Minimizing Electromagnetic Pollution and Power Consumption in Green Heterogeneous Small Cell Network Deployment

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Abstract

An enormously increasing number of mobile communications devices and IoT sensors have driven rapid advance in wireless and cellular network technologies. Owing to limited energy resources, 5G technology has been expected to be designed as a 'green' network system. To achieve the requirement of future 'green' 5G networks to serve a huge number of mobile devices, this work investigates the problem of deployment and sleep control of a 'green' heterogeneous cellular network along a highway composed of base stations (BSs), legacy relay stations (RSs), and small cells (SCs), with two objectives: minimizing the energy consumption to decrease the impact of limited energy; as well as minimizing the electromagnet pollution from radiation of the three device types to avoid the potential harm to creatures. For decision variables, the deployment and sleep control of legacy RSs and SCs affect the total power consumption, and their coverage affects the total electromagnet pollution. First, this work creates a mathematical model for the optimization problem, and then proposes a hybrid algorithm of genetic algorithm (GA) and differential

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evolution (DE) with three local search operators to solve the problem, in which GA and DE can effectively handle discrete and continues decision variables, respectively. Simulation of the concerned green cellular networks verifies performance of the proposed algorithm.

Keywords: Energy efficiency, electromagnetic pollution, deployment, sleep control, hybrid metaheuristic, small cell.

1. Introduction

The number of mobile devices over the world has exceeded 5 billion, and the number of mobile communications devices and Internet of things (IoT) sensors is estimated to reach 50 billion in the next decade [1]. An explosive increasing number of mobile devices and varied demand of mobile users have driven the current 4G technology to advance to the future 5G technology. In addition, diversified mobile applications, including IoT, virtual reality, and vehicle-to-device/infrastructure/vehicle (V2X), have also been pushing development of cellular networks. The requirements of future 5G networks include: serving a huge number of mobile communications devices and IoT sensors, providing a much higher data rate than the current 4G network, and constructing energy-efficient and low-cost mobile infrastructures [2].

As natural resources continue to deplete and the costs of acquiring energy sources increase rapidly, power consumption has become one of the most important criteria when developing ICT devices and technologies. A report in 2012 [3] stated that the annual average power consumption from ICT industries was over 200 GW, and the mobile network of 1.1 million base stations (BSs) consumed over 14 billion kWh of energy. A line of the research on reducing power consumption was to propose different strategies for deploying BSs (e.g., [4]) and scheduling the sleep control of multiple BSs (e.g., [5]) in various mobile infrastructures of cellular networks. Since the communications between BSs and users account for a large ratio of energy consumption in mobile cellular networks [3], some works introduced relay stations (RSs) into cellular networks to relay communications between BSs and users (e.g., [6]).

Heterogeneous networks, including macrocells (BSs), femtocells, picocells, and microcells, have been introduced into cellular networks for their fast, flexible, cost-efficient, and fine-tuned design [7]. The work in [2] proposed analytical models of power consumption in the networks based on macrocells, microcells, picocells and femtocells, which are applied to five different schemes.

Aside from power consumption, the other 'green' concern that has received much attention is the electromagnetic radiation generated from mobile communication infrastructures. Especially, it can be expected that the explosive amount of IoT objects emerge in the future world, so that the range of electromagnetic radiation become increasingly wide. The Council of Europe report stated that the electromagnetic field more or less has biological effects on plants and animals [8], and phone masts have some negative effects on natural defenses, reproduction, and behavioral response of animals [9]. Although there is no clear evidence that the electromagnetic radiation from mobile devices would have adverse effects on human health, more and more works studied the electromagnetic radiation exposure from mobile phones or antennas [10]. To prevent the possible harm to creatures, some works have developed various methods for measuring the electromagnetic pollution. Because the electromagnetic field would be related to the electromagnetic pollution [10], some works evaluated the electromagnetic pollution through the electromagnetic field [11]. Another evaluation for electromagnetic pollution is called electromagnetic pollution index (EPI) [12]. With advance in continuous development of IoT technologies, the EPI has become one of the main concerns of future smart objects [13].

This work considers deploying a highway with a heterogeneous cellular network consisting of BSs, RSs, and small cell (SC). Each of the three device types has its own function and coverage range. BS is a macro cell, through which users can directly access the Internet service through cellular networks. Conventional RS transmits and receives signals with BSs through cellular networks, and serve as a relay node to provide users the service of accessing the Internet through only Wi-Fi technologies. To enhance functions of RSs, SC serve as a relay node through the technologies of integrating LTE and Wi-Fi, to provide a larger-size coverage range and to save more resources. To simplify the problem, this work considers a highway segment with two BSs at the two endpoints of the segment. The problem concerned in this work is to determine the positions of a number of RSs and SCs between these two BSs, and to determine their sleep controls, in which the devices without no packet transmissions can be switched off for saving power consumption. Consider that the coverage radius of BS is set as a fixed value equal to the length of the highway segment; and the coverage radii of SCs and RSs are generally smaller than that of BSs. This work supposes that SCs can serve as an RS in this cellular network. For distinguish the difference, the latter RS device is called legacy RS throughout the rest of this paper. In the cellular network framework, users in vehicles can acquire downlink transmission services from the BSs, SCs, or legacy RSs as long as locations of the vehicles fall within the coverage range of these communications devices. Since the coverage radius of BSs is equal to length of the highway segment, the users can acquire the transmission service directly at any location of the highway.

There are three transmission ways relayed from the BSs to the users in vehicles: 1) a user can directly communicate with either one of the BSs near to the user; 2) a user can communicate with a BS indirectly through a legacy RS to the user; 3) similar to the second transmission way, the BS relays transmission via an SC to the user.

This work investigates the problem of concurrently 1) deploying the positions of SCs and legacy RSs along the highway, 2) scheduling their sleep control, and 3) deciding the coverage radius of each SC with the following 'green' objectives. The first objective is to minimize the total energy consumption since energy resources have depleted sharply over the world as the demand of mobile communications increases rapidly. Secondly, the electromagnetic radiation is concerned because the great amount of BSs has given rise to the concern about human health. Hence, aside from minimizing the power consumption, we attempt to acquire minimization of electromagnetic pollution for green cellular networks in the future 5G system. Different form the SC network deployment problem that we have tackled before in [14], this work has augmented the problem model as follows: for saving power consumption, we minimized the received power of all communications devices rather than the transmission power for making the scenario closer to the real world; and to approach the green concept of future 5G networks; in addition, minimization of electromagnetic pollution has been considered as another objective of the deployment problem which includes the cell sizes of communications devices as decision variables of the model. The problem model designed in this work further includes simultaneously considering power consumption and electromagnetic pollution and the cell size under different scenarios. In order to solve this more complex problem, a new algorithm—hybrid algorithm of genetic algorithm (GA) and differential evolution (DE) (hGADE for short)—different form our previous work in [14] is adapted to solve this problem.

The rest of this paper is organized as follows. Section 2 reviews related literature. Section 3 introduces the system framework and the model created for this problem. Section 4 gives the proposed approach for this problem. Section 5 gives simulation results and analysis. Section 6 concludes this work.

2. Related Work

This work aims to minimize both power consumption and electromagnetic pollution for transmission to users in vehicles in a linear heterogeneous SC network consisting of BSs, SCs, and legacy RSs. Hence, the literature review in this section is organized as follows. The works on vehicular networks and future 5G networks are reviewed first; and then the technologies of power consumption and sleep control in cellular networks are reviewed. As green concerns in wireless technologies takes lots of attention, electromagnetic pollution in cellular networks is reviewed. Then, the works on SCs in the future 5G trend and their related placement problems are reviewed; and comparison of this work with related schemes are made at the end of this section.

