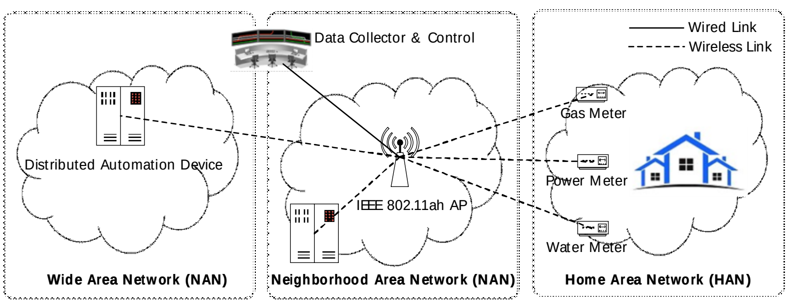

Figure 3: Use Case: Smart Grid in IEEE 802.11ah

The NAN traffic at the initial stage is not heavy because of simple monitoring and control. However, as the number of devices connecting to 1 AP increases and new services like real time surveillance applications that require high bandwidth emerge, then IEEE 802.11ah just for extending transmission range will reach a performance limitation. To overcome this limitation, NAN should be extended to wireless multi-hop networks, and a multi-gateway approach should be adopted to distribute the traffic towards each AP and reduce the bottleneck of each gateway between NAN and WAN [6]. That means that the network utilization can be enhanced by designing multi-gate wireless mesh networks. The key design points in this network are how to find the optimal route and how to share wireless the medium efficiently.

Network Capacity Maximization Mechanisms for Multi-hop Transmission

In multi-hop wireless mesh networks, high capacity can be achieved using the Spatial TDMA(STDMA)-based MAC protocol [9]. This is possible because nodes outside the interference range can transmit data in the same slot using the spatial reuse concept. Research on this MAC protocol has been classified as centralized algorithms [12] and distributed algorithms [13]. Recently, cross-layer design algorithms for considering both discovery and resource allocation in STDMA-based wireless mesh networks have been actively studied. These cross-layer algorithms are based on a heuristic approach for resource allocation at the data link layer [14], [15] or a numerical modeling approach [16], [17].

In [16], route discovery and link resource allocation were adjusted in order to maximize the data transmission rate by using a cross-layer design. But, slot scheduling at the link layer was per-formed only along the path discovered at the initial stage without finding the optimal route after initial scheduling. In [17], set of links which can transmit data simultaneously without interference was formed first, and then available slots for each link group were assigned. But, if the number of flows increase and a specific link is used by many flows, then a bottleneck will occur, and the data rate of these flows decreases, because the dynamic slot adjustment based on traffic condition has not been applied. Consequently, the overall network capacity of wireless mesh net-works becomes reduced.

System Model

We assume that mesh nodes are located in fixed positions and all the links between the nodes are wireless, as shown in Fig. 3.

Network Topology and Flows

The topology graph of the wireless mesh networks consists of node set, N, and link set, A. So, it can be represented as directed graph $G = (N, A)$ considering the bi-directional links between mesh routers. In this topology graph, we assume that N consists of n nodes with one interface and one channel, and A consists of m directed arcs. The link $(i, j) \in A$ means that a transmitting node is i ($i \in N$) and a receiving node is j ($j \in N$), and we assume if link (i, j) is the member of A, then (j, i) is also the member of A.

The link (i, j) has the maximum available capacity, μ_{ij}, without interference. We also assume there are F flows in the wireless mesh networks $G = (N, A)$, and the set of these flows is denoted as $F_s = \{1, 2, \ldots, F\}$. The flow $f \in F_s$ has source and destination pairs denoted as (s_f, d_f). The data rate of each flow, λ_f, is nonnegative and traffic rate allocation vector λ is denoted as $\lambda = [\lambda_1, \lambda_2, \ldots, \lambda_F]$. The λ_f is defined as the number of required slots of flow f per a frame.The capacity of each frame is assumed to be 1,000 slots.

Medium Access Control

In the wireless mesh networks, all the nodes cannot transmit at the same time due to interference and collision. There are two constraints in media access procedure. One is that a node cannot transmit and receive simultaneously, because only half-duplex communication is possible. The second is that a node shares media with neighbor nodes, so interference and collision should be considered to avoid packet reception error.

In this paper, we adopt a special TDMA method for media access control in the designed network, since it has better performance in wireless mesh networks than contention-based MAC, such as CSMA/CA. Considering these constraints, links that can transmit data at the same time are grouped based on the interference model, and these groups become the member of Independent-link Set(IS). We use IS to assign time slots on each link to avoid collision in the media access protocol at the data link layer. If the number of members in IS is 3 in the wireless mesh networks, the independent link set can be represented as $IS = \{IS_1, IS_2, IS_3\}$.

