

RESEARCH ARTICLE

Wireless network power optimisation using relay stations blossoming and withering technique

Aida Al-Samawi^{1*}, A. Sali¹, Liyth Nissirat², Nor Kamariah Noordin¹, Mohamed Othman³ and Fazirulhisyam Hashim¹

¹ Department of Computer and Communication Systems Engineering, Faculty of Engineering, UPM, 43400 Selangor, Malaysia

² Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering, UKM, 43600 Bangi, Selangor, Malaysia

³ Department of Communication Technology and Network, FSKTM, UPM, 43400 Selangor, Malaysia

ABSTRACT

Power consumption of wireless network is increasing as the demands in wireless data rates are escalating in modern life. Base stations are the major power consumption component in the wireless network. Therefore, the main challenge is to reduce the total power consumed in the network while maintaining the network coverage and its capacity. In this paper, a new relay switching perspective is introduced for relay blossoming and withering algorithm. First, relay switching is considered as a function of time representing the rate of active relays. The effect of the rate of active relays, arrival rate and average load factor of relays on the total network power consumption is modelled. It is found that the rate of active relay function that optimises the network power consumption obeys linear first-order ordinary differential equation. The effect of different synthesised arrival rate profiles on the rate of active relay is presented. Moreover, relative relay to base station capacity parameter is defined, and its effect on the power optimisation is investigated. Based on the solutions of the ordinary differential equation, an approximate fuzzy-based relay sleeping mode is introduced. The fuzzy logic sleeping mode utilises the arrival rate and its derivative as inputs. The solution of the differential equations shows that power saving up to 45 and 30 per cent can be achieved in sleeping and idling modes, respectively, in contrast to 42 per cent achieved from the fuzzy sleeping mode. The increasing slope of the arrival rate results in less power saving. Copyright © 2015 John Wiley & Sons, Ltd.

*Correspondence

A. Al-Samawi, Department of Computer and Communication Systems Engineering Faculty of Engineering, UPM, 43400 Selangor, Malaysia.

E-mail: aalsamawi@gmail.com

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1. INTRODUCTION

The effects of carbon footprint on the human life as part of its impact on environment attracted the attention of researchers to study the techniques to reduce the power consumption in modern technology. A survey in [1] explored the energy efficiency optimisation methods in both orthogonal frequency-division multiple access and orthogonal frequency-division multiplexing. They considered the Long Term Evolution (LTE)-advanced and WiMAX technologies in their survey. Although the wireless networks produce less than 2 to 4 per cent of world CO₂ emission [2], the enormous growth in wireless data rate drives to rise that percentage. It is estimated that the base stations (BSs) are responsible for 80 per cent of the total power consumed by wireless networks [3]. These amounts of power consumption inspire the motivation of

using heterogeneous networks (HetNets) to deliberate the reduction of power consumption of the network [4, 5].

Applying sleeping mode on the BSs may reduce more than 10 per cent of the total network power as compared with the situation when all the BSs are permanently operating as concluded in [6]. The distance-aware sleep mode algorithm proposed in [7] is applied on an urban area with constant number of BSs and predefined BSs location. In this algorithm, users are attached to their nearest BS. The results compared the performance of distance-aware sleep mode algorithm with permanently switched-on mode and random sleep mode algorithm. Their algorithm enhances the power reduction by 10 per cent as compared with the random sleep mode algorithm. In contrast to the permanently operating network, achieving up to 29 per cent of power saving is possible by using distance-aware sleep mode.

Traffic aware network energy management is considered in [8, 9] to preserve power consumption. Authors in [10] investigate two sleep mode algorithms, the first algorithm is dynamic sleep mode and the second one is semi-static sleep mode. The semi-static sleep mode algorithm results show that it is efficient at low load traffic, while dynamic sleep mode algorithm results show that it is more efficient in high load traffic.

Resource activation and deactivation in cellular network are studied in [11]. In their work, they considered the quality of service (QoS) as perceived by users. The main objective is to reduce the energy consumption while maintaining a satisfactory QoS. Their algorithm showed a remarkable reduction of energy consumption at low traffic. When the cell is saturated, the energy consumption is comparable with the full operation cell case. Also, they proposed a hysteresis to reduce the ping-pong effect as defined in [12]. However, they noticed a compromise between reducing the ping-pong effect and energy consumption because of hysteresis.

The effect of network antenna tilt optimisation on the total network performance with sleep mode is studied in [13]. The authors investigated the reduction in data rate and user satisfaction for a sleep mode at site and cell levels. In both cases, effect of network tilt optimisation is investigated. Energy saving of up to 33 per cent is achievable with minor effects on user satisfaction in site level sleep mode. Cell level sleep mode, on the other hand, provided more energy saving with the expense of degrading the average user data rate.

Weekly network traffic pattern is considered as a central element of switching on/off energy-saving algorithm developed in [14]. The traffic pattern is presented for a week including weekends and holidays where the peak arrival rate reduced significantly. In their work, they introduced the concept of network impact, which characterises the effect of loading on the neighbouring BS in the case of one BS is turned off. During weekdays, more than 50 per cent energy saving is claimed by their algorithm. During weekends, the energy saving is reported to be up to 80 per cent. In [15], switching on/off algorithm based on traffic estimate is demonstrated to increase the energy efficiency.

The effect of different traffic patterns on the BS switching is investigated in [16]. Analytical investigation is presented in their work to identify the best strategies of switching the BS so as the service availability is maintained. They proved that the role of traffic pattern is central in deciding the switching scheme and the periods for applying the switching. Moreover, in business regions, a significant power saving of up to 90 per cent can be achieved in contrast to 30–40 per cent in other cases.

The implementation of fuzzy logic in BS sleep and zooming algorithms has been addressed in [17–19]. The survey study of different sleep modes and cell zooming algorithm in [17] concluded that static cell zooming algorithms are effective in off-peak durations with possible savings of up to 50 per cent can be achieved. Whereas, in full day traffic, dynamic zooming algorithms yield higher

power efficiency because they are useful for load balancing, which improves the total power saving of the network. Fuzzy cell zooming based on user location algorithm is introduced in [18] for enhancing the power efficiency in the network. The cells in their work never go to complete sleep mode, although power saving up to 40 per cent is claimed by using the fuzzy zooming algorithm as compared with the static coverage BSs without a loss of QoS. In [19], a hierarchical fuzzy logic structure is developed to estimate the required antenna height and transmission power for cell zooming. Their proposed fuzzy scheme improved the network power efficiency by 35.6 per cent.

It can be concluded from the previous work discussed that the inclusion of traffic rate in sleeping mode or zooming algorithms is central. However, the role of the rate of traffic rate is not fully understood nor investigated. Moreover, the discussed algorithms are focusing on BS switching mechanisms. Recently, with the emerging high-density HetNet systems such as LTE-A, the concept of relay station (RS) is introduced. RSs in high-density networks are used for improving the network capacity and coverage particularly in metropolitan and high user density areas. Usually, more than one RS is associated with each BS in the network. The RS is considered as a small version of the BS with lower power consumption and limited capacity. Thus, with the power and capacity characteristics of the RS as compared with the BS, the main concerns of the RS switching on/off can be stated as follows:

- What will be the role of the RS limited capacity and power consumption as compared with the BS on the total power saving achieved by switching off the RS during low traffic rates.
- What parameters that need to be considered for optimal RS switching on/off algorithm, and
- What would be the maximum power saving achieved by switching on/off the RS considering its limited capacity and nominal power consumption.

Partial answers are provided in our previous work [20] where a fuzzy logic scheme is introduced for RS on/off switching in HetNet. The proposed fuzzy system received the derivative of traffic rate as input and optimised the RSs status according to the traffic rate and its derivative. The proposed fuzzy logic system showed the importance of the rate of traffic rate in achieving high power efficiency in HetNet with power saving up to 36.37 per cent was achieved in certain cases by blossoming and withering the RS. However, the effect of the proposed RS blossoming and withering technique on the total network QoS and coverage is not investigated. Moreover, the proposed fuzzy system in our previous work does not show the effect of the RS limited capacity and power as compared with the respective BS on the total power saving achieved. Thus, a detailed mathematical modelling of the power consumption in HetNet employing RS is still needed to provide answers regarding the optimal switching profile concern. It is worth to note that the proposed RS algorithm is suitable

in applications where the BS are meant to stay permanently in operation in HetNet deployed in high user density and metropolitan regions to maintain the network QoS and coverage.