2.1. Future 5G system networks and SC technologies

As communications devices increase enormously, current 4G technologies will not be able to satisfy the requirements of all devices in the future. Hence, the concept of METIS 5G systems was developed to satisfy the future information society. The METIS 5G system addresses three generic 5G services: 1) Extreme Mobile BroadBand (xMBB) which provides extremely high data rates and low-latency communications; 2) Massive Machine-Type Communications (mMTC) which provides numerous wireless connectivity, wide area coverage, and deep indoor penetration; 3) Ultra-reliable MTC (uMTC) which provides ultra-reliable low-latency and/or resilient communication links for network services, e.g., V2X communication and industrial control applications [15]. The works in [16] showed that full duplex communication for 5G SC networks can deliver 30 to 40 percent network throughput over half duplex transmissions. The works in [17] showed that massive MIMO can increase spectral and energy efficiency of wireless networks.

2.2. Power consumption and sleep control in cellular networks

The increasing demand for wireless communications services and the wide deployment of wireless communications infrastructures have led to high power consumption in wireless access networks [18]. The energy used to run such an infrastructure, in most cases supplied by fossil fuel-derived sources, brings an ecological impact due to its associated CO_2 emissions, and hence the costs has grown greatly [19]. Therefore, energy efficiency in cellular networks is a growing concern for cellular operators, not only to maintain profitability but also to reduce the overall environmental effects. According to [20], the amount of CO_2 emitted due to ICT was 151 $MtCO_2$ in 2002, with 43% due to the mobile sector; it is forecasted to rise to 349 $MtCO_2$ by 2020, with 51% originating from the mobile sector [20], [21].

Some works focused on designing sleep control for communications devices to minimize power consumption. Lots of works on sleep control of BSs existed. For example, the work in [22] derived the energy-optimal density of BSs in wireless cellular networks with sleep modes under a given user density and performance constraint. The work in [19] investigated an energy-efficient BS switching-off and cell topology mechanism in both macrocellular and heterogeneous networks. The work in [23] analyzed the existing BS sleeping schemes in a power consumption model of a centralized RAN architecture. Furthermore, some works allowed cell sizes of BSs to be changed. For example, the work in [24] considered deployment strategies of different BS types based on BS power consumption model and Shannon capacity formula, and modeled the problem of finding the optimal cell sizes of BSs so as to maximize a matching degree between energy consumption of BSs and the traffic load.

Since up to 80% of energy consumption in cellular networks is attributed to BSs, some works further introduced deployment of RSs to improve network capacity and quality of service (QoS). For example, the work in [25] proposed a joint BS and RS sleep scheduling in relay-assisted cellular networks.

Recently, some works have studied deployment of SCs for power consumption minimization. For example, the work in [26] created a parametric power model for heterogeneous networks consisting of legacy macrocell networks and SCs. The work in [27] investigated the energy consumption issue when deploying a huge number of SCs with sleep modes in heterogeneous networks.

2.3. Electromagnetic pollution in cellular networks

In parallel with explosive growth of mobile devices in recent years, people have started to be concerned about the electromagnetic radiation generated by those devices. In the work of [8], the Council of Europe report stated that the electromagnetic field more or less has biological effects on plants and animals. The work of [9] also reported that the phone masts have some negative effects on natural defenses, reproduction, and behavioral response of animals. Hence, although there is no clear evidence that the electromagnetic radiation would hurt humans, in order to prevent possible harm, some novel ways to evaluate the degree of electromagnetic pollution were provided for future mobile communication technologies.

The work in [12] proposed the electromagnetic pollution index (EPI) to serve the need for ‘True’ green mobile communications. The authors pointed the relationship between the cell sizes and EPI; and derived the conclusion that a smaller cell size of SC is a key factor for green mobile communications. The work in [13] defined the green degree of smart objects in the IoT, in which the EPI of a smart object is measured by means of medium truth degree (MMTD) based on medium mathematics. The work in [11] have solved a mobile network deployment problem which takes into account minimization of electromagnetic pollution through a new metaheuristic algorithm, the Coral Reefs Optimization (CRO) algorithm. The authors evaluated the electromagnetic pollution through the assumption that the electromagnetic radiation can be calculated via the electromagnetic field [12].

2.4. *Deployment problem*

A lot of works focused on designing metaheuristic algorithms for deploying BSs. For example, the work in [28] proposed a simulated annealing algorithm to adjust locations of BSs according to user distribution in two cases: a network with only macro BSs; and a heterogeneous network with macro and small-cell BSs. The work in [29] proposed a particle swarm optimization approach for deploying locations of BSs.

The work in [12] proposed a bio-inspired algorithm, grouping coral reefs optimization algorithm (GCRO), for grouping optimization problems; and applied it to the mobile network deployment problem (MNDP) under four optimization criteria, including economical cost, coverage level, electromagnetic pollution control, and capacity constraints.

3. System Framework and Problem Model

This section first describes the system framework concerned in this work, and then models the concerned problem in detail.

3.1. *System framework*

This section considers a one-dimensional SC network with three devices: BS, SC, and RS. Each device has its own function and coverage. With the three different devices, this SC network is heterogeneous. Since SC also serves as an RS in this network, the last device is called legacy RS throughout the rest of this paper. Users can acquire downlink transmission services from BS, SC, or legacy RS according to their locations. To simply the model, a segment of highway, illustrated in Fig. 1, with two BSs at the endpoints is considered; and the rest of devices are deployed between the two BSs. Users in vehicles on the highway receive signals from BS, SC, or legacy RS only when falling in the coverage of the device.

There are three transmission ways: direct transmission from a BS to a user; indirect transmission from a BS via SC relaying to a user; and indirect transmission from a BS via legacy RS relaying to a user. The indirect transmission ways continue using the setting in

[30] as follows: only allowing two-hop half-duplex DF relaying. That is, indirect transmission allows only two hops from a BS to a relay node and then to a user, because allowing multiple hops could consume too much circuit power of relay nodes.

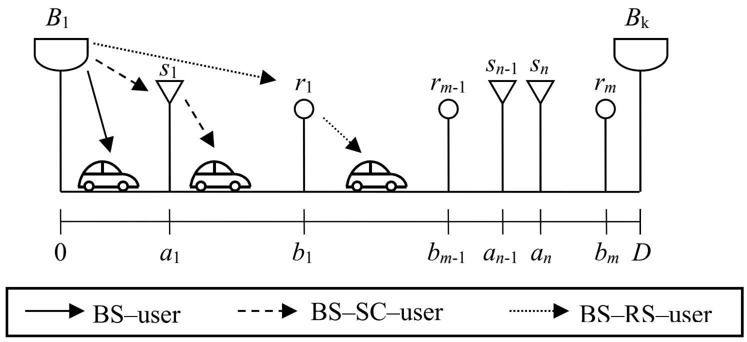

Fig. 1 Illustration of the concerned system framework, in which B_k, s_i, and r_j represent BS, SC, and RS, respectively; and a_i and b_j represent for the locations of SC s_i and RS r_j, respectively, along the highway segment [0, D].

The roles of BS, SC, and legacy RS in this system framework are elaborated as follows. BS is connected to the outside network. If a user would like to communicate with the outside network, the user must communicate with either BS directly or indirectly. To simplify the model, only two BSs are placed at the two endpoints of the highway. Because coverage of each BS is set as the length of the highway segment, any between the two BSs along the highway can directly communicate with both BSs. SCs and legacy RSs serve as the relay nodes between users and BSs. Since long-distance transmission from a user to a BS may consume much power (unfavorable for the first objective of the problem), transmission via delaying of SCs and RSs may reduce the transmission distance from the user to a BS and further reduce the total power consumption. In addition, coverages of SCs determines the amount of electromagnetic pollution (unfavorable for the second objective), it is required to make coverage of SCs as small as possible in this work.

This work aims to minimize both the total received energy consumption and electromagnetic pollution. Firstly, minimization of energy consumption is concerned because energy resources have depleted sharply over the world as the demand of mobile radio communications increases rapidly. Secondly, the growing electromagnetic radiation along with the great amount of BSs gives rise to the concerns about human health. Council of Europe [8] reported that electromagnetic field more or less has biological effects on plants and animals. Hence, besides minimization of power consumption, this work attempts to acquire minimization of electromagnetic pollution for green communications for future 5G systems.

