PAPER

Adaptive Communication System with Renewable Energy Source*

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SUMMARY This paper introduces a communication system model with renewable power supply. As we assumed a battery-free microgrid system with conventional power as a backup power supply, we propose a method of power state and data transmission scheduling for delay-tolerant communication networks, which reduces conventional power consumption by operating adaptively to changes in renewable power. We found through computer simulations that the proposed method efficiently reduced conventional power consumption.

key words: *renewable power, microgrid, communication network*

1. Introduction

The telecommunication infrastructure has been experiencing rapid development for several years, which has led to ever increasing power consumption of it [1], [2]. This is known as the power bottleneck problem [1]. However, the current large-scale power supply architecture also has serious problems like significant transmission and distribution loss [3], [4], or losing economies of scale [4]. Therefore, it is necessary for us to adopt more suitable power supply solutions for telecommunication network systems. Renewable energy-powered microgrids have been considered to be suitable solutions.

Different from conventional large-scale power grids, a microgrid manages power generators and power loads in local limited areas [5]. One of the advantages of a microgrid structure is that it enables an easier way of utilizing renewable power supplies compared with conventional power distribution networks [6]. Renewable energies are the promising alternate energy sources to circumvent energy-related problems within communication network systems. However, they are not stable because natural resources like solar radiation or wind fluctuate in accordance with location, season, and weather conditions [7]. Instead of installing large batteries, we based our discussion on a battery-free microgrid system that uses conventional power as supplementary power. As battery systems still face problems like short life cycles or high installation costs [8], we assumed that this system would help in increasing the penetration of renewable energy into communication network systems.

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In our previous paper [9], we proposed a similar system model with only two routers and a corresponding algorithm that controlled data transmission and the routers' power states in accordance with renewable power generation. This system that was operated with the proposed algorithm proved efficient in reducing conventional energy consumption through simulations. However, when we consider the operation of a system with multiple routers, the situation is different. The power states of the routers in a two-node network are synchronized. However, different routers in a multi-node network can have different power states to reduce power consumption. Thus, the efficiency of power state management over multiple routers will directly determine whether the system is effective or not. Our works in this paper focused on such multi-router transmission control problem within the system. The novelty of our works in this paper is that the scheduling of data transmission is directly adaptive to the short-term changes of solar radiation, while in other similar works, the scheduling is basically adaptive to the long-term changes, as they assume the usage of large-capacity batteries.

The remainder of this paper is organized as follows. A literature review is introduced in Sect. 2. Section 3 then explains the system model of an adaptive communication system with a unique renewable power supply. Section 4 explains the proposed method of controlling data transmission and router power states. After that, simulation settings and simulation results are described in Sect. 5. Finally, Sect. 6 concludes the paper.

2. Related Work

2.1 Microgrid

A microgrid is a power grid architecture that views power generations and associated power loads in a local area as a controllable subsystem [5], [10]. Power generation facilities in a microgrid are usually distributed energy resources (DERs) due to the scale of the power grid. DERs can be wind turbines, photovoltaic cells, or microturbines. Most DERs are not suitable for connecting to the main grid due to adverse effects that originate from the characteristics of DER power generation [5]. As renewable energy is a kind of DER, a microgrid circumvents the problems caused by fluctuation in it [6]. In addition, a controller is usually installed to manage operations in a microgrid [5]. This enables local control of power generation in a microgrid so that power generation meets power demand, and possible separation from the main grid when necessary [5].

Using distributed power generation for communication systems has already been discussed [11]. However, introducing the concept of a microgrid to power supply systems in communication networks seems a fresh idea except our previous papers [9], [12]. In addition, we based our discussion on a battery-free microgrid. Such models that supply households can be found in the literature [13]. However, to the best of our knowledge, efforts on supplying communication systems with unstable renewable power have not been published other than our previous papers.

2.2 Energy-Efficient Communication Systems

Energy-efficient communication systems are a topic that has already been intensively researched. Improving the energy efficiency of communication systems has both economic and environmental impacts. Existing efforts mainly encompass four aspects. The first aspect is improvements to hardware, like faster computing units [14], and high-efficiency power amplifiers [15]. The second aspect is energy-aware network management, examples of which are energy-aware protocols [16], device on-off methods [17], or link rate adaptation schemes [18]. The trade-off between delay and energy discussed in this paper can also be seen in other works like [19]. In addition, the assumption of loose delay constraints can be found in some application-level transmission [20]. The third aspect is changing network paradigms, like switching from copper-based technologies to optical ones [21], or reconsidering the server-client model [14]. Finally, the fourth aspect is using renewable energy sources [11], [22]. Although the pure usage of renewable energy sources does not reduce total power consumption, as renewable energy sources are alternate energy sources and have environmental benefits, these efforts are still part of energy-efficient research when we limit the definition of power consumption to conventional power consumption.