The main contribution in this paper is developing a new theoretical analysis to characterise the optimal RS blossoming and withering strategy in HetNet. Blossoming RS is referred to the fully functional RS during the high traffic rate, whereas the withering RS is the with minimum power consumption during the low traffic periods. This theoretical analysis highlights the significance of different factors that would improve the total power saving achieved by the switching strategy. Furthermore, the importance of the rate of traffic rate (traffic rate derivative) in constructing the switching strategy is clearly identified and investigated quantitatively. The mathematical analysis considers two modes, namely, the RS sleeping and idling modes. The main difference between the two modes is the amount of power consumed by the RS during the low traffic period. In RS sleeping mode, the RS consumes a small fraction of its nominal power supply rating, whereas the power consumption is more in RS idling mode. More importantly, from the theoretical perspective, we demonstrate that the optimal RS blossoming and withering is not only dependent on the traffic rate, as the derivative of the traffic rate (representing the traffic rate slope) is of equal importance to achieve the optimal RS switching scheme and maintaining the QoS. Furthermore, we define the relative RS to BS capacity metric and show its effect in obtaining the optimal RS switching scheme. The relation of the number of RS deployed and the power consumption ratio for different values of the relative RS to BS capacity is also investigated. The rate of power consumption resulted from applying the optimal rate of active RS is calculated for different synthesised arrival rate patterns. The understanding of the parameters affecting the optimal RS blossoming and withering is used to implement a fuzzy logic sleeping mode system. The fuzzy logic utilises the traffic rate and its derivative to produce the RS blossoming and withering pattern. The power efficiency of the fuzzy logic system is compared with the power efficiency calculated in the theoretical RS sleeping mode. Finally, the proposed fuzzy sleeping mode (fuzzy SM) is applied on a real network in Kuala Lumpur and a random network, and the effect of the rate of active RS on the users signal-to-interference-plus-noise ratio (SINR) and received signal strength indicator (RSSI) is investigated.

Section 2 presents the problem formulation, and the theoretical analysis of the RS switching is discussed in Section 3. Section 4 explains the fuzzy system model, and Section 5 explains the data collection campaign and the results and discussion. Finally, the findings of this work are concluded in Section 6.

2. PROBLEM FORMULATION

The network topology considered in this work consists of k major BS; each is associated with a set of n_k RSs. To

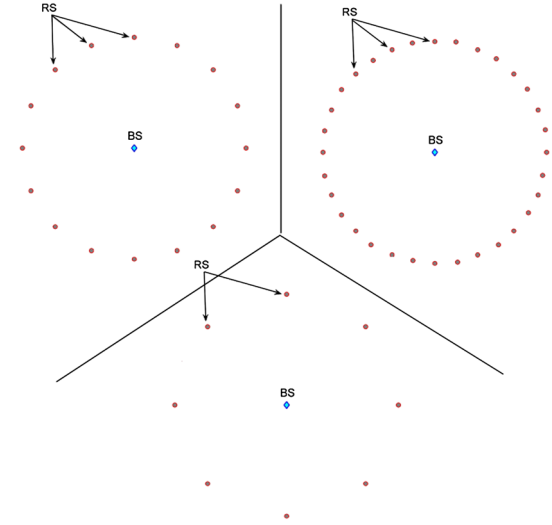


Figure 1. A topology, which consists of three base stations (BSs), each is associated with a set of relay station (RS).

reduce the total power of the network, the RSs will switch on/off according to the traffic rate variation. The switching of each set of RSs is controlled by their respective BS as shown in Figure 1 where, for simplicity, the RSs are shown to be evenly distributed around the BS. In this model, each BS and its set of RSs form a cluster that serves a specific number of users. The switching of each set of RSs is controlled by their respective BS independently. Thus, RS blossoming and withering algorithm can be applied on each cluster autonomously to reduce its total power consumption. For this scenario, the theoretical analysis will consider one BS controlling n RSs. No restrictions are assumed for the distribution, configuration or the number of the RSs deployed as it is assumed to be selected according to the network coverage, capacity and QoS demands. The theoretical analysis focuses on the power saving in the network when applying different switching modes. Linear power consumption model is assumed for the BS and the associated RSs. The switching on/off is not applied on the BSs, and they are considered to operate permanently.

3. THEORETICAL ANALYSIS

Figure 2 shows a general topology of a BS associated with a set of RSs. The RS on/off state is controlled by the BS to accommodate the increase in the traffic rate. The power consumed in the transmitter (BS or RS) is divided into two parts, the constant power associated with the power amplifier and cooling system and the second part is associated with the signalling and transmission. A linear relation is usually employed to model the power consumed in the transmitter [21] as follows:

$$P_{BS} = P_{BS}^o + F_{BS}P_{BS}^L \quad (1)$$

$$P_{RS} = P_{RS}^o + F_{RS}P_{RS}^L \quad (2)$$

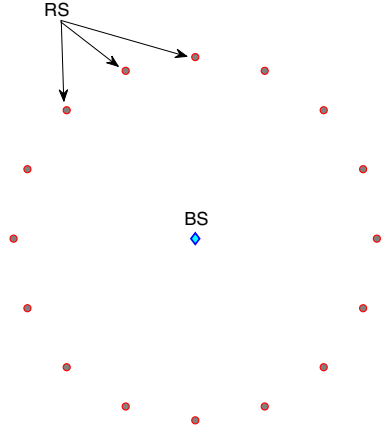


Figure 2. A topology that consists of a base station (BS) and a set of relay stations (RSs).

Where P_{BS}^o and P_{RS}^o are the power consumed in the BS and RS power amplifier and cooling system, respectively, F_{BS} and F_{RS} are the BS and RS transmitter power amplifier efficiency, and P_{BS}^L and P_{RS}^L are the power sensitivity to the load carried by the transmitter. The transmitter power sensitivity to the load is the variation of the transmitter power due to the load variation in the transmitter. By defining the maximum power consumption due to the load as P_{BS}^{max} and P_{RS}^{max} , the power sensitivity to load can be represented as follows:

$$P_{BS}^L = \alpha_{BS} P_{BS}^{max} \quad (3)$$

$$P_{RS}^L = \alpha_{RS} P_{RS}^{max} \quad (4)$$

where α_{BS} and α_{RS} are the normalised load factors of the BS and RS, α_{BS} and $\alpha_{RS} \in [0, 1]$.

Therefore, for k BS, each is associated with a set of n RS, and assuming that the relays are active permanently, the total power consumed at any given time is

$$P_{Total} = kP_{BS}^o + nkP_{RS}^o + \sum_{i=1}^k F_{BS_i} \alpha_{BS_i} P_{BS_i}^{max} + \sum_{j=1}^{nk} F_{RS_j} \alpha_{RS_j} P_{RS_j}^{max} \quad (5)$$

For a single BS ($k = 1$) associated with n permanently active RS, the power is

$$P_{Total} = P_{BS}^o + nP_{RS}^o + F_{BS} \alpha_{BS} P_{BS}^{max} + \sum_{j=1}^n F_{RS_j} \alpha_{RS_j} P_{RS_j}^{max} \quad (6)$$

To simplify Equation (6), the RSs are assumed to be of the same type with equal power sensitivity to load, $P_{RS_j}^{max} = P_{RS}^{max}$, and $F_{RS_j} = F_{BS}$, thus

$$P_{Total} = P_{BS}^o + nP_{RS}^o + \alpha_{BS} F_{BS} P_{BS}^{max} + F_{RS} P_{RS}^{max} \sum_{j=1}^n \alpha_{RS_j} \quad (7)$$

The BS and RS load factors are calculated as the ratio of the occupied resources (voice calls or data line) to the total resources available in the BS or RS. The resources are the bandwidth in Global System for Mobile Communication (GSM) network or subcarriers in LTE network. Assuming that the BS and RSs are capable to provide R_{BS}^{max} and R_{RS}^{max} resources, respectively, the load factor at any moment of time can be calculated as follows:

$$\alpha_{BS} = R_{BS}^{served} / R_{BS}^{max} \quad (8)$$

where R_{BS}^{served} are the resources served by the BS at time t . Similarly for RS

$$\alpha_{RS} = R_{RS}^{served} / R_{RS}^{max} \quad (9)$$

where R_{RS}^{served} are the resources served by the RS at time t .

