Router for Wireless Power Packet Transmission: Design and Application to Intersystem Power Management

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***Abstract*—Power supply for small-scale battery-powered systems such as electric vehicles (EVs and mobile robots) is being actively researched. The authors are particularly interested in energy management, which considers the interconnection of such systems close to each other. This allows for overall redundancy to be maintained without assuming excessive redundancy with individual power sources. Its implementation necessitates a high level of integration between power management and information and communication technology. As one of these methods, this study investigates energy management based on power packetization. When the individual systems to be connected have moving parts or are mobile, wireless power transmission is a promising method for power sharing. However, power packetization has so far only been considered for wired transmission. In this paper, the authors address the integration of power and information in wireless channels using power packetization. A power packet router circuit is proposed for the wireless transmission of power over multiple channels selectively. Furthermore, the authors demonstrate that the developed system can handle both wired intrasystem power management and wireless intersystem power sharing in a unified manner.**

***Index Terms*—Power packetization, Power sharing, Power routing, Power management, Wireless power transmission.**

I. Introduction

RECENT days have witnessed widespread use of electric power systems that are equipped with batteries and can thus be driven without relying on an external and large power grid. Common examples include electric vehicles (EVs) and mobile robots. While much effort has been dedicated to independent power management in such a system, another research trend is the management of a network of such systems. The authors refer to a minimum element of a system that can independently operate a local system throughout the paper. Constituting a networked system addresses shared redundancy of power source capacity as a whole system, rather than as each individual system. That is, when the power demand of one system temporarily increases, power can be supplied not only from the inside power sources but also from the power sources of the other connected systems [1]–[3].

Because local systems are spatially dispersed and can have a time-dependent supply/load profile, managing such a network necessitates advanced sensing, computation, and communication technologies [4]–[6]. Several proposals for power system management with information and communication technologies (ICTs) support have been made [2], [7], [8]. Among them, a power packet dispatching system is an encouraging proposal for the purpose. The system packetizes supplied power; that is, power is divided into time segments, each of which is associated with an information tag via a voltage waveform [9], [10]. Power packetization ensures that information exchange and power transmission occur concurrently in the physical layer, allowing for power management in a network without causing an imbalance in information and physical quantity processing. In the previous study, the authors' group developed a circuit called a power packet router [9]. The authors validated the concept of power packetization and routing with hardware configuration including the routers.

One advantage of power packetization is the ability to easily attach/detach local systems from a larger network. The use of time-division multiplexing and physical tag attachment ensures that each packetized power transfer is independent. In other words, power transfers between different pairs do not get mixed up even on the same power line but can be differentiated physically. This leads to realizing what could be called a plug-and-play from the perspective of power supply.

One difficulty here is that the power packet dispatching system has so far been developed using a wired connection for power transfer. Wireless power transfer (WPT) is a revolutionary technology for supplying power to mobile systems [11], [12], and is recently attracting more and more attention with the emergence of automotive applications [13]. It is beneficial for improved maneuverability of each local system to introduce the WPT to the power packet dispatching system for connections at the boundaries of the local systems. A typical example that benefits from this flexibility includes the vechicle-to-grid (V2G) or vehicle-to-vehicle (V2V) power transactions [14]–[17]. Although there are several power electronics approaches for power sharing between a fixed pair of vehicles, dynamic networking is still at the concept level or limited to the algorithmic proposal from the information system side.

This work was partially supported by JSPS KAKENHI 20H02151, JST-OPERA Program no. JPMJOP1841, and SIP Cross Ministerial Strategic Innovation Promotion Program no.18088028.

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Manuscript received April 19, 2021; revised August 16, 2021.

The target of this paper is to provide a physical basis for such concepts by means of power packetization. However, as discussed in Section IV, simply connecting a WPT circuit to a power packet system does not work in conjunction with packet-based power management in local systems. This research seeks to achieve on-demand power supply concentration and dispersion in the connected network of local systems while ensuring easy attachment/detachment between systems via a wireless connection.

The contributions of this paper are summarized in three as follows.

a) Proposal of the concept of packetized WPT: The concept of power packetization was already proposed for a wired system. This paper extends the concept to a wireless system, establishing a novel multiple input multiple output (MIMO) wireless power and information transfer (WPIT) system. The key concepts developed in this paper are

- MIMO wireless power transmission with robustness to dynamic network structure, and
- WPIT for selective power interaction between a particular pair of a source and a load designated by an information tag.

The superiority of the proposal over the existing approaches lies in their simultaneous realization. This leads to the unique achievement of the selective WPT over multiplexed channels, without compromising the coupling strength of each channel even under the dynamically changing geometrical relationship of the sender and receiver systems (see Section II and Section V-D for a detailed comparison with related works). They are the enabling technologies to push some emerging cyber-physical concepts in the energy management field such as V2G or V2V power transactions up to practical implementation by providing them with a physical basis.

b) Development of packetized WPT technology and routing circuit: A novel physical implementation is developed for the concept of packetized WPT. The realization of the aforementioned two key concepts requires

- method for the physical tag attachment and its reading dedicated to WPT, and
- circuit for integrating and separating power and information.

The former is addressed by an amplitude modulation (AM) tag attachment in a timeframe separate from but adjacent to a corresponding power pulse. Then, for the latter, a novel router circuit that achieves power and information handling on a wireless channel is developed. Particularly, the separate sub-circuits for power and information processing and their coordinated operation scheme are presented to ensure the wireless routing of each power packet according to its tag information. The selective transmission of wireless power packets is confirmed through an experiment with a connected system comprised of three local systems, each of which is equipped with the developed router.

c) Development of power management schemes and experimental demonstration: Based on the developed wireless power packet router, the authors also establish a power packet management scheme not only for wireless intersystem routing of power packets but also for an accommodation of both wireless intersystem and wired intrasystem power management. The latter gives a feasible measure for power sharing in the aforementioned cyber-physical applications. The feasibility of the proposed management is presented through an experiment in the following scenario; among a network of two local systems, each of which supplies a certain demand of its own load via wired connection, surplus power at one system is transferred to another.

II. Related works

There are several preceding research works regarding the aforementioned two fundamental technologies addressed in this paper: the duplex of multiple WPT channels and the WPIT. Table I summarizes the comparison of this paper and the state-of-the-art from this viewpoint. In addition, Table II presents representative pros and cons of the major schemes adopted in this paper and the related works.

Several proposals have been made for the duplex WPT by multiplexing in different domains: time, frequency, and space [19]–[22]. Among them, the authors focus on time and frequency domains since they exhibit high affinity with the magnet-resonant WPT. In magnet-resonant WPT, the frequency characteristics across the coupling channel are an essential factor for efficient power transmission. The frequency division multiplexing (FDM) is based on the individual design for different channels at their dedicated frequency subbands. This provides the advantage of the ease of receiver (RX) side control; the receiving operation becomes completely passive and no active control is required. The drawback is the inherently unavoidable interference between channels in a MIMO situation (see Section V-D for detailed evaluation). The bandwidth available for a certain application is usually restricted by laws or rules, which makes it difficult to avoid interference completely. Furthermore, the coupling network must be redesigned every time the network configuration, such as the number of channels and the geometric relationship between transmitters (TXs) and RXs, is changed. The TDM scheme overcomes this difficulty since multiple channels can share the exactly same frequency. The division is instead done with the time domain separation, relying on active control of the RX side with the support of accompanying information transmission. This active control can pose drawbacks mainly in practical implementation such as communication requirements between TXs and RXs and consequently a higher computational performance requirement for the RX side controller.

