Design and implementation of a power packet network protocol for flexible power routing

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Abstract: A power packet dispatching system and power packet routers with the power storages have been developed. The system is expected to reduce the number of wires, to provide energy on demand and to be applied to various system working with battery such as electric vehicles, robots and so on. In the previous studies, when a router receives a power packet, it is temporarily charged to the storage and immediately transferred to another router or a load. In this paper, we propose more flexible routing protocol for power packet dispatching systems. We have designed a novel protocol with several commands to operate the routers, to charge power to a storage of a router, to reproduce power packets using the charged power, and so on. We have implemented the proposed protocol on the power packet routers and shown that our protocol can transmit the power packets flexibly.

Key Words: power packet, routing, communication protocols, information networks

1. Introduction

The concept of power packets was proposed by Toyoda et al. [1]. The power packets will be dispatched according to the tags attached to the power. Recently, the technologies related to the wide-gap semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are significantly advanced. A gate driver device using a SiC JFET has been proposed in Ref. [2] and a power packet dispatching system has been realized by using it [3]. In Ref. [3], it has been confirmed that the power packets are correctly transmitted to the destination load via a small power packet network using two power packet routers and three loads.

In the conventional power transmission system, the power lines and the control signal lines are separately connected to the loads. In the power packet network, the transmitted power packets can contain information such as control signals or commands, therefore the power and control signals can be transmitted by using a common power line. This makes it possible to reduce the total number of the wire lines. In Ref. [4], advantages of the power packet routing for system control are described in detail.

As an application of the power packet networks, the trajectory control of a robot arm was realized.
in Ref. [5] by power packets. Reference [5] showed that the motor could be controlled without the control line by transmitting power packets directly to the motor in correct timing. Therefore, it is expected that the number of wires for closed equipment such as aircrafts, cars and robots can be reduced by the power packet networks.

In this paper, we design a flexible power packet routing protocol, which actively uses the storage of the power packet routers and the power packet header to contain various information and commands. The conventional power packet routing in Ref. [3, 5, 6] uses a general static routing protocol, and the power packet header contains only the address information of the destination load. On the other hand, our proposed protocol uses the header including various commands for flexible routing.

Our protocol and commands enables the following functionalities to charge the received power packets to the router’s storage, to reproduce and transmit a power packet using the charged power in the storage, to change the route to the destination by commands and so on, for flexible power exchange in the power packet network. Through these functions, a power packet router can temporarily become a power supply source. Therefore, our new protocol enables a short-delay power transmission by using a nearest router as a power source to the destination. Simultaneous transmission of multiple power packets is also possible by using multiple power packet routers as power sources. By using the source routing functionality of our new protocol, it becomes possible to select the best route to the destination according to the congestions or priority of the power to control systems.

This paper is organized as follows. In Section 2, we explain the outline of power packet network and application examples. In Section 3, we describe the details of the proposed protocol. In Section 4, the proposed protocol is designed and implemented on an actual power packet router device. Section 5 shows experimental results to verify the proposed protocol. Some conclusions are given in Section 6.

2. Power packet network and routing [3]

A power packet network shown in Fig. 1 is a network that supplies electrical power from the source to a target destination load. The power packet is generated at a power source with a mixer device. The mixers convert the power resource provided from the power source to the power packet. The power packets are forwarded to correct destinations at each power packet router. The power packet routers are able to recognize the information attached on the received power packet and to regenerate a power packet, which will be forwarded to the destinations. Figure 2 shows the structure of the power packet routers.

![Fig. 1. A power packet network [3].](image)

When the power packet is received, the controller recognizes the header part through the isolator. The controller operates the switches through the gate drivers based on the recognized information. The switches between the input ports and the storages, A, B, C and D, are used to select the storage to charge the power. The switches between the storages and the output ports, A’, B’, C’ and D’ are used to generate the power packets with tagged information and to transmit them to the destinations.

We use a power packet router device shown in Fig. 3, which has the structure described above. This power packet router has 4 inputs, 4 outputs and 4 storages. The capacity of each storage is 1000 µF.
GaN power semiconductor is used for the switching device. The router can input and output power packets with very high switching frequency up to several MHz. The controller part is realized by using FPGA. We implement the software for the FPGA in order to realize the proposed routing protocol.

3. Proposal of a flexible power packet routing

In this paper, we propose a flexible power packet routing protocol by using the current power packet router device. We actively use the storage in the power packet routers, for the flexible power packet routing. The power packet router has capability to recognize the attached information on the header part of the received power packet, not only the destination address of target load bit also the commands to the receivers. The power packet router also has the storage, and makes it possible to transfer the
power packet to the intended destination direction. We use the power packet router devices having the structure shown in Fig. 2.