In this case, the total utilised resources at any given time is

$$R^{served} = R_{BS}^{served} + \sum_{j=1}^n R_{RS_j}^{served} \quad (10)$$

And the maximum available resources is

$$R^{max} = R_{BS}^{max} + \sum_{j=1}^n R_{RS_j}^{max} \quad (11)$$

Then, to ensure that the network QoS is maintained, the normalised total capacity of the system should serve the normalised arrival rate A_r , which is calculated as follows:

$$A_r = \frac{R^{served}}{R^{max}} = \frac{R_{BS}^{served} + \sum_{j=1}^n R_{RS_j}^{served}}{R_{BS}^{max} + \sum_{j=1}^n R_{RS_j}^{max}} \quad (12)$$

For simplicity, assuming a balanced load for the RS, so $R_{RS}^{served} = \overline{R_{RS}^{served}}$, the arrival rate in Equation (12) would be

$$A_r = \frac{R^{served}}{R^{max}} = \frac{R_{BS}^{served} + n\overline{R_{RS}^{served}}}{R_{BS}^{max} + nR_{RS}^{max}} \quad (13)$$

when applying the RS switching on/off mode, at any moment of time only a fraction of the total number of RS is active. Denoting the ratio of active RS as $g(t)$, then

$$g(t) = \frac{N_t}{n} \quad (14)$$

where N_t is the number of active RS at time t .

Replacing n in Equation (13) by the number of active RS, $ng(t)$, the arrival rate as function of $g(t)$ would be

$$A_r = \frac{R^{served}}{R^{max}} = \frac{R_{BS}^{served} + ng(t)\overline{R_{RS}^{served}}}{R_{BS}^{max} + ng(t)R_{RS}^{max}} \quad (15)$$

The distinction between Equations (15) and (13) is that the arrival rate in Equation (13) is served by all the RS at any time, while in Equation (15), only a fraction of the RSs are serving the arrival rate; thus, the active RSs are operating at higher load factor. Although, the switching profile function $g(t)$ should guarantee the total arrival at any given time through Equation (15). From Equations (8), (9) and (15) and calculating for α_{BS}

$$\alpha_{BS} = A_r(1 + ng(t)C_{RS2BS}) - ng(t)\overline{\alpha_{RS}}C_{RS2BS} \quad (16)$$

where $C_{RS2BS} = \frac{P_{RS}^{max}}{P_{BS}^{max}}$ and $\overline{\alpha_{RS}}$ is the average RS load factor.

The withering (idling or sleeping) RS power supply reduces its consumption because of switching off some circuits. This reduction is defined as a consumption factor to P_{RS}^o and denoted as P_f as follows:

$$P_f = \frac{P_{RSW}}{P_{RS}^o} \quad (17)$$

where P_{RSW} is the withering RS power supply consumption.

Substituting Equation (16) in Equation (7) and replacing the $\sum_{j=1}^n \alpha_{RS_j}$ by $ng(t)\overline{\alpha_{RS}}$, the total power supply consumed considering $1 - g(t)$ of the total number of RSs are withering is

$$\begin{aligned} P_{T_{BW}} = & P_{BS}^o + nP_{RS}^o P_f + A_r F_{BS} P_{BS}^{max} \\ & + ng(t) A_r F_{BS} P_{BS}^{max} C_{RS2BS} \\ & - ng(t) (\overline{\alpha_{BS}} (C_{RS2BS} F_{BS} P_{BS}^{max} - F_{RS} P_{RS}^{max}) \\ & - P_{RS}^o [1 - P_f]) \end{aligned} \quad (18)$$

To clarify and to unify the power representation, the total power consumption when all the RSs are active permanently can be computed from Equation (18) by setting $g(t) = 1$, thus

$$\begin{aligned} P_T = & P_{BS}^o + nP_{RS}^o + A_r F_{BS} P_{BS}^{max} \\ & + nA_r F_{BS} P_{BS}^{max} C_{RS2BS} \\ & - n (\overline{\alpha_{RS}} (C_{RS2BS} F_{BS} P_{BS}^{max} - F_{RS} P_{RS}^{max})) \end{aligned} \quad (19)$$

Equations (18) and (19) show the total power in terms of A_r , $g(t)$, P_f and $\overline{\alpha_{RS}}$ in RS blossoming and withering algorithm and the total power when all RSs are active, respectively. The consumption factor P_f is used in this equation to differentiate between different schemes of blossoming and withering. For idling RS, the power supply reduces fraction of its consumption because of switching off part of its circuitry. In complete sleeping mode, on the other hand, the power supply reduces most of its power consumption, and just a fraction of the power is consumed for the awakening circuitry. The ratio of power consumption defined as the ratio of power when applying blossoming and withering algorithm to the total power when all RSs are active permanently is

$$r_{P_{BW}} = \frac{P_{T_{BW}}}{P_T} \quad (20)$$

The ratio of power consumption described in Equation (20) is an implicit function of time through A_r , $\overline{\alpha_{RS}}$ and $g(t)$, and all of them are represented as functions of time. Thus, the ratio of power consumption is a functional of parametric functions, and its variational is subject to the variations of its functions. To represent the ratio of power consumption in integral format, the average ratio of power consumption in a period τ is defined as

$$r_{avg} = \frac{1}{\tau} \int_0^\tau r_{P_{BW}} dt \quad (21)$$

The average ratio of consumption can be minimised by applying the Euler–Lagrange variational criteria and minimising $r_{P_{BW}}$ with respect to its parametric functions [22]. Thus, the optimisation criterion is described as follows:

$$\frac{dA_r}{dt} \frac{\delta r_{P_{BW}}}{\delta A_r} + \frac{d\overline{\alpha_{RS}}}{dt} \frac{\delta r_{P_{BW}}}{\delta \overline{\alpha_{RS}}} + \frac{dg(t)}{dt} \frac{\delta r_{P_{BW}}}{\delta g(t)} = 0 \quad (22)$$

The symbol $\frac{\delta(\cdot)}{\delta(\cdot)}$ represents the variational of the functional with respect to its parametric function, and it is equivalent to the partial differential.

The derivatives in Equation (22) are computed from Equations (18) and (19) as follows:

$$\begin{aligned} \frac{\delta r_{P_{BW}}}{\delta A_r} = & g(t) \left[\frac{c_2}{P_T} - \frac{c_3 (c_4 + nP_{RS}^o (1 - P_f))}{P_T^2} \right] \\ & + \frac{F_{BS} P_{BS}^{max}}{P_T} - \frac{c_3 (c + A_r F_{BS} P_{BS}^{max})}{P_T^2} \end{aligned} \quad (23)$$

$$\begin{aligned} \frac{\delta r_{P_{BW}}}{\delta \overline{\alpha_{RS}}} = & g(t) \left[\frac{c_1}{P_T} - \frac{c_1 (c_4 + nP_{RS}^o (1 - P_f))}{P_T^2} \right] \\ & + \frac{c_1 (c + A_r F_{BS} P_{BS}^{max})}{P_T^2} \end{aligned} \quad (24)$$

and

$$\frac{\delta r_{P_{BW}}}{\delta g(t)} = \frac{c_4 + nP_{RS}^o (1 - P_f)}{P_T} \quad (25)$$

