Matching of Energy Provisions in Multihop Wireless Infra-Structures

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Abstract: Recently there have been large advances in energy technologies for battery-operated systems, including green energy resources and high capacity batteries. The effective use of battery energy resources in wireless infrastructure networks to improve the versatility and reliability of wireless communications is an important issue. Emerging applications of smart cities, Internet of Things (IoT), and emergency responses highly rely on the basic communication network infrastructures that enable ubiquitous network connections. However, energy consumption by nodes in a wireless infrastructure network depends on the transmissions of other nodes in the network. Considering this inter-dependence is necessary to achieve efficient provision of energy in wireless networks. This paper studies the issue of energy provision for wireless relay nodes in Wireless Multihop Infrastructures (WMI) assuming constraints on the total energy provision. We introduce a scheme of Energy Provision Matching (Matching-EP) for WMI which optimizes energy provision based on matching of energy provision with estimates of differentiated position-dependent energy consumption by wireless nodes distributed in the network. The evaluation results show that Matching-EP with 4%–34% improvement in energy matching degree enables 10%–40% improvement of the network lifetime, and 5%–40% improvement of packet delivery compared with conventional WMI networks.

Keywords: energy provision; matching; wireless multihop infrastructures; green energy; network sustainability

1. Introduction

Wireless Multihop Infrastructure (WMI) networks facilitate flexible and quick deployment of communication networks. Multi-hop relay between low-cost base-stations in WMI can greatly extend the network coverage. Access to external networks through gateways can support access to the Internet, smart city networks, IoT and emergency networks [1–3]. Therefore, the WMI networks play an important role as a temporary alternative of conventional network infrastructures in the emergency situations, as well as other temporary networks such as low-cost IoT infrastructures.

A key issue affecting the operation of WMIs is resource constraints such as limited energy supply in the no-charging periods of emergency situations or the no-charging period of solar power supplies at night. Emergency situations may involve failure of network power supplies due to natural disasters such as earthquakes, hurricanes or floods [4,5]. A disaster hit area may be without grid power supply from several days to several weeks. Moreover, the re-charging or replacement

of batteries may be delayed for long times in remote locations or large-scale disaster situations. Consequently, the sustainability of WMI networks with such energy constraints is a serious concern.

Furthermore, with the recent advances in green energy sources and portable energy storage, the supply of energy to wireless base stations (BS) has been experiencing a change from traditional electricity power grid to renewable energy supplies and distributed energy storage [6–10]. This change facilitates the deployment of BSs and operation of sustainable WMI networks in off-grid locations. On the other hand, the supply of energy from renewable energy sources may be intermittent. For example, the no-charging period of solar panels at night time results in the energy constraint that the network should operate a long as possible with limited initial energy power.

Optimizing the energy supply and the operation of the WMI network requires consideration of the wireless activity and energy consumption in the whole network. Failure of any one node due to energy depletion could affect the connectivity of the network and disrupt the operation of the whole network. To date, many studies have been made on energy efficiency of networks with a focus on improving local energy efficiency at nodes, links and routes [11–16]. In many cases, local energy efficiency may lead to global energy efficiency, especially in hierarchical networks or hierarchical node functions such as data aggregation in sensor networks [15,17,18]. On the other hand, there are gaps between local and global energy efficiency. For example, unavoidable uneven energy consumption occurs in multihop networks [19]. This may cause some nodes to fail earlier than others, depending on their position in the network.

A challenging problem in WMIs in the no-charging period is the energy consumption differentiation among BSs in the network. If total energy resources are limited, then in order to optimize the lifetime of the network it is necessary to provide the BS with energy resources according to their differences of energy consumption. We call this the matched energy provision problem. In this paper, we address this problem of matched energy provision in WMI.

First we present a general mathematical formulation of the energy provisioning problem. In particular, we describe the principle of Energy Provision Matching (Matching-EP). Next, we propose a practical method for implementing Matching-EP in WMI based on estimation of position-dependent differentiation of energy consumption among BSs in a WMI. Finally, we validate the effectiveness of the proposed method by conducting packet-level simulation using standard Medial Access Control (MAC) and routing protocols.The evaluation results show that Matching-EP with 4%–34% improvement in energy matching degree enables 10%–40% improvement of the network lifetime, and 5%–40% improvement of packet delivery compared with conventional WMI networks.

The remainder of this paper is organized as follows. Section 2 introduces the related work. Section 3 introduces the system model. Sections 4 and 5 describes the basic concept and details of the proposed scheme of Matching-EP. Section 6 describes the evaluation and numerical results of the proposed scheme and Section 7 concludes the article.

2. Related Work

Energy efficiency in wireless networks has attracted many studies. There is an extensive body of research on energy efficient networking and communication in wireless networks, including energy efficient radio and devices [16,20,21], MAC protocols and sleep control [22,23], routing, clustering and data aggregations [14,15,17,18,24], as well as transport control [25,26], and local recovery mechanism [27–29]. In these works, local energy efficiency at nodes and routes are typically considered. The energy sources and supplies are typically uniform for nodes in a network.

Energy charging and supply methods for networks with green energy supplies have been studied in [7,8]. Reference [8] has modelled an energy buffer as a $G/G/1/\infty$ queue and a $G/G/1/N$ queue. Based on the model, an resource management scheme is proposed to balance traffic load across the mesh network. A solar powered WLAN mesh network is introduced in [7]. With a target of minimizing the enough resource allocation to the solar-powered WLAN, Genetic Algorithm (GA)

based resource assignment is utilized based on the information of input load profile, and historical solar radiation data. These studies focus more on energy resource management at individual nodes than the global combination of energy resource in the networks.

Prolonging network lifetime has been extensively studied in data centric sensor networks. The methods include energy aware routing, energy efficient MAC, relay nodes deployments, and clustering, [12,15,18,19,22,30]. On the other hand, these methods mainly rely on special features in sensor networks such as aggregation of small sensing data, and low cost nodes.

A minimum cost node and energy deployment scheme for heterogeneous sensor networks with a lifetime constraint is proposed in [31]. The study considered a heterogeneous sensor network that has three components: sensors, cluster heads, and aircraft sinks. To ensure a certain data collection cycle by aircraft, sensors and cluster heads are designed with minimum cost using efficient node deployment parameters for density and energy of sensor and cluster head nodes.

A joint approach of energy provision and node placement for sensor networks is introduced in [32]. This paper has a target of prolonging network lifetime. It considers a sensor network that allows hierarchical nodes types, such as sensor nodes, fixed relay nodes, freely deployed relay nodes. Furthermore, more energy can be provided to relay nodes. Based on this network structure, the paper proposed optimal relay node placement and energy provision with linear programming. The approach enables best position setting for freely deployable relay nodes, resulting in long network lifetime.

An energy aware provision scheme in a solar powered WLAN mesh network is introduced in [7]. This paper has a target of minimizing the enough resource allocation in a wireless mesh network that has a sustainable energy support system with solar panel, charge controller, and battery. Based on the information of input load profile, and historical solar radiation data, a GA algorithm is proposed to optimize the resource assignment.

A lifetime optimization scheme using variable batteries in sensor networks is introduced in [33]. This paper has a target of achieving long network lifetime by counterbalancing of non-uniform energy consumption. The sensor network has a basic application of sensor data dissemination and data gathering at a sink node. With a focus on ring area sensor network topology, the paper proposed two deployment approaches. In the first approach, battery capacity at sensor nodes are variably allocated according to the estimated energy consumption based on the number of sensing data transmitted and received at nodes in the ring regions. The second approach is based on non-uniform node deployment in different ring regions.

Summarizing, the related studies mentioned above make progress in the analysis of resource optimization in wireless networks. However, the applications of these approaches have been limited to networks that have hierarchical structure for global energy management, or limited to energy provision according to local energy differences. On the other hand, many networks, such as homogeneous mesh networks, do not have hierarchical structure, and optimization of network lifetime requires global optimization of energy provision and energy consumption.

3. System Model

### 3.1. Wireless Multihop Infrastructures (WMI) Network Model and Application Scenarios

Figure 1 shows the basic WMI network model and its application scenarios. A WMI network consists of a gateway (GW), Base Stations (BSs), and user stations (STAs), supporting multihop wireless access from STAs to an external network. Each BS has integrated wireless access point (AP) function and wireless mesh point (MP) function. The GW has a MP interface and a bridge to an external network. In general, STAs can communicate locally with BSs, or communicate with each other in a WMI network via BSs, or communicate with external networks via BSs and the GW.

This paper concentrates on the discussion of homogeneous WMI networks. The homogeneous type of base stations with regard to the communication protocol stacks and energy support methods facilitate the quick deployment of networks, easy maintenance, and low cost of networks.

