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Femtocell based green power consumption methods for mobile network

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ABSTRACT

This paper presents the analytical models of power consumption in macrocell, microcell, picocell and femtocell based networks. Five case studies are presented in this paper where macrocells, microcells, picocells and femtocells are deployed based on the number of mobile subscribers present in a region, mobile user traffic in that region and the area of the region where cellular coverage has to be provided. A comparative study is performed between the power consumption by the base stations in each of these five cases and that of the only macrocell based network. The simulation results demonstrate that using each of these five strategies the power consumption by the base stations can be minimized than that of only macrocell based network. Based on the power consumption by the base stations in these five schemes, we have categorized the networks into five classes, A, B, C, D and E, each of which contains cells of different types to reduce power consumption to achieve green cellular network.

1. Introduction

Mobile radio communication systems are designed with an aim to provide continuous connectivity to mobile users present arbitrarily in the service area. Now-a-days researches in the field of mobile communication systems are focusing on greener network development i.e. network with low power consumption. In Personal Communication Services (PCSs) network, the service area is divided into a number of location areas (LAs) where each LA contains a number of cells. In each cell there is a base station (BS). According to coverage area cells are of four types: macrocell, microcell, picocell and femtocell. A macrocell has a cell radius of 1–10 km, it is less than 1 km wide for a microcell and 4–200 m for that of a picocell. A femtocell has a cell radius of approximately 10–20 m. A macrocell has to provide radio coverage served by a high power cellular base station to each and every part of a large area, thus providing poor coverage in indoor regions e.g. home, office, shopping malls, etc. Hence Quality of Service (QoS) degrades for mobile terminals in such indoor areas. Previously, mobile network planners used repeaters for quick, cheap coverage inside buildings. But repeaters cause many problems too. They drain capacity from the macro cellular network, distort the cell and can create hazards in interference, handover and manageability. This results in more and more investment of money on cellular networks. In such a scenario, picocell came which unlike repeaters, actually adds capacity to the network while avoiding cell distortion and interference issues, solving handover, and integrating with existing network management systems. A picocell is a small cellular base station typically covering a small area. Microcell was also developed as a solution to this problem. A microcell is served by a low power cellular base station, covering a limited area such as a mall, a hotel, or a transportation hub. A microcell is usually larger than a picocell, though hardly distinguishable. Due to small coverage area, picocell results in low power consumption and thus provides us longer talk time and safer operation. The latest development in this field for reducing power consumption in a cellular network is femtocell. The Femto Access Points provide cellular access in indoor environments and connects to the operator's network through the customer's own broadband connection to the internet.

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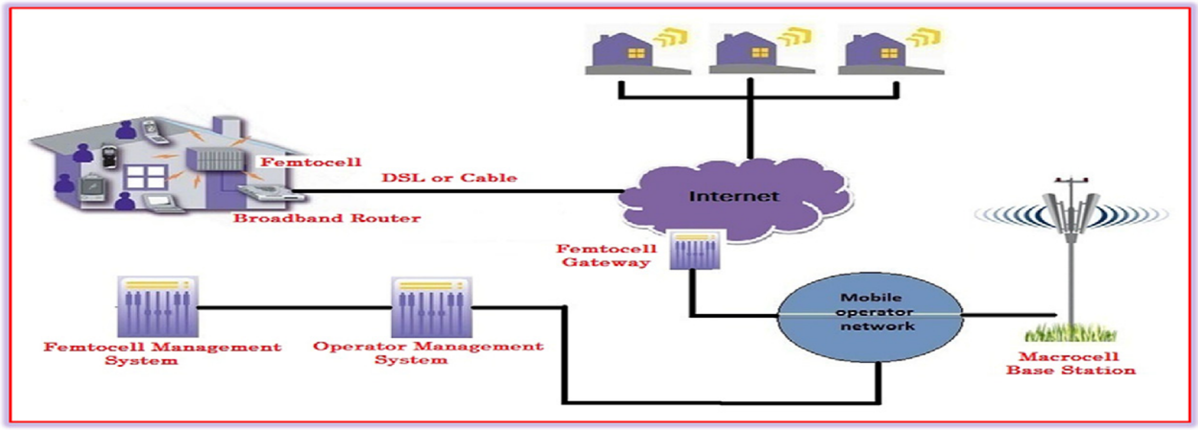

Fig. 1. Deployment of femtocells in a typical cellular network.