The basic IEEE 802.11 MAC protocol, Distributed Coordination Function(DCF), has the characteristics of a distributed, asynchronous frame transmission and a low spatial reuse ratio. But, if Mesh Coordination Function(MCF) based on the IEEE 802.11s is used in media access, then a synchronous transmission is possible. In this scenario, the efficient spatial reuse and resource allocation are also possible by controlling the time slots assigned on each link based on the IS information.

Interference Model

As mentioned previously, the route discovery between the source and the destination has to consider interference among the links. The interference model in wireless networks is usually divided into a protocol interference model and a physical interference model [4]. In this paper, we use a protocol interference model because of its simplicity and easy numerical modeling. We first discover IS and then perform a link scheduling based on the chosen interference model. The other link interference model also can be used for the optimization algorithm proposed in this paper.

In this paper, we use '1-distance edge coloring' [19] to get the IS, as shown in Fig. 4. According to this coloring scheme, links separated by more than 2 hops can transmit at the same time. It is called 'strong edge coloring' [18]. IS_k means a group of links having the same color after edge coloring, and k cannot be greater than the edge chromatic number $\chi(G)$, which is defined as the smallest number of colors need in edge coloring problems, where $k \in \{1, \ldots, \chi(G)\}$. All of the links in the same IS_k can transmit data at the same time without interference, but the links belonging to different IS_k cannot transmit simultaneously.

Interference among links in the '1-distance edge coloring' happens in two cases, as shown in Fig. 5. First, if nodes *u* and *w* transmit to a node *v* on the same channel at the same time, packets collide at the node *v*. Second, if a node *s* transmits to a node *t* and a node *u* transmits to a node *v* on the same channel at the same time, node *t* cannot decode a received data correctly because of the interference from a node *u*. According to the '1-distance edge coloring', the distance is measured as the number of links within the shortest distance between any arbitrary two links. For instance, there is only one link (*t*, *u*) between link (*s*, *t*) and (*u*, *v*). So, the distance is 1 in Fig. 5. Thus, the links (*s*, *t*), (*t*, *u*) and (*u*, *v*) cannot transmit data on the same channel at the same time due to interference, and they should have different colors, respectively. But, links (*s*, *t*) and (*v*, *w*) do not affect each other, and there's no interference between them. So, they can transmit simultaneously on the same channel and can have the same color. All of the links in Fig. 5 can be colored by using only 3 colors based on the '1-distance edge coloring'. The minimum necessary number of colors determines the number of non-interfering time slots in a frame. Fig. 4 shows example coloring of grid topology where the number on the link shows the color number. The required number of different colors is 8. But, this number increases two times if we consider bi-directional transmission of each link, becoming 16. The links with same color number means that they can transmit data simultaneously without interference.

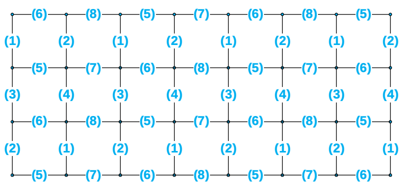

Figure 4: Distance Edge Coloring

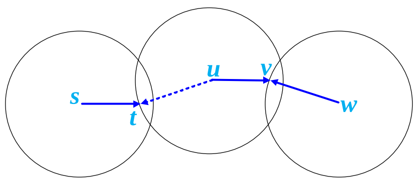

Figure 5: Interference in Wireless Mesh Net works

Proposed Algorithm

The purpose of this paper is to improve the capacity and the availability of STDMA-based wireless mesh networks in the SmartGrid NAN system. To achieve this goal, we divided the problem in the SmartGrid system as a primary problem for discovering the best route and a secondary problem for scheduling time slot resources to links along the selected path. First, we obtained a solution of primary problem and maximized the system capacity by applying the secondary solution to it. After that, we resolved the primary solution under the slot assignments of the secondary solution. These whole steps were iterated until the performance improvement was saturated. This approach can reduce bottlenecks of all links connected to each gateway and enhance the data rate of each flow by finding the best path for the maximum capacity and availability compared to previous works.

Algorithm for Maximizing the Network Capacity

The proposed JRS-SG algorithm focuses on both link scheduling at the data link layer and route discovery to each gateway at the network layer simultaneously in wireless mesh networks. Using this approach, the availability and the capacity of the SmartGrid system can be enhanced. As we explained in the previous section, the proposed algorithm for maximizing the capacity of each given flow can be modeled as Integer Linear Programming problem as follows.