By substituting the derivatives with respect to A_r , $g(t)$ and $\overline{\alpha_{RS}}$ in Equation (22) and rearranging the terms, yields

$$\begin{aligned} \frac{dg(t)}{dt} = & \frac{g(t)}{c_4} \left[\frac{dA_r}{dt} \left(\frac{c_3 c_4}{P_T} - c_2 \right) \right] \\ & + \frac{d\overline{\alpha_{RS}}}{dt} \left(c_1 - \frac{c_1 c_4}{P_T} \right) \\ & - \frac{1}{c_4} \frac{dA_r}{dt} \left(F_{BS} P_{BS}^{max} - \frac{c_3 c_5}{P_T} \right) - \frac{1}{c_4} \frac{d\overline{\alpha_{RS}}}{dt} \left(\frac{c_1 c_5}{P_T} \right) \end{aligned} \quad (26)$$

where

$$c = n (P_{RS}^o P_f + P_{BS}^o) \quad (27)$$

$$c_1 = n(C_{RS2BS}F_{BS}P_{BS}^{max} - F_{RS}P_{RS}^{max}) \quad (28)$$

$$c_2 = nC_{RS2BS}F_{BS}P_{BS}^{max} \quad (29)$$

$$c_3 = n(C_{RS2BS} + 1)F_{BS}P_{BS}^{max} \quad (30)$$

$$c_4 = A_r c_2 - \overline{\alpha_{RS}} c_1 + nP_{RS}^o(1 - P_f) \quad (31)$$

$$c_5 = c + A_r F_{BS} P_{BS}^{max} \quad (32)$$

From Equation (26), it is clear that the optimum ratio of active RS obeys linear first-order ordinary differential equation [23]. Furthermore, the optimum ratio of active RS is related to the arrival rate, the RS average load factor, their derivatives and the relative RS to BS capacity. The significant point in the derivation of Equation (26) is that it does not involve any assumption about the number of RS deployed, their distribution or the order of switching the RS. This is because these assumptions are computed in accordance with the network coverage, capacity and QoS demands. The solutions of Equation (26) are continuous functions representing the ratio of active RS that optimises the total power consumption while maintaining the arrival rate. Runge Kutta of order (4,5) algorithm [24] is used to extract the solutions of Equation (26). The solutions considered are for two modes of blossoming and withering algorithm. The first mode is called in this work as RS idling, and it is characterised by setting the consumption factor $P_f = 0.5$. The second mode is called RS sleeping where the consumption factor is considered to be $P_f = 0.1$.

The key point of the theoretical intuition of Equation (26) is the significance of the arrival rate derivative in the problem of optimising the RS blossoming and withering profile. However, the computational complexity involved in the solution of ordinary differential equations and their sensitivity to the imperfections in the arrival rate limit their applicability in real-time applications. Instead, a fuzzy SM approximate solution is proposed. Noting that the normalised average RS load factor varies in synchronism with the arrival rate, only the arrival rate and its derivative are considered as inputs to the proposed fuzzy system. Calculating the derivative of the arrival rate in real time can be achieved by using the backward Euler derivative approximation [25].

4. FUZZY SYSTEM MODEL

The inputs and outputs of the proposed fuzzy system are mapped into fuzzy domains by means of membership function. The decision from the fuzzy logic is drawn through the expert system as a set of expert rules designed to control the blossoming and withering scheme to follow the desired pattern. The proposed blossoming and withering algorithm has three inputs and two outputs as follows:

Fuzzy inputs:

- the traffic pattern (arrival rate),
- differential of arrival rate and
- the percentage of active RSs

Fuzzy outputs:

- the percentage of active RSs and
- waiting time

The percentage of active RSs is characterised as input and output, which represents a feedback with delay line. This configuration signifies a memory line and enables the system to keep track of the latest percentage of active relays as shown in Figure 3. The expert system of the proposed Fuzzy scheme consists of 45 rules mapping the inputs to outputs. The output Fuzzy space is evaluated in contrast to the designed output membership functions.

4.1. Inputs fuzzification

The inputs are normalised in the interval [0 1]. The input domain is fuzzified as shown in Figures 4 and 5. The traffic rate and its derivative are represented by fuzzy

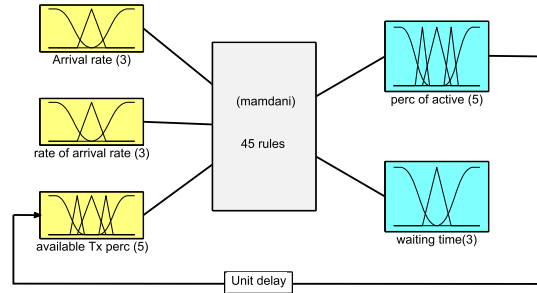


Figure 3. Fuzzy inference system model.

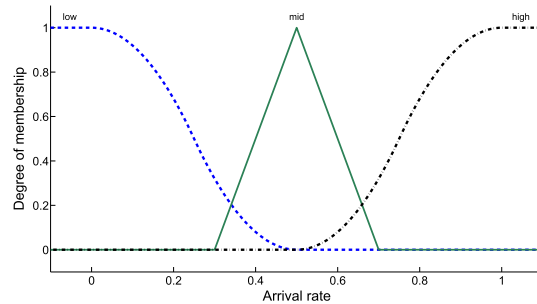


Figure 4. Three Membership Functions (MMF) distribution.

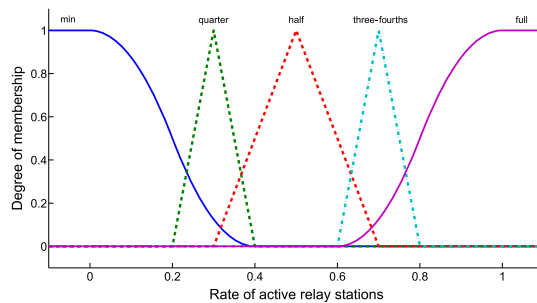


Figure 5. Five MMF distribution.

intervals, namely, low, mid and high. The percentage of the active relays, on the other hand, is divided into five intervals characterised as min, quarter, half, three fourth and full.

4.2. Outputs fuzzification

The percentage of active RSs in Figure 5 is fed back to the fuzzy system inputs; hence, the fuzzification of this output takes the same format as to its respective input. The waiting time is designed in relation to the arrival rate and its differential. The member function fuzzification of the waiting time output is matching the arrival rate and its differential as shown in Figure 4.

4.3. FIS rules

The fuzzy system first and second inputs are fuzzified to three membership functions each, whereas five membership functions are used for the third input. Thus, the number of the expert rules in the proposed FIS can be calculated as $3 \times 3 \times 5$, which results in 45 rules that associate the inputs to the outputs [26, 27]. The rate of active relays relation to the inputs is represented as surfaces as depicted

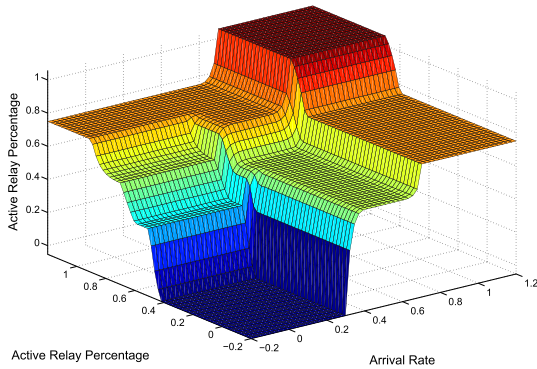


Figure 6. Rate of active relays surface with respect to the arrival rate and rate of active relays.

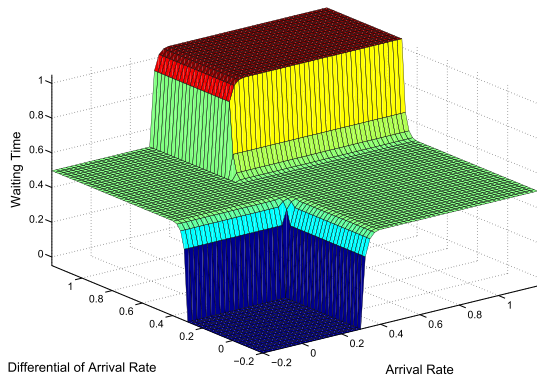


Figure 7. Waiting time surface with respect to arrival rate and its differential.