The functionalities of a femtocell BS are almost the same as that of a typical macrocell BS. But the price of femtocell BS can be significantly lower because: (1) a femtocell BS is expected to serve a small number of users and (2) a relatively low transmission power is enough to cover the service area [1–21]. Fig. 1 shows the deployment of femtocells.

Femtocells are low-power wireless access points that operate in licensed spectrum to connect standard mobile devices to a mobile operator's network using residential DSL or cable broadband connections [5]. They, by virtue of their small size, low cost and high performance, are a potentially industry changing disruptive shift in technology for radio access in cellular network [6]. The femtocell technology is widely accepted as femtocell BSs can be bought in the market by users and easily installed in a plug-and-play manner [21]. A femtocell can usually support a maximum of 2–5 users in its range. There are currently two kinds of Femtocell Access Point (FAP) available in the market: (1) Home FAP-Can provide services to 3–5 users in its coverage area, and (2) Enterprise FAP-Can provide services to 16–32 users in its coverage area [22]. As a femtocell BS does not have to send the signals for a long distance, there will be reduction in the transmission power compared to that of a picocell BS, microcell BS and a macrocell BS, thus aiming towards a greener cellular network. Deploying femtocell networks embedded in the macrocell coverage greatly benefits communication quality in variety of manners [23].

2. Related works

Extensive researches are being carried out to minimize the power of a macrocell BS. A macrocell provides the largest area of coverage within a mobile network. Macrocells provide radio coverage over varying distances depending on the frequencies used, the number of calls made and the physical terrain. Macrocell base station has a typical power output in tens of watts. A brief survey of methods has been presented in [24] to improve the power efficiency of cellular networks. It has been also discussed how heterogeneous network deployment based on micro, pico and femtocells can be used to build a "green" cellular network [24]. In [7], a method is proposed to calculate the power of a macrocell BS. But it has been observed that the deployment of microcells, picocells and femtocells has helped in the reduction of total transmission power in a cellular network. So presently, calculating the power of a microcell BS, picocell BS and femtocell BS and to what extent they can be used to build a greener cellular network is an emerging area of interest. Microcell systems are advantageous as they increase system capacity significantly, and are also low power systems and minimize equipments that reduce cost and can be easily deployed [25]. In [8], a method has been provided for controlling transmission power of a picocell base station. This method is comprised of the following steps done by the picocell base station: transmitting a signal; receiving a report from a mobile terminal that the signal is received within a pre-determined quality range; depending on the received report detecting the number of neighboring macrocells by the mobile terminal; and controlling the transmission power of a further signal depending on the number. In [26], a method of adjusting transmission power of pilot signals from picocell base stations for radio communications to a user terminal in radio connection with the picocell base station has been provided.