Different deployments have been adopted for acquiring minimization of total power consumption and electromagnetic pollution, respectively. The sleep control of BSs and RSs is considered as well for reducing circuit power consumption. Hence, this work is unique because deployment locations and sleep control are considered concurrently to minimize the total received power consumption. Another factor that we have considered in the problem is coverage of communications devices. The cell size of each SC is changeable in this work to minimize the whole electromagnetic radiation in the network.

This work has the following main assumptions: 1) Based on the specification in [2], each of RS, SC, and legacy RS has its own coverage range. 2) Since coverage of the two BSs at the endpoints of highway is set as the length of highway, any user between the two BSs along the highway can always communicate directly with both the two BSs. 3) The first objective of the concerned problem is to minimize the total received power consumption; hence, interference among devices is assumed to be neglected, for simplicity. 4) This work only focuses on power consumption of downlink transmission form the three types of devices to users, i.e., the uplink transmission is not concerned. 5) Each of SCs and RCs (excluding BSs) can be switched to the sleep mode for reducing power consumption.

3.2. Problem model

Under the system framework of a one-dimensional SC network described above, we consider a highway segment with two BSs at the endpoints of the highway. The concerned problem has two objectives: minimizing both the total received power consumption and the total electromagnetic pollution. The deployment locations, sleep controls, quantities of SCs and legacy RSs, as well as the coverage radius of SCs are determined so that the total received power consumption and electromagnetic pollution are minimized simultaneously.

The concerned problem model additionally considers SCs in the model with BSs and RSs in [30]. Consider a segment of highway of length D with two BSs at the endpoints of the highway. Suppose that the highway segment is along an x-axis in which the left endpoint of the segment is located as the origin of this x-axis; hence, locations of the two BSs (denoted by B_k, $k=1, 2$) are 0 and D, respectively. The concerned deployment problem is to deploy n SCs (denoted by $s_1, s_2, \ldots, s_n$) and m RSs (denoted by $r_1, r_2, \ldots, r_m$) and to decide radii of n SC coverages (denoted by $R_{s_1}, R_{s_2}, \ldots, R_{s_n}$) along the highway between the two BSs, i.e., to determine three vectors $a = (a_1, a_2, \ldots, a_n)$, $b = (b_1, b_2, \ldots, b_m)$, $R_s = (R_{s_1}, R_{s_2}, \ldots, R_{s_n})$ where a_i is the location of SC s_i along the x-axis for each $i \in \{1, 2, \ldots, n\}$; b_j is the location of the RS r_j for each $j \in \{1, 2, \ldots, m\}$; $0 \le a_i, b_j \le D$; and $R_s^{\min} \le R_{s_i} \le R_s^{\max}$.

For simplify this problem, consider that each mobile user in a vehicle along the highway has a constant vehicle speed v m/s, and has a request to communicate with a BS at a constant data rate r bits/s. Each mobile user has the following three possible transmission ways: 1) The user communicates with the closer BS directly; 2) The user falls within the coverage range of some SC, so the BS closer to the SC transmits to the SC, and then the SC relays the transmission to the user; 3) The user falls within the coverage range of some legacy RS, so the BS closer to the legacy RS transmits to the legacy RS, and then the legacy RS relays the transmission to the user. If the user does not fall within the coverage range of any SC or legacy RS, this work supposes that the user can always communicate with a BS.

To make the model closer to the real scenario, the received power consumptions of communications devices on the highway are given by [2]. The received power consumption form one device to another is calculated as follows:

$$P^{\gamma} = P^{\tau} G_{\tau} G_{\gamma} \left(\frac{\lambda}{4\pi R_{\tau}} \right)^2 \tag{1}$$

where P^{τ} is the transmission power; G_{τ} and G_{γ} are gains for transmitter and receiver antenna; λ is wavelength in meters; R_{τ} is the coverage radius of the communications device.

If direct data transmission is applied, the user rate ε is computed as follows [30]:

$$\varepsilon = W \log_2 \left(1 + \frac{\eta_{Bu} P^{\tau}_{B_k u}}{d^{\alpha}_{B_k u}} \right) \tag{2}$$

where W is the cannel bandwidth; η_{Bu} is the ratio of the antenna gain from the BS to the user and thermal noise; $P^{\tau}_{B_k u}$ is the transmission power from the BS B_k to the user; $d_{B_k u}$ is the distance between the user and the BS B_k that is closer to the user, i.e., $d_{Bu} = \min\{u, D-u\}$; α is the path-loss exponent, and is commonly 2, 3, or 4.

Rearrange the above equation. The transmission power $P^{\tau}_{B_k u}$ from the BS B_k to the user in direct data transmission is computed as follows:

$$P^{\tau}_{B_k u} = \frac{\left(2^{\varepsilon/W} - 1\right) d^{\alpha}_{B_k u}}{\eta_{Bu}} \tag{3}$$

Applying Equation (1) for the first data transmission way (direct data transmission), the received power consumption $P^{\gamma}_{B_k u}$ for one user at location u is computed as follows:

$$P^{\gamma}_{B_k u} = P^{\tau}_{B_k u} G_B G_u \left(\frac{\lambda}{4\pi R_B}\right)^2 \tag{4}$$

where G_B and G_u are gains for the BS and a mobile terminal user; λ is wavelength in meters; R_B is the coverage radius of the BS.

Consider the second data transmission way (i.e., indirect transmission via SC relaying). If a user falls within the coverage range of some SC s_i, so the BS closer to the SC transmits to the SC, and then the SC relays the transmission to the user. For the first step of transmission, the transmission power $P^{\tau}_{B_k s_i}$ from the BS B_k to the SC s_i is calculated as follows:

$$P^{\tau}_{B_k s_i} = \frac{\left(2^{2\varepsilon/W} - 1\right) d^{\alpha}_{B_k s_i}}{\eta_{Bs}} \tag{5}$$

where d_{Bs_i} is the distance between SC s_i and the BS B_k closer to SC s_i, i.e., $d_{B_k s_i} = \min\{a_i, D-a_i\}$; η_{Bs} is defined similarly to η_{Bu} corresponding to the link from a BS to an SC. Note that half-duplex relaying of an SC or a legacy RS requires two time slots, such that the user rate for each hop requires 2ε. And the received power $P^{\gamma}_{B_k s_i}$ from the BS B_k to SC s_i is computed as follows:

$$P^{\gamma}_{B_k s_i} = P^{\tau}_{B_k s_i} G_B G_s \left(\frac{\lambda}{4\pi R_B} \right)^2 \tag{6}$$

where G_B and G_s are gains for the BS and SC.

For the second step of transmission, the transmission power $P^{\tau}_{s_i u}$ from SC s_i to the user is computed as follows:

$$P^{\tau}_{s_i u} = \frac{\left(2^{2\varepsilon/W} - 1\right) d^{\alpha}_{s_i u}}{\eta_{su}} \tag{7}$$

where $d_{s_i u}$ the distance between SC s_i and the user, i.e., $d_{s_i u} = |u - a_i|$; η_{su} is defined similarly to η_{Bu} corresponding to the link from an SC to a user. And the received power $P^{\gamma}_{s_i u}$ from the SC s_i to the user is calculated as follows:

$$P^{\gamma}_{s_i u} = P^{\tau}_{s_i u} G_s G_u \left(\frac{\lambda}{4\pi R_{s_i}} \right)^2 \tag{8}$$

where G_s and G_u are gains for the SC and a mobile terminal user; R_{s_i} is the coverage radius of the SC. Note that R_{s_i} is a decision variables in the concerned problem, because different R_{s_i} values lead to different electromagnetic pollution, which will be detailed later. For the second data transmission way, the total received power consumption for one user on the highway is the sum of $P^{\gamma}_{B_k s_i}$ and $P^{\gamma}_{s_i u}$.