Regarding WPIT schemes, several proposals have been made in different contexts [4], [23]–[26]. These proposals can be classified into two categories: parallel or integrated transfer of power and information. The parallel technique essentially assumes that a power transmission channel has already been established. Then, information is transmitted concurrently with the power, or vice versa, regardless of the status of the other. In this scheme, the information transmission is active at any time as long as the channel is kept, which leads to its advantageous feature of maximum bitrate for the information channel. This fact, in return, brings difficulty in

Table I
COMPARISON OF THE PROPOSAL AND RELATED WORKS.

	Multiplex	WPIT	Modulation method
Proposed	TDM	Integrated	ASK
[19], [20]	FDM	-	-
[21]	TDM & FDM	-	-
[23]	-	Parallel	ASK
[24]	-	Parallel	OAM
[26]	-	Integrated	ASK, FDM

applications to the dynamically changeable configuration of multiple transmitters and receivers in a MIMO situation. It is necessary to establish a handshake between TXs and RXs in any way before starting the communication, but this method alone cannot do it since it assumes an already established channel. The integrated scheme addresses this drawback by combination with the TDM of power delivery. Letting each unit of power delivery be accompanied by information related to a channel handshake, the scheme is capable of selectively establishing a designated channel in a MIMO situation. The drawback of this scheme is less bitrate than the parallel scheme due to the separated time intervals for power and information transmission.

The two technical aspects, multichannel WPT and WPIT, have so far been studied separately, and their simultaneous realization was not discussed yet. The WPT standard called Qi adopts separate information and power transmission, sending information just before the start of power transmission [26]. However, it is a unidirectional signal from the RX to the TX for confirming that the receiver is Qi-compatible, not for selective power transfer in a MIMO situation. The TDM of WPT is discussed in [21]. However, they use FDM in combination for achieving selectivity of power transmission. This leads to the disadvantage of FDM, the complexity of frequency domain design, in return for the simplified control of the RX side.

On the contrary, the proposal of this paper fully exploits the advantage of the TDM, the unified frequency even for a MIMO situation. The requirement for active control of the RX side is addressed by the integrated WPIT. As mentioned above, the proposal possesses the disadvantage of less bitrate for information, so the suitability of the method should be assessed in accordance with its application target. The authors' focus is on controlling the spatiotemporal distribution of power in a dynamically changing network of multiple agents such as vehicles. When it comes to power transactions across vehicles, it is essential to avoid the disparity between the physical quantity exchanged and information related to the transaction demand or record. The major type of information considered here is related to intersystem power delivery. Intrasystem signals requiring more bitrate, such as feedback signals for electric machine control, can be handled separately, e.g. on a conventional wired basis. The disadvantages of the proposals are justified in this sense. In this way, this method provides not only a novel way of wireless power routing technique but also realizes integrated power management including both wireless and wired networks.

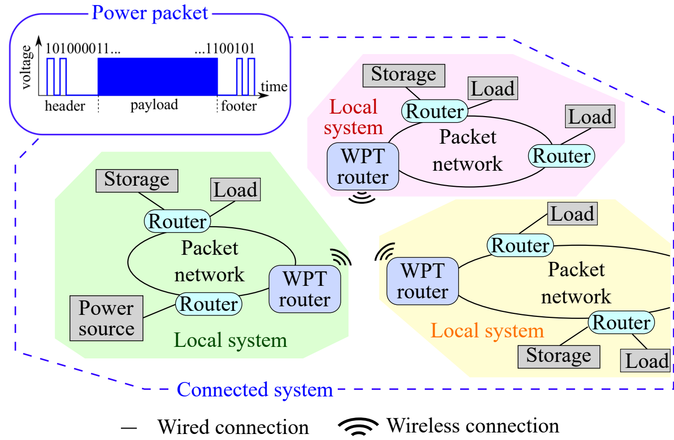

Fig. 1. Surplus power supply via wireless power transfer between power packet networks.

III. Outline of power packet dispatching system

This section presents the basic configuration of power packets and their dispatching system. A discussion is also provided on the advantages and limitations of the system compared to other power management systems.

A. *Constitution of power packet*

As depicted in Fig. 1, a power packet is a unit of power management in the system. A power packet comprises pulse-shaped electric power called a payload and an information tag, a header, and a footer, which are attached just before and after it. The information tag is a logic bitstream realized by a voltage waveform without current. The tag can include any information, like the origin, destination, and length of the power packet.

The physical tag attachment enables power packet transmission to be time-division multiplexed. Power from different sources and destinations is transmitted on the same channel while remaining distinct from one another. This feature sets the power packet dispatching system apart from conventional systems that treat power as a continuous flow.

B. *Network configuration of power packet dispatching system*

Each local system of Fig. 1 denotes a local system configuration example. Routers connect power sources, storage, and loads to the network in this system. A power packet router is installed as a node that connects multiple transmission lines. The router forwards power packets by selecting a transmission line according to the packet's tag information [10].

A power packet is routed from a source to a specific destination via several routers. The path to the load is not required to be unique and can be changed dynamically depending on the situation. This feature facilitates flexible power management in conjunction with a dynamic supply relationship. The following section presents a development of a router that can perform this function even with a wireless connection.

Table II
PROS AND CONS OF PHYSICAL IMPLEMENTATIONS FOR THE KEY CONCEPTS.

	Scheme	Pros	Cons
Power Multiplexing	TDM	- Unified freq. band for every channel - No mutual influence across different channels	- Requires active control at both TX and RX sides
	FDM	- Passive operation of RX side	- Interference between channels due to limited freq. band - Requires re-design when network structure changes
WPIT	Integrated	- Strict coincidence of power and info. transmission - No mutual influence between power and info.	- Limited time available for information transmission
	Parallel	- Capable of maximizing information bitrate	- Difficulty in dynamic channel establishment in MIMO situation

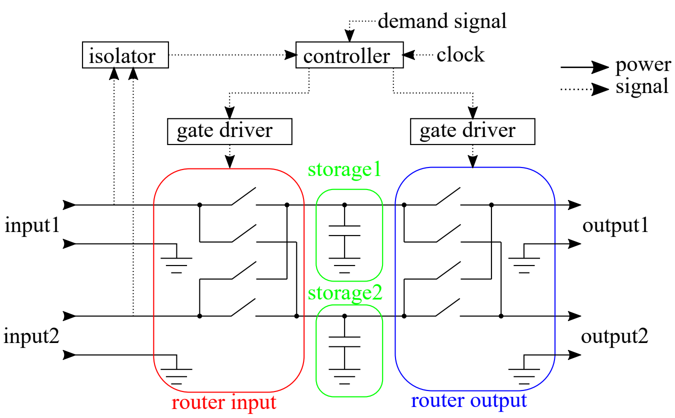

Fig. 2. Circuit example of 2 input 2 output router [9].