Objective function

$$Maximize \sum_{f=1}^{F} \lambda_f \quad \text{(Error! Bookmark not defi}$$

Subject to

$$\sum_{j:(i,j)\in A} \lambda_f x_{ij}^f - \sum_{j:(j,i)\in A} \lambda_f x_{ji}^f = \lambda_f \quad ; i = s_f, \forall f \in F_s \quad (2)$$

$$\sum_{j:(i,j)\in A} \lambda_f x_{ij}^f - \sum_{j:(j,i)\in A} \lambda_f x_{ji}^f = -\lambda_f \quad ; i = d_f, \forall f \in F_s \quad (3)$$

$$\sum_{j:(i,j)\in A} \lambda_f x_{ij}^f - \sum_{j:(j,i)\in A} \lambda_f x_{ji}^f = 0 \quad ; \forall i = \{N - s_f, d_f\}, \forall f \in F_s \quad (4)$$

$$\sum_{j:(i,j)\in A} x_{ij}^f = 1 \quad ; i = s_f, \forall f \in F_s \quad (5)$$

$$\sum_{j:(j,i)\in A} x_{ji}^f = 1 \quad ; i = d_f, \forall f \in F_s \quad (6)$$

$$\sum_{j:(i,j)\in A} x_{ij}^f \le 1 \quad ; \forall i \ne s_f, \forall f \in F_s \quad (7)$$

$$\sum_{j:(j,i)\in A} x_{ji}^f \le 1 \quad ; \forall i = d_f, \forall f \in F_s \quad (8)$$

$$x_{ij}^f \in \{0,1\} \quad ; \forall f \in F_s \quad (9)$$

$$\lambda_f \ge 0 \quad ; \forall f \in F_s \quad (10)$$

$$\sum_{j:(i,j)\in A} \lambda_f x_{ij}^f \leq u_{ij} \qquad ; \forall (i,j) \in A \qquad (11)$$

The objective function for maximizing the flow capacity in the given linear programming is in (1) and constraint equations are in (2) - (11). The x_{ij}^k represents whether link (i, j) is used for the path of flow k or not. As shown in equation (9), in case of $x_{ij}^k = 0$, link (i, j) is not used for the path of flow k. On the contrary, in case of $x_{ij}^k = 1$, it is used. From this, we can figure out the path of each flow.

The equation (1) is a convex objective function used to maximize the sum of the transmission rate of all flows, and equations (2) to (4) are the constraint equation for flow conservation. According to equations (2) and (3), each flow has a λ_f or -λ_f rate at the source or destination node of the given flow, respectively. It means all data transmitted at the source node can be received by a destination node without loss. The equation (4) also represents that any flow incoming to an intermediate node must go out from that node without any loss.

(5) to (8) are equations for each flow only taking a single path, not taking multiple paths. The equation (5) is means that the outgoing link from the source node must have one link, and (6) that the incoming link to the destination node also has to have only one link. According to (7) and (8), a path from an intermediate node to the next node or from a previous node to the intermediate node must be single. Lastly, (10) shows that the data rate of each flow should be nonnegative.

In (11), we give constraints that the sum of all flows on a link (i, j) cannot exceed the available capacity, u_{ij}. In conclusion, the given integer linear programming can discover a route for maximizing the data rate of all flows under the constraint of available capacity, u_{ij} in (11). We can also figure out the current resource usage condition of each link after route discovery. If we perform link scheduling to assign more slots to the bottleneck links using the remaining spare slots from the links with low traffic loads after discovering a route, we can enhance system throughput further. If these steps are repeated, then the maximum flow capacity can be greatly enhanced compared to the previous works in [16-17].

Iterative Heuristic Algorithm

The equations (1) to (11) basically correspond to a convex optimization problem. The objective function given in (1) is a linear convex function and constraint equations from (2) to (11) are also convex set so that the optimal solution can be obtained by convex optimization problem [20]. The algorithm used in this paper is a kind of descent method which uses iteration in order to maximize the minimum value of the remaining link resources by the bisection method [21]. This method is iterated until traffic is assigned to each link evenly and the objective function can be maximized. This approach can speed up the linear search process.

Algorithm 1: Iterative Heuristic Algorithm

Definition

C = 1000 (number of slots per a frame)

Input

1. 1-Distance Edge Coloring Results

   χ(G) = 14

   IS = { IS_1, IS_2, IS_3, IS_4, IS_5, IS_6, IS_7, IS_8, IS_9, IS_{10}, IS_{11}, IS_{12}, IS_{13}, IS_{14} }

2. Source-Destination fairs
3. Adjacency Matrix

Initialization

$\Phi_k = \frac{C}{\chi(G)}; \quad \forall k \in \{1, ..., \chi(G)\}$

$u_{ij} = \Phi_k, \ (i,j) \in IS_k; \quad \forall (i,j) \in A, \ \forall k \in \{1, ..., \chi(G)\}$

Main Iteration

while $\Delta\Phi_{decision} \leq \epsilon$ **do**

STEP 1. Solving a problem for maximizing network capacity

Maximize

$$\sum_{f=1}^{F} \lambda_f \tag{1}$$

Solution

$$C_{ij} = \sum_{f=1}^{F} \lambda_f x_{ij}^f; \quad \forall (i,j) \in A \tag{2}$$

STEP 2. Calculating used capacity

$$uc_k =^{argmax}_{(i,j) \in IS_k} (C_{ij}); \quad \forall (i,j) \in A, \ \forall k \in \{1, ..., \chi(G)\} \tag{3}$$