The basic format of our proposed power packet is shown in Fig. 4. After the start signal, destination address, option length and options are contained in the header of the power packet. The power packet router recognizes the starting point of the packet header by reading the start signal. Addresses contained in the Destination address field are assigned uniquely to each router and each load. The power packet router decides the forwarding direction based on the destination address. If Option length field is not 0, the option will be also contained in the header. Some commands to the router or load will be contained in this Option field. Only the necessary information will be store in the Option by setting the Option length.

![Fig. 4. A proposed power packet format.](image)

The payload of the power is attached after the header. Although the footer was defined in Ref. [3], the proposed protocol in this paper omits the footer by defining the end of the packet that the number of bits 0 exceeded a certain number.

In the Option field, information corresponding to commands and operation is stored. The commands are assigned to each type of actions. By recognizing the commands, the router decides the operation to perform. Each command may have argument, which will be attached with Tags and Values. Tags are used to specify the argument type, and Values are argument itself having specified type. Concrete examples of Commands, Tags and Values will be described in the next section.

4. Design and implementation of the flexible routing protocol for power packet networks

In the proposed protocol in this paper, in addition to the normal routing operation, we define 4 types of commands. To charge the received packet to the storage, we defined the command, Charge. To reproduce the packet using the power charged in the storage, we define the command, Send. To decide the route at the source, we defined the command, SourceRouting. To send message or commands to the destination load, we define the command, Message.

The length of option is variable according to the Option length field. When the Option length is 0, option is omitted. The corresponding power packet is shown in Fig. 5. In this case, the power packet router behaves normal operation to forwards the packet to the destination. The power router transfers the packet to the output port corresponding to the destination address in the routing table.

![Fig. 5. A power packet for multi-hop routing destined to a load.](image)

When a power packet router receive the packet destined itself with the Charge command, it should charge the received power to its storage. The corresponding power packet having Charge command is shown in Fig. 6. The Charge command may have two types arguments. If the Storage ID is specified in the argument, the power packet router will charge the power packet to the specified storage. If the Voltage is specified in the argument, the power packet router will charge the power packet to the storage charged with the specified voltage.
When a power packet router receive the packet destined itself with the Send command, it should reproduce the power packets using the power stored in its storage and send them to the specified destination. The corresponding power packet having Send command is shown in Fig. 7. The Send command have seven types arguments. If the Storage ID is specified in the argument, the power packet router will use the power stored in the specified storage. If the Voltage is specified in the argument, the power packet router will use the power stored in the storage, which is charged with the specified voltage. If the Payload Length is specified in the argument, the power packet router will reproduce the power packet having the specified length of the payload. If the Number of Packets is specified in the argument, the power packet router will reproduce the specified number of power packets. If the Duration to Send is specified in the argument, the power packet router will periodically send the power packet during the specified duration of time. If the Start to Send is specified in the argument, the power packet router will start to send power packet periodically until it receives the Send command with the argument, Stop to Send. If the Destination Address is specified in the argument, the power packet router will send the reproduced packet to the specified destination address.

When a power packet router receive the packet with the SourceRouting command, it should forward the packet to the specified router in specified order. The corresponding power packet having SourceRouting command is shown in Fig. 8. The SourceRouting command should have arguments of the destination router addresses in specified order.

When a power packet router receive the packet with the Message command, it will forward it as normal routing. The Message command should contain the Message which should be transmitted to the destination.

These four commands are summarized in Table I. We assign 3 bits to express each command. The list of arguments and corresponding Tags are shown in Table II. We assign 4 bits to express each Tag to specify the arguments.

We have implemented the proposed protocol on a real power packet router devices, which has 4 input, 4 output ports and 4 storages. Since the router has 4 storages, we assign 2 bits for the storage ID. For the option length field, we assign 3bits to express 8 different length, 0, 8, 16, 24, 32, 40, 48 and 56 bits. If the actual length of Option did not become these numbers, we add bit 0 as the padding bits. For the payload length field, we assign 2bits to express 4 different length, 50bits, 100bits, 150 bits and 200bits.

5. Experiments for verification
In this paper, the protocol is verified by performing four experiments. The first experiment verifies the multi-hop routing of the power packets. The second experiment verifies the capability to the charge
### Table I. Examples of implemented commands and bit assignment.

| Command          | Bits | Functionality                                           | List of arguments                  |
|------------------|------|---------------------------------------------------------|------------------------------------|
| Charge           | 001  | Charge power to the destination route                   | StorageID                          |
|                  |      |                                                         | Voltage                            |
| Send             | 010  | Reproduce packets using charged power in router and     | Storage ID                         |
|                  |      | transmit it to destination                              | Voltage                            |
|                  |      |                                                         | Payload Length                     |
|                  |      |                                                         | Number of Packets                  |
|                  |      |                                                         | Duration to send                   |
|                  |      |                                                         | Destination Address                |
| SourceRouting    | 011  | Forward power packets in the order that the Source      | Routing Order                      |
| Message          | 100  | Transmit a message to the destination                   | Message                            |