C. Routing method for power packets

Here is introduced a characterization of the circuit configuration of a router and the principle of its routing operation [9], [27], [28]. Fig. 2 depicts the circuit configuration of a previously proposed, wire-connected router [29]. The circuit consists of two sections: an input section that receives power packets from the transmission network and an output section that forwards power packets to the transmission network. The operation of the input part is initialized when a power packet reaches the router. The input section includes a signal reading circuit for reading the logic signals of information tags. When the router recognizes that the incoming power packet is addressed to it, it turns on the corresponding semiconductor switches to receive the payload power. For circuit protection, the signal reading circuit electrically separates its signal output from the power supply lines using a device such as a photocoupler. The incoming power packet is temporarily stored before being forwarded to the next hop. The output part generates power packets from the temporal storage in response to the demand. In some cases, the circuit can be reduced to just the input or output section. When installed just next to the source, for example, the output section with the storage replaced by a power source is sufficient to produce a generated packet. Similarly, a circuit just before a load can only be the input part, with the storage replaced by a load.

To read the logic signals of power packets, clocks corresponding to the one-bit width of a power packet must be synchronized among adjacent routers. This can be accomplished by installing an additional wire for a common clock input, or by adding another signal to the header for autonomous clock synchronization [30]. In this paper, the authors employ a simple autonomous clock synchronization scheme, in which the clock period is fixed in advance, the first three bits of the header are set to 010, and the phase is shifted if the 010 is not detected within a certain period.

The information tag consists of bits 1–3, which implies 010 for clock synchronization, and bits 4–7, which imply the address of the output destination. Bits 8 – 100 correspond to the payload. For simplicity, the packet length is fixed at 100 bits and this setting is shared by all routers. In this way, the footer is omitted.

D. Target applications, advantages, and limitations

The main target of the power packet dispatching system is a small-scale power system that is driven independently from an external large power source. Typical examples include sensor networks, Internet of Things (IoTs), EVs, and mobile robots. These systems can only load a limited capacity of battery due to space and weight restrictions. In addition, these systems employ an increased number of sources following the recent development of renewable and energy-harvesting technologies. Their inclusion is a promising way for prolonging the system's lifetime without increasing battery capacity. However, their intrinsically unpredictable fluctuation of output complicates instantaneous power management to balance supply and demand. Even when the energy balance is maintained within a certain time interval, there is no guarantee for instantaneous power balance.

Today's common power systems comprise a bus and sources and loads all of which are connected to the bus with switching power converters. This configuration works fine when one of the sources has a sufficiently large capacity to compensate for the fluctuation of other sources and load demands. However, this is not always the case with the aforementioned independent systems. Particularly, the uncertainty becomes more prominent as the small and fluctuating power supplies occupy a large part of the whole power supply.

The power packet dispatching system addresses this issue in the following way. First, the multiplexing in a time domain ensures that the power supply relationship is always one-to-one at each time instance. This is different from the bus-based systems, where power supplies between all the pairs of sources and loads are superimposed on the bus. The fluctuation of the other elements does not affect a supply of a particular pair. Second, the power supply in the system is not a continuous flow but a sequence of unit pulses called payloads. The regulation of energy supply is then attributed to a density modulation of the supplied power packets. This leads to multiple possible sequences of power packets to meet the demand in terms of energy in a certain period. A desirable sequence can be selected according to the changeable sources' availability. This is implemented as a function of the power packet routing network.

The above discussion mainly focuses on a wired power system. The same challenges apply to systems that include WPT. Moreover, the introduction of WPT provides even more complexity in balancing supply and demand. The wireless connection naturally involves frequent variations of power supply due to the change in the distance or even the presence/absence of coupling. This motivates the development of wireless power packet transmission in the following sections.

It is clear from the above that the power packet dispatching system is not necessarily suitable for power management with a power source of ample capacity. Such systems are within the scope of the conventional bus systems, and the introduction of power packetization to such systems may bring some drawbacks. For example, the throughput of the power packet transmission relies on the switching frequency since it adopts TDM for multiplexing. In some cases, this may require a higher switching frequency than usual in conventional systems when the number of pairs of sources and loads increases. Although the recent development of wide bandgap devices even supports the feasibility of such a high-frequency switching, there are still challenges to be addressed for its practical application e.g. an unmatured transistor drive method and higher costs of related components at the current market. Another possible drawback comes from the redundancy of the power routing paths. The proposed system can enhance the redundancy of the power supply by increasing the number of routers on the network and providing additional routes for power transmission. On the other hand, when the power supply has a large capacity and is itself redundant, the redundancy of the paths is unnecessary and can instead lead to decreased efficiency due to conduction and switching losses at the routers. The proposed system should be employed when the advantages gained outweigh these drawbacks.

IV. Router design for wireless transmission of power packets

In this section, the authors propose a router configuration for wireless transmission of power packets. Magnetic resonant coupling is employed for the wireless transmission. This method is capable of transmitting large power over long distances with high-efficiency [11]. This circuit is powered by AC, whereas the power packet dispatching system is powered by DC. The current must be converted to incorporate WPT into power packet routing. Fig. 3 depicts a conceptual diagram of the voltage and magnetic flux density in the wireless power packet transmission. Using a magnetic resonant coupling circuit that includes an inverter and a rectifier, DC is converted to AC and then back to DC after wireless transmission. The following section describes the router design.

It should be noted that the inclusion of wireless transmission in the power packet dispatching system was first proposed in the authors' previous report [31]. In the report, the wireless transmission was not packetized but introduced as a one-to-one transmission channel without any tag attachment. In this paper, the authors propose a novel router configuration that bring the functions of physical tag attachment and its reading to the wireless power transfer. These functions not only realize the physical packetization of wireless power transmission but also extends its use to packet-based power management as introduced in Section VI.

A. Wireless transmitter of the power packet

Fig. 4 depicts a router circuit for wireless power packet output. The configuration includes an inverter circuit connected to the router's output section, as described in Section III-C. For DC/AC conversion, a class-E inverter [32] is used. This circuit uses the resonance phenomenon to achieve a highly efficient AC output. The resonant frequency of the LC circuit comprising C_1, C_2, and L_1 is required to match the carrier wave frequency. Since L_1 is given by the wireless coupling coil, the parameters C_1 and C_2 are to be designed. There is a known procedure to determine the values; see [32] for details.

The output circuit wirelessly transmits both the header signal and the payload power. In this paper, the inverter's input is presented as a form of packetized power. The current flowing through the coil and the magnetic flux density induced in the coil is thus modulated in an amplitude-shift-keying (ASK) manner according to the shape of the power packet, as depicted in the middle of Fig. 3. It should be noted here that the header signal transmission must minimize power consumption while the payload transmission must maximize the amount of power transferred. The two requirements cannot be met solely through the transmitter's operation, but rather through the design of the receiver side. This point will be covered in greater detail in the following section.

It is in general important for WPT systems to be carefully designed to meet the electromagnetic compatibility (EMC) requirements. This study focuses on the proof of principle concept and thus there is still room for improvement to suppress electromagnetic interference (EMI). Still, it is reasonable to suppose that existing technology and its near-future development can address this issue. There are indeed many proposals for EMI reduction in WPT systems from various perspectives. For example, an improved inverter design is proposed to reduce harmonics as a transmitter-side technique, including the filter design [33] and spectrum spreading [34]. There are also approaches in the coupling part, e.g. a suppression method of an undesirable leakage of a magnetic field by adding a

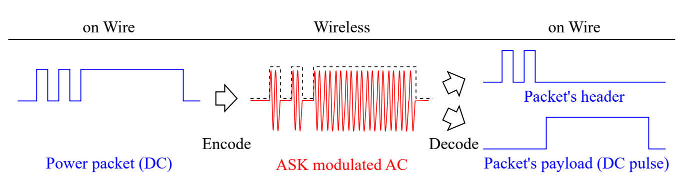

Fig. 3. A waveform concept during wireless transmission of power packets.