This paper discusses the power state and traffic scheduling of a group of devices that can adapt to fluctuations in renewable power generation. Although numerous on-off schemes have been proposed in the literature, to the best of our knowledge, such work based on unstable renewable power has not been presented.

3. System Model

3.1 System Model

As discussed in Sect. 1 and Sect. 2.1, individual microgrids operate independently in small areas. We call such areas limited areas. In the meantime, we can also consider that communication network systems operate separately in corresponding areas, as autonomous systems. Thus the whole system in each limited area works individually.

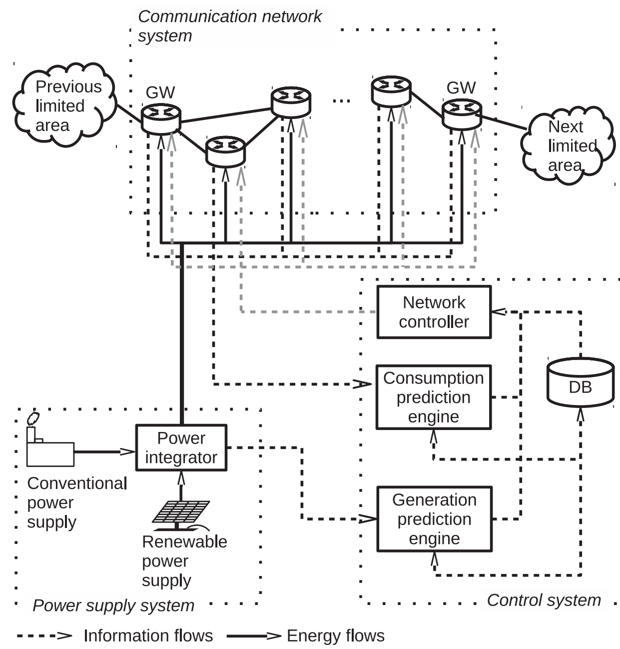

Fig. 1 System model.

In this paper, we focused on the operation in one limited area. The system model in one limited area is outlined in Fig. 1. Basically, this system consists of three subsystems: the power supply system (PSS), which manages power generation and power supplies to the system, the communication network system (CNS), in which routers forward data to their destinations, and the control system (CS), which regulates routers' behaviors in the CNS.

The PSS is based on a microgrid structure, in which only two power supplies are present. The first is the conventional power supply and the second is the renewable power supply. The power flows from them are integrated in the power integrator (PI). Due to the exclusion of batteries as was explained in Sect. 1, the conventional power supplier acts as a supplementary energy source. In addition, the PI is called an integrator not a switch because it can simultaneously make use of these two power supplies, and fully use the renewable power supply until it does not have enough power to satisfy the demands of the system.

Data in CNS are modelled as chunks. A chunk can be an aggregated data set of sensing data or a piece of a large file, which has loose transmission time requirements. Such kinds of assumptions can be found in information-centric delay-tolerant networks [23] or delay-tolerant bulk data transfer [24]. Focusing on transmissions of chunks, the system employs an active-sleep strategy to save conventional power consumption, a basic case of which was discussed in our previous paper [9]. A router generally has three power states: busy, idle, and sleep. Most components inside a router in the sleep state are shut down, while a router is fully powered in the idle state. The busy and idle states can both be called active states. The difference between them is that in the busy state, a router is transmitting or receiving data, while in the idle state, a router is not carrying any workload. As the power consumption of a router in the sleep state is much less than that of a router in the active states, properly controlling the power states of routers can reduce conventional power consumption.

