Packet Switched Power Network with Decentralized Control Based on Synchronized QoS Routing

Hisayoshi Sugiyama
Dept. of Physical Electronics and Informatics, Osaka City University
Osaka, Japan
sugi@info.eng.osaka-cu.ac.jp

Abstract — Decentralized packet switched power network is proposed based on synchronized QoS routing in data packet networks. An electric energy packet network has advantages of affinity with decentralized generating plants such like a photovoltaic power generation and of manageability of energy coloring in the process of power distribution. However, differing from a data packet network, it is required that any packet discard should not be occurred during the network operation and that extraneous loss by Joule heat should not be generated in case of mutual packet transmissions. In this paper, it is described that the proposed method resolves the requirements on the electric energy packet network and that reliability of the network in disasters is obtained as an inherent advantage of a decentralized scheme.

Keywords: *smart grid, electric energy packet, QoS, synchronized routing.*

I. Introduction

Smart grid technologies have been investigated for the purpose to enhance efficiency and reliability of current power systems with smooth integration of renewable and alternative energy sources[1]. As one of the basics of this upcoming power grid, electric energy packet transmission is proposed to distribute electric power over the network[2], [3], [4].

The power networking with electric energy packets has advantages as follows:

1) It has affinity with decentralized generating plants such like a photovoltaic power generation. In current power systems, reverse power flow from decentralized plants causes voltage fluctuations that degrade power source quality to neighboring customers[5]. On the other hand, reverse power flow with electric energy packets never cause such voltage fluctuations in principle.
2) It has manageability of energy coloring in the process of power distribution. Energy coloring is defined as the identification which power source the electric energy is generated by[6], [7]. This information assists customers to select renewable or alternative energy sources if they are conscious of greenhouse gas emissions or such global scale problems.

However, differing from data packet networking, that with electric energy packets must resolve following requirements:

1) An electric energy packet should not be discarded. During data packets transmission, some packets possibly be discarded and retransmitted according to the protocol of TCP or so. This discarding is caused by a packet collision or a buffer overflow at some relay node within the transmission path. On the other hand, because an electric energy packet discard directly mean power dissipation and it cannot be recovered, the packet collision and the buffer overflow should not occur in electric energy packet networking in order to avoid the packet discards.
2) Two equivalent electric energy packets must be canceled each other if they are transmitted bidirectional through the same power link[1]. The payload of an electric energy packet is only a power and cannot be distinguished from that of other packets. Therefore, it makes no meaning to transmit two packets bidirectional if they have the same amounts of payload, and they must be canceled each other in order to reduce the extraneous loss by Joule heat within the power link.

In addition, because the upcoming power grid is desired to be reliable against disasters or terrorisms, the basic scheme of the grid must be decentralized where every unit consisting the system performs autonomously without controls from some center stations.

However, these requirements have not been considered well in papers that focus on the electric energy packet transmission in power systems. In [2], electricity-power-packet (EPP) is proposed as a basis of supplemental power network that assists cooperative operations among IOUs and IPPs. In [3], in-home power distribution systems are proposed with power packet dispatching system for the purpose to reduce the fluctuations of output power, frequency, and voltage in home power network. In [4], the packet power grid (PPG) is proposed based on the analogies with telecommunication network and a hypothetic PPG architecture is suggested in relation with the components of current data network.

In contrast to these works, this paper focuses on the

[1] A power link means an electric wire connecting two electric energy routers or end users. This link corresponds with a data link in a data packet network.

requirements themselves on the electric energy packet networking above mentioned, and proposes *synchronized power network* for the upcoming power grid with electric energy packet transmission. This scheme of power networking is an application of *synchronized QoS routing* in the area of data packet networking[8], [9]. The synchronized QoS routing has been investigated to assure transmission bandwidth in wireless ad hoc networks. Taking over the aspects of this routing scheme in data packet transmissions, the synchronized power network resolves the requirements on the electric energy packet networking as follows:

1) Because the synchronized QoS routing causes no packet discarding during the network operation, the first requirement is resolved immediately.
2) In the synchronized QoS routing, every packet has the same amount of payload and every node comprehends the number of packets to be transmitted or received within each synchronized frame structure. Therefore, the second requirement can be resolved based on these aspects of the routing scheme.