STEP 3. Calculating scheduling margin

$$\Delta\Phi_1 = \Phi_1 - uc_1 \tag{4}$$

$$\Delta\Phi_2 = \Phi_2 - uc_2 \tag{5}$$

$$...$$

$$\Delta\Phi_{\chi(G)} = \Phi_{\chi(G)} - uc_{\chi(G)} \tag{6}$$

STEP 4. Calculating $\Delta\Phi_{kmax}, \ \Delta\Phi_{kmin} \ and \ \Delta\Phi_{decision}$

$$\Delta\Phi_{kmax} =^{argmax}_{k=1,...,\chi(G)} (\Delta\Phi_k) \tag{7}$$

$$\Delta\Phi_{kmin} =^{argmin}_{k=1,...,\chi(G)} (\Delta\Phi_k) \tag{8}$$

$$\Delta\Phi_{decision} = \Delta\Phi_{kmax} - \Delta\Phi_{kmin}; \quad k \in \{1, ..., \chi(G)\} \tag{9}$$

STEP 5. Updating $\Delta\Phi_{kmax}, \ \Delta\Phi_{kmin}$

$$\Phi_{kmax} = \Phi_{kmax} - \frac{\Delta\Phi_{kmax}}{2}(\Delta\Phi_k); \quad k \in \{1, ..., \chi(G)\} \tag{10}$$

$$\Phi_{kmin} = \Phi_{kmin} + \frac{\Delta\Phi_{kmax}}{2}(\Delta\Phi_k); \quad k \in \{1, ..., \chi(G)\} \tag{11}$$

end

Solutions (rate, route, and allocated slots)

$\lambda_f, \ x_{ij}^f \ and \ \Phi_k$

Figure 6: Iterative Heuristic Algorithm

At the initial stage, all of the slots in a frame are evenly distributed to each link group in IS and the available link capacity of the link (i, j), u_{ij}, is set to this value. The u_{ij} value indicates the available link capacity, excluding the interference from the other links. If the number of flows passing on a specific link increases, that link becomes a bottleneck, because the available capacity cannot be dynamically adjusted depending on the traffic load. In this case, we have to assign more time slots to that link or discover a new route under the network traffic conditions in order to prevent any bottleneck problems and increase system throughput. The proposed algorithm is shown in Fig. 6.

The basic idea shown in Fig. 6 enables the minimum available bandwidth to be maximized in networks. To do this, the proposed algorithm forces the traffic to be distributed over all links and prevents a specific link from being overloaded.

According to the proposed algorithm, the same number of slots are assigned to all IS_k in IS as shown in (12) at the initial stage. So, the u_{ij} value is the same for all of the links at the initial stage as in (13). Under this initial assignment, the route discovery is performed using the integer linear programming. After finding the best path, the slots assigned to each link are adjusted by the bisection method to distribute the remaining spare capacity evenly throughout all of the links. This can be achieved by giving some slots from links with low loads to other links with heavy loads. After adjusting u_{ij} of each link (i, j), the new route discovery is performed using integer linear programming, and the slots are reassigned. These steps are repeated until all of the links have almost the same remaining spare capacity and the objective function given in (1) is maximized.

$$\phi_k = \frac{C}{\chi(G)} \qquad ; \forall k \in \{1, \ldots, \chi(G)\} \tag{12}$$

$$u_{ij} = \phi_k, (i,j) \in IS_k \qquad ; \forall (i,j) \in A, \forall k \in (1, \ldots, \chi(G)\} \tag{13}$$

For example, we can get 14 independent link sets based on the '1-distance edge coloring' in the wireless mesh networks in Fig. 7. Then, k value of IS_k is 14, and IS can be denoted as follows.

$$IS = \{IS_1, IS_2, IS_3, IS_4, IS_5, IS_6, IS_7, IS_8, IS_9, IS_{10}, IS_{11}, IS_{12}, IS_{13}, IS_{14}\}$$

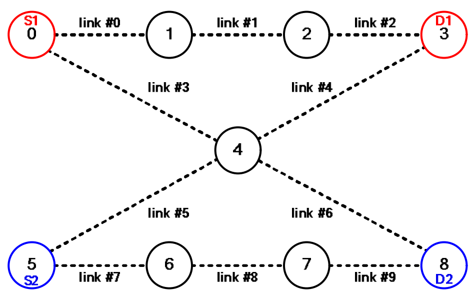

Figure 7: Butterfly Topology

We assume the number of slots in a frame, *C*, is 1000. So, the initial u_{ij} value of each link (*i, j*) is 1000/14 = 71 slots. This means 71 slots are assigned to all links initially. Under this link capacity, we can find an initial route to maximize the sum of throughput of all flows. The number of assigned slots to links belonging to IS_k is ϕ_k, where the edge chromatic number, $\chi(G)$, is 14. If the ϕ_k value is not an integer, it is approximated to an integer not exceeding ϕ_k, and a few slots are not used. Using the previous equations, the number of used slots on the link (*i, j*), C_{ij}, is obtained from (14). This value is used for ongoing resource assignment procedure.