The control of data transmission and router power states is enabled by CS. The consumption prediction engine in CS predicts the amounts of data that are going to be generated in every router and the power consumption required to forward them, while the generation prediction engine predicts how much energy will be generated by the renewable power generator. Although how these prediction mechanisms are implemented exceeds the scope of this paper, we assumed that both of these prediction engines referred to the statistic data stored in the data base. Based on the information provided by the prediction engines, the network controller (NC) generates the scheduling tables that contain the instructions for data transmissions and power states of routers at constant interval T, which we call a short period (SP). As the scheduling table cannot contain instructions for any infinitely small time, SP is the smallest unit length of time that the NC is capable of handling. In one SP, the system keeps constant until the next SP, which means that a chunk only finishes one-hop transmission in such periods of time. The production of the scheduling table will be introduced in Sect. 4.

3.2 Conventional Power Consumption

As was described in the previous sections, only one renewable power supply and one conventional power supply are present in our system model. Conventional power consumption should be reduced to enable renewable power to be efficiently used. We define the conventional power consumption from time t to time time $t + T$ as $E_C(t)$, and this is expressed as:

$$E_c(t) = \begin{cases} E_w(t) - E_g(t) & if E_w(t) > E_g(t) \\ 0 & else \end{cases}$$

in which $E_w(t)$ and $E_g(t)$ correspond to the whole CNS power consumption and the renewable power produced in one SP from t. $E_w(t)$ can be expressed as:

$$\begin{aligned} E_w(t) = & E_{busy}(t) * b(t) \\ & + E_{idle} * i(t) \\ & + E_{sleep} * s(t) \end{aligned} \tag{1}$$

where $E_{busy}(t)$, E_{idle}, and E_{sleep} are the power consumption of a router in specified power states in one SP, and $b(t)$, $i(t)$, and $s(t)$ are the numbers of routers in corresponding power states. $E_{busy}(t)$ in the above is variant to workload. However, by assuming a linear relation between power consumption and workload, we can express $E_{busy}(t)$ as:

$$E_{busy}(t) = E_{idle} + N(t) * E_{chunk} \tag{2}$$

in which $N(t)$ is the number of chunks forwarded by the router and E_{chunk} is the necessary energy for forwarding a chunk.

4. Proposed Method

4.1 Problem Forming

As was described in Sect. 3.1, routers' power states and data transmission behaviors are regulated by the NC with scheduling tables in our system model. Because in our system model, we focused on the scheduling problem rather than the routing problem, we assumed that all chunks were transmitted through the shortest paths, so that the scheduling of transmission times was the only factor that controlled data transmission within the system.

The scheduling variables in the chunk transmission scheduling problem include routers' power states and chunks' transmission times. However, these two kinds of variables are not independent. Once a chunk is scheduled to be transmitted at time t, the transmitter router and the receiver router of this chunk should be in active states at time t. As long as no chunks will pass a router at time t, this router will be in the sleep state at time t when we assume that power consumption should be minimized. If the power state of router i at time t is denoted as $s_{i,t}$, and the time when chunk j is transmitted by router i is defined as $\tau_{i,j}$, given the schedule of chunks' transmission times, routers' power states can be determined by:

$$s_{i,t} = CalState(\tau_{i,0}, \tau_{i,1}, \tau_{i,2} ...)$$

in which $CalState()$ is a function that calculates the power state of a router by given transmission times of chunks that will pass this router at any time: if $\tau_{i,t}$ exists in the given vector, the power state of router i at SP t is assigned as "active"; while if it does not exist, the corresponding power state is assigned as "sleep". If we further define a vector, $T_j = \{\tau_{i_0,j}, \tau_{i_1,j}, \tau_{i_2,j}, ...\}$, elements of which represent the times when chunk j is forwarded by routers $i_0, i_1, i_2, ...$ in the path to its destination, the optimizing problem is to minimize conventional power consumption

$$min : E_c(T_0, T_1, T_2, ...)$$

subjected to the constraint that chunks should pass each router in order and arrive at their destinations before their deadlines:

$$\tau_{i_0,j} < \tau_{i_1,j} < \tau_{i_2,j} < ... < D_j$$

where $E_c()$ is a function that calculates conventional power consumption from the scheduling information on chunk's transmission, and D_j is the transmission deadline of chunk j.

4.2 Proposed Method

We propose a simple algorithm as a solution to the transmission scheduling problem instead of solving it directly in this paper. As a scheduling table consists of instructions for more than one SP, it can be produced by repeating the scheduling operation introduced below.