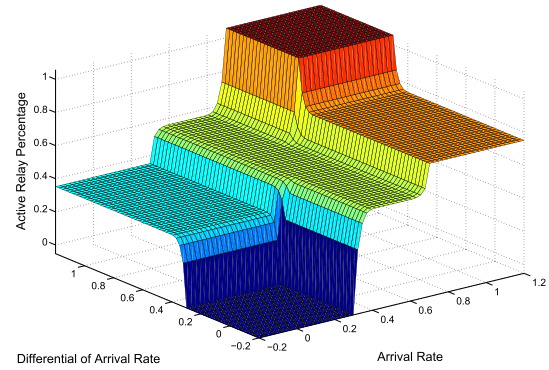


Figure 8. Rate of active relays surface with respect to arrival rate and its differential.

in Figures 6–8. The increase in arrival rate is the main factor to increase the rate of active relays. The rate of active relays proposed by the Fuzzy Inference System (FIS) is the maximum when both the arrival rate and its differential are high as shown in Figure 8. Apparently, the relation between the rate of active relays input and rate of active relays output is direct, this is clarified in Figure 6. In this proposed system, the activated RS will stay on for a minimum waiting time. This waiting time is a function of the arrival rate and its derivative as depicted in Figure 7. Hence, the waiting time is higher at high arrival rates to accommodate the high services demand increase, and at low arrival rate, the waiting time reduces to the minimum. This variation of the waiting time allows preserving more power. Moreover, the derivative of the arrival rate has a similar relation to the waiting time proposed.

4.4. Propagation model

The RSSI is calculated for each test point (users) as follows:

$$RSSI_i = P_{t_i} - P_L \quad (33)$$

where

$RSSI_i$: the received signal strength index for users i in (dB).

P_{t_i} : the transmitted power from the BS associated with user i in (dB).

P_L : the pathloss at the location of user i in (dB).

The urban ERICSSON 9999 pathloss model is used to determine the attenuation that resulted from the network BS configurations. In general, ERICSSON 9999 pathloss model is written as follows:

$$\begin{aligned} Pl = & a_0 + a_1 \log_{10}(d) + a_2 \log_{10}(h_b) \\ & + a_3 \log_{10}(h_b) \log_{10}(d) \\ & - 3.2(\log_{10}(11.75h_r))^2 \\ & + 44.49 \log_{10}(f) - 4.78(\log_{10}(f))^2 \end{aligned} \quad (34)$$

Table I. Pathloss parameters.

Parameter	Description
h_b	The BS height (m)
h_r	The MS antenna height (m)
d	The distance between the BS and MS (m)
f	The carrier frequency (MHz)
a_0	36.2
a_1	30.2
a_2	-12
a_3	0.1

BS, base station; MS, mobile station.

The parameters used in Equation (34) are listed in Table I. The effect of terrain irregularities and man-made structures is modelled as a lognormal distributed noise with mean zero and standard deviation σ . The intercept point a_0 and the slope in Equation (34) are calculated by measurements regression methods.

4.5. Signal-to-interference-plus-noise ratio

The SINR at the location of every user is calculated by considering the ratio of the signal strength from the user respective antenna (BS or relay) to the total interference from all the available antennas including the associated RSs in the same cluster serving the user. Mathematically, the SINR at user i location is calculated as follows:

$$SINR_i = \frac{RSSI_i}{\sum_{j=1, j \neq i}^n RSSI_j + N} \quad (35)$$

where $SINR_i$ is the signal-to-noise ratio at user i location. N denotes Gaussian noise received at user i

4.6. Coverage probability

The calculation of the cell coverage probability follows the method in [28]. The shadow fading margin (SFM) at the edge of the cell is assumed to satisfy the condition:

$$Pl(r) + SFM < \overline{Pl}(R) \quad (36)$$

where:

$\overline{Pl}(R)$: the mean pathloss at the edge of the cell, and R is the radius of the cell.

$Pl(r)$: the pathloss at distance r .

The cell edge pathloss can be calculated as

$$Pl(r) = P_t - G_t - L_b - SINR_{min} + G_r - L_r - N_r \quad (37)$$

Where

P_t : the transmitting power of every BS.

G_t : the transmitter gain = 18 dBi.

L_b : body losses = 4 dB.

G_r : the receiver antenna gain = 0 dBi.

L_r : the receiver losses = 0.5 dB.

N_r : receiver noise = -132.28 dB.

The $SINR_{min}$ depends on the network type. For LTE network, the minimum allowable SINR is in the range of 11 to 16.5 dB. The SFM can be calculated as

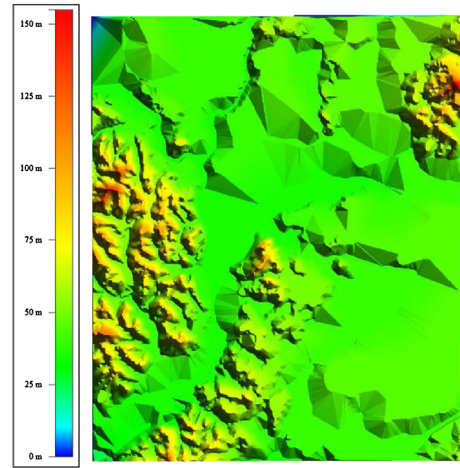
$$SFM = P_t - Pl(R) \quad (38)$$

5. RESULTS AND DISCUSSION

5.1. Data collection

The area of interest (AoI) of this work is Kuala Lumpur, which is the capital city of Malaysia. The digital terrain map (DTM) of AoI is provided by Jabatan Ukur Dan Pemetaan Malaysia with a resolution of 1:5000 m. The DTM covers an area of 54 km² in the metropolitan region of Kuala Lumpur city. World Geodetic System (WGS84) is the projection used in the provided DTM as shown in Table II including the longitude and latitude details of the map. The DTM of Kuala Lumpur metropolitan area is shown in Figure 9.

The initial network plan in the AoI is provided by the Malaysian Communications and Multimedia Commission. The details of the antenna configuration and transmission

**Figure 9.** Kuala Lumpur digital terrain map.**Table II.** Map attributes.

Title	Value
Projection	WGS84
Left top corner	3.19264568126254, 101.675051755914
Right top corner	3.19264568126254, 101.735764982316
Right bottom corner	3.11965924350193, 101.735764982316
Left bottom corner	3.11965924350193, 101.675051755914
Pixel scale	0.0001306

WGS, World Geodetic System.

power are listed in Table III. The initial network plan contains 160 BSs transmitting on 2112.4 MHz for downlink and 1922.4 MHz for uplink. This plan has been optimised by the Genetic Algorithm (GA) developed in [29]. The GA optimised the plan by selecting the active antenna positions, heights and transmission power so as the QoS of the network is maintained. In this work, the optimised network considers the BSs to be installed on the locations selected by the GA only, and then each BS is associated with a set of RSs to enhance the network coverage and capacity.

The traffic rate reflects the amount of services demanded from the network at any given time. Usually, this service amount demonstrates a temporal variation and a 24-hour local mean pattern characterised as diurnal cycle with 1 day period [30]. In addition to the local mean of the traffic rate, a Poisson distributed random variable is usually added to the traffic pattern to model the randomness of user traffic in the network. In this work, the traffic rate pattern through the week (including weekends) is emulated as a simple cyclic function with lower peak traffic rate at weekends as depicted in Figure 10, which resembles the periodicity of the network traffic load. This assumption maintains the non-linearity of the traffic rate over time. Thus, the derivative of the traffic rate is useful to reveal the amount of traffic change per unit time at any given moment during the day. However, this assumption is considered ideal

Table III. Network antenna parameters.

Parameter	Description
Heights	15 from ground level in metres
Power (EIRP)	14 dBW
Antenna type (model)	Kathrin model 742 215
Spacial location format	Decimal latitude/longitude format
Projection	WGS84
Antenna gain	18 dBi
Polarisation	Polarised horizontally with continuously adjustable electrical tilt from 0–10°

EIRP, Effective Isotropic Radiated Power; WGS, World Geodetic System.