In addition, because synchronized QoS routing is based on pure decentralized scheme where each node can perform autonomously only with data exchanges among neighbors, the synchronized power network provides the upcoming power grid with inherent reliability of decentralized systems against disasters or so.

In section 2, the network configuration and the essential components of the synchronized power network are introduced. In section 3, the operation of the network with proposed scheme is explained where the requirements on the power packet networking are resolved in principle. In section 4, the transmission capacity of the synchronized power network is estimated by computer simulations for the purpose to confirm the network performance and to design the system in detail.

II. Basics of synchronized power network

In this section, the basics of the synchronized power network are explained. The basics consists of the network configuration, the frame structure for packet transmission, and the electric energy router for packet switching.

A. Network configuration

An example of the configuration of the synchronized power network is shown in Fig. 1. As shown in the figure, this network consists of end users, electric energy routers, and an electric energy gateway. The end users usually consume power supplied from neighboring electric energy router connected with them. However, some of the users possibly be decentralized plants that reversely transmit power to the network through the router. The electric energy router controls these energy flows by packet switching. The electric energy gateway connects this synchronized power network with bulk or medium power network in outer areas.

Actually, the end user means an electric energy gateway of home network of each user. This hierarchical network structure can be extended to the whole power distribution system including bulk or medium power network to be an integrated synchronized power network.

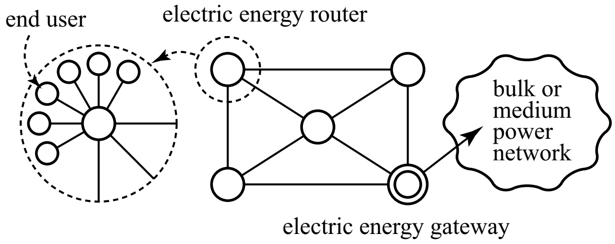

Fig. 1. An example of synchronized power network.

B. Synchronized frame structure

In synchronized power network, time axis is divided into frames of equivalent length and each frame is equally subdivided into N energy slots. Each frame is synchronized among all users and routers in the network. Electric energy packets are transmitted at some of energy slots in the synchronized frame. Figure 2 shows this frame structure[2].

Payload amount of electric energy packets are assumed to be the same. Therefore, the number of energy slots in one frame used for the packet transmission specifies the total power transmission. Because of this reason, from now on, the amount of power at each electric power transmission is denoted by the number of energy slots in one frame.

As mentioned in the next section, positions of energy slots for the packet transmission in each frame are reserved exclusively throughout the transmission path from the source to the destination. In addition, number of packets buffered in every router does not exceed N. Therefore, an electric energy packet discard caused by a packet collision or a buffer overflow never occur in principle in the operation of synchronized power network.

C. Electric energy router

In the original scheme of synchronized QoS routing that assumes wireless networking, each router can use only one slot at one time to receive or transmit a data packet. Whereas, in the synchronized power network, because the network is wired, more flexible router design is possible to process electric energy packet switching.

[2]This frame structure seems like that of TDMA where every node has its own position of data slot that is specified by a center station. In contrast, in the proposed scheme, every energy slot is shared among all nodes and reserved by a temporal user with pure decentralized process as described in the next section.

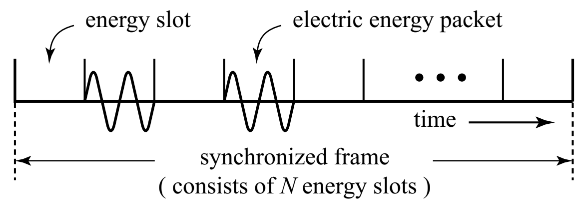

Fig. 2. Configuration of synchronized frame.