The scheduling procedures in one SP are described in Algorithm 1 while its sub-procedure is defined in Algorithm 2. Basically, this method follows "most urgent sent first" policy, and minimizes the number of routers in active states. The parameter that describes how urgent a chunk is is its C value, which is defined as:

$$C = D - h$$

where D is the time remaining until a chunk's deadline, and h is the necessary time for transmitting the chunk to its destination. Both D and h are measured in SP. In addition, for one chunk, the router that forwards a chunk to the next hop router is called its forwarder, and the next hop router is called its receiver. When a chunk is being transmitted, both its forwarder and receiver should be in the active states.

The algorithm can be summarized in five steps:

STEP 1 Calculate C value and sort the chunk list

STEP 2 Transmit urgent chunks whose C values are 0

STEP 3 Transmit chunks whose forwarder and receiver are both in the idle state

STEP 4 Transmit chunks whose forwarder or receiver is in the idle state

STEP 5 Transmit chunks whose forwarder and receiver are both in the sleep state

The chunk list is sorted in STEP 1 in accordance with the calculated C values so that urgent chunks have higher priorities in the scheduling of data transmission. Then in STEP 2, all chunks with C values equal to 0, which means that if they are not transmitted immediately their delay requirements will not be satisfied, are scheduled for transmission. In STEP 3 to STEP 5, the algorithm schedules the transmission of non-urgent chunks as long as $E_w < E_g$ is still true after one more chunk is scheduled to be transmitted. E_w is the accumulator that estimates the power consumption of the CNS if current scheduling is achieved. Ensuring $E_w < E_g$ in STEP 3 to STEP 5, is to reduce conventional power consumption by making use of the delay tolerant characteristics of the chunks. However, the algorithm tries to reduce the number of routers in the idle state to transmit as many chunks as possible. Thus, when routers' power states are changed in STEP 4 or STEP 5, the algorithm goes back to STEP 3, so that more chunks can be transmitted at low power cost.

5. Simulation

5.1 Simulation Setting

The simulation is fundamentally based on the system model introduced in Sect. 3.1.

```
list ← list of chunks exist in the CNS ;
E_g ← available renewable power;
E_w ← E_sleep * numOfRouters ;
Sort list by C in ascending order;
foreach chunk in list do
    if C = 0 then
        E_w ← E_w + ForwardChunk(chunk, list);
    end
end
repeat
    chunk ← first chunk in list that both forwarder and
    receiver are idle ;
    if chunk not empty and E_g ≥ E_w + E_chunk then
        E_w ← E_w + ForwardChunk(chunk, list);
        continue;
    end
    chunk ← first chunk in list that only forwarder or receiver
    is idle;
    if chunk not empty and E_g ≥ E_w + E_chunk + E_idle − E_sleep
    then
        E_w ← E_w + ForwardChunk(chunk, list);
        continue;
    end
    chunk ← first chunk in list that neither forwarder nor
    receiver is idle;
    if chunk not empty and E_g ≥ E_w + E_chunk + 2E_idle − 2E_sleep
    then
        E_w ← E_w + ForwardChunk(chunk, list);
        continue;
    end
until no more chunks are scheduled to be transmitted;
```

Algorithm 1: Proposed method.

```
Function ForwardChunk(chunk, list)
    E_a ← 0 ;
    if forwarder is in the sleep state then
        make forwarder idle;
        E_a ← E_a + E_idle − E_sleep ;
    end
    if receiver is in the sleep state then
        make receiver idle;
        E_a ← E_a + E_idle − E_sleep ;
    end
    forward chunk;
    E_a ← E_a + E_chunk;
    remove chunk from list;
    return E_a ;
```

Algorithm 2: ForwardChunk function.

In PSS, we assumed that the renewable power supply was a solar panel. To simulate solar power generation, we downloaded historical solar radiation data from the National Renewable Energy Laboratory's Solar Radiation Research Laboratory [25]. The data were sampled every minute, and we selected segments that lasted from 6:00 to 18:00 on July 1st, 2013 as the solar radiation data for simulation. The selected segments are plotted in Fig. 2. By using the radiation data, instant solar radiation $P_r(t)$ is specified. Then, the following equation is used to calculate $E_g(t)$:

$$E_g(t) = \mu * P_r(t) * T$$

in which μ is the conversion factor determined from the size

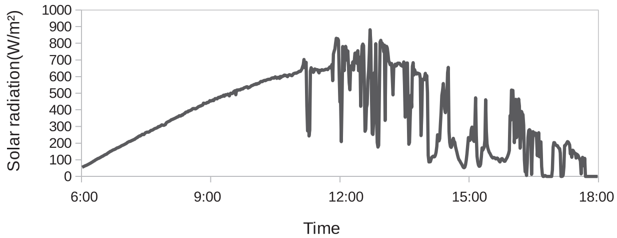

Fig. 2 Radiation data.