A femtocell network where a new class of users can haphazardly deploy indoor base stations, is enhancing the indoor received signal quality and coverage, reducing the burden of the macrocell network (Macro-network) and enabling variety of user-specific applications and has received considerable attentions [27–30]. According to [15], femtocell BSs are low-power, very small-service-area cellular base stations that will significantly impact the cellular landscape in the next several years. By using femtocell technology the mobile network can become far more energy efficient than it is today [31]. Significant areal capacity gains and improved cellular coverage can be achieved by hierarchical deployment of FAPs over an existing cellular network [32]. An architecture of a "Green Femtocell" is suggested in [33] which demonstrates the concept of a very-low-radiation distributed antenna system (VLR-DAS) for the distribution of various radio-protocols including 3G, LTE, IMT-Advanced and WiMAX as radio-over-X (optical fiber, Coax, power-line, Cat-5, etc. [34]). As the expected massive adoption of home femtocell base stations will increase the overall power consumption requiring eco-designed sleep modes, a method is proposed in [35] to switch off the femtocell base station and wake it up when necessary. According to [16], femtocells have been designed to be deployed in indoor environments in order to improve both radio coverage and spectrum efficiency. It has been mentioned in [17] that two-tier femtocell networks that are comprised of a conventional macro-cellular network plus embedded femtocell hotspots, offer an economically viable solution to achieve high cellular user capacity and improved coverage. A green and distributed algorithm to dynamically optimize the coverage of a femtocell group by adjusting their transmitting power in an Administrative Domain has been proposed in [1]. In [2], a joint power and admission control algorithm has been developed for interference management in two-tier cellular network wherein femtocell users, who communicate with their home-owner-deployed base stations, share the same frequency band with macrocell users by code-division multiple access (CDMA) technology. Since macrocell users have strictly higher priority in accessing the available radio spectrum, their QoS expressed in terms of the minimum required signal-to-interference-plus-noise ratio (SINR) should be maintained at all times [2]. It has been investigated in [3] how femtocells can make conventional cellular networks greener. An energy consumption modeling framework to evaluate total energy consumption in a cellular network with femtocells has been presented in [3]. Various network environments including indoor propagation environment, user distribution near the femtocells and a femtocell access policy, which have effect on the performance of the cellular network, have been considered in [3].

A time-division-duplex (TDD) frame structure is proposed in [36] for femtocells and it is referred as listening-TDD frame (LTDDF). In LTDDF, the uplink duration in macrocell is used as listening duration in femtocell. This is used in turn to overhear signals from the surrounding users present at macrocell for obtaining their channel quality information (CQI). Based on the CQI of the macrocell users, femtocell base-station adaptively adjusts its transmission power and hence the interference on macrocell users is reduced in [36]. For femtocells situated within a macrocell with a given transmitter power, the problem of determining the femtocell transmitter power levels that maximize the SINR achieved in the femtocells, has been solved and subject to a constraint on the minimum SINR realized in the macrocell [37]. An opportunistic power control (PC) algorithm is proposed in [38] to mitigate the aggregate interference (AGGI) from active femtocells in uplink transmission. A power adaptation algorithm based on frame utilization of femtocells is proposed in [39]. In [4], a spatial two-tier model and two new metrics for analyzing the cellular network have been introduced followed by the analysis of the downlink energy consumption. Then an energy efficient spectrum allocation strategy in macro–femtocellular networks to approach the minimal downlink energy consumption has been provided in [4]. It has been stated in [9] from the operator's and customers' viewpoints that femtocells' usage reduces cost as there is reduction in power consumption. "Small cell networks" (SCNs) have been discussed in [10] which state that a small cell BS is a small, humanly portable, low cost and low power device. SCNs comprise of low power micro, pico and femtocell BSs of which femtocell BSs have the least transmission power, as inferred from various researches. In [11], it has been proposed that very low transmission power base stations (femtocell base station) can be used in small isolated areas with insufficient or no macrocell coverage to provide very high bit rates to users at close proximity of the base stations. It also evaluates the impact of femtocells operating on the same frequency as macrocells in terms of several performance indicators in a realistically modeled single carrier High-Speed Downlink Packet Access (HSDPA) network by dynamic system level simulations. Various power control mechanisms for femtocells have been proposed in [12–14].