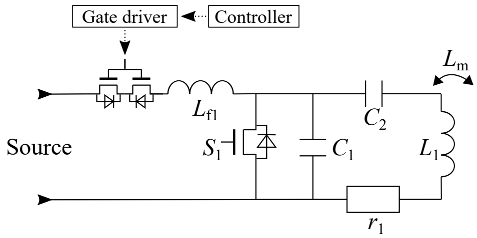

Fig. 4. Wireless transmitter of the power packet.

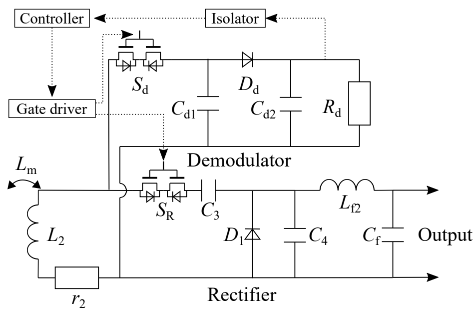

Fig. 5. Wireless receiver of the power packet.

shielding coil [35]. The proposed system does not preclude these techniques since the proposal has no restriction on the configuration of the inverter or the coupling coils.

B. Wireless receiver of the power packet

To receive a wirelessly transmitted power packet, demodulation of the ASK-modulated header signal and highly efficient AC/DC conversion of the payload are necessitated. The proposed circuit shown in Fig. 5 meets both requirements by dividing the demodulator into two circuits. The signal demodulation circuit reads the header, and a class-E rectifier receives the payload. The detailed procedure is provided below. Initially, the switch $\mathrm{S_d}$ connected to the signal demodulation circuit is turned on, while the $\mathrm{S_R}$ connected to the rectifier circuit is turned off. For signal demodulation, the envelope of the voltage across the secondary circuit's resonant capacitor is passed through an RC low-pass filter. The router's controller then samples it at a predetermined clock cycle to convert it into a logical sequence. The controller activates the switches that connect the coil to the rectifier circuit when it determines from the tag that the power packet is addressed to itself. This causes a class-E rectifier to convert the wirelessly transmitted payload into DC output. When the power packet is directed at another router, the router's controller disconnects both circuits and opens the coil. The detachment is used to avoid the influence of the unintended connection and the resulting impedance change, which may degrade power transmission at the addressed connection. At the end of the previous power packet, the controller turns on the switch to the demodulation circuit to prepare for the next power packet. The end of a power packet is detected by simply counting the length of the payload in 100-bit intervals.

Of course, simply connecting the signal demodulation circuit and the Class-E rectifier in parallel allows to read the header and receive the payload. However, when receiving the header, the current passes through the Class-E rectifier, and when receiving the payload, it passes through the demodulation circuit. Such a current contributes nothing to the receiving operation but results in power loss. Because this type of loss is much greater than the loss caused by the switching of the two demodulation circuits, the proposed scheme can greatly reduce the loss.

The specific design guideline for the receiver circuit is as follows. For the rectifier, the resonance frequency of the circuit comprising L_2, C_3, and C_4 is required to match the carrier wave frequency. Since L_2 is given by the wireless coupling coil adopted, C_3 and C_4 are to be designed. See [32] for the detailed procedure to determine their values. For the demodulator circuit, C_{d1} and C_{d2} are the design parameters. The appropriate value of C_{d1} is derived so that the resonance frequency with L_2 matches the modulation frequency. The capacitor C_{d2} and resistor R_d constitute a lowpass filter, where R_d is defined as the input impedance of the signal isolation circuit. The value of C_{d2} is determined so that the cutoff frequency is greater than the modulation frequency, in order to correctly sample the modulated amplitude changes.

C. Experimental setup

The frequency of the carrier wave used for magnetic resonant coupling is $1\,\mathrm{MHz}$. The wireless router's constants are determined as shown in Table III. The design is conducted in the following manner, regarding [32]. The coil has a diameter of $100\,\mathrm{mm}$, a wire diameter of $1\,\mathrm{mm}$, several turns of 10, and a thickness of $12\,\mathrm{mm}$. The transmission circuit's rise time was measured to be $25\,\mu\mathrm{s}$. The rise time is defined as the time required for the output voltage to attain $90\,\%$ of its steady-state value. The steady-state value was obtained under the test condition where the load was $47\,\Omega$ resistor and the vertical distance between the coils was $50\,\mathrm{mm}$. Based on this, the authors determined that the bit width of the power packet should be $100\,\mu\mathrm{s}$, which is sufficiently larger than the rise time. That is, the modulation frequency is $10\,\mathrm{kHz}$. The demodulation circuit is designed to demodulate signals with a cutoff frequency of about $100\,\mathrm{kHz}$.

Table III
DESIGN VALUES OF CIRCUIT CONSTANTS.

Primary side		Secondary side			
		Rectifier		Demodulator	
f	$1\,\mathrm{MHz}$	L_2	$19.2\,\mu\mathrm{H}$	C_{d1}	$1.0\,\mu\mathrm{F}$
L_{f1}	$100\,\mu\mathrm{F}$	r_2	$0.88\,\Omega$	C_{d2}	$820\,\mathrm{pF}$
C_1	$3.3\,\mathrm{nF}$	C_3	$1.56\,\mathrm{nF}$	R_{d}	$12\,\mathrm{k\Omega}$
C_2	$1.44\,\mathrm{nF}$	C_4	$1.68\,\mathrm{nF}$		
L_1	$19.3\,\mu\mathrm{H}$	L_{f2}	$100\,\mu\mathrm{H}$		
r_1	$0.88\,\Omega$	C_{f}	$0.47\,\mu\mathrm{F}$		
L_{m}	$1.75\,\mu\mathrm{H}$				

V. VERIFICATION OF SELECTIVE RECEPTION OF WIRELESSLY TRANSMITTED POWER PACKETS

In this study, the authors consider one-to-many or many-to-many wireless power sharing among several local systems

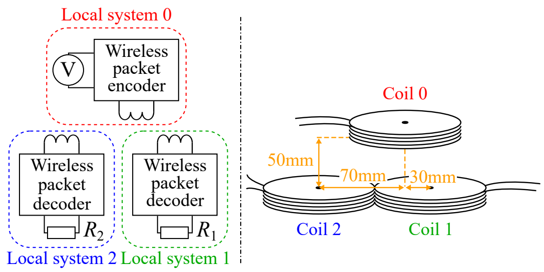

Fig. 6. Network configuration with 3 local systems for verification of selectivity of wirelessly transmitted power packet.

placed close to each other. The packetization and time-division multiplexing methods enable simultaneous supplies between different pairs of a transmitter and a receiver while completely distinguishing them. Here is presented an experiment with three local systems, one transmitting and two receiving nodes. It is demonstrated that the two receivers can selectively accept or reject power packets based on the attached information tag. The number of local systems and their connection relationship can of course be easily expanded and modified due to packetization.