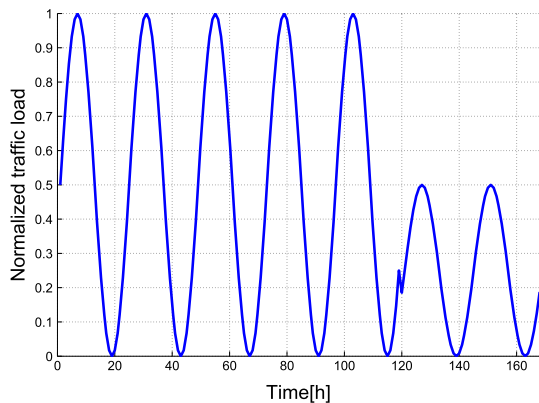


Figure 10. Traffic pattern sinusoidal shape.

traffic rate scenario with equivalent periods of high and low traffic rates according to the mean traffic rate value in the day. Thus, the power saving achieved by applying this pattern of traffic rate would reflect the standard cases only.

5.2. Numerical results

To investigate the effect of the arrival rate derivative on the power saving, the solutions of Equation (26) are considered for three different synthesised arrival rates with different slopes as shown in Figure 11. The number of RS considered in this solution is fixed at 64 and the constant C_{RS2BS} is fixed at 0.15 for the three cases. The power parameters of the BS and RSs are taken from energy aware radio and network technologies project [31] and listed in Table IV

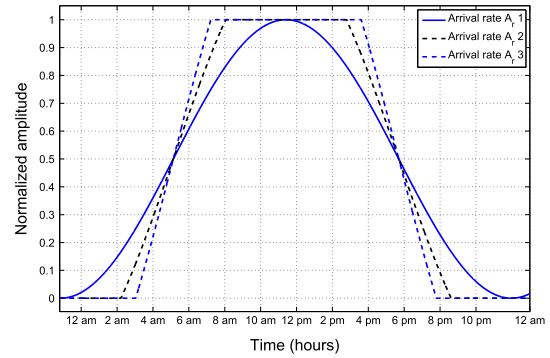


Figure 11. Different arrival rate profiles with different slopes.

Table IV. The parameters of the base station and relay station for idling and sleeping.

Base station		Relay station	
Parameters	Value	Parameters	Value
P_{BS}^o [W]	106	P_{RS}^o [W]	19.91
P_{BS}^{max} [W]	603	P_{RS}^{max} [W]	5
F_{BS}	6.36	F_{RS}	5.6
—	—	P_{RSS} [W]	5

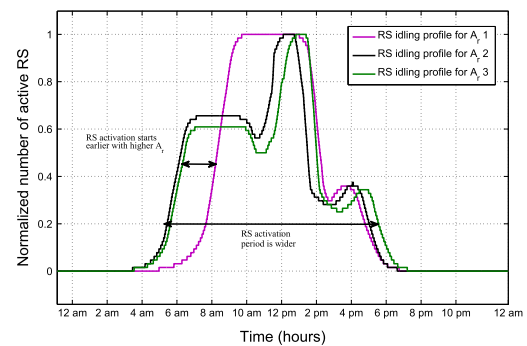


Figure 12. Relay station (RS) idling profiles for different arrival rates, 64 relays, solution of Equation (26), $P_f = 0.5$.

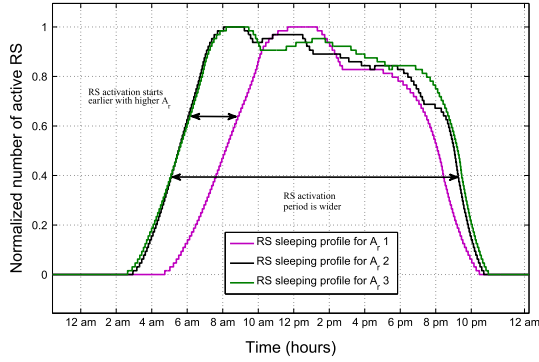


Figure 13. Relay station (RS) sleeping profiles for different arrival rates, 64 relays, solution of Equation (26), $P_f = 0.1$.

Table V. Power saving percentage for different relay stations for 64 relay.

Switching mode	A_r 1 (per cent)	A_r 2 (per cent)	A_r 3 (per cent)
Idling mode	22.40	21.31	21.28
Sleeping mode	41.06	32.64	31.6
Proposed fuzzy sleeping mode	40.4	32.3	27.07

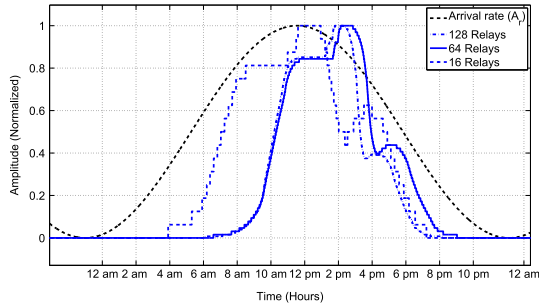


Figure 14. Relay station idling profiles for 16, 64 and 128 relays with A_{r1} , solution of Equation (26), $P_f = 0.5$.

for both idling and sleep modes. RS blossoming and withering profile that resulted from the three arrival rates is depicted in Figure 12 for idling mode and Figure 13 for sleeping mode. It is clear that higher arrival rate slope (represented as derivative) results in earlier activation of RS to accommodate the sharp rise of number of users, and moreover, the activation period of the RS in both idling and sleeping modes is wider. This results in less power conservation in both cases as can be noticed in Table V. The effect of the arrival rate slope on power saving is more significant in RS sleeping mode. Obviously, this is because the power supply of the RS will operate for longer period. The effect of number of RS on the RS blossoming and withering profile is shown in Figures 14 and 15 for RS idling and sleeping modes, respectively, resulted from A_{r1} . It can be noticed that in idling mode, the period of activating the

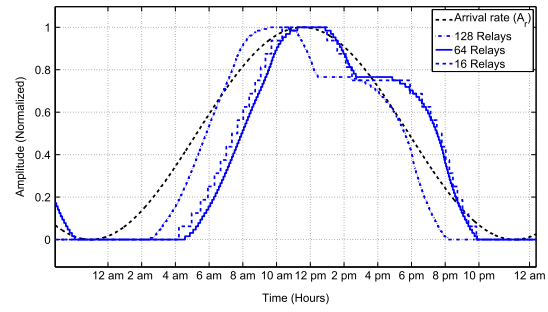


Figure 15. Relay station sleeping profiles for 16, 64 and 128 relays with A_{r1} , solution of Equation (26), $P_f = 0.1$.

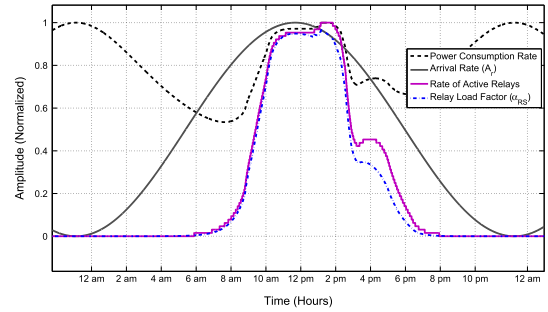


Figure 16. Power consumption rate and active relay station load factor for 64 relays idling mode, solution of Equation (26), $P_f = 0.5$.

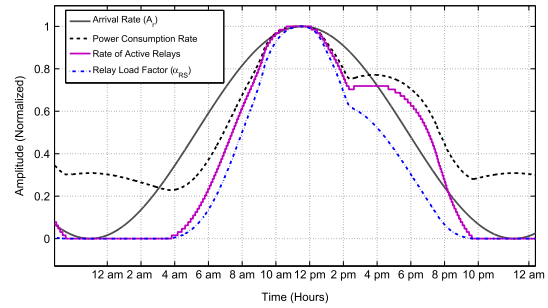


Figure 17. Power consumption rate and active relay station load factor for 64 relays sleeping mode, solution of Equation (26), $P_f = 0.1$.