Two interference mitigation strategies that adjust the maximum transmission power of femtocell users to suppress the cross-tier interference at a macrocell base station have been proposed in [18]. Cross-tier interference control methods have been developed by using transmission power control in [19,20] and time hopping coupled with antenna sectoring [17] for a two-tier CDMA network. Without the knowledge from the femtocell of whether the service users are present indoor or outdoor, the outdoor users are likely to experience low QoS due to inefficient coverage management and power control from the femtocells [40]. To resolve such problem, a method of discriminating indoor and outdoor users in a simplified way has been provided in [40]. Also, based on such discrimination, a downlink power control scheme is provided in [40]. In [41], the proposed scheme reduces the femtocell BS's power consumption based on a voice traffic model. A method has been proposed in [42] for a femtocell user to estimate the path loss between itself and any macrocell user independently. An interference control method is presented in [43] where the macrocell bandwidth is partitioned into sub bands, and the short-range femtocell links adaptively allocate their power across the sub bands based on a load-spillage power control method. Though femtocells are usually deployed in indoor environment to provide in-building coverage enhancements, service can be provided to outdoor users also in vicinity by deploying portable femtocells.

In this paper we have considered a network in which cells of different sizes have been deployed depending on mobile user density, traffic and coverage such that power consumption can be minimized without compromising with the QoS.

3. Power consumption model in proposed small cell based networks and comparison with power consumption in macrocell based network

In this section we have studied five cases where small cells i.e. femtocell, picocells and microcells have been deployed in the network. We have developed analytical models of power consumption in the proposed five schemes and drawn comparison with the existing macrocell based network. The parameters used in calculation of power consumption are shown in Table 1.

3.1. Calculation of transmission power of macrocell BS, microcell BS, picocell BS and femtocell BS

The received power (in Watt) by a MT at a distance d from the base station in a cell is given by [44],

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

The minimum received power (in Watt) by a MT is the received power by it when it is situated at the border region of the cell. Received power by the MT situated at the border region of a cell having radius R is given by,

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 L} \tag{2}$$

Maximum path loss (in dB) for a MT in a cell having radius R is given by [44],

$$PL_{dB} = -10\log_{10}\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 R^2 L}\right) \tag{3}$$

Thus, the transmission power of a base station (in dB) is given by,

$$P_{tdB} = P_{rdB} + PL_{dB} = 10\log_{10}\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 L} - 10\log_{10}\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 R^2 L}\right) = 10\log_{10}(P_t) \tag{4}$$

Hence, the transmission power (in dB) of a macro BS is given by,

$$P_{tdBm} = P_{rdBm} + PL_{dBm} = 10\log_{10}(P_{tm}) \tag{5}$$

Similarly transmission power (in dB) of a micro BS is given by,

$$P_{tdBmi} = P_{rdBmi} + PL_{dBmi} = 10\log_{10}(P_{tmi}) \tag{6}$$

Similarly transmission power (in dB) of a pico BS is given by,

$$P_{tdBp} = P_{rdBp} + PL_{dBp} = 10\log_{10}(P_{tp}) \tag{7}$$

Now the transmitted power (in Watt) by a femtocell base station is given by [5],

$$P_{tf} = \frac{S 4\pi R_f^2}{D G_{tf}}$$

where S is the minimum received power density (Watt/m^2) and D is the normalized radiation pattern in the direction (θ, ϕ) i.e. D is equal to unity in the direction of maximum radiation. Area of a femtocell having radius R_f is $(3\sqrt{3}/2)R_f^2$. The minimum received power (in Watt) by a MT in a femtocell having radius R_f is given by, $P_{rf} = S \cdot (3\sqrt{3}/2)R_f^2$ which implies $S = \frac{P_{rf}}{(3\sqrt{3}/2)R_f^2}$.

Replacing power density S by $\frac{P_{rf}}{(3\sqrt{3}/2)R_f^2}$ we obtain,

$$P_{tf} = \frac{P_{rf} 4\pi}{(3\sqrt{3}/2) D G_{tf}} \Rightarrow P_{rf} = \frac{P_{tf}(3\sqrt{3}/2) D G_{tf}}{4\pi}$$

Thus the minimum received power (in dB) by a MT in a femtocell is given by,

$$P_{rdBf} = 10\log_{10}\frac{P_{tf}(3\sqrt{3}/2) D G_{tf}}{4\pi}$$

The path loss (in dB) in a femtocell is given by,

$$PL_{dBf} = P_{tdBf} - P_{rdBf} = 10\log_{10} P_{tf} - 10\log_{10}\frac{P_{tf}(3\sqrt{3}/2) D G_{tf}}{4\pi} = 10\log_{10}\left(\frac{4\pi}{(3\sqrt{3}/2) D G_{tf}}\right)$$

Table 1
Parameters used.