A. Experimental setup for selective reception

The entire network configuration is depicted in Fig. 6. Local system 0 alternately sends power packets to local systems 1 and 2, and systems 1 and 2 receive only those that match their addresses. Power packet header addresses are set to 0001 and 0010 for systems 1 and 2, respectively. Local system 0 consists of a circuit from Fig. 4 and a DC power supply of 12 V. Local systems 1 and 2 comprise a circuit of Fig. 4 with a load resistor of 47 Ω connected to the output port.

Although the transmitting and receiving roles of the local systems are fixed for simplicity, it is possible to transmit power packets bidirectionally by modifying the circuit configuration [36]. Therefore, this assumption will not lose generality in power sharing.

To ensure that the router's operation is not affected by the distance between the coils, the coil positions are set as shown in Fig. 6. The coils of local systems 1 and 2 are placed at the same vertical distance 50 mm as the coil of local system 0, but the horizontal distance is 30 mm and 70 mm, respectively.

B. Receiving mode confirmation

First, the authors examine the switching behavior between the header signal demodulator and the payload rectifier circuit, as designed in Section IV. Fig. 7 depicts an internal signal of the router of local system 1 that represents the receiver's operation mode. The router was in the header mode every 10 ms, which corresponded to the transmission cycle of the power packets. Immediately after the header mode, the router switched to the payload mode every two power packet deliveries. During the payload mode, power was supplied to the designated load. This suggests that the controller received the header while connected to the demodulation circuit and then switched to the rectifier circuit in payload mode after

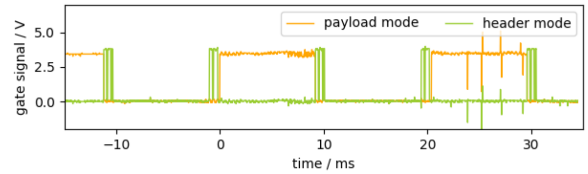

Fig. 7. Verification of router operation mode for wirelessly transmitted power packets.

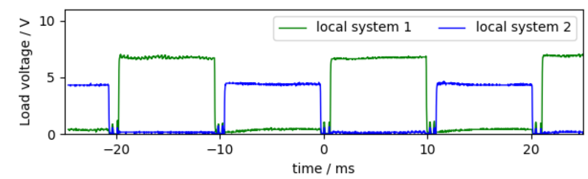

Fig. 8. Voltages at two loads in local systems 1 and 2.

recognizing the address. This result confirms that the proposed router can correctly route power packets on the wireless channel.

C. Confirmation of selective reception function

Second, the authors confirm that, according to the tag information, the local systems received time-division multiplexed power packets. The load voltages of the routers of local systems 1 and 2 are depicted in Fig. 8. It can be seen that local systems 1 and 2 received power alternately, indicating that they selectively accepted or denied receiving power packets based on the attached destination address signal. Here, local system 1's supply voltage was higher than that of local system 2. This is because the output is proportional to the distance between the coils. This means that, regardless of whether the output value is larger or smaller, the router's selective reception is unaffected by the difference in distance between the coils.

D. Performance evaluation

This subsection provides a performance evaluation of the selective receive function during multiplex transmission. Especially, the focus is on the comparison with an FDM-based multiplexing method, which is used in the related works for the multiplexing purpose. As discussed in Section II, the multiplexing method affects the WPT performance. The following discussion presents how the proposed method based on TDM addresses the disadvantage of the state-of-the-art scheme based on FDM in a MIMO situation.

The FDM schemes require multiple resonant frequencies set with a high Q-value for each to reduce interference. This brings about design tightness and consequently less robustness to variation of parameters. Especially, the geometric displacement of coils yields the change in the coupling coefficient between coils and consequently a performance degradation of the selective transmission. The displacement is likely to occur in the target applications of this paper, e.g. in a network of EVs and mobile robots that is constantly moving around. Below,

Table IV
CIRCUIT PARAMETERS USED FOR SIMULATIONS OF FIG. 9 AND 10.

Parameters	Value
r_1, r_2, r_3	$0.5\,\Omega$
R_1, R_2, R_3	$5\,\Omega$
L_1, L_2, L_3	$20\,\mu$H
$L_{12}, L_{21}, L_{13}, L_{31}$	$0.26\,\mu$H
L_{23}, L_{32}	$-3.6\,\mu$H
C_1, C_2	2 nF
C_3	1 nF

this performance degradation is discussed through a numerical simulation.

Here is considered again a connected system shown in Fig. 6, a configuration with one transmitter and two receivers. In FDM multiplexing, a cross-coupling between receiver coils must be taken into consideration as well as the coupling between the transmitter and receivers. The coupling strength varies according to their relative position. This variation affects the performance of power transmission to each multiplexed channel. To evaluate this effect, a generalized three-coil system model shown in Fig. 9 (a) is introduced. The coupling of coils no.m and no.n is represented by their mutual inductance L_{mn} $(m, n = 1, 2, 3)$, where $m = n$ cases correspond to the self-inductance: $L_{mm} = L_m$. The circuit equation is represented as

$$\mathbf{V} = \mathbf{ZI}, \quad (1)$$

where $\mathbf{V} = [v_1, v_2, v_3]^{\mathrm{T}}$ and $\mathbf{I} = [i_1, i_2, i_3]^{\mathrm{T}}$ represent the voltage and current phasor of the three local systems, respectively, and (m, n)-element of the impedance matrix $\mathbf{Z}$ is defined as follows.

$$z_{nm} = \begin{cases} r_n + \mathrm{j}(\omega L_n - 1/\omega C_n) & (n = m) \\ \mathrm{j}\omega L_{nm} & (n \neq m) \end{cases} \quad (2)$$

With additional constraints $v_m = -R_m i_m$ $(m = 2, 3)$ applied, v_2, v_3, i_1, i_2, i_3 can be given in the form that includes the source voltage v_1. Thus, the input or output power and the transmission ratio at each load can be obtained with the following relationship

$$P_1 = \Re[v_1 \bar{i_1}], \quad P_2 = \Re[v_2(-\bar{i_2})], \quad P_3 = \Re[v_3(-\bar{i_3})], \quad (3)$$
$$\eta_{12} = P_2/P_1, \quad \eta_{13} = P_3/P_1, \quad (4)$$

where $\bar{\cdot}$ and $\Re[\cdot]$ denote the complex conjugate and the real-part extraction, respectively. The model equations are used to calculate the system performance with parameters shown in Table IV. The sign ”$-$” of the values for L_{23} and L_{32} indicates that the mutual inductances are negative due to the coils' geometrical relationship. Fig. 9 (b) presents the variation of η due to a weak cross-coupling. The frequency response curves move with a slight change in their shapes. Moreover, a nonnegligible interference occurs at the resonant frequency of channel 3. That is, an unintended power supply to load 2 accompanies the channel 3 supply.

This paper proposes TDM transmission for the multiplexing purpose. Simply applying a TDM, however, also faces difficulty avoiding interference between channels since the

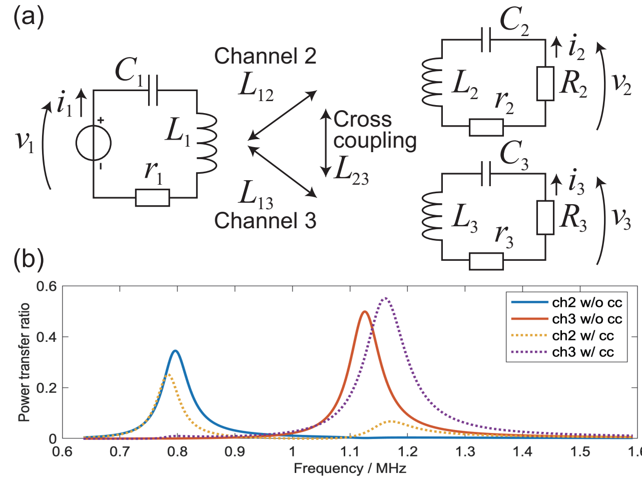

Fig. 9. Performance of selective power transmission with FDM. (a) System configuration, (b) Power transmission ratio to the source frequency with and without cross-coupling (denoted by cc in the plot).