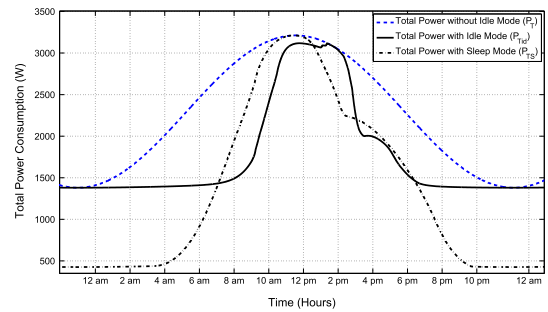


Figure 18. Total power consumption profile for 64 relays idling and sleep modes, comparison between Equation (26) $P_f = 0.5$ and $P_f = 0.1$.

RS is longer with less number of RS. On the other hand, sleeping mode does not exhibit the same behaviour. The power consumption rate and the active relay load factor are shown in Figures 16 and 17 for RS idling and sleeping modes, respectively, for 64 relays. The active RS load factor is calculated as the normalised total load factor for the active RS. In both idling and sleeping modes, the active RS load factor is maximum at the peak arrival rate. The total consumed power in comparison with the power consumed when all the RSs are active permanently is shown in Figure 18 for both idling and sleeping modes considering 64 relays. The constant C_{RS2BS} represents the ratio of RS to BS capacity and is playing a crucial role in solving Equation (26). To study the effect of C_{RS2BS} on the total power saving, the solutions of Equation (26) have been calculated for different values of C_{RS2BS} . For idling mode in Equation (26), the C_{RS2BS} assumed is in the range from 0.15 to 0.6, while for the sleeping mode, it is assumed to be from 0.25 to 0.65. The number of RS is varied from 4 to 128 for theoretical investigation and validation of the proposed analysis purposes. The effect of C_{RS2BS} on the power saving for the idling mode and sleeping mode is shown in Figures 19 and 20, respectively. Unlike the slope of arrival rate, the effect of C_{RS2BS} on the RS idling mode is more significant compared with the sleeping mode. This can be clarified by noticing that in idling RS mode the main power saving contributor is the load carried by the RS compared with BS. Thus, higher C_{RS2BS} value will allow the RS to

carry more load. In RS sleep mode, on the other hand, the main power saving contributor is the power supply switching off during the RS inactive state. Hence, the effect of C_{RS2BS} is minor.

5.3. Simulation results

In this work, a metropolitan area is considered with two different network plans; each is consisting of 160 BSs initially. The first network plan is distributed randomly, while the second plan is provided by an operator. Both network plans are optimised by a GA [29] to extract the optimum locations where the main BSs are installed so as to maintain the coverage and QoS in the AoI. The GA optimisation process proposed 78 and 86 BSs for the random network and operator network, respectively. The optimised plans are used in this simulation by adding a set of n RSs associated with every BS. The RSs are positioned in a circle centred at the BS with 800 m radius. The transmission power and height of every BS is configured by the GA. For the RSs, the heights are assumed to be 15 m from ground, and their transmission power maximum is 5 W (Table VI), and it changes linearly with the load. Network BS capacity can be calculated at any moment using Shannon capacity equation:

$$N_c = B \log_{10}(1 + \text{SINR}) \quad (39)$$

where

N_c is the BS available bandwidth
 B is the available bandwidth
 SINR is the signal-to-noise ratio

Table VI. Simulation parameters.

Parameter	Value
Carrier frequency	2100 MHz
Bandwidth	10 MHz
Transmission power (base station [BS])	20, ..., 70 W
Antenna gain(BS)	18 dBi
Antenna gain (small BS)	9 dBi
Antenna height (small BS)	15 m
Mobile user height	1.5 m

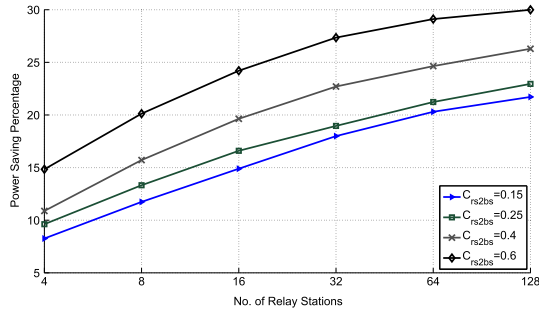


Figure 19. Power saving versus number of relay idling mode, solution of Equation (26), $P_f = 0.5$.

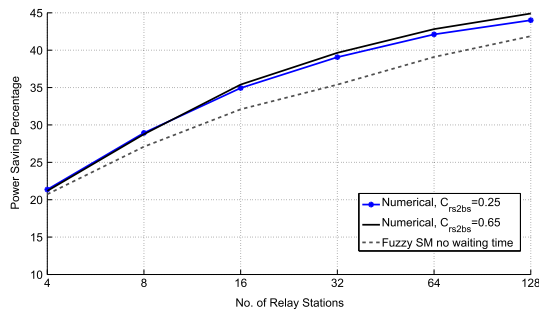


Figure 20. Power saving versus number of relay sleeping mode, solution of Equation (26) with $P_f = 0.1$ and fuzzy sleeping mode (SM).

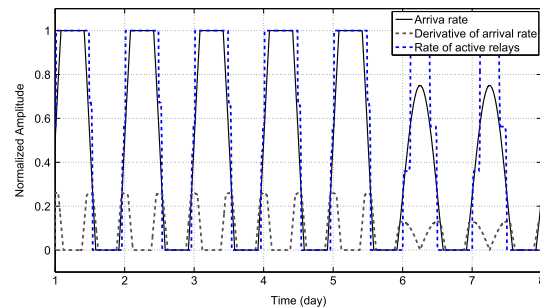


Figure 21. Normalised transmission power and traffic pattern.

The users are distributed randomly in the AoI and are considered immobile. The attachment of users with the serving BS or RS is based on distance metric only. The results are considered for 1 week traffic data unless otherwise stated. The outputs of the FIS are in the interval $[0 \ 1]$ and scaled to represent the waiting time in minutes and number of activated RSs. The waiting time is scaled in the interval $[1 \ d]$, where d is the maximum allowed waiting time, while the number of activated relays is scaled in the interval $[0 \ n]$. The simulation updates the calculations every minute of the week.

5.3.1. Total transmission power pattern.

The variation of transmission power in contrast to the traffic pattern is shown in Figure 21. The percentage of power saving depends on the number of RSs used as depicted in Figure 20 for the number of RS ranging from 4 to 128. Power saving of more than 20 up to 45 per cent can be achieved in RS sleeping mode compared with 7 up to 30 per cent is achieved in idling mode. Fuzzy SM power saving is in the range of 20 up to 40 per cent, which is in close match to the theoretical power saving. The power saving of the proposed fuzzy SM algorithm is also affected by the slope of the arrival rate as shown in Figure 22. As the slope of the arrival rate is higher, less power saving is achieved as listed in Table V. This loss of power saving efficiency is attributed to the fact that with higher arrival rate slope the algorithm responds by increasing the number of active relays to accommodate the services.

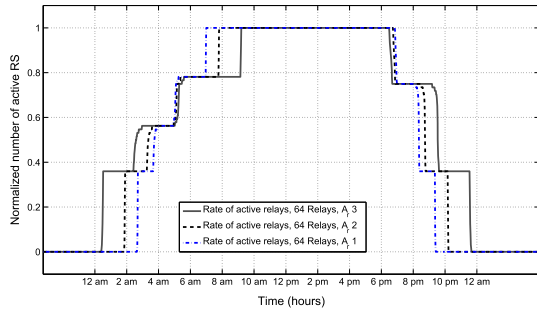


Figure 22. Percentage of active relays for 24-h cycle, fuzzy sleeping mode. RS, relay station.