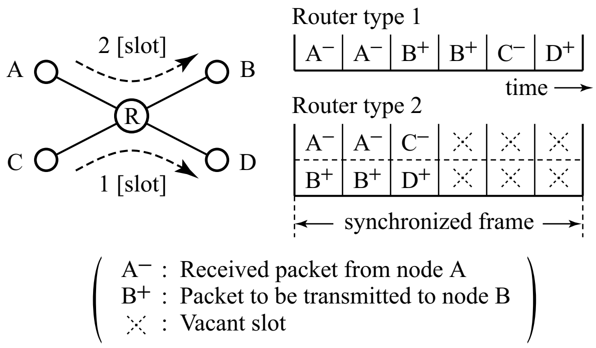

Fig. 3. An example of electric energy router operation with two types of router.

In this paper, the power packet switching with two types of electric energy router are assumed to be investigated. The first type is called as *Type 1*. This Type 1 router is equivalent to the router in synchronized QoS routing. Though this type of router cannot transmit and receive packet simultaneously, it can be constructed by only one system consisting of a power switch and a capacitor. This simple structure brings about the constructability of the router with small number of components and also brings the reliability and restorability on the router against disasters or such destructive affairs.

The second type is called as *Type 2*. The packet processing system is dualized in this type of router. Therefore, each energy slot can be used to packet transmission and reception simultaneously. Though the structure becomes complicated, this type of router improves slot utilization and therefore possibly increase transmission capacity of the network.

An example of the electric energy router operation with two types of router is shown in Fig. 3. Assuming that each frame is divided into six slots, two power transmission paths are indicated in the left side of this figure: node A to B with two slots, and node C to D with one slot. Here, two slots means that two electric energy packets are transmitted at two energy slots in each frame. Both of the paths are relayed by a router R. The difference of slot occupation of R depending on the router type is indicated in the right side of the figure.

For example, with router type 1, the packet reception from A (denoted by A^-) is done at the first two slots and these packets are transmitted to B (denoted by B^+) at succeeding two slots. One packet from C is relayed to D similarly[3]. On the other hand, with router type 2, the packet reception and transmission is done simultaneously as the chart indicates. The upper and lower area of the chart indicates the energy slots for reception and transmission, respectively. In this case, only three slots are used and the others are left vacant.

III. Operation of synchronized power network

As mentioned in section 1, electric energy packet discarding does not occur in the operation of synchronized power network. This scheme also makes possible to cancel bidirectional packet transmission that causes extraneous loss by Joule heat at power links.

In this section, these aspects of the proposed scheme in the network operation are explained. First, the *power transmission capacity table* is introduced as the essential component of the network operation. This component corresponds with the *bandwidth table* in the synchronized QoS routing in data networks. Then, mutual cancellation of electric energy packets is explained that becomes possible in the network operation based on the power transmission capacity tables.

A. Power transmission capacity table

In synchronized power network, each router and end user has its own power transmission capacity table. This table indicates the capacity of the transmission path to each destination (from now on, this capacity is called as the *channel capacity*) that can be reserved at the point of time. An example of the table is shown in Fig. 4.

In this example, a part of entries in the table of some node (assumed to be 'A') is indicated. In both of these entries, the destination (denoted by 'dst') of power transmission is node B as located at the first column. The second column 'nxt' and third one 'hop' means the next hop node and the hop count to the destination beyond the next hop, respectively. The fourth column 'slt' indicates the channel capacity by number of available slots for transmission in one frame. Succeeding columns denoted by *available slots* specify which slots can be used to transmit packets to the next hop node[4].

These contents of the power transmission capacity table are updated frequently by exchanging information among neighboring nodes in the network. The details of table construction are described in the original paper of the synchronized QoS routing[8]. The information exchange among nodes can be through optical fibers bundled with power links or other wireless channels that have been investigated as the basis of upcoming power grids[1].