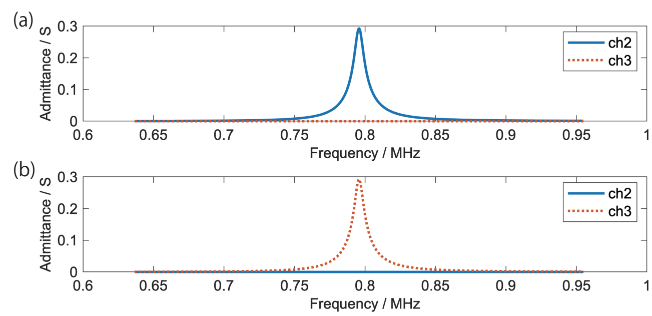

Fig. 10. Admittance of channel 2 and channel 3 when (a) payload is addressed to R_2 and (b) payload is addressed to R_3.

receiving circuits are in general normally on. The proposed scheme addresses this issue with the packet-based TDM method. The integrated information transmission by the tags allows the receivers to be normally off. Only the tag reading circuits are normally on to detect the power transmission sign. The power receiving circuits are left open to prevent interference unless its tag reading circuit detects its incoming power transmission request. Fig. 10 shows the admittance of channel 2 and channel 3 when packet-based TDM is applied. The admittance is calculated by eliminating the cross-coupling term with other parameters kept the same. It can be seen that there occurs no interference between the local systems. This feature is also confirmed in the experimental result of the selective receipt shown in Fig. 8. During the tag transfer intervals just before the payloads, both of the two receiving local systems are in tag-reading mode and accept no power inflow. In addition, while one local system is receiving power, no power inflow occurs to the other local system.

Consequently, the energy efficiency of each packet forwarding by the proposed router is determined as a one-to-one relationship even in the multiplexing condition. This means that the existing efficiency-maximization methods for a one-to-one WPT, e.g. the power electronic compensation at the receiver side [37], can directly be applied to the proposed system. Although this study focuses on the proof of concept

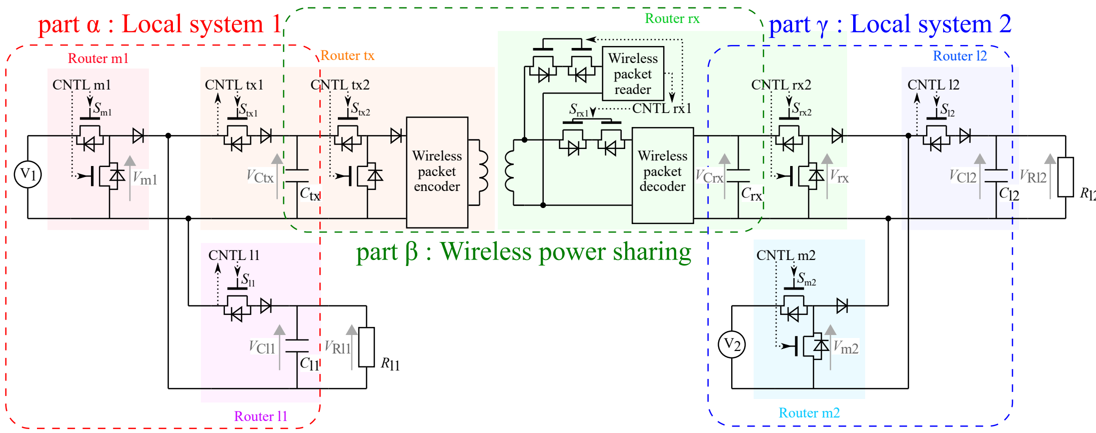

Fig. 11. Configuration of the network with 2 local systems connected wirelessly.

and does not fine-tune the circuit for efficiency, it is reasonable to suppose that the efficiency can be raised to at least the same level as in the state of the art.

The ability to unify the resonant frequency for all the channels also contributes to system flexibility. Consider the case where a new local system is about to be added to a particular network already established by some local systems. The above discussion indicates that, if FDM is to be applied, the resonance characteristics must be designed properly not only for a particular local system but also for the whole connected system. This may require a re-design of many components and thus is often impractical when the connected system is already running. On the contrary, the proposed method accepts the overlapped resonant frequency, which provides the ability to freely add or remove a local system even while the system is running.

VI. Confirmation of Power-Sharing in the Wirelessly Connected Systems

Next, in wirelessly connected local systems, the authors validate power management based on power packetization. The authors consider two local systems where the local power supply is primarily managed via a wired connection. Every local system consists of an internal power source, a capacitor, a wireless transmission circuit, and a resistive load. The authors set a wirelessly connected networking system comprising two such local systems, as shown in Fig. 11. While each local system supplies its source to its load, wireless power packet transmission compensates for excess or deficient power. Each system's goal is to keep the voltage supplied to the load above a certain level.

The proposed scheme deals with a connected system whose elements are subject to dynamic changes, such as variable distance between local systems and time-dependent connection/disconnection of local systems. Dealing with such dynamic changes altogether in a centralized controller is not ideal. Distributed control of power packet transmission, however, is an effective method of accommodating such unpredictability. In this paper, the authors adopt a distributed control scheme of packet-based power management [38], in which power packet transmission is managed only between adjacent routers. The following section describes the operation flow of the connected systems.

A. Operation flow in connected systems

Capacitors are installed in the connected systems to generate and output power packets to the load. Power packets are sent so that the voltages of these capacitors exceed a certain threshold.

The demand signal to the router for on-demand packet transmission can be given by information tags in power packets or by using another channel such as radio signals [38]. In this paper, an external wire is used to transmit demand signals for simplicity. An input high is given to the controller of the next router when the storage voltage falls below the threshold.

The configuration of Fig. 11 is divided into the following three parts that are managed independently.

- α Transmission from router m1 to router tx and router l1
- β Transmission from router tx to router rx
- γ Transmission from router rx and router m2 to router l2

The three parts' basic operation principles are described below.

In part α, when the voltages across C_{tx} and C_{l1} fall below the threshold, demand signals are transmitted to the router m1 respectively. Router m1 generates and sends power packets to the destination from which the demand signal is received. In the event of overlapping demand signals, priority is given to router l1 to keep the load voltage stable.

In part β, router rx sends a demand signal to router tx when the voltage across C_{rx} falls below the threshold. Router tx generates and sends power packets to router rx based on the demand signal.

In part γ, when the voltage across C_{l2} drops below the threshold, a demand signal is initially sent to router rx. If a power packet is not delivered from router rx to router l2 within a certain amount of time, the demand signal is sent to router m2, which generates and sends a power packet to router l2.