There are various radio types of base stations with regards to diversity of capacity, interfaces, and frequency utilizations. On the other hand, the most basic radio type of a BS is with single interface and shared channel for easy configuration and quick applications [34–36]. From the application aspect, this paper focuses on the applications of quick network deployment, low cost BSs for emergency situations, event networks, and temporary networks, *etc*. Therefore, we basically adopt single interface BS stations with shared communication channel in this paper.
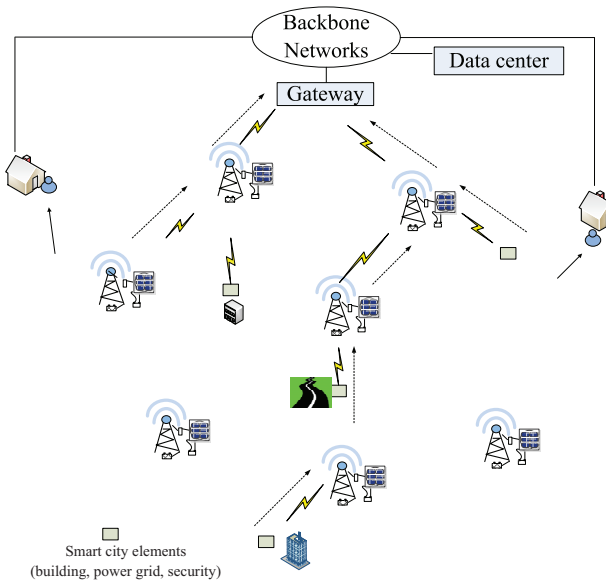
(a) Night scenario example
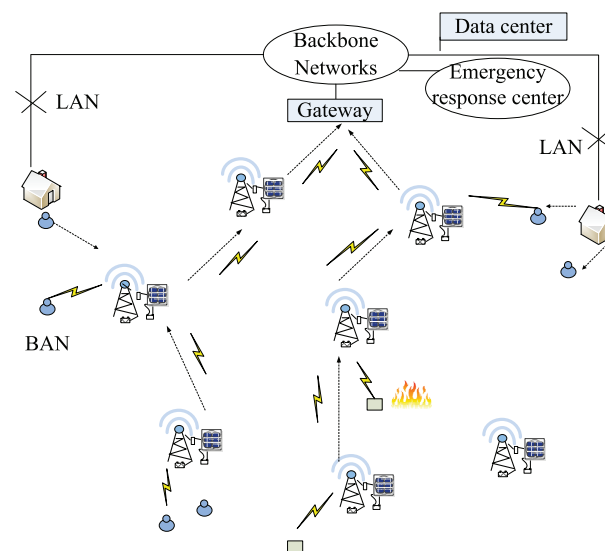
(b) Emergency situations

Figure 1. WMI network scenarios. (**a**) Night-time operation of a smart sensor network; (**b**) Emergency operation of a network for emergency information and support services.

3.2. Application Scenarios and Traffic

This paper focuses on scenarios where it is necessary for BS to operate using power supplied by batteries. As specific examples, we mention night-time operation of smart sensor networks, and emergency operation of access networks. In a smart sensor network, STAs could be used by smart city monitoring devices such as sensors in smart buildings, smart power grids, and smart roads. A WMI network can be connected via the external network to services such as data centers providing storage and analysis of data collected from STAs. On the other hand, in emergency scenarios, such as in disaster areas, where local wired networks are disrupted, the WMI could be used by people to access emergency information and services in the external network.

The flow of application traffic will depend on the application scenarios. For example, the traffic of the smart sensor network in a smart city may be polarized with most traffic flowing from sensors to the data centers in the external network [2,37], as shown in Figure 1a. On the other hand, traffic due to persons communicating with each other may be more evenly distributed within the WMI. Accordingly, the traffic could be more polarized during the night, when people are less active and the traffic is dominated by sensor traffic or time shifting of Internet access [38].

In the case of an WMI operating in an emergency scenario, as shown in Figure 1b, the majority of network traffic may be access to the external network, either by smart city elements reporting to data centers, or people communicating with emergency support centers [4,37]. In this case, the traffic in the WMI may be highly polarized with a dominant flow between STAs and the GW. In both types of WMI scenarios, night-time operation of smart-sensor networks, and emergency scenarios, the energy consumption by nodes in the network may be highly differentiated due to the polarized traffic, depending on the position of the node and the routes to the GW.

3.3. Network Energy Supplies

In this paper we consider the situation that BSs have limited energy sources and the GW is part of a dependable system that does not have limited energy source. Although there are various method of energy supply sources, this paper takes account of homogeneous type of energy supplies for BSs in a WMI for a certain application scenario, as stated in Section 3.1. A block diagram of a BS power supply is shown in Figure 2a. A BS may have a set of backup batteries with fixed initial charge for emergency uses, as well as have a set of solar-battery power generation system for normal energy supply during the network operation.

(a) Energy sources   **(b)** Energy charging
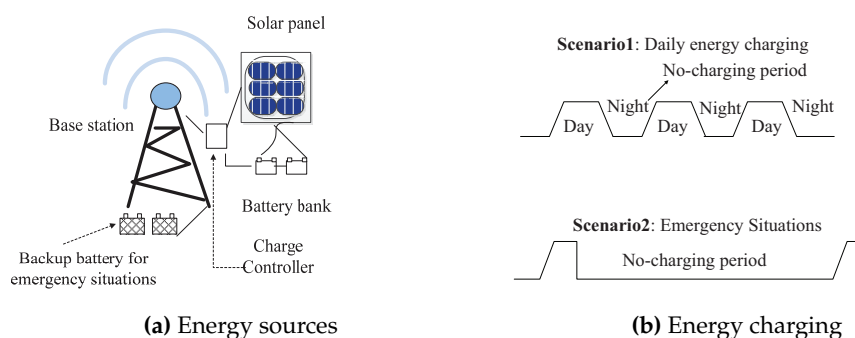
Figure 2. Energy models of BS in WMI networks.

In this paper, the provision of energy sources includes the provision of back-up batteries as well as charging capacity of a solar-battery for night time period. In the case of a solar power system, the absolute generation capacity depends on both the capacity of solar panel-battery as well as on the amount of sunlight during the network operation time (e.g., Average Offered Capacity Profile (AOCP)) available at each BS location [6]). On the other hand, for a local WMI network in a limited

region of a city, the rate of energy generation and charging at a unit set of solar-battery will have the similar level.

3.4. Energy Consumption Model

Next we present a model of energy consumption by wireless communication. A radio device is assumed to have a fixed operating voltage V and an operating current that depends on whether it is transmitting, receiving, or idle. The transmit current is I_{TX}, the receiving current is I_{RX} and the idle current I_I. We assume that all BS transmit at the same power and the currents are the same for all BS. Note that a radio device consumes energy receiving packets even if they are not addressed to it. We will call this "overhearing".

4. Matching of Energy Provision: Basic Concepts

The goal of efficient energy provisions in this paper is to enable matching between the energy supply and energy requirement at each BS in the network in order to maximize the network lifetime that the network can continue to operate. More specifically, this paper aims to match the energy provision differences with the energy differentiation among BSs in a WMI network.

The proposed approach can be employed in practical scenarios given a WMI topology in the following two types of applications. (a) Provision of backup batteries for each BS according to the estimation of explicit energy differentiation among BSs. This application is essential for the sustaining a network in the no-charging period of emergency situations. As for user applications, we especially consider the main application of Internet access through the multihop wireless infrastructure; (b) Provisions of solar-rechargeable batteries at each BS for use at night during the no-charging period of solar energy systems. The application is essential for sustaining a network during the night time no-charging period of a solar-powered network.This application is useful for temporary low-cost networks used at temporary locations and events. As for user applications in night time, we especially consider the main applications of data collection from sensors, and IoT communications using multihop wireless infrastructure.

Figure 3, illustrates the basic idea of efficient energy provisioning. Figure 3a shows a case in which all BS have equal energy provision, but run out of energy at different times. If the energy consumption rates of the BS are different, some BS will be able to operate for a longer time than others. In contrast, Figure 3b, shows the case where the BS have unequal energy provision and all BS run out of energy at the same time. The network may cease to operate if any BS runs out of energy. Energy will be wasted if some BS have energy remaining after the network ceases to operate. In this sense, the optimal provision of energy should result in all BS having the same lifetime.

(a)   **(b)**
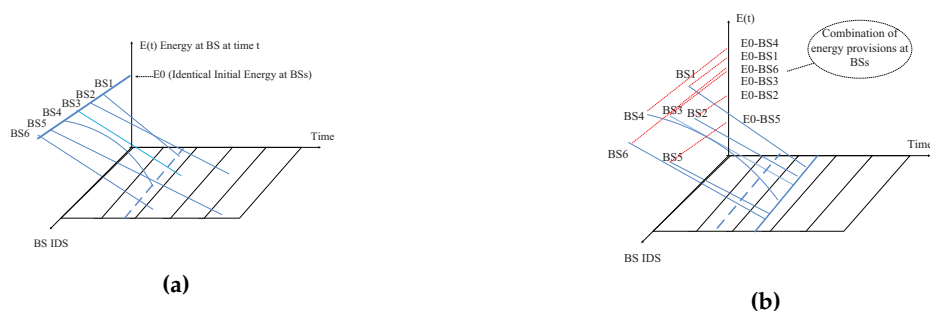
Figure 3. The basic concept of energy provision for a given total resource of network energy. (**a**) Same energy provision; (**b**) Diversity of energy provision.