An example of electric power transmission process based on this table is as follows:

1) Node A intends to transmit power to B by three packets in one frame.
2) Then, A tries to find an entry in its power transmission capacity table that satisfies the channel capacity with

dst	nxt	hop	slt	available slots							
				1	2	3	4	5	6	7	8
B	C	3	2	○	○	×	×	×	×	×	×
B	D	5	4	×	×	×	○	○	×	○	○

Fig. 4. An example of power transmission capacity table.

[3]This chart only indicates the slot occupations. Actually, each packet received is stored in buffer and transmitted at the next frame according to the process of synchronized QoS routing[8].

[4]Different positions of the slots may be used from the next hop to its further next one. This positions are determined according to the power transmission capacity table of the next hop node itself.

minimum hop count to the destination B[5].

3) As A finds the entry with next hop D, it selects three slots among four available slots indicated and sends a reserve signal to B via the next hop D.
4) In case that A receives the acknowledge signal from B, this means that the transmission path is reserved and A begins to transmit the intended amount of power to B. Or, if error signal is returned from some intermediate node within the path, this means that the reservation is failed and A must wait until a satisfiable entry appears in its table[6].
5) At the end of the power transmission, A sends a release signal to B then all of the reserved energy slots within the transmission path are released.

Because the power transmission capacity table is updated frequently, some trouble occurring in electric energy routers or power links within the transmission path will soon affect the table to be changed accordingly. In this case, node A reselects another satisfiable entry in its table to continue the power transmission, or cease it if such entry cannot be found. In both cases, successive discardings of electric energy packets will not occur. In addition, these local troubles in the network may not bring about regional outage of the power system because of the decentralized property of the update process of power transmission capacity table.

B. Mutual cancellation of electric energy packets

In synchronized power network, bidirectional packet transmission means that a number of energy slots are used to transmit electric energy packets bidirectionally in the same frame in a power link. This bidirectional transmission of packets does not occur between an end user and an electric energy router. This is because the end user only receives packets from an neighboring router for his power consumption or reversely transmits packets to the router if he has enough power generated by his plant. These operations do not overlap each other.

On the other hand, bidirectional packet transmission possibly occurs at a power link between routers. An example is shown in Fig. 5. In this figure, node A transmits electric power by four energy slots in one frame to B via router E and F. Similarly, node D transmits three slots to C via F and E. These elemental power transmissions are indicated by dashed arrows in the figure. In this case, bidirectional packet transmission occurs between router E and F.

[5]In the network shown in Fig.1, node A corresponds with one of the electric energy routers because any of them has plural next hops. In contrast, because every end user indicated has only one next hop, the user has only one entry in its table toward each destination 'dst' and cannot select another one.

[6]This failure possibly be caused by another reservation signal precedently cross the transmission path from A to B. Similar problem occurrings in a channel reservation process can be reduced by more frequent update of power transmission capacity tables.

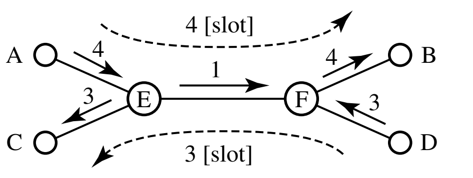

Fig. 5. An example of mutual cancellation of electrical energy packets.

However, because these elemental power transmissions relayed by routers E and F are partitioned by synchronized frames, these routers can eliminate same number of bidirectional packets in each frame cooperatively. This cancellation of bidirectional packets changes the packet flow to unidirectional and reduces the number of slots of packet transmission between the routers. In this case, the mutual cancellation of electric energy packet between the routers results in one slot of electric energy packet transmission from E to F as indicated by solid arrows in Fig. 5.