Besides the three principles, two constraints are imposed on the operation of routers tx and rx. First, they do not output power packets if the voltages across its capacitor, C_{tx} or C_{rx}, is lower than a certain value. To transmit power packets, there must be an adequate potential difference between the source and the destination. This constraint guarantees the possible difference between the source and destination capacitors and guarantees the reliable transmission of power packets. Second, the routers are not enabled to input and output power packets simultaneously. When both switches are switched on simultaneously, the circuits before and after the router are linked parallel. In this case, the output impedance measured from the power supply (capacitor) located before the router is lower than when only the input switch is turned on. This can result in an overcurrent at the source and a rapid drop in capacitor voltage. The second constraint is levied to avoid this situation. This configuration may prevent the router rx from emitting power on occasion. Even if this occurs, router m2 can supply power packets to keep router l2's voltage stable.

A comment is provided on the stability of the proposed system. The previous study [28] developed a packet-based modulation scheme to create a power packet sequence to meet the demand of loads. The scheme ensures power supply stability with the wired power packet supply within a local system without power sharing. Then, it can be recognized that the proposed power sharing via a wireless channel replaces some of the power packets in the aforementioned sequence only when possible. Furthermore, the procedure defined above lets the wireless router serve as a boundary of local systems to decouple them and avoid interference across the local systems. Consequently, these setups ensure the stability of the overall system even when the power sharing is coordinated into the power management in each local system.

B. Verification of connected systems operation

To test the operation of the connected systems, the authors set the supply voltages $V_1 = 15\,\mathrm{V}$ and $V_2 = 7\,\mathrm{V}$. To create a voltage gradient, the threshold voltages of capacitors C_{l1}, C_{tx}, C_{rx} and C_{l2} are set as $10\,\mathrm{V}$, $9\,\mathrm{V}$, $7\,\mathrm{V}$ and $5\,\mathrm{V}$, respectively. The capacitance of the tx, rx, l1 and l2 routers is set uniformly at $1000\,\mu\mathrm{F}$, and the resistance of the loads R_{l1} and R_{l2} are both set at $33\,\Omega$. These values are selected to make the time constant of the load consumption greater than the power-packet length so that the capacitor voltage will not change drastically within the interval of one power packet. The circuits related to wireless power and information transmission are designed in the way described in IV with the parameters presented in Table III. The wireless coupling coils described in IV are adopted for the coupling between routers tx and rx. The coils are arranged so that they face each other in parallel and their centers are on the same axis. The distance between coils is set at $50\,\mathrm{mm}$.

It is worth noting that the routers' wired channel switch units have been replaced with unidirectional ones. As previously discussed, the symmetry of the circuit allows to restrict the flow of power packets to one direction without sacrificing generality. The circuit generates high by activating switch $\mathrm{S}_{\mathrm{out-s}}$, and low by activating switch $\mathrm{S}_{\mathrm{out-p}}$. The diode prevents reverse current from flowing through the body diode of $\mathrm{S}_{\mathrm{out-s}}$.

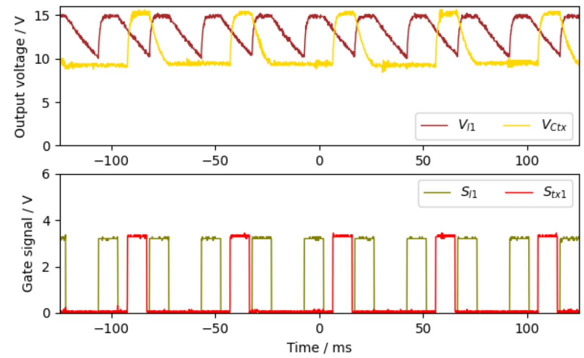

Fig. 12. State of switches and voltage of capacitors in part α.

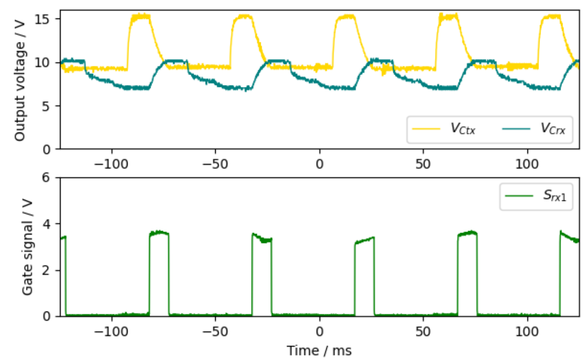

Fig. 13. State of switches and voltage of capacitors in part β.

1) Confirmation of autonomous maintenance of capacitor voltage: The authors demonstrate the transmission of power packets and the modifications in voltages of each capacitor installed in part α, β and γ.

Fig. 12 depicts the voltages V_{l1} and V_{tx} of the capacitors C_{l1} and C_{tx} in part α and the gate signal of the switches S_{l1} and S_{tx1} that controlled the route of the power packets. It is observed that V_{l1} and V_{tx} were sustained above the threshold voltages. The voltages V_{l1} and V_{tx} elevated when switches S_{l1} and S_{tx1} were driven. This demonstrates that capacitors C_{l1} and C_{tx} effectively received power packets and were charged. Furthermore, switching operation of S_{l1} and S_{tx1} did not overlap at any time. This result correlates to the setup that the transmission of power packets to C_{l1} is prioritized (see Section VI-A for the details).

Fig. 13 depicts the voltages V_{tx} and V_{rx} of the capacitors C_{tx} and C_{rx} in part β and the gate signal of the switch S_{rx} that controlled the power packet reception of the router rx. Comparing the top and bottom graphs shows that V_{tx} declined and V_{rx} elevated while S_{rx} was on. This implies that power packets were wirelessly transmitted successfully from router tx to router rx. It can also be validated that S_{rx} turned off when V_{tx} attained the threshold voltage. This implies that the system satisfied the constraints defined in Section VI-A, which hampers the output of power packets under the threshold voltage.

Fig. 14 depicts the voltages V_{rx} and V_{l2} of the capacitors

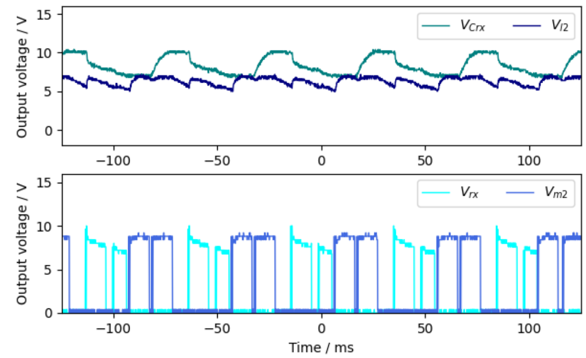

Fig. 14. Power packets and voltage of capacitors in part γ.

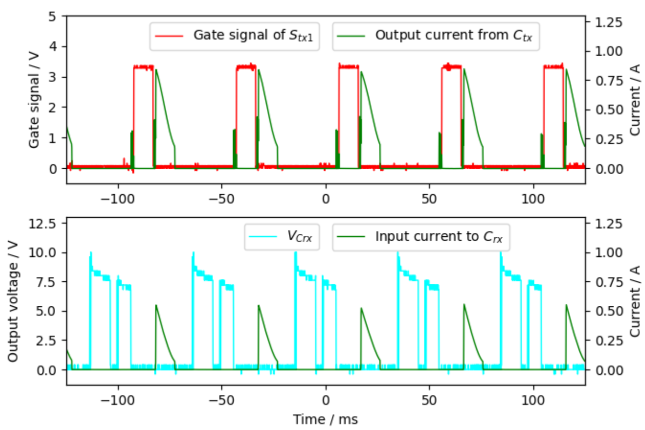

Fig. 15. Input / output current and voltage of $C_{\rm tx}$ and $C_{\rm rx}$.