Table 1 Power demand model.

	Power Consumption
P_{busy}	18.7 W
P_{idle}	11 W
P_{sleep}	0.9 W

of the solar panel and its conversion efficiency, and T is one SP. A realistic estimate of $E_g(t)$ from $P_r(t)$ is much more complicated. However, because a study on photovoltaic calculations is beyond our scope, a simplified model was used here.

As for CNS, to calculate power consumption, the power demand model summarized in Table 1 was used. This model was based on measurements conducted on a notebook computer with an Intel(R) Core(TM) i7-3520M CPU, 16 G of RAM, a gigabit Ethernet adaptor, and the Ubuntu 12 operating system, which we introduced in our previous paper [9]. Specifically, P_{busy} here was measured while the notebook computer is forwarding 3000 chunks per second.

Based on this power demand model, we can calculate E_{idle} and E_{sleep} with:

$$E_{idle} = P_{idle} * T$$
$$E_{sleep} = P_{sleep} * T$$

To calculate E_{chunk}, we can first derive $E_{busy}(t)$ as:

$$E_{busy}(t) = P_{busy} * T$$

E_{chunk} can then be obtained by setting $N(t) = 3000$ in Eq. (2).

In CNS, we assumed 100 routers were present. We also assumed that the network topology was a small world network, as research has revealed that the Internet topology exhibits small-world behaviors [26], [27]. To be more specific, we used the Watts and Strogatz (WS) model [28] in this simulation, in which nodes are initially connected to $K = 8$ neighbours and each link is rewired by a probability of $p = 0.225$, and the Barabasi and Albert (BA) model [29], in which the number of initial nodes is $M_0 = 4$ and each time a new node is added it is connected to $M = 4$ existing nodes to generate the network topology.

In addition, a certain number of chunks were generated at the beginning of each SP in the simulation, with their source and destinations randomly determined. This can be viewed as the simulation of data collection in real systems. The deadlines for generated chunks were randomly chosen within $[t + h, t + T_{max}]$, where t is the current SP, h is the minimum number of SPs for a chunk to finish transmission, and T_{max} is a specified constant. As we assumed a chunk would only finish one hop's transmission within one SP, h was equal to the number a hops along the shortest path from a chunk's source to its destination. Moreover, because we focused on the energy-limited constraints rather than hardware-limited constraints, we assumed that the bandwidths of the links between routers and the storage sizes of routers were unlimited, so that no chunks would be aborted during buffering. For the same reason, we also did not explicitly consider the size of chunks in this simulation.

The simulation parameters are summarized in Table 2.

Table 2 Simulation parameters.

Topology	WS model ($K = 8$, $p = 0.225$) BA model ($M = 4$, $M_0 = 4$)
Number of routers	100
Simulation time	6:00 to 18:00, July 1, 2013
Length of one SP	1 min
Chunk generation rate	10, 20
E_{idle}	660 J
E_{sleep}	54 J
E_{chunk}	0.00257 J
T_{max}	300 min
μ	1

5.2 Compared Methods

This subsection introduces the direct-forward method and the solar-proportion method. When describing these two methods, we also focus on the scheduling procedure in one SP.

Direct-forward method

The direct-forward method is described in Algorithm 3. It is the current common approach that does not take into consideration power constraints or make use of chunks' delay-tolerant characteristics. Thus, for every SP, it just allows all chunks to be forwarded immediately and idles corresponding routers.

```
list ← list of chunks exist in the CNS ;
foreach chunk in list do
    ForwardChunk(chunk, list);
end
```

Algorithm 3: Direct-forwarding method.

Solar-proportional method

The solar-proportional method is similar to the proposed method. The scheduling of chunk transmission in this method is also adaptive to the generation status of renewable power. However, it is based on an allocation number, AC, that is directly proportional to renewable power output rather than a calculated power budget. This method is described in Algorithm 4. Here, AC determines the maximum number of chunks that can be transmitted in one SP. It is calculated by:

$$AC = H_{total} * E_g(t)/E_{w\_est}$$

where H_{total} is the number of chunks existing in the CNS in current SP, and E_{w_est} is the estimated power consumption if all chunks in CNS are allowed to be transmitted in the current SP.

```
list ← list of chunks exist in the CNS ;
E_g ← available renewable power;
AC ← H_total * E_g / E_w_est ;
SC ← 0 ;
Sort list by C value in ascending order;
foreach chunk in list do
    if C = 0 then
        ForwardChunk(chunk, list);
        SC ← SC + 1;
        continue;
    end
    if SC < AC then
        ForwardChunk(chunk, list);
        SC ← SC + 1;
    end
end
```

Algorithm 4: Solar-proportional method.