Though the actual packet flows are changed by this mutual cancellation, virtual flows sill remain as indicated by dashed arrows and are accessible as a data stored at the routers. Therefore, energy coloring is still possible based on the virtual packet flows even after the mutual packet cancellation.

IV. Network capacity estimation

As described in the previous section, the power transmission capacity table of each node plays an essential role in the operation of synchronized power network. However, its construction algorithm is available only when all of the routers are type 1 and mutual cancellations of packets are not executed throughout the network operation. In this case, the construction algorithm of the table is equal to that in the synchronized QoS routing[8].

Therefore, it must be estimated first that which router between type 1 and 2 is preferable for the network operation. Then, the construction algorithm for the power transmission capacity table is to be designed with the preferred type of routers and mutual packet cancellations. In this estimation, the tradeoff is essential between the constructability and derivative qualities of the type 1 router and the expected performance of networking brought by type 2 routers.

In this section, as a part of the estimation above mentioned, the examples of network capacity with these types of routers are measured by computer simulations. Though this measurement is on specific case of network configuration and system parameters, the results may roughly assist the estimation that which type of router is preferable to be investigated as the component of the synchronized power network.

A. Simulation system model

Figure 6 shows the simulation system model with twelve end users (node 1 $\sim$ 12) and five electric energy routers (node 13 $\sim$ 17). Differing from the example of system configuration shown in Fig. 1, electric energy gateway is omitted in this model.

The amount of each power transmission in this network is assumed to be N_p slots in one frame. This value N_p is fixed among all of the power transmissions. Whereas, the number N of energy slots in one frame is set to 20.

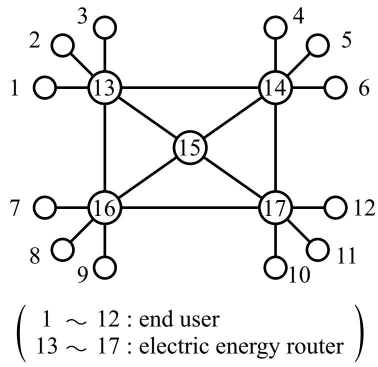

Fig. 6. Simulation system model.

The simulation procedure is as follows:

1) A half of the end users are selected randomly to be the transmitters of electric power and the residual ones are assumed to be the receivers.
2) Among these end users, a pair of transmitter and receiver is selected randomly and its power transmission path is searched through the routers.
3) This selection of a transmitter and a receiver and the establishment of power transmission path between them is repeated until the transmission path cannot be found any more.
4) Finally, the network capacity is determined as the summation of N_p over all of the established power transmission path.

In this procedure, the essential process is the search of each transmission path. In an actual power transmission in the synchronized power network, every end user and electric energy router simply refers its power transmission capacity table and determines the next hop node according to the table description. Whereas, in this simulation, because the power transmission capacity table is not available, the search of each transmission path is executed as follows:

1) All of the different paths are searched from the transmitter to the receiver according to tree search algorithm under the restriction of reasonable hop count. Each of these paths are referred to as a *potential path*.
2) Among the potential paths searched above, one with the smallest hop count is selected first. Then, through the selected one, allocations of energy slots are randomly tried repeatedly until the path with power amount N_p is found successfully or until the repeat count exceeds some predetermined value.
3) This search process is executed on every potential paths in order of its hop count until a path with N_p is found successfully. Or, if the path is not found finally, it is determined that the path does not exist between the transmitter and the receiver.

Though this search process of transmission path is based on random trials and therefore may not bring the optimal solution, the network capacity of the simulation model can roughly be estimated provided the number of search trials is adequately large.

B. Simulation results

As described in the previous subsection, the network capacity of the synchronized power network shown in Fig. 6 is derived from one run of the simulation. By averaging the derived values from many runs of the simulation, the success rate of electric power transmission is evaluated and is shown in Fig. 7.