Parameter	Definition
P_t	Transmission power (in Watt) of a BS
P_r	Received power (in Watt) by a mobile terminal (MT)
λ	Wavelength given by $\frac{c}{f_c}$ where c is the speed of light and f_c is the frequency of the carrier wave
R	Radius of a cell
P_{tm}	Transmission power (in Watt) of a macrocell base station (macro BS)
P_{tmi}	Transmission power (in Watt) of a microcell base station (micro BS)
P_{tp}	Transmission power (in Watt) of a picocell base station (pico BS)
P_{tf}	Transmission power (in Watt) of a femtocell base station (femto BS)
P_{tdBm}	Transmission power (in dB) of a macro BS
P_{tdBmi}	Transmission power (in dB) of a micro BS
P_{tdBp}	Transmission power (in dB) of a pico BS
P_{tdBf}	Transmission power (in dB) of a femto BS
P_{rm}	Minimum received power (in Watt) by a MT in macrocell
P_{rmi}	Minimum received power (in Watt) by a MT in microcell
P_{rp}	Minimum received power (in Watt) by a MT in picocell
P_{rf}	Minimum received power (in Watt) by a MT in femtocell
P_{rdBm}	Minimum received power (in dB) by a MT in macrocell
P_{rdBmi}	Minimum received power (in dB) by a MT in microcell
P_{rdBp}	Minimum received power (in dB) by a MT in picocell
P_{rdBf}	Minimum received power (in dB) by a MT in femtocell
R_m	Radius of a macrocell
R_{mi}	Radius of a microcell
R_p	Radius of a picocell
R_f	Radius of a femtocell
A_m	Area of a macrocell
A_{mi}	Area of a microcell
A_p	Area of a picocell
A_f	Area of a femtocell
L	System loss not related to path loss and its value is greater than or equals to 1
G_t	BS antenna gain
G_{tm}	Macro BS antenna gain
G_{tmi}	Micro BS antenna gain
G_{tp}	Pico BS antenna gain
G_{tf}	Femto BS antenna gain
G_r	Mobile terminal antenna gain
PL_{dBm}	Maximum Path loss (in dB) for a MT in macrocell
PL_{dBmi}	Maximum Path loss (in dB) for a MT in microcell
PL_{dBp}	Maximum Path loss (in dB) for a MT in picocell
PL_{dBf}	Maximum Path loss (in dB) for a MT in femtocell

Subsequently, the transmission power (in dB) of the femto BS is given by,

$$P_{rdBf} + PL_{dBf} = 10\log_{10}\frac{P_{tf}(3\sqrt{3}/2)DG_{tf}}{4\pi} + 10\log_{10}\left(\frac{4\pi}{(3\sqrt{3}/2)DG_{tf}}\right) = 10\log_{10}P_{tf}$$

The average duty cycle of a femto BS is calculated as,

$$T_D = \frac{P_{on}}{P_{on} + P_{off}} \tag{8}$$

where P_{on} and P_{off} represent the average clock cycles during which the femto BS is powered on or off respectively and $T_D \leqslant 1$. Thus the transmission power (in dB) of a femto BS is given by,

$$P_{tdBf} = T_D \times 10\log_{10}P_{tf} = 10\log_{10}P_{tf}^{T_D} \tag{9}$$

From Eq. (2) we obtain,

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 L} \Rightarrow P_t = \frac{P_r (4\pi)^2 R^2 L}{G_t G_r \lambda^2} \tag{10}$$