Consider the third data transmission way (i.e., indirect transmission via legacy RS relaying). If a user falls within the coverage range of some legacy RS, the BS closer to the legacy RS transmits to the legacy RS, and then the legacy RS relays the transmission to the user. For the first step of the third data transmission way, the transmission power $P^{\tau}_{B_k r_j}$ from the BS B_k closer to legacy RS r_j to the legacy RS is computed as follows:

$$P^{\tau}_{B_k r_j} = \frac{\left(2^{2\varepsilon/W} - 1\right) d^{\alpha}_{B_k r_j}}{\eta_{Br}} \quad (9)$$

where $d_{B_k r_j}$ is the distance between legacy RS r_j and the BS B_k closer to legacy RS r_j, i.e., $d_{Br_j} = \min\{b_j, D - b_j\}$; η_{Br} is defined similarly to η_{Bu} corresponding to the transmission from a BS to a legacy RS. And the received power $P^{\gamma}_{B_k r_j}$ from the BS B_k closer to legacy RS r_j is computed as follows:

$$P^{\gamma}_{B_k r_j} = P^{\tau}_{B_k r_j} G_B G_r \left(\frac{\lambda}{4\pi R_B}\right)^2 \quad (10)$$

where G_B and G_r are gains for the BS and RS.

For the second step of the third transmission way, the transmission power $P^{\tau}_{r_j u}$ from RS r_j to the user is computed as follows:

$$P^{\tau}_{r_j u} = \frac{\left(2^{2\varepsilon/W} - 1\right) d^{\alpha}_{r_j u}}{\eta_{ru}} \quad (11)$$

where $d_{r_j u}$ is the distance between legacy RS r_j and the user, i.e., $d_{r_j u} = |u - b_j|$; η_{ru} is defined similarly to η_{Bu} corresponding to the transmission from a legacy RS to a user u. And the received power $P^{\gamma}_{r_j u}$ from the legacy RS r_j to the user is computed as follows:

$$P^{\gamma}_{r_j u} = P^{\tau}_{r_j u} G_r G_u \left(\frac{\lambda}{4\pi R_r}\right)^2 \quad (12)$$

where G_r and G_u are gains for a legacy RS and a mobile terminal user; R_r is the coverage radius of the RS. For the third data transmission way, the total received power consumption for one user is the sum of $P^{\gamma}_{Br_j}$ and $P^{\gamma}_{r_j u}$.

Let $c(a_i)$ and $c(b_j)$ denote the coverage ranges of SC s_i at location a_i and legacy RS r_j at location b_j, respectively. The value of $c(a_i)$ for $i \in \{1, 2, \dots, n\}$ equal to $2R_s$ and the value of $c(b_j)$ for $j \in \{1, 2, \dots, m\}$ equal to $2R_r$. Each user with location u chooses one of the above three data transmission ways, and hence, the total received power for one user at any location is calculated as follows:

$$\min\left\{ P_{B_k u}^{\gamma} \bigcup_{\substack{k\in\{1,2\} \\ i\in\{1,2,\ldots,n\} \\ u\in c(a_i)}} \left\{ P_{B_k s_i}^{\gamma} + P_{s_i u}^{\gamma} \right\} \bigcup_{\substack{k\in\{1,2\} \\ j\in\{1,2,\ldots,m\} \\ u\in c(b_j)}} \left\{ P_{B_k r_j}^{\gamma} + P_{r_j u}^{\gamma} \right\} \right\} \tag{13}$$

In the above formula, if the first transmission way is chosen, the received power is $P_{B_k u}^{\gamma}$, meaning that the user does not fall in the coverage range of any SCs or RSs; if the second transmission way is chosen, the user must fall within the coverage range of some SC s_i (i.e., $u \in c(s_i)$), and the total received power is the sum of the received powers from the BS B_k to SC s_i and from SC s_i to the user (i.e., $P_{B_k s_i}^{\gamma} + P_{s_i u}^{\gamma}$); if the third transmission way is chosen, the user must fall within the coverage range of some legacy RS r_j (i.e., $u \in c(r_j)$), and the total received power is the sum of the received powers from the BS B_k to legacy RS r_j and from legacy RS r_j to the user (i.e., $P_{B_k r_j}^{\gamma} + P_{r_j u}^{\gamma}$).

Aside from deployment of SCs and legacy RSs, their sleep controls also affect the total received power consumption. Since real vehicle arrival cannot be forecasted, especially in the condition at a low arrival rate, low active probability of some SCs or RSs may help reduce the total received power consumption. Therefore, if the user falls within the coverage range of some asleep SC or RS, the user cannot communicate with the asleep device.

As a result, this work considers that SCs and legacy RSs can independently switch to the sleep mode to save the received power consumption. Let the active probability of the n SCs and m legacy RSs in the proposed model be denoted by $\beta = (\beta_1, \beta_2, \ldots, \beta_n)$ and $\rho = (\rho_1, \rho_2, \ldots, \rho_m)$, respectively, where $0 \leq \beta_i, \rho_j \leq 1$ for $i \in \{1, 2, \ldots, n\}$ and $j \in \{1, 2, \ldots, m\}$. Suppose that no cooperation of sleep controls among SCs and legacy RSs exists. Since three data transmission ways (i.e., direct transmission, SC relaying, and legacy RS relaying) are considered by a user, the expected received power $P(u, a, b, \beta, \rho)$ for one user at location u is calculated as follows:

$$E\left\{\min\left\{P^{\gamma}_{B_k u} \bigcup_{\substack{k\in\{1,2\}\\ i\in\{1,2,\ldots,n\}\\ u\in c(a_i)}} \left\{P^{\gamma}_{B_k s_i} + P^{\gamma}_{s_i u}\right\} \bigcup_{\substack{k\in\{1,2\}\\ j\in\{1,2,\ldots,m\}\\ u\in c(b_j)}} \left\{P^{\gamma}_{B_k r_j} + P^{\gamma}_{r_j u}\right\}\right\}\right\} \tag{14}$$

The above equation is computed as follows:

$$\begin{aligned}
&P(u,a,b,\beta,\rho) = \\
&\sum_{\substack{k\in\{1,2\}\\ i\in\{1,2,\ldots,n\},\\ u\in c(s_i)}} \left(\sum_{\substack{k\in\{1,2\}\\ j\in\{1,2,\ldots,m\},\\ u\in c(b_j)}} \Big(\min\left\{P_{B_k u}, P_{B_k s_i} + P_{s_i u}, P_{Br_j} + P_{r_j u}\right\}\cdot \beta_i \cdot \rho_j \right. \\
&\qquad + \min\left\{P_{B_k u}, P_{B_k s_i} + P_{s_i u}\right\}\cdot \beta_i \cdot (1-\rho_j) \\
&\qquad + \min\left\{P_{B_k u}, P_{B_k r_j} + P_{r_j u}\right\}\cdot (1-\beta_i)\cdot \rho_j \\
&\qquad \left. + P_{B_k u}\cdot (1-\beta_i)_i \cdot (1-\rho_j)\Big)\right) \\
&+ \sum_{\substack{k\in\{1,2\}\\ i\in\{1,2,\ldots,n\},\\ u\in c(s_i)}} \left(\sum_{\substack{k\in\{1,2\}\\ j\in\{1,2,\ldots,m\},\\ u\notin c(b_j)}} \Big(\min\left\{P_{B_k u}, P_{B_k s_i} + P_{s_i u}\right\}\cdot \beta_i + P_{B_k u}\cdot (1-\beta_i)\Big) \right) \\
&+ \sum_{\substack{k\in\{1,2\}\\ i\in\{1,2,\ldots,n\},\\ u\notin c(s_i)}} \left(\sum_{\substack{k\in\{1,2\}\\ j\in\{1,2,\ldots,m\},\\ u\in c(b_j)}} \Big(\min\left\{P_{B_k u}, P_{B_k r_j} + P_{r_j u}\right\}\cdot \rho_j + P_{B_k u}\cdot (1-\rho_j)\Big) \right) \\
&+ \sum_{\substack{k\in\{1,2\}\\ i\in\{1,2,\ldots,n\},\\ u\notin c(s_i)}} \left(\sum_{\substack{k\in\{1,2\}\\ j\in\{1,2,\ldots,m\},\\ u\notin c(b_j)}} P_{B_k u} \right)
\end{aligned} \tag{15}$$

In the above equation, since all probability cases can be divided into β cases and ρ cases, the expected value is computed in the two case types.