Let us describe this formally. Assume the BS have unique labels i ($1 \leq i \leq N$). Denote the ith BS as BS(i). We define the lifetime of a BS as the time from starting operation until the time when all its

energy is completely depleted. Denote the lifetime of BS(i) as $T_{BS}(i)$, where $1 \leq i \leq N$. Denote the network lifetime as:

$$T_{network} = \underset{1 \leq i \leq N}{\text{minimum}} T_{BS}(i) \tag{1}$$

Proposition 1. *The maximum value of network lifetime $T_{network}$ is achieved when the lifetime of each BS is identical: $T_{BS}(i) = T_{BS}(j) = ...T(N)$*

Proof. We use the contradiction method to prove the proposition. Suppose the network lifetime is maximum but the BS lifetimes are not identical. Then there will be at least one BS(i) that has a longer lifetime compared with $T_{network}$, which is the minimum lifetime among BSs, and such BS will have energy remaining, say $\triangle E(i)$, at the time $T_{network}$. Then an energy provision that re-assigns some of $\triangle E(i)$ of BS(i) to all the BS with the shortest lifetime will achieve a longer value of $T_{network}$. This is in contradiction with the assumption that the network lifetime is maximum. □

Next we describe how matching of energy provisioning to energy consumption leads to the maximum network lifetime. Suppose BS(i) has energy provision $E_0(i)$ and average energy consumption rate $E_{CR}(i)$ during its lifetime $T_{BS}(i)$. By definition, $E_{CR}(i) = E_0(i)/T_{BS}(i)$.

Let the average of energy provision at all BSs in the network be E_{0-BS}, and the average of average energy consumption rate at all BSs be E_{CR-BS}. The matching degree at $BS(i)$ is defined as:

$$MDegree(i) = 1 - \left| E_0(i)/E_{0-BS} - E_{CR}(i)/E_{CR-BS} \right| \tag{2}$$

The maximum value of matching is $MDefree = 1$, The maximum value is attained when the ratio of energy provision at a BS to the average energy provision is the same as the ratio of the average energy consumption rate at the BS to the average energy consumption rate.

Proposition 2. *The optimal energy provision achieving the maximum network lifetime $T_{network}$ corresponds to $MDefree = 1$ for all BS.*

Proof. By definition $T_{BS}(i)E_{CR}(i) = E_0(i)$. If $MDefree(i) = 1$ then $T_{BS}(i) = E_0(i)/E_{CR}(i) = E_{0-BS}/E_{CR-BS}$. As a result, all BSs that have $MDefree = 1$ will have the same lifetime. If all BS have $MDefree = 1$ then all BS have the same lifetime $T_{BS}(i) = T_{BS}(j) = ...T(N)$. Consequently, MDefree = 1 for all BS achieves maximum network lifetime. □

Next, we introduce the relative energy consumption ratio and the energy differentiation factor. The relative energy consumption ratio is written as:

$$\mu(i) = \frac{E_{CR}(i)}{\sum_{i=1}^{N} E_{CR}(i)} E_{0-all}, \, 1 \leq i \leq N \tag{3}$$

where E_{0-all} is the total energy provision, defined as the product of E_{0-BS} and N, $E_{0-all} = E_{0-BS}N$.

The energy differentiation factor is written as:

$$Diff(i) = \frac{E_{CR}(i)}{\sum_{i=1}^{N} E_{CR}(i)/N} \tag{4}$$

Note that we can rewrite the relative energy consumption ratio in terms of the energy differentiation factor as follows, $\mu(i) = Diff(i)E_{0-BS}$

Proposition 3. *The energy provision solution of $(E_0(1), E_0(2), ..., E_0(N)) = (\mu(1), \mu(2), ..., \mu(N))$ where each $\mu(i)$ is defined as in Equation (3), results in the perfect energy matching of all BSs.*

Proof. For each BS(i), let $E_0(i) = \mu(i) = \dfrac{E_{CR}(i)}{\sum_{i=1}^{N} E_{CR}(i)} E_{0-all}$. We can obtain that $E_0(i)/(E_{0-all}/N) =$

$\dfrac{E_{CR}(i)P}{(\sum_{i=1}^{N} E_{CR}(i)P)/N}$, that leads to perfect energy matching of $MDegree(i) = 1$ for each BS(i), $1 \leq i \leq N$. □

The Proposition 3 expresses the basic principle of optimal energy provision in a WMI with a given total energy provision and a set of energy differentiation factors $(Diff(1), Diff(2), ..., Diff(N)$ at the BSs in the WMI.

5. Energy Differentiation Factor for Energy Provision in WMI Networks

In Section 4, we showed that the optimal energy provision matching, Matching-EP, that achieves maximum network lifetime depends on the energy differentiation factors of the BSs in the network. The challenge of realizing Matching-EP in practice is that in general it is difficult to know precisely the traffic activities among nodes in a network. Hence it is difficult in practice to achieve optimal matching. However, Matching-EP can be used as a basic guiding principle for energy provision to improve energy efficiency and increase the lifetime of WMI networks. We present an analytical framework for various network models.

Main notations in the energy consumption analysis are shown in Table 1.

Table 1. Definitions of notations.

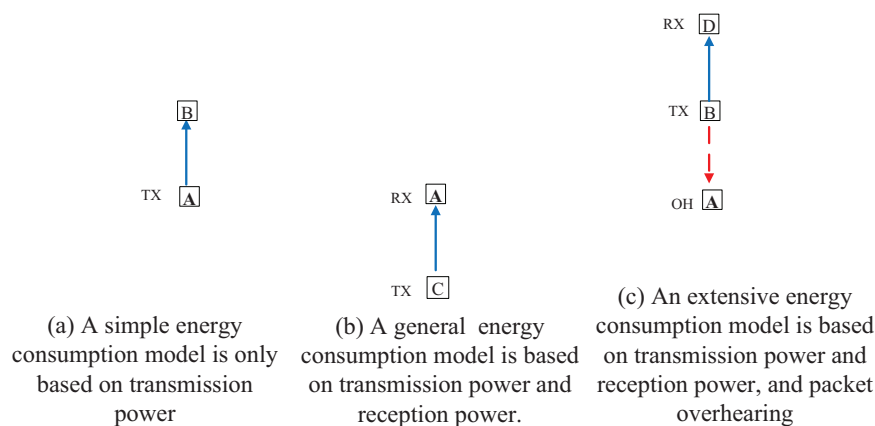| Notation	Description
$d(i)$	the topological distance from BS(i) to the gateway
N	the number of BSs in the WMI networks
$E_0(i)$	the initial energy of BS(i)
E_{0-all}	the total initial energy of all BSs for polarized traffic activities
$E_{CR}(i)$	the energy consumption rate at BS(i)
$E_c(i)$	the energy consumption at BS(i)
$E(i)$	the current remaining energy at BS(i)
$E_r(i)$	the remaining energy at BS(i)
$zone(k)$	the zone in which BSs have hop distance k to GW
$Diff(i)$	the energy differentiation factor at BS(i)
$E_Z(h)$	the energy consumption at zone(h)
$Src(i)$	the number of packets initiated at BS(i) in a WMI
$TX(i)$	the number of transmitted packets at BS(i)
$RX(i)$	the number of received packets at BS(i)
$OH(i)$	the number of overheard packets at BS(i)
E_{Others}	the energy consumption other than that of *TX*, *RX*, and *OH*
$Oth(i)$	E_{Others} at BS(i)
E_{Pt}	the average energy consumed for transmitting a packet
E_{Pr}	the average energy consumed for receiving a packet
$N_z(k)$	the total number of BSs in zone(k)
$ZTX_{self}(k)$	the number of packets initiated in zone(k)
$ZTX(k)$	the number of transmitted packets in zone(k)
$ZRX(k)$	the number of received packets at in zone(k)
$ZOH(k)$	the number of overheard packets in zone(k)
$E_{Total-Z}(k)$	the total energy consumption in zone(k)
$E_{Total-B}(k)$	the total energy consumption at a BS in zone(k)
$Diff_{ZBS}(k)$	the differentiation presenting factor of a BS in zone(k)
D	the density of BSs relative to hop-distance based area
H	the largest hop distance of BSs to GW
K_{RT}	the ratio of energy consumption for receiving a one-bit message to that of transmitting a one-bit message
K_{OH}	the ratio of *OH* energy consumption at a zone to the *TX* energy consumption of the upstream neighbour zone

5.1. Differentiation of Energy Consumption in WMIs

The energy consumption of a BS and the distribution of network energy consumption in WMI depend on the wireless transmitting (*TX*) and receiving (*RX*) activities of BSs. The energy consumption information that is required for efficient energy provision can be estimated based on energy consumption differentiation at each BS. This section shows how to analyze energy differentiation by estimating the traffic flow at each BS. In order to improve the accuracy of the estimate, it is necessary to consider the overhearing (*OH*) effect in the shared communication media of a WMI network. Figure 4 shows how nodes can overhear transmissions between another pair of nodes. To date, few studies have explicitly considered the *OH* effect on energy consumption in network energy analysis.