The area of a hexagonal cell with radius R is given by,

$$A = \frac{3\sqrt{3}}{2}R^2 \Rightarrow R^2 = \frac{2A}{3\sqrt{3}} \tag{11}$$

Replacing R^2 by $\frac{2A}{3\sqrt{3}}$ in Eq. (10) we obtain,

$$P_t = \frac{P_r (4\pi)^2 L}{G_t G_r \lambda^2}\frac{2A}{3\sqrt{3}} \Rightarrow P_t \propto A \tag{12}$$

Hence it is observed that transmission power of a BS is directly proportional to its coverage area.

As, $R_f < R_p < R_{mi} < R_m$ then $A_f < A_p < A_{mi} < A_m$ which implies $P_{tf} < P_{tp} < P_{tmi} < P_{tm}$.

From Eq. (2) it is observed that,

$$P_r \propto P_t \tag{13}$$

Thus $P_{rm} > P_{rmi} > P_{rp} > P_{rf}$. Hence we can conclude that the transmitted power by the BS as well as received power by the MT in femtocell network is less than that of other cell categories. Due to this reason, by deploying femtocells, greener network can be obtained. We have considered five cases where femtocells have been deployed in the network. The cell radius differs for each of macro, micro, pico and femtocell where a macrocell has the maximum cell radius and the femtocell has the minimum. A mobile terminal will receive signal from its nearest base station which can be either of macro, micro, pico or femtocell base station. As the path loss for a MT is directly proportional to the distance between itself and the base station [44], the mobile terminal will receive signal from its nearest base station in order to minimize the path loss.

3.2. Case 1: Femtocells are used in an area instead of macrocells

In this section we have considered an area (x) containing only macrocells to provide coverage in that macrocellular area. Because of high transmission power of macro BS, such a macrocell based network results in high power consumption, but due to large coverage area it causes poor QoS specially at indoor and border region. To deal with such issue, in the respective case we have considered a network where femtocells are allocated in the total area (x) replacing the macrocells. The total power transmitted by all these femtocell base stations allocated in total area (x) is calculated and compared to the total transmission power of the macrocell base stations previously allocated to that area (x).

The area of a macrocell having radius R_m is given by,

$$A_m = \frac{3\sqrt{3}}{2}R_m^2$$

The area of a femtocell having radius R_f is given by,

$$A_f = \frac{3\sqrt{3}}{2}R_f^2$$

Thus, the number of femtocells required to cover the area (x) is given by,

$$N_{fx} = \frac{x}{A_f} = \frac{x}{\frac{3\sqrt{3}}{2}R_f^2} \tag{14}$$

Hence, the total transmitted power (in dB) by the femto BSs is given by the product of the number of femtocells required to cover the total area (x) calculated using Eq. (14) and the transmission power of each femto BS calculated using Eq. (9),

$$P_{tottdBfx} = N_{fx} \times P_{tdBf} = \frac{x}{\frac{3\sqrt{3}}{2}R_f^2} \times \left(10\log_{10}\left(P_{tf}^{T_D}\right)\right) = 10\log_{10}(P_{tf})^{T_D\frac{2x}{3\sqrt{3}R_f^2}} \tag{15}$$

As only the femtocells have been used to cover the entire area, they should be active at all time instants. Thus we have considered in this particular case that all the femtocells are switched on i.e. the value of $T_D = 1$. Thus the total transmitted power (in dB) by N_{fx} femtocell base stations is given by,

$$P_{tottdBfx} = 10\log_{10}(P_{tf})^{\frac{2x}{3\sqrt{3}R_f^2}} \tag{16}$$

Similarly, the number of macrocells required to cover the area (x) is given by,

$$N_m = \frac{x}{A_m} = \frac{x}{\frac{3\sqrt{3}}{2}R_m^2} \tag{17}$$

Hence, the total transmitted power (in dB) by the macro BSs is given by the product of the number of macrocells required to cover the total area (x) calculated using Eq. (17) and the transmission power of each macro BS calculated using Eq. (5),

$$P_{totdBm} = N_m \times P_{tdBm} = N_m \times 10\log_{10}(P_{tm}) = 10N_m\log_{10}(P_{tm}) \tag{18}$$