This algorithm can be summarized in three steps:

STEP 1 Calculate the C value and sort the chunk list

STEP 2 Transmit urgent chunks whose C values are 0

STEP 3 Transmit chunks if $SC < AC$

STEP 1 and STEP 2 are exactly the same as those in the proposed method. SC in STEP 3 is used as the counter of the number of chunks scheduled to be transmitted. While scheduling chunk transmission, $SC < AC$ is guaranteed, which makes the scheduled traffic adaptive to solar power generation.

5.3 Simulation Result

This section discusses the results obtained from the simulations based on the parameters introduced in Sect. 5.1.

First, Figs. 3 and 4 plot the simulation results when the network topology is a WS model for the former or a BA model for the latter, where the chunk generation rate is set to 10. In both figures, we can observe that the proposed method consumes much less conventional power than the direct-forwarding method and the solar-proportional method. Even though the absolute values in Fig. 4 are smaller than those in Fig. 3 due to variations in the lengths of transmission paths, by comparing these two figures, we can conclude that network topology does not severely affect the performance of the proposed method when the traffic load is moderate.

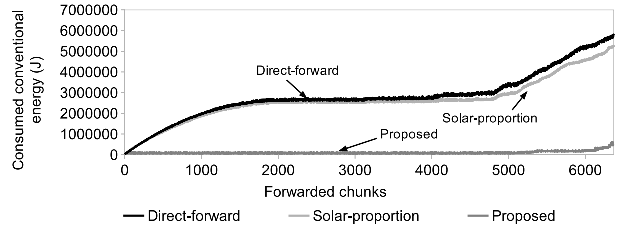

Fig. 3 Conventional power consumption (WS model, chunk generation rate of 10).

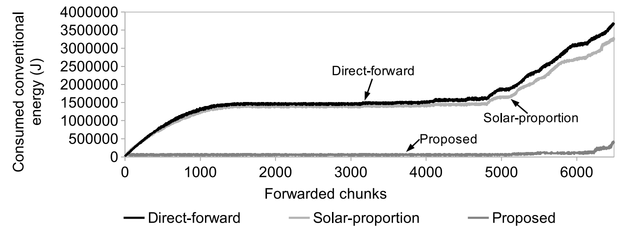

Fig. 4 Conventional power consumption (BA model, chunk generation rate of 10).

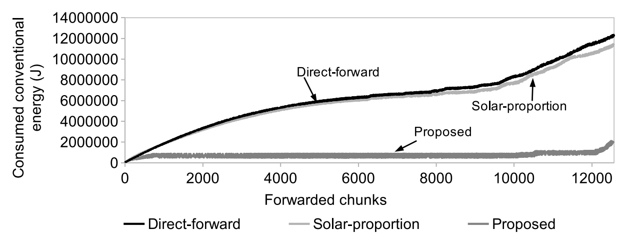

Fig. 5 Conventional power consumption (WS model, generation rate of of 20).

Second, Fig. 5 plots the simulation results when the chunk generation rate was changed to 20 for a network generated by the WS model. By comparing Fig. 3 and Fig. 5, we can see that when the data generation rate increases, although the power consumption by the proposed method increases significantly, its advantage over the two compared methods does not change.

In Figs. 3, 4 and 5, we plotted consumed conventional energy over forwarded chunks, which are the chunks successfully transmitted to their destinations. Here forwarded chunks represents the system throughput, which is a more dependent factor in energy consumption, rather than times.