There are many activities associated with radio energy consumption, among which this paper focuses on the *TX*, *RX*, *OH* data packet activities and their differentiation. This is because that *TX*, *RX* and *OH* are the main communication activities in wireless networks [39].

In general, it is difficult to analyze the long-term network activities and the correlated energy consumption differences at BSs even if we know energy consumption in a single event. This section examines the energy differentiation in a WMI network based on the correlations of *TX*, *RX* and *OH* network activities among BSs. We introduce the line model and zone based model to quantitatively represent the energy differentiation based on the correlation of network activities in WMIs with various topologies.

(a) A simple energy consumption model is only based on transmission power

(b) A general energy consumption model is based on transmission power and reception power.

(c) An extensive energy consumption model is based on transmission power and reception power, and packet overhearing

Figure 4. *TX-RX-OH* interactions and enery consumption models.

First we present an analytical framework for analysis of energy consumption at BS based on the number of *TX*, *RX* and *OH* operations. As shown in Table 2, we assume N is the number of BS in the network, and $TX(i)$, $RX(i)$, and $OH(i)$ are respectively the number of *TX*, *RX* and *OH* packets in a certain time interval of duration T, which increase in proportion to the value of T. $TX_{local}(i)$ is the number of packets which originate at BS(i).

Table 2. The traffic, energy consumption and differentiation at BSs.

BS	TX_{local}	TX	RX	OH	E_{Others}	E_c	$Diff$
BS(1)	$Src(1)$	$TX(1)$	$RX(1)$	$OH(1)$	$Oth(1)$	$E_c(1)$	$Diff(1)$
...	...	...	...	...	...	...	...
BS(i)	$Src(i)$	$TX(i)$	$RX(i)$	$OH(i)$	$Oth(i)$	$E_c(i)$	$Diff(i)$
...	...	...	...	...	...	...	...
BS(N)	$Src(N)$	$TX(N)$	$RX(N)$	$OH(N)$	$Oth(N)$	$E_c(N)$	$Diff(N)$

An estimate of energy consumption E_c of a node BS(i) can be expressed as a linear function of packet numbers as shown in Equation (5).

$$E_c(i) = E_{Pt}TX(i) + E_{Pr}RX(i) + E_{Po}OH(i) + Oth(i) \tag{5}$$

where E_{Pt}, E_{Pr} and E_{Po} are the energy consumed per packet by *TX*, *RX* and *OH* operations, and *Oth* represents other energy consumption that does not depend on packet number.

Oth is assumed to be a constant times the measurement time interval.

5.2. Differentiated Energy Consumption in a Line Topology

In this subsection, we demonstrate the method of estimating differentiated energy consumption with an example of a WMI network with line topology. An example of line topology WMI network with 5 BSs is shown in Figure 5. We suppose that BS are deployed in a line and assume that the dstance between neighboring BS corresponds to the wireless transmission range, so each BS can only receive or overhear packets from its neighbors. We also suppose that each BS generates a number TX_{local} of packets for transmission upstream to the external network via the GW. Let each BS be labelled with an identifier (ID) in a sequence corresponding to the topological distance from the GW, so that a BS that has a topological distance of i hop to the GW, has ID equal to i. With these assumptions, we then introduce the basic relations between *TX* and TX_{local}, *RX* and *TX*, as well as *OH* and *TX*, according to the multihop packet relay features in the line-topology WMI. First, the number of *TX* packets at each BS(i) can be written in terms of the amount of TX_{local} packets as follows.

$$TX(i) = \sum_{k=i}^{N} TX_{local}(k) \tag{6}$$

We call this relation the $TX\text{-}TX_{local}$ relation.
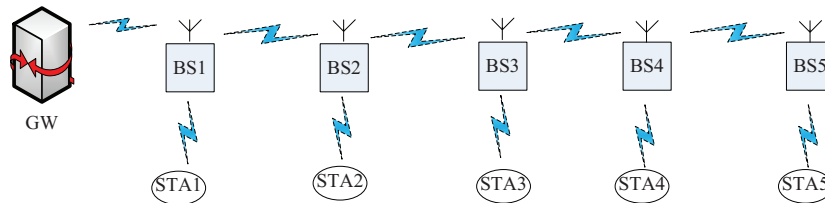
Figure 5. A line-topology WMI example with 5 traffic flows.

Second, the number of *RX* packets at each BS(i) can be expressed according to the amount of *TX* packets as:

$$RX(i) = \begin{cases} TX(i+1) & 0 < i < N \\ 0 & i = N \end{cases} \tag{7}$$

We call this relation the *TX-RX* relation.

Third, the number of *OH* packets at each BS can be described in terms of the amount of *TX* packets by:

$$OH(i) = \begin{cases} TX(i-1) & 2 < i \leq N \\ 0 & i = 1 \end{cases} \tag{8}$$

That is, each BS(i) overhears the packets transmitted at BS($i-1$). We call this relation the *TX-OH* relation.

In the example of a line topology WMI network that is shown in Figure 5, there are 5 BSs and 5 STAs in the network. Each STA is associated with one of the BS and generates a flow of packets for

delivery via its BS and the WMI to the external network through the GW. Given the TX_{local} generation amount in a certain time duration D, we can derive the activity and energy differentiation in the network. To be specfic, we let the generation amount be the same at each BS, let the energy E_{Others} be equivalent to 6 units, and let the energy consumption be 1 unit per packet in *TX*, *RX* and *OH*. Note that since we only need the ratios of energy consumption, it is not necessary to specify the absolute units of energy.

The number of each type of packet operation (*TX*, *RX*, *OH*), the energy consumption, and the matching energy provision for each BS are illustrated in Table 3. Differentiation factors can be derived based on Equations (4) and (5). The optimal energy provision for BSs is obtained according to Equation (3), We can see that the energy consumption and energy differentiation factor is largest at node BS(2).

Table 3. The traffic, energy consumption and differentiation at each BS in a line-topology WMI wth 5 BS, each generating $TX_{local} = 1$ packet. $E_{0-all} = 50$ J.

BS	$TX_{\mathbf{local}}$	*TX*	*RX*	*OH*	$E_{\mathbf{Others}}$	$E_{\mathbf{c}}$	*Diff*	$E_{\mathbf{0}}[i]$
BS(1)	1	5	4	0	6	15	1.09	10.9
BS(2)	1	4	3	5	6	18	1.30	13.0
BS(3)	1	3	2	4	6	15	1.09	10.9
BS(4)	1	2	1	3	6	12	0.87	8.7
BS(5)	1	1	0	2	6	9	0.65	6.5

$$\underbrace{\begin{pmatrix} E_0(1) \\ E_0(2) \\ E_0(3) \\ E_0(4) \\ E_0(5) \end{pmatrix}}_{Provision} = \underbrace{\left(E_{0-all}/N = 10 \right)}_{Average} \times \underbrace{\begin{pmatrix} Diff(1) \\ Diff(2) \\ Diff(3) \\ Diff(4) \\ Diff(5) \end{pmatrix}}_{Diff}$$

This simple model serves to illustrate the idea of differentiated energy consumption and Matching-EP. In practice, the accuracy of the estimate of energy consumption will depend on how well the model estimates the actual wireless activity. One way of using this simple model in practice is to consider energy consumption factors as average quantities, including estimates of average energy required for multiple-retransmissions per packet, and the energy of transmissions required for network management.

Finally, we note that the analysis of energy differentiation in the line-topology WMI can be easily extended to WMI with multiple separated line paths, as shown in Figure 6. Given a WMI with multiple separate line paths to the GW, the dependence of energy consumption differentiation on BS hop distance from the GW is smilar to that for the simple line topology.

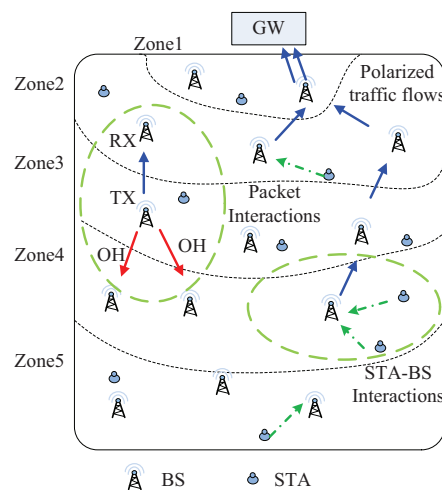*5.3. Zone Model of Differentiated Energy Consumption in 2D Topology*

In this section, we introduce a zone model for estimating differentiated energy consumption in a WMI with a two-dimensional topology.

In the zone model, the WMI is partitioned into zones according to the topological distance of BS to the GW, so that the traffic flow can be represented by aggregate packet flows between contiguous zones. The topological distance is the relay hop count. The energy-consuming packet operations in the network include transmitting, receiving and overhearing. We define zone(k) as the set of all BSs in the network with the number of hops from BS(i) to the GW equal to k.