### Table II. Examples of implemented tags attached for each argument and bit assignment.

| Argument          | Tag name | Bits | Detail                                                                 |
|-------------------|----------|------|------------------------------------------------------------------------|
| Storage ID        | Tag-Sto  | 0000 | Storage ID inside of the router                                        |
| Voltage           | Tag-Vol  | 0001 | Voltage of power packet, which can be used for Charge and Send         |
| Payload Length    | Tag-Leg  | 0010 | Payload length of reproduced power packet for Send command             |
| Number of Packets | Tag-Num  | 0111 | Number of reproduced and transmitted packets for Send command          |
| Duration to Send  | Tag-Tim  | 0100 | Length of time to periodically transmit packets for Send command       |
| Start to Send     | Tag-Sta  | 0101 | Start to periodically transmit packets for Send command                 |
| Stop to Send      | Tag-Stp  | 0110 | Stop to periodically transmit packets for Send command                  |
| Destination Address| Tag-Des  | 0111 | Destination address for Send command                                   |
| Routing Order     | Tag-DesOrd| 1000 | Order of router address for SourceRouting                               |
| Message           | Tag-Mes  | 1001 | Message or commands to destination                                     |

Power to the router storage. The third experiment verifies the capability to generate and transmit the power packets using charged power in the routers. The fourth experiment verifies the capability of the source routing. All experiments are performed on an experimental network topology shown in Fig. 9. Figure 10 shows the photograph of the experimental setting. The addresses of routers and loads are defined by 5bits digits as shown in Table III.

In the following experiments, the resistors are connected to the input side of the power packet router to protect the switches. We set the transmission rate at 1Mbps. The payload length is fixed at 100bits, therefore the length of one packet is around 100μs.

### 5.1 Experiment on multi-hop routing

We conduct an experiment to transfer packets generated by the mixer to the load 2. The transmitted packet format is shown in Fig. 5. By multi-hop routing among the routers A, B, D, F, the power...
packets will achieve to the load 2. Figure 11, shows the packets at the output time series of the mixer, the router A, the router B, the router D and the router F, respectively. As shown in Fig. 11, it is confirmed that the transmitted packet from the mixer could be forwarded towards the load 2 by multiple hops transfer.

5.2 Experiment on charging power packet to storage
We verify the functionality of the proposed protocol to charge the power of the power packet to the storage of the destination router. The packet containing the Charge command is transmitted from the mixer. The destination is the router E. The transmitted packet format is shown in Fig. 6.

In this experiment, the source mixer device continuously repeats transmission of the same packets that charge the storage of the router E. Figure 12 shows the time series of the packets with the
Charge command, which is forwarded to the router E, via the routers A and B. As shown in Fig. 12, it is confirmed that the packets with the Charge command can be successfully forwarded to the router E with carrying the command headers. The time series shown in Fig. 12 are not starting from the empty storage, but after receiving enough packets to charge the storage of the router E. Therefore, the voltage of the capacitor of the router E looks almost constant and almost same as the voltage of the Charge command packet.

![Fig. 12. The time series of the power packets containing Charge command, which are transmitted from the mixer to the router E, via the routers A and B.](image)

5.3 Experiment on reproducing and transmitting of power packets at a router

We verify the functionality to generate and to transmit the power packets using the power charged in a selected router storage. We send the power packets containing Send command, but which does not contain the power payload. The transmitted packet format is shown in Fig. 7. Figure 13 shows the time series of the power packets containing the Send command, which are transmitted from the mixer to the router E. It has been verified that the router E reproduces and transmits the power packet according to the received command, as shown in Fig. 13. Because we use the large capacity storage with 1000µF in the power packet routers and the short packets with around 100µs length, the output electrical charge of one power packet is relatively very small compared to the stored power in the storage. Therefore, the output from the storage looks almost constant.

![Fig. 13. The time series of the power packet containing the Send command transmitted from the mixer to the router E, via A and B. The router E reproduces the power packet according to the received command.](image)
5.4 Experiments on a source routing to enable change of the route
We verify the functionality source routing. We send the power packets containing SourceRouting command with the routing order of the router addresses. The transmitted packet format is shown in Fig. 8. Figure 14 shows the time series of the power packets forwarded in specified order to the Load 2 via A, B, E. This order is different from the preset routing order as the result shown in Fig. 11. Therefore, it has been verified that source routing is also possible in our design and implementation of the proposed protocol.

![Fig. 14. The time series of the power packet containing the SourceRouting transmitted from the mixer to the router Load 2, via A, B and E.](image)

6. Conclusion
In this paper, we have proposed a flexible power packet routing protocol. We have enhanced the functionalities of the router by actively using the storages in the routers. We have designed the protocols with a new packet format including the commands to the power packet routers. We have defined the commands to forward the packets to destinations, to charge the power to the router storage, and to transmit the power from the router storage. We have implemented these protocols using the real power packet router devices. Our experiments have verified that each functionality have successfully works in multi-hop power packet networks.

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