This work supposes orthogonal channels in each cell to serve users. Hence, the total received power is the sum of received power for all users along the highway. Therefore, the average total power consumption P_{total} is calculated as follows:

$$P_{\text{total}} = \frac{h}{v}\int_0^D P(u,a,b,\beta,\rho)\ \mathrm{d}u \tag{16}$$

where h is the vehicle arrival rate (i.e., number of the vehicles that enter the concerned highway per second).

The second objective in the concerned problem is to minimize the total electromagnetic pollution. Under the system framework of one-dimensional SC network, the work in [11] has been transferred to the scenario of a highway segment. Referring to the assumption in [12], the electromagnetic radiation is calculated through the following electric field E:

$$E = \sqrt{P^{\gamma}\frac{4\pi^2}{\lambda^2 G}120} \tag{17}$$

For the first transmission way, substituting (4) into (17), when the BS B_k transmits to the user, the electric field $E_{B_k u}$ generated by the BS B_k is:

$$E_{B_k u} = \sqrt{P_{B_k u}^{\gamma}\frac{4\pi^2}{\lambda^2 G_B}120} \tag{18}$$

For the second transmission way, substituting (6) into (17), when BS B_k transmits to SC s_i, the electric field $E_{B_k s_i}$ generated by the BS B_k is:

$$E_{B_k s_i} = \sqrt{P_{B_k s_i}^{\gamma}\frac{4\pi^2}{\lambda^2 G_B}120} \tag{19}$$

Substituting (8) into (17), when SC s_i transmits to the user, the electric field $E_{s_i u}$ generated by SC s_i is:

$$E_{s_i u} = \sqrt{P_{s_i u}^{\gamma}\frac{4\pi^2}{\lambda^2 G_s}120} \tag{20}$$

For the third transmission way, substituting (10) into (17), when BS B_k transmits to RS r_j, the electric field $E_{B_k r_j}$ generated by BS B_k is:

$$E_{B_k r_j} = \sqrt{P_{B_k r_j}^{\gamma} \frac{4\pi^2}{\lambda^2 G_B} 120} \tag{21}$$

Substituting (12) into (17), when RS r_j transmits to the user, the electric field $E_{r_j u}$ generated by RS r_j is:

$$E_{r_j u} = \sqrt{P_{r_j u}^{\gamma} \frac{4\pi^2}{\lambda^2 G_r} 120} \tag{22}$$

Similarly to the formula for power consumption in Equation (15), the expected total electric field $E(u, a, b, \beta, \rho)$ is calculated as follows:

$$\begin{aligned}
&E(u,a,b,\beta,\rho) = \\
&\sum_{\substack{i\in\{1,2,\dots,n\},\\ u\in c(s_i)}} \left(\sum_{\substack{j\in\{1,2,\dots,m\},\\ u\in c(b_j)}} \Big(\min\left\{E_{B_1u}, E_{B_2u}, E_{Bs_i} + E_{s_iu}, E_{Br_j} + E_{r_ju}\right\} \cdot \beta_i \cdot \rho_j \right. \\
&\qquad + \min\left\{E_{B_1u}, E_{B_2u}, E_{Bs_i} + E_{s_iu}\right\} \cdot \beta_i \cdot (1-\rho_j) \\
&\qquad + \min\left\{E_{B_1u}, E_{B_2u}, E_{Br_j} + E_{r_ju}\right\} \cdot (1-\beta_i) \cdot \rho_j \\
&\qquad \left. + \min\left\{E_{B_1u}, E_{B_2u}\right\} \cdot (1-\beta_i) \cdot (1-\rho_j) \Big) \right) \\
&+ \sum_{\substack{i\in\{1,2,\dots,n\},\\ u\in c(s_i)}} \left(\sum_{\substack{j\in\{1,2,\dots,m\},\\ u\notin c(b_j)}} \Big(\min\left\{E_{B_1u}, E_{B_2u}, E_{Bs_i} + E_{s_iu}\right\} \cdot \beta_i \right. \\
&\qquad \left. + \min\left\{E_{B_1u}, E_{B_2u}\right\} \cdot (1-\beta_i) \Big) \right) \\
&+ \sum_{\substack{i\in\{1,2,\dots,n\},\\ u\notin c(s_i)}} \left(\sum_{\substack{j\in\{1,2,\dots,m\},\\ u\in c(b_j)}} \Big(\min\left\{E_{B_1u}, E_{B_2u}, E_{Br_j} + E_{r_ju}\right\} \cdot \rho_j \right. \\
&\qquad \left. + \min\left\{E_{B_1u}, E_{B_2u}\right\} \cdot (1-\rho_j) \Big) \right)
\end{aligned}$$

$$+\sum_{\substack{i\in\{1,2,\dots,n\},\\ u\notin c(s_i)}}\left(\sum_{\substack{j\in\{1,2,\dots,m\},\\ u\notin c(b_j)}}\min\left\{E_{B_1u}, E_{B_2u}\right\}\right) \tag{23}$$

Similarly to Equation (16), the average total electric field (electromagnetic pollution) E_{total} is calculated as follows:

$$E_{\text{total}} = \frac{h}{v}\int_0^D E(u,a,b,\beta,\rho)\ \mathrm{d}u \tag{24}$$

where h is the vehicle arrival rate (i.e., number of the vehicles that enter the concerned highway per second).

With the above setting, the problem of minimizing power consumption and electromagnetic pollution is modeled as follows:

$$\text{Minimize } P_{\text{total}} \tag{25}$$

$$\text{Minimize } E_{\text{total}} \tag{26}$$

$$\text{s.t.}\quad R_{s_i}^{\min} \le R_{s_i} \le R_{s_i}^{\max} \tag{27}$$

$$0 < a_i < D,\quad \forall i = 1,\dots,n \tag{28}$$

$$0 < b_j < D,\ \ \forall j = 1,\dots,m \tag{29}$$

$$0 \le \beta_i \le 1,\quad \forall i = 1,\dots,n \tag{30}$$

$$0 \le \rho_j \le 1,\quad \forall j = 1,\dots,m. \tag{31}$$

This problem is explained as follows. Objectives (25) and (26) are to find radii of SCs (i.e., R_{s_i}) and deployment of SCs and legacy RSs (i.e., a and b), and their active probabilities β and ρ, such that the average total power consumption P_{total} and electromagnetic pollution E_{total} are minimized. The Constraints (27) enforces the range for coverage radius of SCs, based on the specification in [2]. Constraints (28) and (29) enforce the range of locations a_i and b_j to be $(0, D)$. Constraints (30) and (31) enforce the range of active probabilities β_i and ρ_j to be [0, 1].

Since Equations (1) and (17) is complex piecewise functions, and it is impossible to precisely forecast the vehicle arrival rate, it is hard to solve the concerned problem analytically. Hence, this work proposes a metaheuristic algorithm for this problem.

4. The Proposed Approach

The problem of minimizing power consumption and electromagnetic pollution is a multi-objective optimization problem and the corresponding objective functions, Equations (1) and (17), are complex. Also, the decision variables in the concerned model are of two different types: radii of SC coverages are set to be integers; and locations and active probabilities of the RSs and SCs are real numbers. Note that the SC coverage radius is set discretely for convenience of practical use. Since hGADE [35] is suitable for mixed-integer nonlinear problems (MINLP), this work proposes an hGADE for the concerned problem.

GA is a powerful tool for efficiently addressing MINLPs, especially in integer optimization. DE algorithm can efficiently cope with continuous optimization problems, and is also a population-based algorithm like GA that can be used to address complex optimization problems [36]. Therefore, we encode each solution to two parts: 1) the integer part (i.e., radii of SC coverages), and 2) the real number part (i.e., locations and active probabilities of SCs and RSs). In the proposed hGADE, GA is adopted to address the first part, and DE is adopted to address the second part. Note that the two parts can be respectively determined, but both of them affect performance of the solution. The main steps of the proposed hGADE are given as follows:

Step 1. Randomly initialize a number of candidate solutions (CSs), called the current CS population.

Step 2. Evaluate the normalized cost of each CS in the current CS population.