The energy consumption difference in the zone-based model can be analysed in terms of aggregate numbers of packet operations (*TX*, *RX* and *OH*) in each zone. Figure 7 shows an example of zones in a 2D mesh network, and Table 4 shows the packet operations, energy consumption and differentiation factors in each zone.
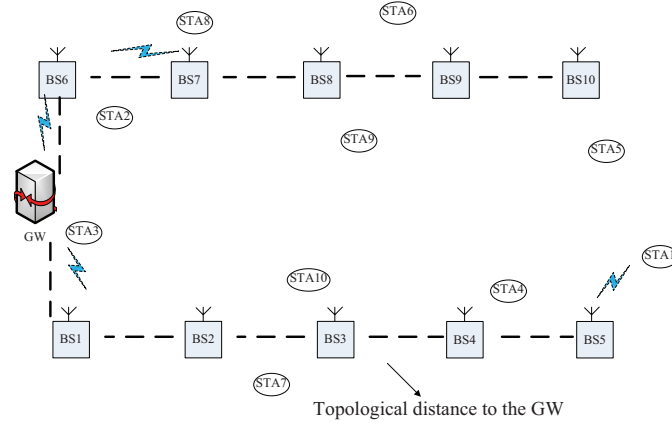
Figure 6. Applications of line-topology WMI analysis. Energy consumption analysis of line-topology WMI can be applied to a WMI with multple separated lines paths to the GW.

Figure 7. Zone model of network traffic and energy consumption.

Table 4. The traffic, energy consumption and differentiation in BS zones.

zones	N_Z	ZTX_{local}	ZTX	ZRX	ZOH	E_{others}	$E_{Total-Z}$	$E_{Total-B}$	$Diff_{ZBS}$
zone(1)	$N_Z(1)$	$Src_Z(1)$	$ZTX(1)$	$ZRX(1)$	$ZOH(1)$	$Oth(1)$	$Total_Z(1)$	$Total_B(1)$	$Diff(1)$
...	...	...	...	...	...	...	...	...	...
zone(k)	$N_Z(k)$	$Src_Z(k)$	$ZTX(k)$	$ZRX(k)$	$ZOH(k)$	$Oth(k)$	$Total_Z(k)$	$Total_B(k)$	$Diff(k)$
...	...	...	...	...	...	...	...	...	...
zone(H)	$N_Z(H)$	$Src_Z(H)$	$ZTX(H)$	$ZRX(H)$	$ZOH(H)$	$Oth(H)$	$Total_Z(H)$	$Total_B(H)$	$Diff(H)$

The total energy consumption in a zone(*k*) is given by:

$$Total_Z(k) = E_{Pt}ZTX(k) + E_{Pr}ZRX(k) + E_{Pr}ZOH(k) + Oth(k) \tag{9}$$

where $ZTX(k)$, $ZRX(k)$, $ZOH(k)$ are the number of *TX*, *RX* and *OH* packets, respectively.

The average energy consumption at a BS in zone(*k*) is given by:

$$Total_B(k) = Total_Z(k)/N_Z(k) \tag{10}$$

where $N_Z(k)$ is the number of BS in zone(*k*).

Consequently, for each BS in zone(*k*), the differentiated energy consumption ratio $Diff(k)$ can be expressed as:

$$Diff(k) = \frac{Total_B(k)}{\sum_{i=1}^{N} Total_B(i)/N} \tag{11}$$

where *N* is the total number of BS.

Let $ZTX(k)$, $ZRX(k)$ and $ZOH(k)$ represent the number of packet operations *TX*, *RX* and *OH* in a zone(*k*), respectively. Let $ZTX_{local}(i)$ be the number of packets originating at *BSs* in zone(*i*).

According to the packet flow feature in the network, The *TX-TX_{local}* relation among zones can be approximately expressed by:

$$ZTX(k) = \sum_{i=k}^{H} ZTX_{local}(i) \tag{12}$$

The *TX-RX* relation among zones can be given by:

$$ZRX(k) = \begin{cases} ZTX(k+1) & 0 < k < H \\ 0 & k = H \end{cases} \tag{13}$$

The overhearing in WMI with 2D topology is more complex than in the line-topology WMIs. We assume that each BS in a zone(*i*) may overhear packets from the upstream zone(*i*−1), the zone(*i*), and the down-stream zone(*i* + 1). To simplify the analysis, we define a *OH* factor K_{OH} such that the *TX-OH* relation can be described consistently with that in line-topology WMI. Let $K1_{OH}$, $K2_{OH}$, and $K3_{OH}$ stand for the average numbers of neighbors in upstream zone, same zone, downstream zones of a BS, excluding the *RX* neighbors. Then a general description of $ZOH(k)$ can be given by:

$$ZOH_{Full}(k) = \begin{cases} ZTX(k-1)K1_{OH} + ZTX(k)K2_{OH} + ZTX(k+1)K3_{OH} & 2 < k \leq H \\ ZTX(k)K2_{OH} + ZTX(k+1)K3_{OH} & k = 1 \\ ZTX(k-1)K1_{OH} + ZTX(k)K2_{OH} & k = H \end{cases} \tag{14}$$

To provide a more simplified basic *TX-OH* relation among zones, we express the *TX-OH* relation in terms of an integrated factor K_{OH} by:

$$ZOH(k) = \begin{cases} ZTX(k-1)K_{OH} & 2 < k \leq H \\ 0 & k = 1 \end{cases} \tag{15}$$

where K_{OH} is a constant denoting the approximate ratio of packet overhearing to the packet overhearing from the upstream zone.

Hence, given ZTX_{local} in a grid WMI, Equation (9) can be obtained by substituting $ZTX(k)$, $ZRX(k)$, and $ZOH(k)$ based on Equations (12), (14) and (15). In addition, we can calculate Equation (10) based on Equation (9). Consequently $Diff(k)$ can be obtained according to Equation (11). We can then express the energy provision at a BS in zone(*k*) as:

$$E0_{BS}(k) = \frac{Diff(k)}{\sum_{i=1}^{H} Diff(i)} E_{0-all} = \frac{Total_B(k)}{\sum_{i=1}^{H}(i)Total_B(k)} E_{0-all} \tag{16}$$

The zone analysis model can be used in a WMI network with a given topology. Based on the zone model, the network is divided into several zones according to the topological distance to the GW. Then energy resources, such as backup batteries, and solar-battery sets are assigned to the BSs according to the zone they resides. BSs in the same zone will be assigned with the same amounts of energy resources. BS in the different zones will be assigned with the different amount of resources according to the analysis of differentiation of energy consumption analyses.

6. Numerical Evaluation

In this section, we show the evaluation results with respect to the proposal of energy provision and analyses described in Sections 4 and 5. We do network simulations using the discrete event network simulator NS-3 to study the impact of energy provision on the network performance [40]. In a WMI network, battery powered BSs are provided with various amounts of initial energy. The total amount of initial energy in the WMI network is constant. We evaluate the proposed protocol Matching-EP in comparison with the conventional conventional energy provision approach, here called Same-EP, in which all BS have the same initial energy.