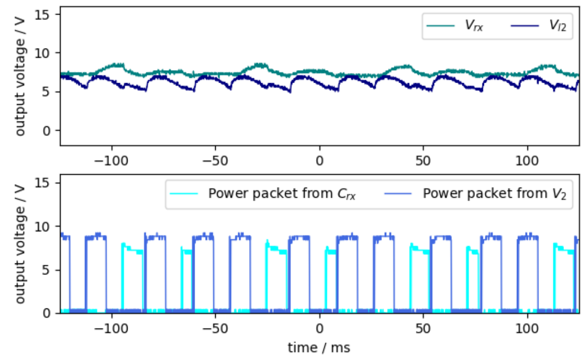

Fig. 16. Power packets and voltage of capacitors in part γ of case (ii) : gap $100\,\mathrm{mm}$.

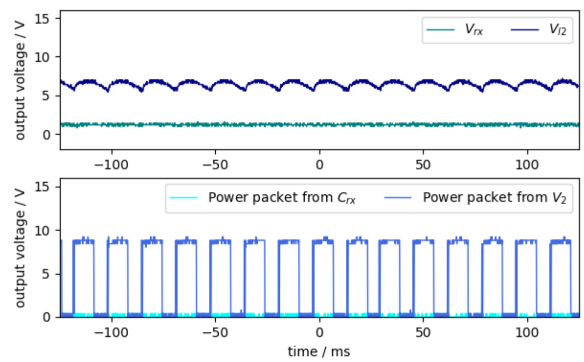

Fig. 17. Power packets and voltage of capacitors in part γ of case (ii) : gap $250\,\mathrm{mm}$.

$C_{\rm rx}$ and $C_{\rm l2}$ in part γ and voltage waveforms of power packets outputted from routers rx and m2. When $V_{\rm l2}$ dropped below the threshold voltage, router rx transferred power packets to router m2 so that $V_{\rm l2}$ was kept above the threshold. Now the focus is put on the operation around $t = 25\,\mathrm{ms}$ when $V_{\rm rx}$ attains the threshold voltage. Router rx stopped outputting the power packets, and simultaneously, router m2 started sending power packets. These findings suggest that the selective routing protocol specified in Section VI-A worked; the load sent the demand signal to the router rx at first, and if no packet was transmitted, then sent to the router m2.

In Fig. 14, there exists a possible difference between the voltage of the power packet and $V_{\rm l2}$. This was induced by the forward voltage drop across the diode installed to prevent backflow current. This loss can be repressed by using a switch instead of a diode. Thus, there is no impact on the verification of the principle.

Fig. 15 depicts the gate signal of $S_{\rm tx1}$, output current from $C_{\rm tx}$, input current to $C_{\rm rx}$, and the output voltage waveforms of router rx. When $C_{\rm tx}$ was outputting current, $C_{\rm rx}$ was receiving current. This implies that the transmitted power packet was received without failure. Since router tx did not output power packets when $S_{\rm tx1}$ was on, $S_{\rm tx1}$ and $S_{\rm tx2}$ were driven solely. Similarly, $S_{\rm rx1}$ and $S_{\rm rx2}$ were driven solely. From the above findings, it can be deduced that the connected system achieves the load voltage maintenance with wireless power supply between local systems 1 and 2 by following the control procedure defined in Section VI-A.

2) Association between the percentage of power supply and the utilized power source: The percentage of power transferred on the wireless channel depends on the distance between the transceiver/receiver coils. Hence, in the previous experiment's setup, increasing the coil gap reduced the power supply capability from the local system 1 to 2. The proposed control scheme of the routers can accommodate such a gap change by choosing an appropriate supply channel. To test this operation, the authors compare the amount of wireless power transmission and the power source selection in the local system 2 at various distances between the coils. Three cases are set with different distances: (i) $50\,\mathrm{mm}$ (the same as in the previous experiment), (ii) $100\,\mathrm{mm}$, and (iii) $> 250\,\mathrm{mm}$. Note that only the distance is changed and the coils remain to face each other in parallel with their centers placed on the same axis. The setup in case iii is supposed to be large enough to prevent wireless transmission.

Fig. 16 and 17 depict the voltage $V_{\rm rx}$ and $V_{\rm l2}$ and the power packets output by routers rx and m2 in cases ii and iii. Please refer to Fig. 14 for the result in case i. The larger the distance between the coils, the less frequently the router rx outputted power packets and the lower its average voltage got. On the

Table V
INPUT/OUTPUT POWER OF THE ROUTERS IN LOCAL SYSTEM 2 AT EACH GAP.

Case	Gap	Router rx input	Router rx output	Router m2 output	Total output
i	50 mm	0.50 W	0.46 W	0.73 W	1.19 W
ii	100 mm	0.20 W	0.17 W	0.94 W	1.11 W
iii	> 250 mm	0.00 W	0.00 W	1.13 W	1.13 W

other hand, V_{l2} maintained above the threshold in all cases.

Table V demonstrates the average of the input/output power of router rx and the output power of router m2 during the measured time 250 ms for different distances. The input/output power of router rx fell and the output power of router m2 rose as the distance became larger. Meanwhile, the total output power of router rx and router m2 had a slight change. This finding implies that the output power of router m2 compensates for the fall in the output power of router rx.

From the above, it is asserted that the load voltage can be sustained autonomously by the proposed distributed control scheme. Even when the amount of wireless transmission falls, the local system compensated for it with a wired supply.

VII. CONCLUSION

In this paper, the authors developed a platform for wireless power packet transmission for power management among numerous local systems.

First, a novel power packet router configuration capable of wireless transmission is proposed. The ASK modulating circuit is installed on the router's output side for both information and power transmission, with the power packet serving as a power source. The input side includes a demodulation circuit for both information and power receipt. The circuit shifts between a signal demodulation circuit and a power rectifier circuit to read the header and receive the payload power, respectively. Not only does the switching configuration separate the incoming signal and power, but it also reduces unnecessary power consumption during the receiving operation.

Using this router, the authors then verified the wireless power packet routing following the information tag. Physical tag attachment and wireless power packet time-division multiplexing allowed receiving routers to distinguish the power packet based on its destination address. The result shows that the proposed configuration allows for the selective transmission of wireless power packets between multiple nearby local systems. This prevents interference with the irrelevant power supply.

Next, flexible coordination of inter- and intrasystem power management is considered. The former was accomplished through the wireless transmission of power packets, while the latter was accomplished through a wired supply. For this purpose, the authors created a distributed control scheme for the routers. A local system transmitted power packets wirelessly to another when it had enough power while keeping the voltage of its load as a top priority. The experiments revealed that the two types of operation were coordinated successfully. Furthermore, the proposed distributed control scheme chose an appropriate supply channel based on the power interaction availability between the local systems. The authors validated this operation by altering the gap between the coils of the two local systems, demonstrating that the inter- or intrasystem power management was successfully chosen to satisfy the local loads' demand.

From the above verifications, it is deduced that wireless power packet transmission can improve power management capability in a connected power packet dispatching system by selectively cooperating wired and wireless power packet transmission.

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