Step 3. Apply the GA to handle the first parts of the current CS population as follows:

1) Based on the crossover rate CR_1, we apply the GA binary tournament selection to choose a number of CSs from the current CS population as the parent CS pool.

2) For each pair of parent CSs, generate a random number from [0, 1]. If it is less than $Q[1]$, then the one-point crossover operator is applied to the two parent CSs to generate two offspring CSs; otherwise, the two-point crossover operator is applied. Note that cuts in both crossover operators only appear in the first part of each CS, i.e., the second parts must not be crossovered.

3) Dynamically adjust $Q[1]$ and $Q[2]$ (which represent the probabilities of selecting one-point and two-point crossover operators, respectively) [32].

4) Based on the mutation rate MR_1, we randomly select a part of offspring CSs. Then, conduct the GA mutation operator on the first parts of offspring CSs.

Step 4. Apply the DE to handle the second parts of the offspring CSs as follows:

1) Based on the mutation rate MR_2, we randomly select a part of the offspring CSs generated in the previous step. Then, conduct the DE mutation operator on the second parts of the selected offspring CSs.

2) Based on the crossover rate CR_2, we randomly select a part of the offspring CSs. Then, conduct the DE crossover operator on the second parts of these selected offspring CSs.

Step 5. Conduct a repair operation on each offspring CS.

Step 6. Evaluate the normalized cost of each offspring CS.

Step 7. The worse CSs in the current CS population are replaced by better offspring CSs.

Step 8. Apply the local search operator on the current CS population as follows:

1) A part of CSs (denoted by C_s) is selected from the current CS population.

2) For each CS in C_s, generate a random number from [0, 1]. If it is less than $S[1]$, then the standard local search operator on some coverage radius (i.e., perturbing coverage radius for some SC) is conducted on the concerned CS;

otherwise, if the random number is less than $S[2]$, the standard local search operator on some location (i.e., perturbing location of some SC or legacy RS) is conducted on the concerned CS; otherwise, the random local search operator (i.e., perturbing locations for all SCs and legacy RSs) is conducted on the concerned CS.

3) Dynamically adjust probabilities $S[1]$, $S[2]$, and $S[3]$ (which represent the probabilities of selecting standard local search operators on coverage radii and locations, and random local search operators on locations, respectively).

Step 9. Increase the iteration number by 1. If the maximal iteration number is not achieved, go back to Step 3.

Step 10. The CS with the smallest normalized cost is decoded as the final output solution of the algorithm.

The key of using the hGADE framework to solve the problem is to design how to encode a CS (i.e., solution representation) and then evaluate a CS (i.e., cost evaluation) as the final solution of the GA and DE. In addition, the dynamic local search operator selection mechanism in this work is different from our previous work in [14], and hence, is introduced in more detail in this section.

4.1. Solution encoding

The problem of this work is to determine locations of n SCs and m legacy RSs, their active probabilities β and ρ, and radii of n SC coverages, such that both the average total power consumption and the average total electromagnetic pollution are minimized. Hence, a CS in the hGADE is represented as a $(3n + 2m)$-length string: $X = \langle R_{s_1}, R_{s_2}, \ldots, R_{s_n} \mid a_1, a_2, \ldots, a_n \mid b_1, b_2, \ldots, b_m \mid \beta_1, \beta_2, \ldots, \beta_n \mid \rho_1, \rho_2, \ldots, \rho_m \rangle$, which consists of two parts according to their numerical types. The first part represents radii of n SC coverages, and each parameter in this part is an integer from $[R_s^{\min}, R_s^{\max}]$. The second part is of real number type, and is further divided into four partitions. The first two partitions represent locations of n SCs and m legacy RSs, and each parameter in the two parts is a real number from $(0, D)$.

The latter two partitions represent active probabilities of n SCs and m legacy RSs, and each parameter in the two parts is a real number from [0, 1].

4.2. Solution decoding and cost evaluation

To evaluate performance of a CS, the *cost* corresponding to this CS is designed as follows. The two objectives (16) and (24) of the concerned problem to be minimized include an integral of users along the highway over [0, D], but the real number of users and their possible locations along the highway cannot be estimated precisely. To cope with this problem, it is assumed to distribute a fixed number η of users evenly along the highway. Then, based on the locations of η users, objectives (16) and (24) of CS x consisting of a, b, β, and ρ are represented as $\varphi_1(x)$ and $\varphi_2(x)$, respectively, as follows:

$$\varphi_1(x) = \frac{\sum_{u=D/(\eta+1)}^{\eta \cdot D/(\eta+1)} P(u,a,b,\alpha,\beta)}{n+m}; \tag{32}$$

$$\varphi_2(x) = \frac{\sum_{u=D/(\eta+1)}^{\eta \cdot D/(\eta+1)} E(u,a,b,\alpha,\beta)}{n+m} \tag{33}$$

Since the maximal value of $\varphi_1(x)$ (i.e., the worst total power consumption) and $\varphi_2(x)$ (i.e., the worst electromagnetic pollution) occur when each η user applies direct transmission and consumes power of P_{Bu} and has electromagnetic pollution of E_{Bu}. Hence, the maximal average power consumption $\varphi_1^{\max}$ and the maximal average electromagnetic pollution $\varphi_2^{\max}$ are calculated, respectively, as follows:

$$\varphi_1^{\max} = \sum_{u=D/(\eta+1)}^{\eta \cdot D/(\eta+1)} P_{Bu} \tag{34}$$

$$\varphi_2^{\max} = \sum_{u=D/(\eta+1)}^{\eta \cdot D/(\eta+1)} E_{Bu} \tag{35}$$

Hence, the normalized cost of CS x is calculated as follows:

$$\varphi(x) = w_1 \cdot \frac{\varphi_1(x)}{\varphi_1^{\max}} + w_2 \cdot \frac{\varphi_2(x)}{\varphi_2^{\max}} \tag{36}$$

where w_1 and w_2 are weights for the concerned two objectives, respectively. Note that the work in [30] proposed a projected Newton method to cope with the problem integral of users, in which locations of users are randomly re-generated at each iteration, such that the optimal objective value is undeterministic. And, this method does not reflect real user locations. Hence, this work does not follow their work.

4.3. Selection operation

After CSs are generated randomly into CS population, some of CSs in the CS population constitute a so-called mating pool. The CSs from the mating pool are used to generate offspring CSs. This work applies the binary tournament selection to selecting CSs to constitute the mating pool. Tournament selection is popular in the GA, and is explained as follows. First, two CSs are selected randomly from the CS population. Then, the CS with the lower normalized cost is inserted into the mating pool, while the other one is eliminated.

4.4. GA crossover operation

The first parts of the CS population are handled by the GA [31]. The way that this work adopts the GA is different from our previous work in [14], and is explained as follows. Since this work further considers radii of SC coverages to be changeable, the cost evaluation for the concerned problem is more complex. Hence, the GA crossover operation is only performed on the first integer parts of CSs, because GA has better performance on binary and integer optimization. This work continues our previous work in [14], which considered a probability to dynamically select either one-point or two-point crossover operations to be applied. The probability is adjusted dynamically according to performance of the two crossover operations.

4.5. GA mutation operation

To avoid falling into local optimum and increase population diversity, the GA mutation is conducted on the first part of CS (i.e., radii of SC coverages). Radii of SC coverages are integers within the range $[R_s^{\min}, R_s^{\max}]$. When executing swap mutation on a CS, two genes in the first part of the CS are randomly chosen, and their positions are exchanged.

4.6. *Dynamic local search operation*

Our previous work in [14] considers a dynamic local search selection probability to dynamically conduct two types of local search operations: standard local search (i.e., perturbing only one parameter within the feasible range) and random local search (i.e., perturbing all parameters randomly within the feasible ranges). Different from [14] that considered local search on only locations of SCs and legacy RSs, this work additionally considers coverage radii of SCs. Therefore, this work considers three selection ratios $S[1]$, $S[2]$, and $S[3]$, respectively, for 1) standard local search on radii of some SC coverage, 2) standard local search on location of some SC or legacy RS, and 3) random local search on locations of all SCs and legacy RSs.