In the evaluation, we focus on the impact of network sizes, network topology, and routing protocols on the proposed energy deployments. We consider two scenarios for the evaluation. The first scenario, scenario-1, evaluates the basic routing-independent case of the line-topology network. Various size networks are evaluated, as shown in Figure 8. Four cases of networks with different network sizes and different number of static STAs are studied. The second scenario, scenario-2, employs a grid-topology WMI network, that enable us to examine different routing protocols. The network topology for scenario-2 is shown in Figure 9. Mobile STA with random mobility are employed in the network. This scenario lets us to examine the impact of energy deployment in the combined environment of routing and STA mobility.
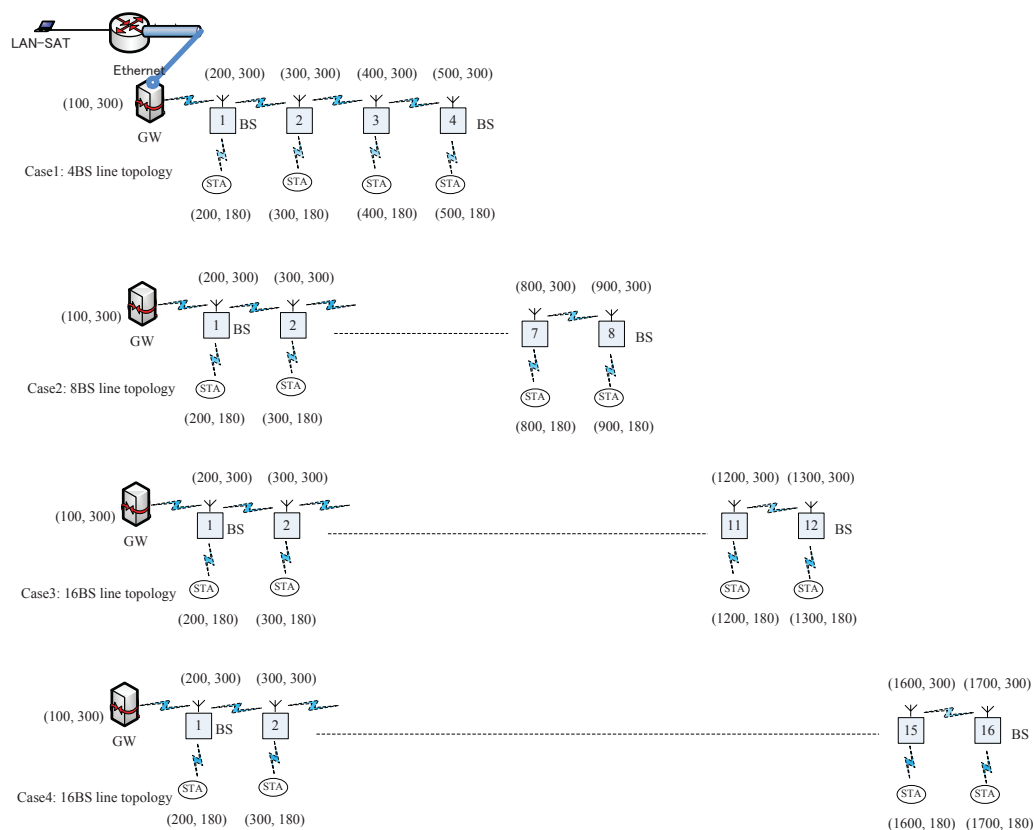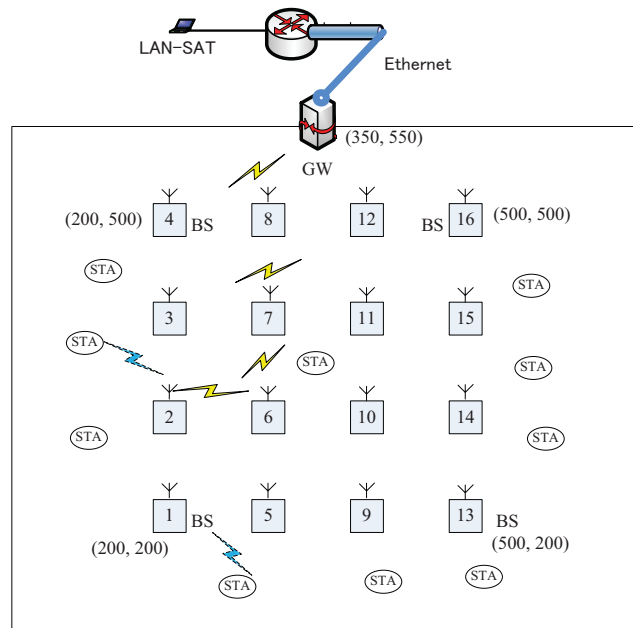

Figure 8. Line topology scenarios (such as WMI for roads).

Figure 9. Grid network topology model in senario-2.

Four routing protocols based on proactive Hybrid Wireless Mesh Protocol (HWMP) in IEEE 802.11s mesh networks are evaluated in the scenario 2. In addition to proactive HWMP in IEEE 802.11s mesh networks, we developed three routing protocols based on HWMP with various routing metrics so as to evaluate the energy matching performances of shortest path, energy and connectivity aware routing protocols [41].

- HWMP proactive routing (HWMP): As defined in IEEE 11s [34], default proactive tree-based routing adopts the airtime cost metric.
- Shortest path HWMP routing (SP-HWMP): A proactive HWMP routing with shortest path selection. A cost metric for shortest path selection can be defined for each BS by $C_{sp}(i) = 1$, so that the path cost is the sum of each BS cost $C_{sp}(i)$ in the path, *i.e.*, $C_R(i) = \Sigma C_{sp}(i)$.
- Energy aware HWMP routing (E-HWMP): A proactive HWMP routing with residual energy as BS cost metric, given by $C_{Er}(i) = \dfrac{100}{E_r/E_0}$ where E_r is the residual energy at BS(i).
- Energy-Connectivity aware HWMP routing (EC-HWMP): A proactive HWMP routing with both residual energy and network connectivity as the cost metric. The cost metric is given by $C_{EC}(i) = C_{Er}(i) \times H_{GW}(i)$ where $H_{GW}(i)$ is the hop distance from the BS(i) to the GW.

Main evaluation metrics in the simulation are shown in Table 5. The metrics in our evaluations include: network lifetime, successfully received packets, matching degree between energy consumption and energy provisions, *etc.*

Table 5. Evaluation Metrics.

Network Lifetime	The duration from the start time of the network to the time when the first BS runs out of its energy
Successfully Received Packets	The total number of successfully received packets at the GW
Node Energy	The remaining energy at each BS
Matching Degree	As defined in Equation (2)

Unless otherwise stated, the simulation is set up as shown in Table 6. The simulation environment includes not only packet level routing operations, but also MAC Protocols dealing with carrier sensing, packet collisions, packet retransmission. This allows us to obtain realistic results with regard to energy consumption in the network. The simulation adopts the log-distance path loss model as the default propagation loss model. The current consumed in the three wireless device activity states, *TX*, *RX* and *IDLE*, are set up based on default radio energy model in NS-3 simulator version ns-3.15 [40]. In the simulation, the default total E_{others} factor in energy provision is set to 50% of total energy provided in the network.

Table 6. Simulation set-up parameters.

Parameters	Scenario-1	Scenario-2
Simulator	NS3	
MAC/PHY layer model	IEEE 802.11s [34]	
MAC protocol	CSMA	
Propagation loss model	Log-distance path loss model	
Mobility model	static	Random mobility
Number of static BSs	4, 8, 12, 16	16
Number of STAs	4, 8, 12, 16	10
Number of GW	1	
Application traffic	From STAs to GW	
Initial energy of Battery	16 J for Same-EP case	
TX current I_{TX}	17.4 mA	
RX current I_{RX}	19.7 mA	
IDLE current I_I	426 μA	
Battery energy at BSs	All BSs	
Packet size	1024 bytes	
Data rate	54 Mb/s	

6.1. Numerical Results in Scenario-1: Line Topology

First, in order to evaluate basic performance of energy provision that is independent of routing protocols in multihop wireless networks, we consider line topology scenarios. In this scenario, each BS has an associated STA traffic source generating Poisson traffic.

To validate the energy differentiation analysis, we illustrate the result of energy differentiation observed in an example of line-topology WMI with 4 BSs. Table 7 shows results of energy differentiation analysis for the case of a line-topology WMI with four BS. The first row shows $Diff_M(i)$, the time-average value of energy differentiation measured in the simulation evaluation with SP-HWMP routing. The second row shows the value of energy differentiation expected if the energy consumption obeys the uniform energy consumption model. The third row shows the value of energy differentiation expected if the energy consumption obeys the *TX-RX-OH* relations. The last column shows the accuracy of the models, compared with the $Diff_R(i)$ results obtained by the simulation. The accuracy of the analysis is defined in terms of the analyzed value and the results from the packet-level simulations. The analysis accuracy in regard to energy differentiation at is defined by:

$$accuracy = 1 - \frac{\sum_{i=1}^{N} \frac{|Diff(i) - Diff_M(i)|}{Diff_M(i)}}{N} \tag{17}$$

where $Diff_M(i)$ is the averaged differentiation factor of BS(*i*) obtained from simulation result over time from the start and to network lifetime. The ideal accuracy of analysis is 1, which indicates that each the analysed differentiation factor is same with the results of energy differentiation factor

$Diff_M(i)$. It can be seen that the analysis based on *TX-RX-OH* relations achieves the high analysis accuracy up to 0.925. *TX-RX-OH* based analysis improves about 27% accuracy compared with the case of $Diff(i) = 1$ corresponding to uniform energy consumption in the line-topology WMI of 4 BSs.

Table 7. The accuracy of energy differentiation analysis in line-topology WMI based on *TX, RX, OH* relations among BSs.

| Items	BS(1)	BS(2)	BS(3)	BS(4)	Accuracy
Time average value of simulation value $Diff_M(i)$ result	1.09	1.33	0.97	0.61	1
Diff(i) for uniform energy consumption	1	1	1	1	0.751
Diff(i) from *TX-RX-OH* analysis	1.074	1.218	0.975	0.733	0.925

The energy differentiation result is shown in Figure 10. From the results, it can be seen that energy differentiation occurs although each BS has the same initial energy. The energy consumption is correlated with the topological position of each BS. The results show that the BS(1) that is nearest to the GW does not have the largest energy consumption. Instead, we can see that BS(2) has the largest energy consumption. These results are different with previous studies of multihop wireless network such as sensor networks, in which node near the gateway or sink node has the largest energy consumption [19,33].
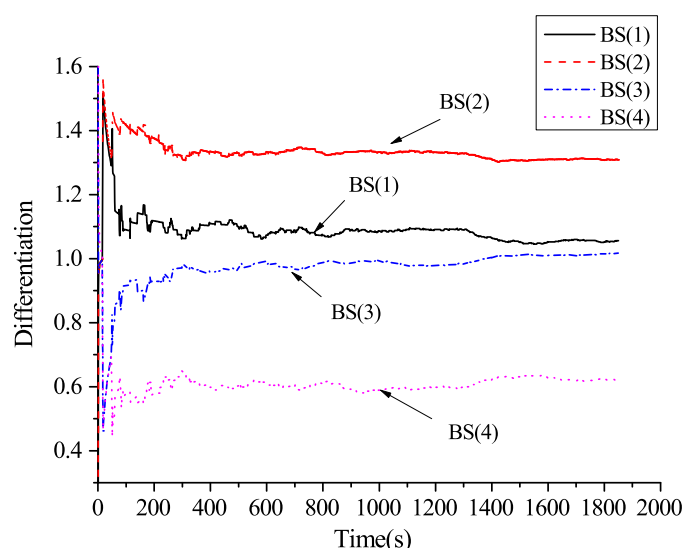
Figure 10. An example of energy differentiation of BSs in the line-topology WMI wih 4 BSs.