$$C_{ij} = \sum_{f=1}^{F} \lambda_f x_{ij}^f \quad ; \forall(i,j) \in A \tag{14}$$

The number of the actual assigned slots for the links belonging to IS_k, uc_k, is obtained from C_{ij}, as shown in (15). It is the maximum of the number of the used slots on all of the links belonging to IS_k.

$$uc_k = {}^{argmax}_{(i,j)\in IS_k} (C_{ij}) \quad ; \forall(i,j) \in A, \forall k \in \{1,\ldots,\chi(G)\} \tag{15}$$

For example, if link #0 and #7 belonging to IS_1 use 60 slots (C_{ij}, = 60) and 45 slots (C_{ij}, = 45), respectively, then both links need at least 60 slots for interference-free transmission with other links belonging to other IS_1 links. So, $uc_1$is 60 based on equation (15). Other uc values, $uc_2 - uc_{14}$, belonging to $IS_2 - IS_{14}$ can also be obtained from (15).

The number of unused slots can be obtained from (16) after assigning the flow data on the links belonging to IS_k. The $\Delta\phi_k$ in (16) means that the number of the unused slots for the data transmission on the links with color *k*. This value is used for the ongoing re-allocation of the slots on every link based on real traffic patterns. From (16), we can figure out how many slots are free in some links and which links need more slots.

For example, if we assign $uc_1 = 60$ from (15), then $\Delta\phi_1 = 11$ can be obtained from (16), because $\phi_1 = 71$ at the initial stage. Then, $\Delta\phi_2 - \Delta\phi_{14}$ of $IS_2 - IS_{14}$ can also be obtained from (16).

$$\Delta\phi_1 = \phi_1 - uc_1, \Delta\phi_2 = \phi_2 - uc_2, \quad \ldots \ , \Delta\phi_{\chi(G)} = \phi_{\chi(G)} - uc_{\chi(G)} \tag{16}$$

At the initial stage, all ϕ_k values of each IS_k are the same as in Table 1, but as the iteration is being executed, the slots on the links with low traffic loads are transferred to links with high traffic loads. So, ϕ_k and $\Delta\phi_k$ values of each IS_k is changed during each iteration. If we get all of the $\Delta\phi_k$ values of each IS_k from (16), $\Delta\phi_1 - \Delta\phi_{\chi(G)}$, the number of slots assigned to link (i, j), u_{ij}, can be adjusted and a new route discovery for increasing flow's transmission rate will be executed under this new assignment condition during the next step. These iterations are executed until the unassigned remaining slots are evenly distributed over all links and the objective function of maximizing system capacity is achieved.

First of all, the maximum value from $\Delta\phi_1$ to $\Delta\phi_{\chi(G)}$, $\Delta\phi_{kmax}$, and minimum value, $\Delta\phi_{kmin}$, should be found from (17) and (18). IS_k, which has $\Delta\phi_{kmax}$ ($\Delta\phi_{kmin}$), has the largest (smallest) number of unused slots.

$$\Delta\phi_{kmax} = \underset{k=1,\dots,\chi(G)}{argmax} (\Delta\phi_k) (17), \Delta\phi_{kmin} = \underset{k=1,\dots,\chi(G)}{argmin} (\Delta\phi_k) \quad (18)$$

The proposed algorithm first discovers a route for the maximum flow capacity under the condition of the same slot assignment at the initial stage, as shown in Fig. 9. If the path of the flow is determined, the used capacity uc_k and the scheduling margin $\Delta\phi_k$ on each link is calculated. After that, slot reassignment is performed by moving some slots from links belonging toIS_k with $\Delta\phi_{kmax}$ to links with $\Delta\phi_{kmin}$. These steps are iterated until the $\Delta\phi_{decision}$in (19) is less than the predefined value ϵ as shown in (20). This condition means all of the links in networks have nearly the same number of remaining available slots. The sum of all of the flow capacity can be maximized with this condition, and we can finally obtain λ_f, $x_{ij}^f$and ϕ_k finally. But, if $\Delta\phi_{decision}$ exceeds ϵ as in (21), then the route discovery and the slot re-assignment should be done using (22) and (23). That is, ϕ_k with $\Delta\phi_{kmax}$ is reduced by half of $\Delta\phi_{kmax}$, and $\frac{\Delta\phi_{kmax}}{2}$ slots are added to links belonging to IS_k with $\Delta\phi_{kmin}$ as in (23).

$$\Delta\phi_{decision} = \Delta\phi_{kmax} - \Delta\phi_{kmin} \quad ; k \in \{1, \dots, \chi(G)\} \quad (19)$$

$$\Delta\phi_{decision} \leq \epsilon \quad (20), \quad \Delta\phi_{decision} > \epsilon \quad (21)$$

$$\phi_{kmax} = \phi_{kmax} - \frac{\Delta\phi_{kmax}}{2} \quad ; k \in \{1, \dots, \chi(G)\} \quad (22)$$

$$\phi_{kmin} = \phi_{kmin} + \frac{\Delta\phi_{kmax}}{2} \quad ; k \in \{1, \dots, \chi(G)\} \quad (23)$$

Table 1 shows the initial link coloring and scheduling example for networks having $\chi(G) = 14$ in Fig. 7.