4.7. *DE mutation operation*

This work applies the DE for the second real number parts of CSs, i.e., locations of the SCs and RSs ranged within (0, D), and active probabilities of SCs and RSs ranged within [0, 1]. The problem of minimizing power consumption and electromagnetic pollution is a multimodal and nonseparable problem. Thus, the rand/2/dir DE variant [37] is adopted in this work for our concerned problem. Let $X_{i,t}$ denote the second part of the i-th selected offspring CS at the t-th generation. The result $V_{i,t}$ after the mutation is computed as follows:

$$V_{i,t} = X_{i,t} + \frac{F}{2}\left(X_{r_1,t} - X_{r_2,t} + X_{r_3,t} - X_{r_4,t}\right) \tag{37}$$

where $X_{r_1,t}$, $X_{r_2,t}$, $X_{r_3,t}$, and $X_{r_4,t}$ are the second parts of four CSs randomly chosen from the CS population at the i-th generation, in which $\varphi(X_{r_1,t}) < \varphi(X_{r_2,t})$ and $\varphi(X_{r_3,t}) < \varphi(X_{r_4,t})$; F is a scaling factor for enlarging the difference of each pair of CSs.

4.8. *DE crossover operation*

To increase diversity of CSs, the DE binomial crossover operation is conducted after the DE mutation operation. Recall that $X_{i,t}$ denotes the second part of the i-th selected offspring CS at the t-th generation, and $V_{i,t}$ denotes the resultant CS after DE mutation. Then, the second part of the resultant CS $U_{i,t} = (u_{1,i,t}, u_{2,i,t}, \ldots, u_{2n+2m,i,t})$ after DE crossover operation is generated by crossing $X_{i,t}$ with $V_{i,t}$ according to the crossover rate CR_2 [35]. To ensuring that at least one element is from $V_{i,t}$, we first generate a random number q_{rand} from {1, 2, …, 2n + 2m}. Then, for q = 1, 2, …, 2n + 2m, each element $u_{q,i,t}$ in $U_{i,t}$ is computed as follows:

$$u_{q,i,t} = \begin{cases} v_{q,i,t}, & \text{if } rand_{q,i}[0,1] \le CR_2 \text{ or } q = q_{rand}; \\ x_{q,i,t}, & \text{otherwise.} \end{cases} \quad (38)$$

where $v_{q,i,t}$ and $x_{q,i,t}$ are the q-th element in $V_{i,t}$ and $X_{i,t}$, respectively; $rand_{q,i}[0,1]$ is a random real number within [0, 1] generated for the q-th element of the i-th selected offspring CS.

4.9. Repair operation

The concerned problem considers a highway segment with two BSs at the two endpoints of the segment in which SCs and RSs are deployed between the two BSs. Hence, it is impossible to deploy any two SCs or RSs at the same position. However, this situation may occur when executing the hGADE, especially after crossover operation during early evaluation [38]. Hence, infeasible solutions need to be repaired after every operation. The repair operation for overlapping locations of SCs or RSs is explained as follows. With loss of generality, consider a CS in which an RS s_i and an SC r_j are deployed at the same location, as shown in Fig. 2. Then, the repair operation moves RS s_i or SC r_j a distance $R_{s_i} + R_r$ to the left or right. By doing so, the total coverage range can be increased.

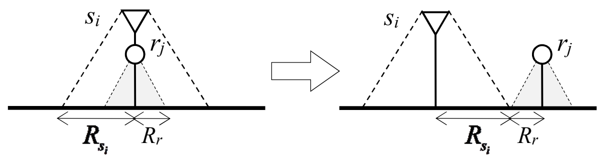

Fig. 2 Illustration of a simple example of the repair operation, in which s_i and r_j represent the i-th SC and j-th RS, respectively; and R_{s_i} and R_r are their coverage radii, respectively. Note that dotted lines indicate the farthest transmission lines of the devices.

5. Implementation and Experimental Results

Based on the design in the last sections, the proposed algorithm is implemented in C++ language. The simulation is conducted on a PC with Intel i7-3770 CPU and 16 GB memory. The parameter setting used in the simulation is given in Table 1. The parameters on mobile devices are set based on [33], [34] and our previous work in [14]. Continuing the GA parameters set in [14], number of iterations is set to 2000, the crossover rate is set to 0.6 and the mutation rate is set to 2 %. The parameters of hGADE algorithm are set based on [37] because our problem is multimodal and nonseparable.

Table 1. Parameter setting.

Parameter	Value
Highway length D	10000 m
User rate γ	1 GHz
Vehicle arrival rate h	0.5, 1, 1.5 /s
Bandwidth W	28 GHz
Vehicle speed	90, 70, 50 km/hr
Coverage radius of a BS R_B	Highway length D
Number of SCs	4-8
Minimum of SC's coverage radius $R_s^{\min}$	50 m
Maximum of SC's coverage radius $R_s^{\max}$	200 m
Number of legacy RSs	4-8
Coverage radius of legacy RSs R_r	250 m
Parameters of η's	$\eta_{Bs}=3.5\eta_{Bu}$, $\eta_{Br}=4\eta_{Bu}$, $\eta_{Bu}=\eta_{su}=\eta_{ru}$
Path-loss exponent α	2, 3, 4
Number of iterations	2000
Number of CSs	80
Selection scheme of CSs	Binary tournament selection
Scaling factor F	0.9
GA crossover rate CR_1	0.6
GA mutation rate MR_1	2 %
DE crossover rate CR_2	0.9
DE mutation rate MR_2	9 %
BS antenna gain G_B	18 dBi [33]
SC antenna gain G_s	5 dBi
legacy RS antenna gain G_r	12 dBi [33]
User terminal antenna gain G_u	1 dBi
wavelength λ	4.106746 mm
(given by c/f_c where c is the speed of light and f_c is the frequency of the carrier wave)	f_c = 73GHZ [34]

From our previous work in [14], the best simulation result for the problem with only power consumption minimization has 4 legacy RSs and 5 SCs when considering 200 vehicles; 6 legacy RSs and 7 SCs when considering 510 vehicles; and 8 legacy RSs and 7 SCs when considering 1080 vehicles. Hence, the simulation analysis conducted in this section further considers different maximal SC coverage ranges in the three cases to minimize both objectives of power consumption and electromagnetic pollution under different weight ratios for two objectives (i.e., w_1 versus w_2). The reason why to set different weight ratios for two objectives is that setting equal weights of objectives may not achieve the best deployment to respond to various circumstances, e.g., different highway locations, different amounts of vehicles, and uncertain vehicle arrivals and departures.

The simulation results in the case when considering 200 (resp., 510 and 1080) vehicles and different maximal SC coverages are given in Fig. 3 (resp., Figs. 4 and 5), in which the horizontal axis indicates the ratio of weights for two objectives (i.e., w_1 versus w_2); while the vertical axis represents the normalized cost. For example, when the ratio is 1:9 on the horizontal axis, we focused more on electromagnetic pollution but less on power consumption. In the case in Fig. 3, the normalized cost when the ratio is 5:5 is the best in all cases of maximal SC coverage. When the ratio is 1:9 (i.e., power consumption is more concerned), the normalized costs for 100m and 150m maximal SC coverages are larger, i.e., power consumption is larger, because the direct transmission with BSs is applied frequently in the two cases. But, if the maximal SC coverage is enlarged to 200m, the performance is improved. In the cases of Figs. 4 and 5, the normalized cost when the ratio is 6:4 is the best.

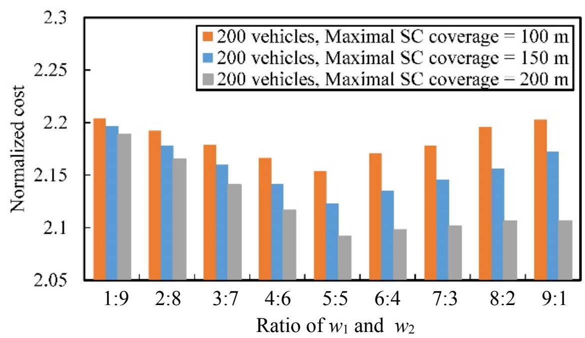

Fig. 3. Comparison of results under different ratios of weights for two objectives when considering 200 vehicles and different maximal SC coverages.