To illustrate the position dependency of energy consumption at each BS, we show the relation between the residual energy and position for each BS. Since it is difficult to show the spatial distribution of energy consumption at many moments in time, in Figure 11 we show results for two representative times near the start of network operation and near the end of network lifetime. We can see that the overall energy consumption of BSs in this evaluation is unbalanced for all networks that utilize the Same-EP . This is because the network traffic is delivered from STAs to the GW by multi-hop relays of wireless links, resulting in the concentrated network traffic at the nodes near the GW. In general, BSs that are close to the GW position have more energy consumption than BSs that are far away from the GW position. However, the topological position of BSs with maximum energy consumption is not in zone(1) but at the center of zone(2), the center of which is around the BS2 at the position of (300, 300). The reason for this phenomenon is the total packet activity, including transmission, receiving and overhearing, at BS2 is largest. From the figure, we see that Matching-EP

enables much better energy balance among BSs. The average matching degree of networks employing Matching-EP is much higher than the network with uniform initial energy deployment.
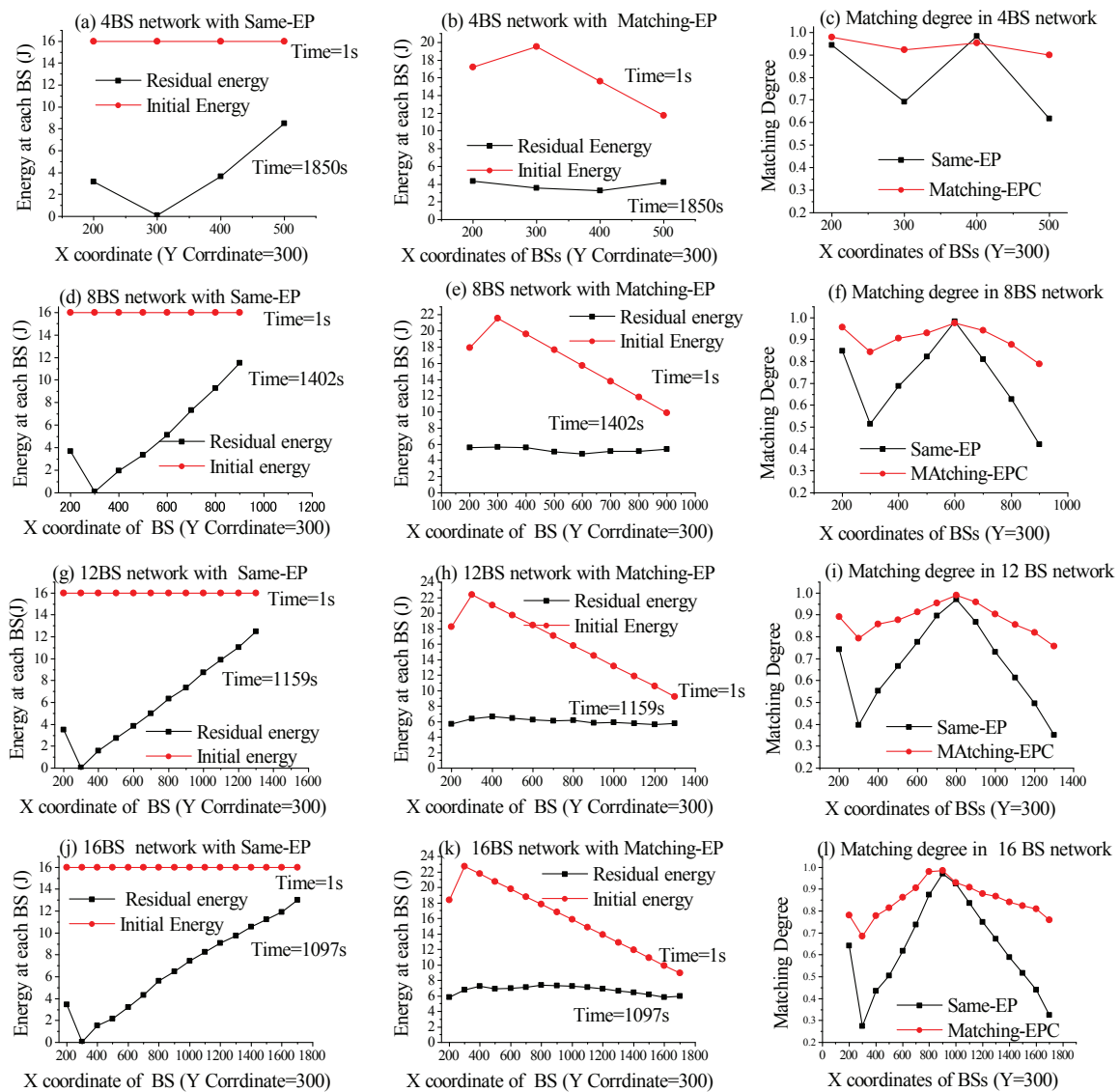

Figure 11. Energy consumption distribution and energy mapping in scenario-1 (Line Scenario).

Figure 12a shows the results of the network lifetime of the WMI. Comparing with Same-EP approach, the Matching-EP approach enables 27%–41% improvement of network lifetime. From the result, it can be seen that the networks with smaller number of BSs result in larger lifetime. This is because there are smaller amounts of STA traffic in networks with smaller number of BSs.

Figure 12b illustrates the amount of successful packet delivery with varying BS number. Matching-EP results in a larger amount of packet delivery with a improvement ratio ranging from 22% to 41% for packet delivery during the network lifetime. The improvement is significant at the networks with a larger BS number. This is because that there is a larger difference of energy consumption with Same-EP in a network with a larger BS number.

Figure 12c shows the average value of Matching Degree, the matching of energy provision to energy consumption. For the network with 4BSs, the average energy matching degree of BSs increases from 0.81 to 0.938 with an improvement of 15.9%. For the network with 8 BSs, the energy matching degree of BSs increases from 0.71 to 0.90. For the network with 12 BSs, the energy matching degree

of BSs increases from 0.67 to 0.88. For the network with 16BSs, the energy matching degree of BSs increases from 0.63 to 0.85 with an improvement of 34.6%.
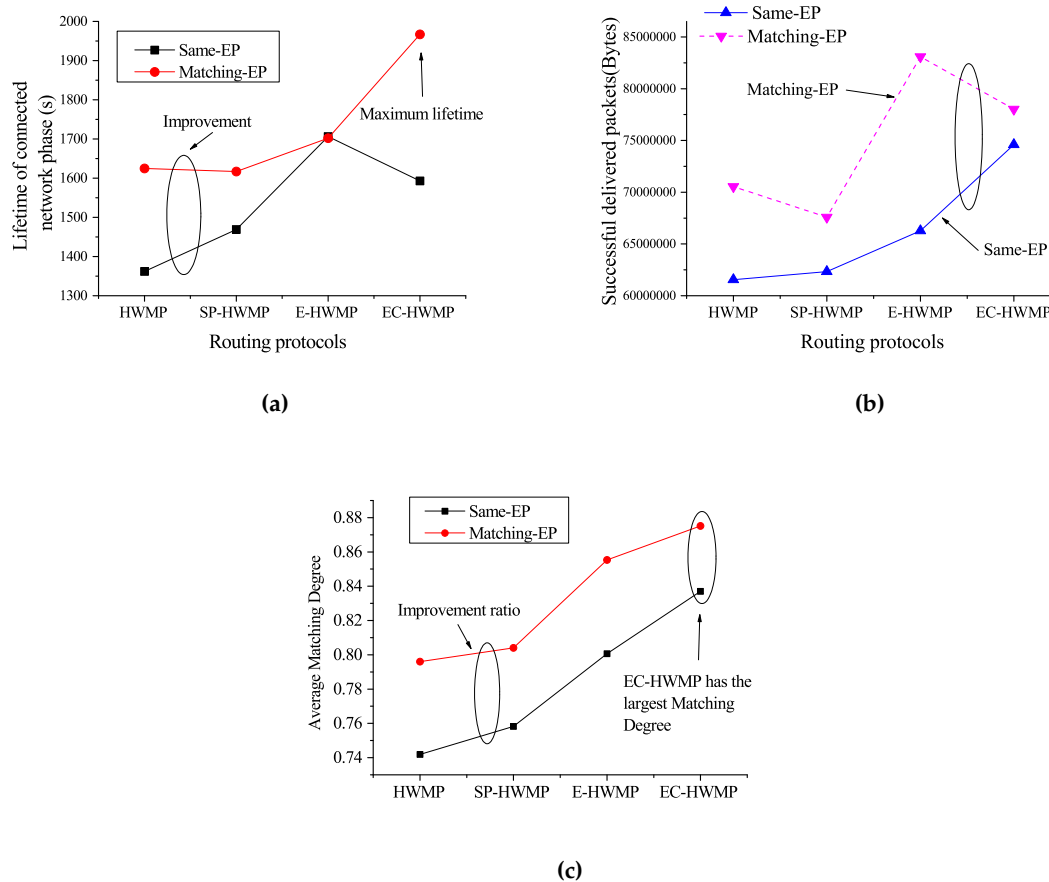