To enable better understanding of these simulation results, a comparison of the number of active routers over time and the distribution of transmission delays in chunks are presented in Fig. 6 and Fig. 7, whose simulation settings are the same as those in Fig. 3. We can see from Fig. 6 that the number of active routers are closely related to renewable power generation when the system is operated with the proposed method and the solar-proportion method, while the number

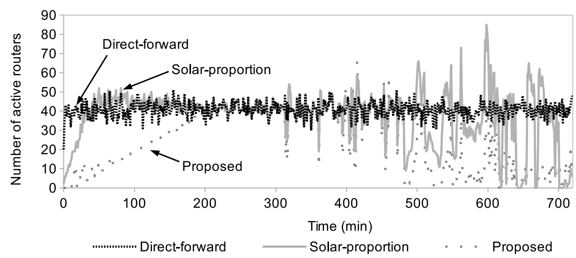

Fig. 6 Number of active routers over time.

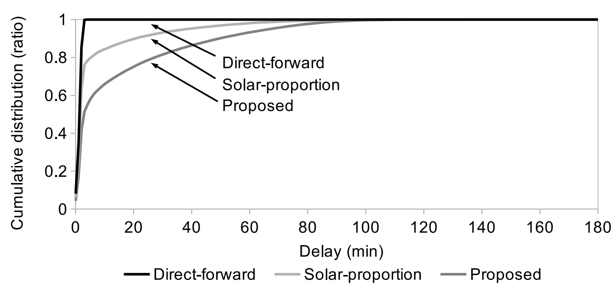

Fig. 7 Delay distribution of chunks.

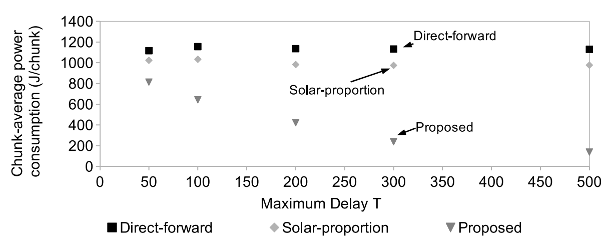

Fig. 8 Conventional power consumption under different delay constraints (WS model, generation rate of 10).

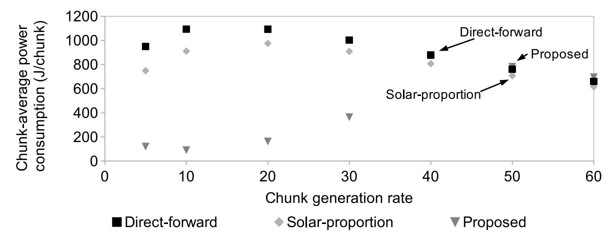

Fig. 9 Chunk-average power consumption with different chunk generation rates (WS model).

is relatively stable over time with the direct-forward method. We can also observe that for most of the time, this number with the proposed method is smaller than it is with the solar-proportion method. Even though the solar-proportion method also takes into account fluctuations in renewable power, it does not take into consideration the distribution of chunks, which causes it to activate more routers. As the main cause of power consumption is idle power consumption rather than transmission power, this figure explains why the proposed method can reduce conventional power consumption significantly while the solar-proportion method fails to do so. This explanation can also be confirmed from Fig. 7, where we can observe that the delays in chunks with the proposed method are longer than those with the compared methods. This figure indicates a clear trade-off between transmission delay and power consumption and the limitations of the application of this system to delay-tolerant networks. In addition, Fig. 8 indicates that the performance of the proposed method depends on the delay-tolerable characteristics of chunks. However, as we have assumed that chunks have loose delay constraints, we assumed these results were generally valid.

Finally, a comparison of chunk-average power consumption under different chunk generation rates is plotted in Fig. 9. We can see from this graph that the proposed method had great advantages over the compared methods in the low-traffic range, while in the heavy-traffic range, the proposed method failed. This is because in the heavy-traffic range, more routers are forced to be active to transmit urgent chunks, which increases the power consumption for the proposed method, while for the compared methods, more chunks passed the same router, which decreased the chunk-average power consumption.

These simulation results generally prove that the system worked well in reducing conventional power consumption in different cases when related parameters were within a certain range in delay-tolerant networks.

6. Conclusion

This paper introduced a communication system model based on a renewable energy-powered battery-free microgrid and discussed its control algorithm. According to the simulation results, the proposed system model performed well in terms of reducing conventional power consumption in delay-tolerant networks.

Future work will include the interoperation of neighboring limited areas, and the search for possible solutions to further reduce of conventional power consumption.

Acknowledgment

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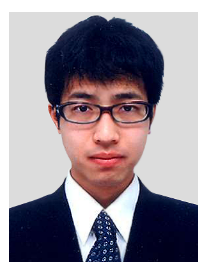

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