The $\pi(schedule) = \pi(\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7, \phi_8, \phi_9, \phi_{10}, \phi_{11}, \phi_{12}, \phi_{13}, \phi_{14})$ represents the number of slots to each IS_k.

Table 1: Initial link scheduling example for network in Fig. 7

Indep. Set	links	π(schedu	Initial TSs	Indep. Set	links	π(schedu	Initial TSs
IS_1	*link #0, link #7*	ϕ_1	71	IS_8	*link #10, link #17*	ϕ_8	71
IS_2	*link #1, link #8*	ϕ_2	71	IS_9	*link #11, link #18*	ϕ_9	71
IS_3	*link #2, link #9*	ϕ_3	71	IS_{10}	*link #12, link #19*	ϕ_{10}	71
IS_4	*link #3*	ϕ_4	71	IS_{11}	*link #13*	ϕ_{11}	71
IS_5	*link #4*	ϕ_5	71	IS_{12}	*link #14*	ϕ_{12}	71

IS_6	*link #5*	ϕ_6	71	IS_{13}	*link #15*	ϕ_{13}	71
IS_7	*link #6*	ϕ_7	71	IS_{14}	*link #16*	ϕ_{14}	71

Performance Analysis

In this section, after we perform the mathematical modeling of the proposed JRS-SG algorithm by using a cross-layer optimization method, we analyze its performance by utilizing an optimization analysis tool. First, we explain the operation of the proposed algorithm compared to the shortest-path first routing algorithm using 'butterfly topology', as shown in Fig. 7. After that, we compare the performance of the proposed algorithm and the simulation result of IEEE 802.11s network simulator (ns-2) [22] which implements a shortest-path first routing algorithm on a multiple gateway SmartGrid network proposed in this paper as shown in Fig. 12. By comparing the results of total transmission rate $\sum_{f=1}^{F} \lambda_f$ and routing paths of given flows for the two algorithms, we show that the proposed algorithm in this paper can greatly improve the total transmission capacity of the network by properly distributing the traffic load at the bottleneck point in the multi-gateway SmartGrid network.

Butterfly Topology

In Fig. 7, it is assumed that there are two traffic flows on a butterfly topology which has a bidirectional link between nodes. The two flows have sources nodes *S1*, *S2* and destination nodes *D1*, *D2*. It is also assumed that they have equal node distances and equal transmission rates. We use this 9-node butterfly topology to explain the repeated procedures of the algorithm proposed in this paper, since it has low complexity in order to be easily understood.

If a shortest-path first routing algorithm is applied to the topology in Fig. 7, the routing result becomes two paths traversing node 4 without considering interference, as denoted in Fig. 8. In this case, each flow can only use 1/4 of the time slots of the whole frame due to the interference of the other flow. Thus, each flow utilizes 250 time slots and total sum $\sum_{f=1}^{F} \lambda_f$ becomes 500 slots.

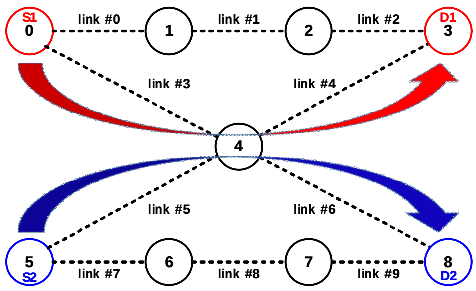

Figure 8: Results from Shortest-Path First Search

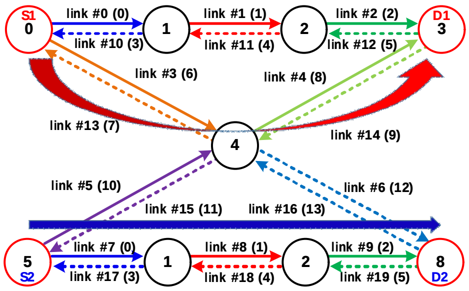

Figure 9: Results from the First Iteration of the Proposed Algorithm

However, if we use another routing algorithm that considers interference between traffic flows, it is possible to improve the total transmission rate. Fig. 9 represents the first iteration result of the routing path of the proposed algorithm. The link color corresponding to each IS_k is different from each other according to the initial result of the link scheduling. Here, we use the '1-distance edge coloring' algorithm and the number in the parentheses, which means the kind of different link color. The links corresponding to the same IS_k have the same color, and the total number of link colors are 14.

At the initial stage of the proposed algorithm, 71 timeslots are uniformly allocated to u_{ij} of each IS_k, because the link capacity of 1000 timeslots is divided by the number of 14 colors. Thus, two flows are transmitted without each other's interference, and the total sum $\sum_{f=1}^{F} \lambda_f$ becomes 142 timeslots. However, through the iterative procedures of routing and resource allocation of the algorithm, we can improve the total sum $\sum_{f=1}^{F} \lambda_f$ upto 650 timeslots, as shown in Fig. 11. The final routes of the two flows computed by the algorithm become two paths shown in Fig. 10.