The horizontal axis of this figure represents the total power transmission. Whereas, the vertical axis represents the success rate of electric power transmission. This rate means the possibility that all of the power transmissions are accomplished successfully in many random trials. Parameters are the type of routers and the power amount N_p of each transmission. Solid lines and dashed lines indicate the network performance with mutual packet cancellation and without that, respectively.

For example, focusing on the leftmost dashed line, 12[slots] of horizontal axis corresponds with about 60% of vertical axis. This means that the success rate of establishing three power transmission paths in the network is 60% provided the router type is 1, power amount of each path is 4[slots], and mutual packet cancellations are not executed.

On the other hand, the leftmost solid line shows that this undesirable success rate improves up to about 80% if mutual packet cancellations are executed. Similarly, the performance of mutual packet cancellations is confirmed in this figure regardless of parameters and the amount of total power transmission.

Figure 7 shows three points as follows:

1) The network capacity of synchronized power network is defined in relation with the success rate of electric power transmission. For example, when 80% is specified as the success rate, the leftmost solid line indicates that the network capacity is 12[slots].
2) The network capacity varies with the router type and the type 2 is preferable to type 1. This is because the utilization factor of energy slots in each frame improves with routers of type2 as shown in Fig. 3. In this figure, vacant slots can be used to other packet transmissions and therefore the utilization factor increases.

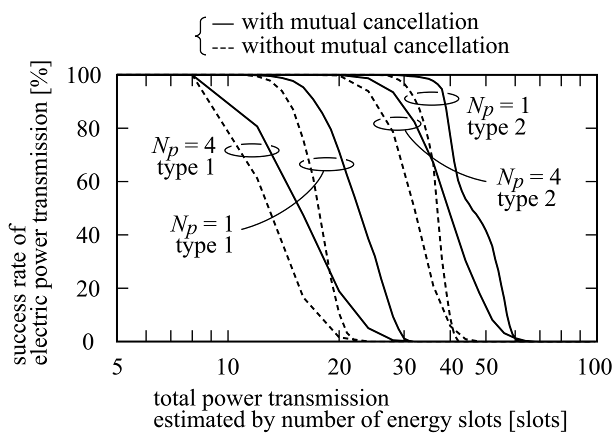

Fig. 7. Success rate of electric power transmission .

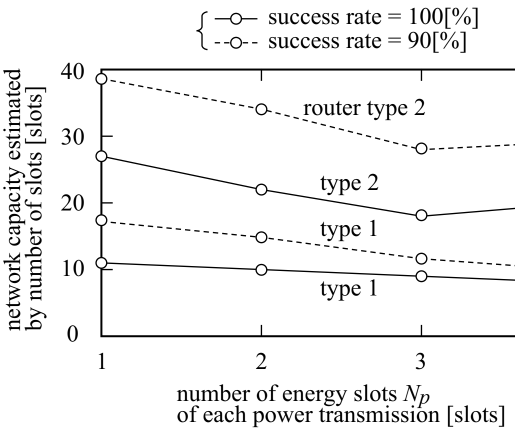

Fig. 8. Network capacity with two types of routers and mutual packet cancellation.

3) The power amount N_p of each transmission path also affects the network capacity and N_p of 1 is preferable to that of 4. This advantage of smaller N_p is not comprehensible as that of router type 2. This is because a group of packets of smaller number has higher possibility to occupy available slots in a frame. Therefore, the utilization factor of the slots increases with smaller N_p and the network capacity improves accordingly.

Regarding the first point above mentioned, the relationship of network capacity to the success rate and other parameters are derived and shown in Fig. 8. The horizontal axis represents the number of energy slots N_p of each power transmission. The vertical axis represents the network capacity in slots. Parameters are the router type and the success rate. Two cases of the success rate: 100% and 90% are adopted and are indicated by solid lines and dashed lines, respectively. Mutual packet cancellation is assumed to be executed.