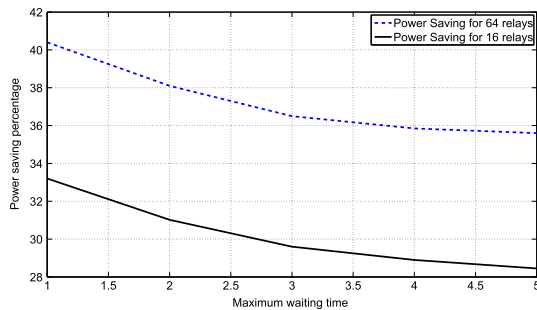


Figure 23. Effect of the fuzzy sleeping mode waiting time on the power saving percentage.

Power saving rate achieved in theoretical and fuzzy RS sleeping mode is in the range of power saving described in [16] for residential case applied on eight BS. It is important to mention that the work in [11–15] consider a BS sleep mode, whereas in this work, RS sleep mode is investigated. Practically, BS consumes more power compared with the RS as shown in Table IV. Evidently, switching off BS at low traffic rate periods would result in more power efficient network as compared with switching off RS. Moreover, the theoretical derivation in this paper shows analytically the effect of the traffic pattern and its derivative in increasing the RS activation period and, consequently, reducing the rate of power saving achieved.

The waiting time is the minimum activation time for the relay. This time is to prevent the relay from performing unnecessary switching on/off that may occur because of imperfections in the arrival rate. The waiting time effect on the power saving is shown in Figure 23.

5.3.2. Quality of service.

Quality of service is measured by the RSSI and the signal-to-noise ratio (SINR). The Cumulative Distribution Function (CDF) of the RSSI for different numbers of RSs for the operator plan is shown in Figure 24. From that figure, it can be deduced that addition of RSs improved the RSSI significantly compared with the original plan. As

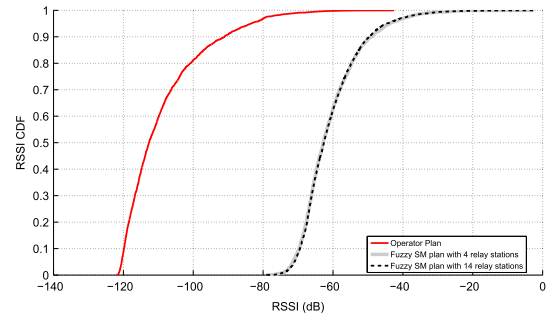


Figure 24. Fuzzy sleeping mode (SM) CDF received signal strength indicator (RSSI) of operator plan for 4 and 14 relay stations.

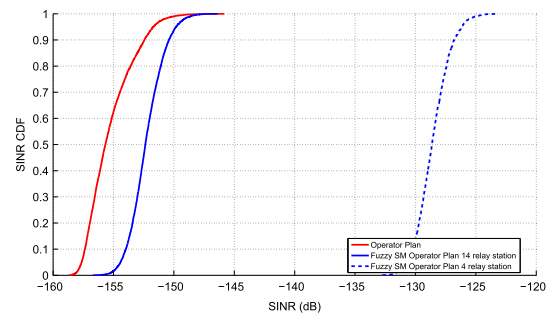


Figure 25. Fuzzy sleeping mode (SM) CDF signal-to-interference-plus-noise ratio (SINR) of operator plan for 4 and 14 relay stations.

the RSs activation is based on the traffic pattern, the RSSI levels viewed by the users are not affected by the number of RSs used. This is evident by noticing the matching CDF of RSSI between 4 and 14 RSs scenarios. Moreover, the SINR levels are improved by the RSs. However, as the number of RSs increases, the SINR is reduced as depicted in Figure 25. This is because the RSs are considered a source of noise to users attached to other stations. Consequently, as the number of RSs increases, the users will experience higher noise levels. The improvement of the SINR and RSSI resulted from applying the proposed Fuzzy SM is independent of the network plan configuration as can be deduced from Figures 26 and 27, respectively. Fuzzy SM applied on random and operator network plans proposed on the same AoI resulted in improved SINR level in both scenarios as shown in Figure 26. It can be noticed that the improvement of the RSSI levels in the operator plan after applying the proposed SM algorithm is more significant compared with the RSSI of the random plan as shown in Figure 27.

This improvement in the RSSI and SINR emphasises the validity of the proposed fuzzy SM algorithm in providing scalability of total power consumption according to the traffic pattern profile and maintaining the QoS of the network.

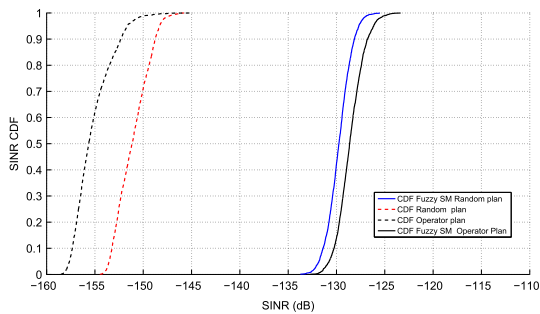


Figure 26. Fuzzy sleeping mode (SM) and original plans signal-to-interference-plus-noise ratio (SINR) comparison.

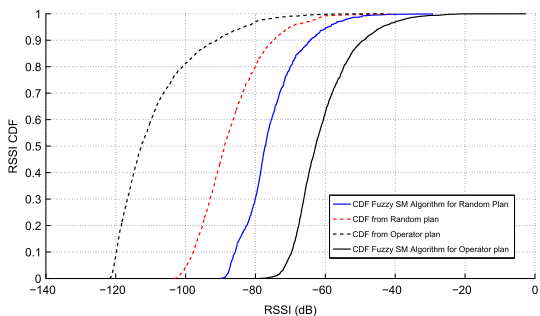


Figure 27. Fuzzy sleeping mode (SM) and original plans received signal strength indicator (RSSI) comparison.

6. CONCLUSION

In this work, a new perspective of relay switching is introduced. The relay switching profile is defined as a function in time, and its effect on the total power consumption is modelled for sleeping and idling modes. The power consumption ratio is defined as the total power consumed when applying the RS blossoming and withering to the total power consumed when all the RSs are permanently active. Minimising the power consumption ratio at any given time is achieved through selecting the proper RS blossoming and withering profile. This optimisation criterion shows that the optimum RS blossoming and withering profile obeys linear first-order ODE. The significance of this model is that it clarifies the importance of the arrival rate derivative in optimising the RS blossoming and withering profile. The derivative of the arrival rate represents its slope. Two blossoming and withering modes are discussed. The first mode is when the RS consumes 0.5 of its power supply rating, and this mode is called RS idling. The second mode is characterised by consuming 0.1 of its power rating, and this mode is called RS sleeping. It is noticed that a remarkable power saving up to 30 and 45 per cent can be achieved by optimising the switching pattern of the RS in RS idling and RS sleeping modes, respectively. As more RSs are deployed, the power efficiency enhances in general. In addition to that, the capacity of the RS in relation to the BS affects the percentage of power saved. Deploying larger RS (in terms of the capacity) will improve the power efficiency of the network significantly because it allows the RS to handle more users. Although, in RS sleeping mode, the effect of the ratio of RS to BS capacity is minor. This is attributed to the fact that in RS sleeping, the main contributor in power saving is the power supply, which reduces its consumption significantly during the sleeping period. On the other hand, the effect of the slope of the arrival rate on the power efficiency in sleeping mode is more significant compared with the idling mode. The RS sleeping mode power efficiency is almost 150 per cent better than RS idling in general. Finally, in regions where the arrival rate increases fast, such as metropolitan and business regions, the activation time of the RS should be increased to accommodate the fast rise in the number of users, which would reduce the power efficiency of the network. Deploying larger capacity RS and adopting RS sleeping mode would counter the effect of high slope arrival rate and provide better power savings in such regions.

The computational complexity and resource demand required in solving the ODE limit its application in real-time applications. Therefore, alternative approximated solution is proposed via fuzzy logic. Fuzzy logic provided a satisfactory solution to the problem in hand. The power saving achieved by the fuzzy logic is in good match to the theoretical results. Simulation results of the proposed fuzzy in a real network showed the validity of the proposed scheme in reducing the total power consumption up to 40 per cent while improving the RSSI. The effect of the RS on the users SINR level is not significant.

ACKNOWLEDGEMENTS

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