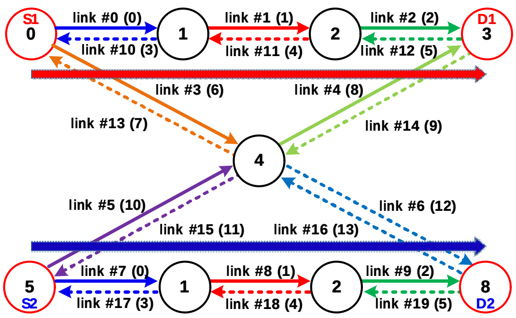

Figure 10: Final Routes of the Proposed Algorithm

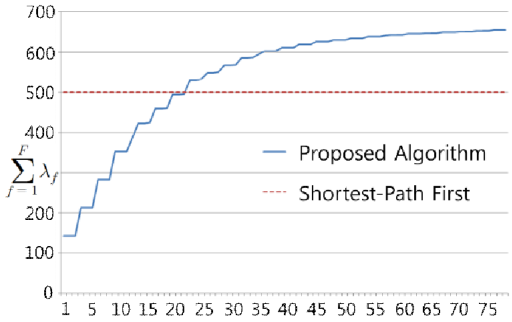

Figure 11: Changes of total transmission rate by Iterating the Proposed Algorithm

Multi-Gateway Smart Grid NAN Topology

In this section, we compare the performances of the proposed JRS-SG algorithm and shortest-path first routing algorithm based on IEEE 802.11s for the multi-gateway SmartGridNAN networks considered in this paper. We assume the link speed 6 Mbps in the network. The analysis and simulation results show that the proposed algorithm is able to improve the total transmission rate, because the algorithm performs resource allocation and routing simultaneously and can properly distribute heavy traffic load at the bottleneck gateway in SmartGrid networks better than shortest path routing. For performance comparison, we utilize a multi-gateway topology in which every node has bidirectional link and equal distance between nodes, as shown in Fig. 12. In this topology, we intentionally generated uplink traffic flows to create a bottleneck in one gateway by traffic concentration. We performeda simulation initially using two flowsand increased the number of flows one by one.

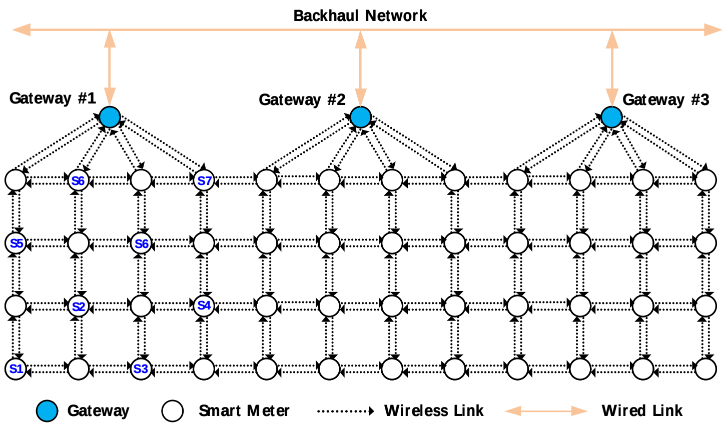

Figure 12: Proposed Multi-Gateway Smart Grid Topology

Fig. 13 shows the variation of the total sum of traffic according to algorithm iteration. One can see that the transmission rate increases as the number of flows increase. This means that increased flows can take routes that have less interference through the network uniformly. Thus, performance increases from the spatial reuse effect. The proposed algorithm effectively prevents traffic concentration into some special links and mitigates gateway bottlenecks, even when the traffic flow increases. Fig. 14 shows the performance comparison between the proposed algorithm and the IEEE 802.11s. Here, we compare the variation of the total sum $\sum_{f=1}^{F} \lambda_f$ according to the increase in the number of flows under the same simulation environment as in Fig. 12. For the simulation of IEEE 802.11s, we use Constant Bit Rate (CBR) traffic and properly control the amount of traffic to keep each transmission saturated.

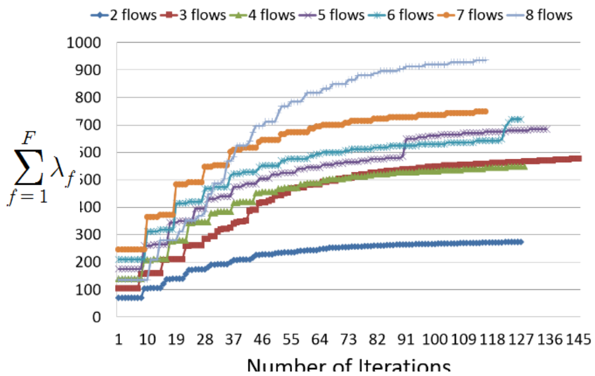

Figure 13: Comparison of $\sum_{f=1}^{F} \lambda_f$accord- ing to the number of Flows for the Proposed Algorithm