On the other hand, we analyze the results using different numbers of legacy RSs and SCs in the case when applying 100m, 150m and 200m maximal SC coverage in Figs. 6, 7, and 8, in which the normalized costs of three possible numbers of vehicles (i.e., 200, 510, and 1080) are shown, and we assume the weights of the objectives of power consumption and electromagnetic pollution to be equal (i.e., $w_1 = w_2$). From Fig. 6 (i.e., the case for 100m SC coverage), the results using 7 legacy RSs and 8 SCs would be the best in overall. From Fig.

7 (i.e., 150m SC coverage), the results using 7 legacy RSs and 7 SCs would be the best in overall. Relatively, the case for 200m SC coverage shows better performance than the cases in Figs. 6 and 7. From Fig. 8, the best results occur when 6 legacy RSs and 5 SCs are applied in the case of 200 vehicles; and when 8 legacy RSs and 7 SCs are applied in both cases of 510 vehicles and 1080 vehicles. Hence, in overall, the result using 6 legacy RSs and 7 SCs would be the best.

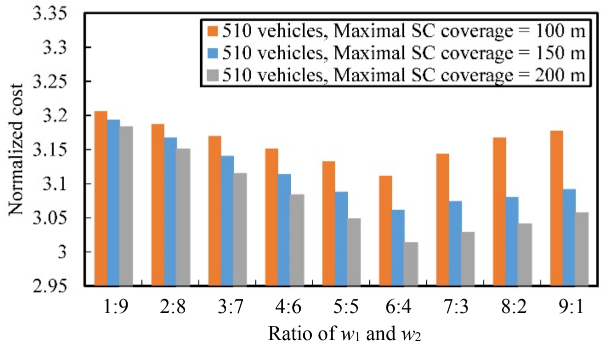

Fig. 4. Comparison of results under different ratios of weights for two objectives when considering 510 vehicles and different maximal SC coverages.

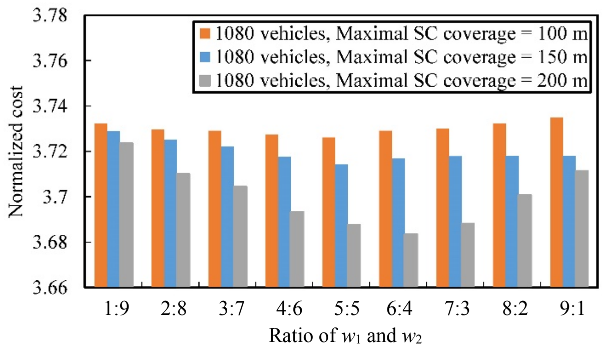

Fig. 5. Comparison of results under different ratios of weights for two objectives when considering 1080 vehicles and different maximal SC coverages.

Furthermore, we analyze the results in Figs. 6-8. In the case with 1080 vehicles, the lowest normalized costs under 100m maximal SC coverage (with 8 RSs and 8 SCs in Fig. 6) and 150m maximal SC coverage (with 8 RSs and 7 SCs in Fig. 7) are higher than 200m maximal SC coverage (with 6 RSs and 7 SCs in Fig. 8) because small-size coverage leads to BS transmission, which costs more energy. In the case with 510 vehicles, the lowest normalized costs under setting of 150m maximal SC coverage (with 7 RSs and 7 SCs in Fig.

7) and 200m maximal SC coverage (with 6 RSs and 7 SCs in Fig. 8) are very close, because of the tradeoff between power consumption and electromagnetic pollution. But, the normalized costs under 200m SC coverage are lower, because fewer legacy RSs are used in this case. In the case with 200 vehicles, the lowest normalized costs under 100m maximal SC coverage (6 RSs and 5 SCs in Fig. 6) is lower than those under 150m maximal SC coverage (6 RSs and 5 SCs in Fig. 7) and 200m maximal SC coverage (6 RSs and 5 SCs in Fig. 8), because fewer vehicles only require fewer legacy RSs and SCs. A larger SC coverage leads to a higher normalized cost. In overall, the case with 200m maximal SC coverage performs the best.

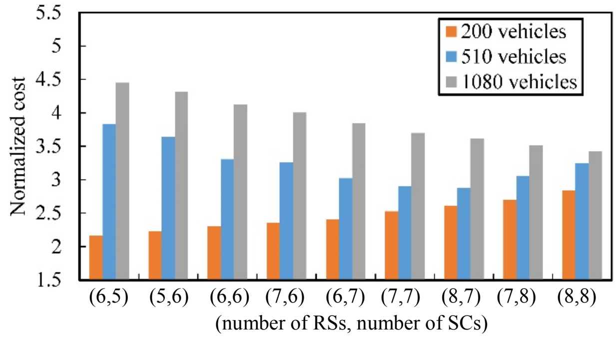

Fig. 6. Comparison of results using different numbers of legacy RSs and SCs when applying 100m maximal SC coverage and three possible numbers of vehicles.

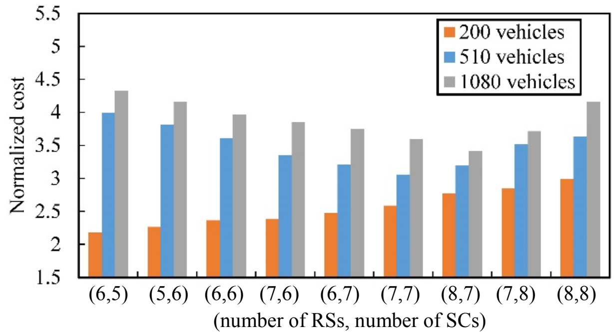

Fig. 7. Comparison of results using different numbers of legacy RSs and SCs when applying 150m maximal SC coverage and three possible numbers of vehicles.

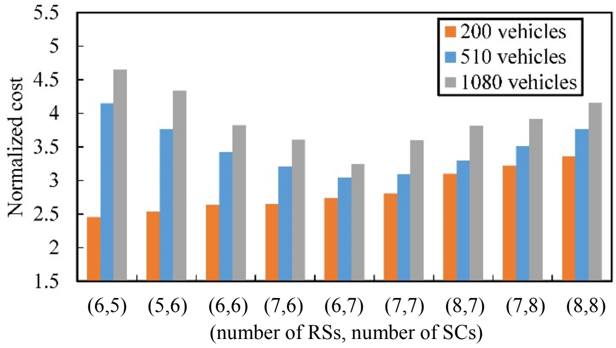

Fig. 8. Comparison of results using different numbers of legacy RSs and SCs when applying 200m maximal SC coverage and three possible numbers of vehicles.

From the above experiment results, we suggest the following strategies while constructing a cellular network along the highway. When the highway is constructed in an urban area (meaning that the daily traffic loading on the highway might be very heavy), it would be better to apply a larger SC radius and moderate amounts of RSs and SCs. Our experiment results show that deploying 6 relay stations and 7 SCs with 200m SC radius performs best in the case with 1080 vehicles. When the highway is constructed in a rural area (meaning that the daily traffic loading on highway might be relatively light), it would be better to apply a smaller SC radius and fewer amounts of RSs and SCs. Our experiment results show that deploying 6 RSs and 5 SCs with 100m SC radius performs best in the case with 200 vehicles.

6. Conclusion

Minimization of power consumption and electromagnet pollution is important for future 5G green networks when deploying mobile communications devices and IoT sensors. This work has considered a one-dimensional cellular network with BSs, SCs, and legacy RSs along a highway segment. We have investigated the joint problem of determining cell sizes of SCs for minimizing the total electromagnet pollution generated from mobile devices; and determining the sleep controls of SCs and legacy RSs for minimizing the total power consumption of the whole cellular network. This problem model is more complex than previous works because of various transmission ways from BSs to users. Therefore, a hybrid algorithm of GA and DE is proposed to resolve this complex deployment problem to achieve less energy consumption and less electromagnet pollution concurrently for future 5G green networks.

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