This figure clearly shows that the network capacity improves with routers of type 2 almost twice or more than that with type 1 routers regardless of other parameters. The difference of success rate specified also affect the network capacity. However, the number of energy slot N_p of each power transmission does not affect the network capacity monotonically. Especially, when routers are type 2, the capacity when N_p equals 3 becomes lower than that when N_p equals 4 conflicting with the point 3 above described.

This may because each frame is assumed to have 20 energy slots and this value is not dividable by three slots of power transmission. Therefore, the utilization factor of energy slots possibly not increase with this value of N_p than the case with N_p of four that can divide the number 20 of slots in one frame.

N_p	1	2	3	4
router type 1	0.263	0.209	0.151	0.320
router type 2	0.302	0.301	0.242	0.242

TABLE I
RATE OF MUTUAL PACKET CANCELLATION OCCURRING.

This suggests that some restriction may be necessary on the slot number of each power transmission in the synchronized power networking.

Table I shows the rates of mutual packet cancellation occurring calculated from the simulation results. For example, the top left corner value 0.263 means that the cancellation has occurred in 26.3% of the power transmission paths established when N_p equals 1 and type 1 routers relayed them. These values roughly indicate the performance of Joule loss reduction in power links during the operation of the synchronized power network.

V. CONCLUSION

Decentralized packet switched power network: *synchronized power network* is proposed based on *synchronized QoS routing* in data packet networks. Taking over the aspects of this routing scheme for data packet transmissions, the synchronized power network resolves the requirements on the electric energy packet networking: packet discards should not be occurred and bidirectional packets transmission should be canceled each other. Moreover, system reliability inherent in the decentralized network is also obtained with the proposed scheme. The transmission capacity of the synchronized power network is estimated by computer simulations for the purpose to confirm the network performance and to design the system in detail.

In further studies, first, the construction algorithms of routers with mutual packet cancellation must be designed. Then, the network protocol appropriate for the power distribution system must be designed where a receiver of power transmission makes a call first in contrast to the data network where the transmitter makes it first. In addition, the protocol should allow that plural transmitters coordinately send their power to one receiver. Based on these studies, more detailed design of the network and its performance estimation should be executed further.

REFERENCES

[1] V. C. Gungor, et al., "Smart Grid Technologies: Communication Technologies and Standards", *IEEE Trans. Industrial Informatics*, Vol.7, No.4, pp. 529-539, 2011.
[2] J. Toyoda, H. Saitoh, "Proposal of an Open-Electric-Energy-Network (OEEN) to Realize Cooperative Operations of IOU and IPP," *EMPD'98*, Mar. 1998.
[3] T. Takuno, M. Koyama, and T. Hikihara, "In-Home Power Distribution Systems by Circuit Switching and Power Packet Dispatching," *SmartGridComm*, pp. 427-430, Oct. 2010.
[4] V. Krylov, D. Ponomarev, and A. Loskutov, "Toward the Power InterGrid," *IEEE Energy Conference*, pp. 351-356, Dec. 2010.
[5] H. Hatta, M. Asari, and H. Kobayashi, "Study of Energy Management for Decreasing Reverse Power Flow from Photovoltaic Power Systems," *SAE2009*, pp. 1-5, Sept. 2009.
[6] T. Kato, et al., "Appliance Recognition from Electric Current Signals for Information-Energy Integrated Network in Home Environmens," *Int. J. Assistive Robotics and Systems*, Vol.10, No.4, pp. 51-60, 2009.
[7] K. Saito and Y. Okabe, "Quality-Aware Energy Routing Toward On-Demand Home Energy Networking," *CCNC2011*, Jan. 2011.
[8] C. R. Lin and J. S. Liu, "QoS Routing in Ad Hoc Wireless Network", *IEEE J. Select. Areas Commun.*, Vol.17, No.8, pp. 1426-1438, 1999.
[9] H. Sugiyama, "Bandwidth Table Construction Regarding CDMA Interferences in Synchronized QoS Ad Hoc Networking," *ISABEL2011*, Oct. 2011.