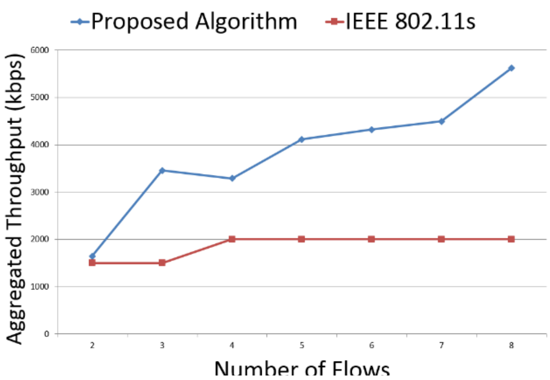

Figure 14: Comparison of $\sum_{f=1}^{F} \lambda_f$accord- ing to the number of Flows in the IEEE 802.11s and the Proposed Algorithm

Fig. 14 shows the total transmission rate $\sum_{f=1}^{F} \lambda_f$ of the IEEE 802.11s shortest-path routing is saturated when the number of flows increases over some specific value, but that of the proposed algorithm can grow further until the overall network resources are fully saturated. While the traffic in IEEE 802.11s is concentrated to a specific gateway and causes the bottleneck phenomenon, the routing in the proposed algorithm properly distributes the traffic load by controlling the routing path through the entire network. Thus, the proposed algorithm can accommodate a larger amount of traffic until the entire network reaches saturation.

In Fig. 15, we present the routing results of the proposed algorithm for 8 flows, starting from ‘Gateway #1 region’. The traffic flows are distributed almost evenly throughout the networks. If the shortest-path routing is applied to this problem, then all of the routing paths will be directed to Gateway #1 and may cause a bottleneck.

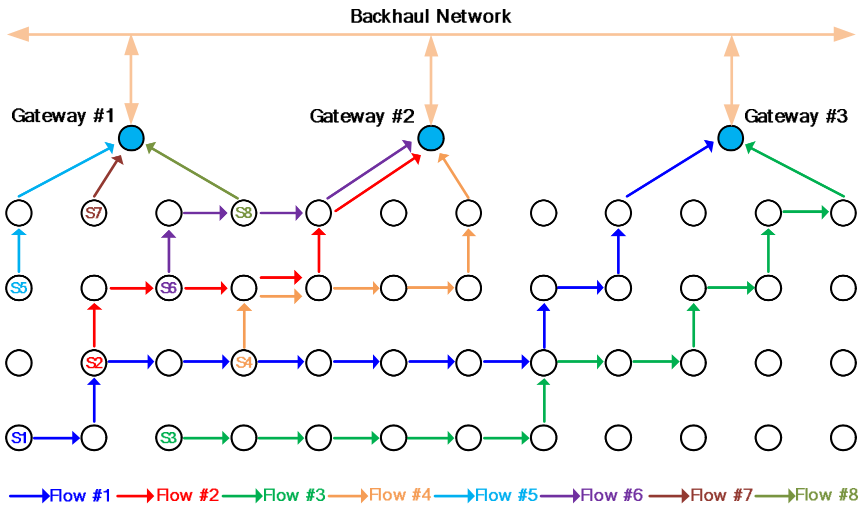

Figure 15: The Routing Results from the Proposed Algorithm

Conclusions

In this paper, we have proposed an optimization algorithm, JRS-SG,which properly controls resource allocation and traffic routing consistently in order to improve the total transmission capability using a cross-layer design for the multi-gateway SmartGrid networks based on the wireless mesh networks. The proposed algorithm combines network routing and a resource allocation strategy that performs dynamic resource allocation by transfering the remaining bandwidth resources of unused links to congested links. So, it can enhance transmission performance and achieve proper load balancing all over the networks in which there are many bottleneck points due to increasing traffic flows.

In this paper, we have demonstrated that the proposed cross-layer design method improves the transmission capability and proper load balancing for the SmartGrid networks of butterfly topology and multiple gateway topology through mathematical analysis and simulation. Also, by comparing its performance with that of IEEE 802.11s HWMP routing, we have shown that the proposed algorithm can accommodate many more traffic flows for the same network, because it properly distributes the traffic load all over the network and utilizes the bandwidth resources rather uniformly. This algorithm can be utilized for the design of the network in which rough traffic predictionsare possible for the number of traffic flows and their characteristics, such as bandwidth requirement, burstiness and so on. If any traffic situation changes greatly, the resource allocation and the routing paths for the entire network are easily recomputed and reconfigured by a central controller. The proposed mechanism is appropriate for the network design of which traffic requirement is generally predictable, as in the design of the SmartGrid networks for some residential areas.

For future studies, we plan to extend the proposed algorithm in this paper to include multi-interface multi-channel nodes in the multi-gateway SmartGrid networks and analyze its performanceimprovement.

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