(a)

(b)

(c)
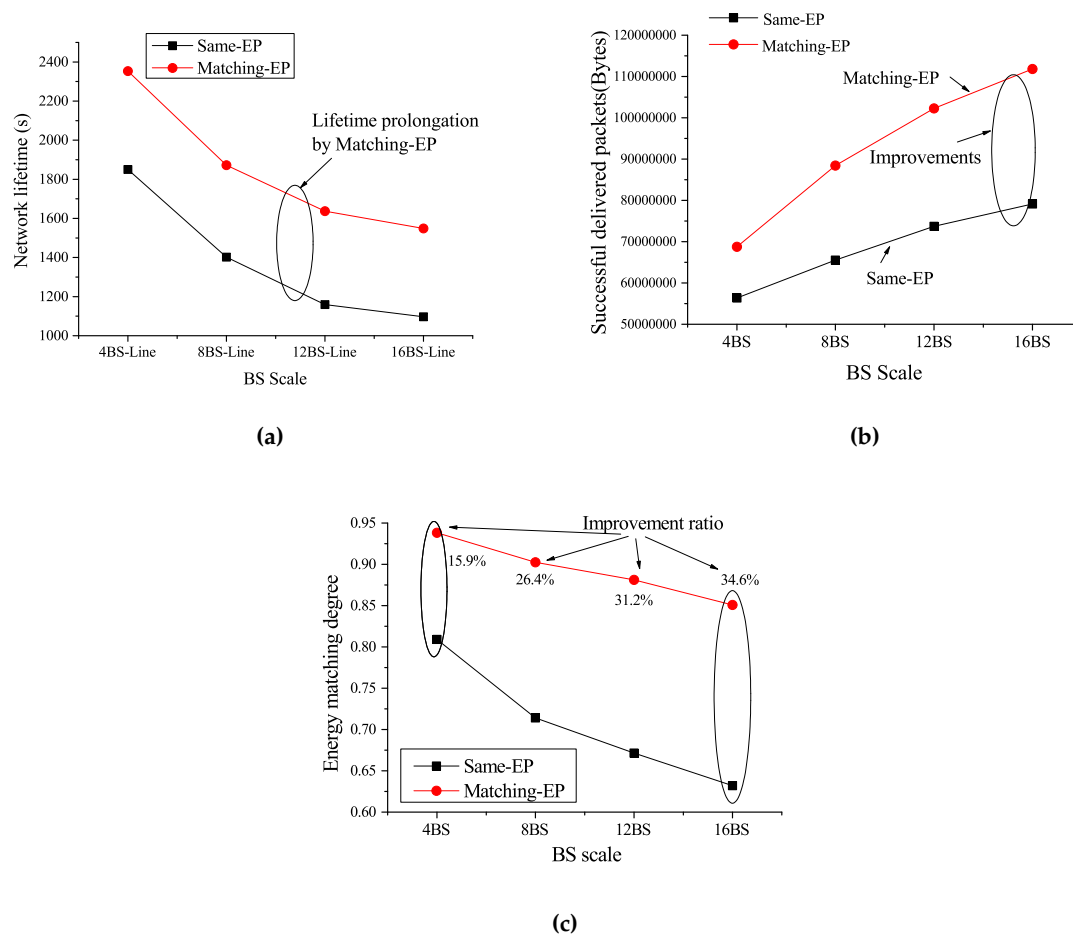
Figure 12. The network performace in line BS networks. (**a**) Line network lifetimes; (**b**) Successful delivered packets from all STAs to the GW in line BS scenario; (**c**) The average matching degree in Line BS scenario.

6.2. Numerical Results in Scenario-2: Grid Topology

The network lifetimes of various routing protocols in the grid-topology scenario are shown in Figure 13a. Matching-EP has improvements of 19, 10 and 23 in HWMP, SP-HWMP, and EC-HWMP, respectively. But E-HWMP has roughly the same network lifetime for Same-EP and Matching-EP. This is because E-HWMP routing will be highly affected by energy provided at each BS. EC-HWMP with Matching-EP has the longest network lifetime up to 1960s. This is because that the EC-HWMP employs both energy and connectivity awareness in HWMP.

The result of successful packet delivery is shown in Figure 13b. Matching-EP in E-HWMP routing results in the largest number of delivered packets during the network lifetime.

Figure 13c shows the average matching degree of energy provision to the energy consumption with various routing protocols. In the network with HWMP protocol, the average energy matching degree of BSs increases from 0.74 to 0.80 by utilizing Matching-EP. As for SP-HWMP protocol, the energy matching degree of BSs increases from 0.76 to 0.80 by utilizing Matching-EP. As for E-HWMP protocol, the energy matching degree increases from 0.80 to 0.86 by utilizing Matching-EP. As for EC-HWMP, the matching degree increases from 0.84 to 0.88 by utilizing Matching-EP.

(a)

(b)

(c)

Figure 13. The network performance in grid BS networks. (**a**) Network lifetimes; (**b**) Successful delivered packets from all STAs to the GW; (**c**) The average mactching degrees.

Table 8 shows the simulation result of average $Diff_M(i)$ obtained in the evaluation of Grid WMI with SP-HWMP routing, comparing with the energy differentiation analysis results. The differentiation analysis are according to zone-based *TX-RX-OH* relations described in previous section, and are based on the simulation setup. It can be seen that the analysis based on *TX-RX-OH* relations achieves the high analysis accuracy up to 0.92. *TX-RX-OH* based analysis improves about 8% accuracy compared with the uniform energy provision in the Grid WMI of 16 BSs.

Table 8. The energy differentiation of BSs in zones and the accuracy of differentiation analysis in Grid WMI. (The related setup: short path routing, $K_{OH} = 3$ in *TX-RX-OH* relation based analysis).

Items	*Diff*($z1$)	*Diff*($z2$)	*Diff*($z3$)	*Diff*($z4$)	*Diff*($z5$)	Accuracy
Time average value of simulation value $Diff_M(i)$ result	1.103	1.1211	1.1286	0.880	0.639	1
Diff(i) for uniform energy consumption	1	1	1	1	1	0.833
Diff(i) from *TX-RX-OH* analysis	1.073	1.160	1.029	0.844	0.860	0.915

7. Conclusions

This paper has discussed a new energy provision approach for WMI networks. We investigate the special features of energy consumption in WMI networks that are powered with intermittent energy sources. In particular, we focus on energy consumption features during non-charging periods with polarized traffic flow toward the network gateway. An energy provision matching approach, called Matching-EP, is proposed to enable the matching between energy consumption and energy

provision at BSs. Matching-EP copes with potential energy consumption differences in the long-term among BSs by employing topological position dependent energy assignment. In this study, we firstly take into account practical wireless features such as overhearing of packets, as well as the distribution of BSs and STAs in modelling the energy consumption and the energy provision difference among BSs. We propose basic models for energy consumption in WMI networks with line and grid topologies. These basic models can be used as estimates to for the implementation of Matching-EP in WMI networks. The numerical evaluation of Matching-EP for various topologies and network routing protocols is conducted by extensive packet-level simulations. The evaluation results show that Matching-EP enables high energy matching degrees at BSs, leading to 10%–40% improvement of network lifetime, as well as 5–40 improvement of user packet deliveries. In summary, matched energy provision can improve the performance of battery-powered networks, in terms of increasing network lifetime and volume of packets delivered. An approximate theoretical estimate of the data flow in a multi-hop wireless network can improve the effectiveness of matched energy provision. We envision that the proposed energy provision matching approach can be effectively applied to wireless networks powered with renewable energy power or wireless networks in emergency situations.

Author Contributions: Study design, modelling, analyses, simulation and writing: Rui Teng, Huan-Bang Li, and Ryu Miura; modelling and writing: Tatsuya Yamazaki; analyses, simulation and writing: Peter Davis.

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