Subtracting Eq. (16) from Eq. (18) and replacing the value of N_m by $\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}$ we obtain,

$$P_{totdBm} - P_{tottdBfx} = \left(10 \times \frac{x}{\frac{3\sqrt{3}R_m^2}{2}} \log_{10}(P_{tm})\right) - \left(10\log_{10}(P_{tf})^{\frac{2x}{3\sqrt{3}R_f^2}}\right) = \left(10\log_{10}(P_{tm})^{\frac{2x}{3\sqrt{3}R_m^2}}\right) - \left(10\log_{10}(P_{tf})^{\frac{2x}{3\sqrt{3}R_f^2}}\right) \quad (19)$$

As $P_{tm} \gg P_{tf}$, $R_m \gg R_f$ and transmission power of a femto BS (P_{tf}) is itself a very small quantity,

$$(P_{tm})^{\frac{2x}{3\sqrt{3}R_m^2}} \gg (P_{tf})^{\frac{2x}{3\sqrt{3}R_f^2}} \Rightarrow 10\log_{10}(P_{tm})^{\frac{2x}{3\sqrt{3}R_m^2}} \gg 10\log_{10}(P_{tf})^{\frac{2x}{3\sqrt{3}R_f^2}}$$

which implies,

$$P_{totdBm} > P_{tottdBfx} \quad (20)$$

Thus it is observed that total transmitted power by the base stations in an area can be reduced by using only femtocells in that area instead of only macrocells. As in Eq. (13), it has been presented that received power by a MT is directly proportional to the transmission power of the BS, the power consumption and radiation by each MT is also minimized using only femtocell based mobile network.

3.3. Case 2: Femtocells used at urban area, macrocells used at suburban area and portable femtocells at rural area

In this case we have considered an area some portions of which is populated i.e. used land (urban and suburban area) and some portions are unused land (rural area containing sea, forest, etc.). Let the number of users present at urban, suburban and rural area are U_u, U_{su} and U_r respectively. In the urban area, due to high population the number of mobile subscribers is high. In the suburban area due to medium population, the number of mobile subscribers is medium. Rural area contains very low number of mobile users due to low population. Hence $U_u > U_{su} > U_r$. Let the average number of call request per user in the network is *Call*. The mobile user traffic generated in urban, suburban and rural area are [44], $(Call \times U_u)$, $(Call \times U_{su})$ and $(Call \times U_r)$ respectively.

As $U_u > U_{su} > U_r$, then $(Call \times U_u) > (Call \times U_{su}) > (Call \times U_r)$. Thus the urban area has high mobile user traffic, suburban area has moderate amount of mobile user traffic and rural area has very low mobile user traffic. Femtocells are deployed to handle high traffic load in urban area because each femto BS can serve 16–32 users in its very small coverage area. Macrocells are deployed to deal with moderate amount of traffic load in suburban area. Because of very low traffic, portable femtocells are deployed at rural area when required. Thus femtocells, macrocells and portable femtocells are allocated at urban, suburban and rural area respectively depending on mobile user density and mobile user traffic as shown in Fig. 2. The numbers of femtocells and macrocells to be deployed are decided based on the coverage area required.

Let the total area = x, the urban area = y, suburban area = z, rural area = w. Hence,

$$x = y + z + w \quad (21)$$

The number of macrocells covering the suburban area (z) is calculated as,

$$N'_m = \frac{z}{\frac{3\sqrt{3}}{2}R_m^2} \quad (22)$$

The total transmitted power (in dB) by these macro BSs is obtained by multiplying the number of macrocells covering the suburban area (z) calculated using Eq. (22) with the transmission power of each macro BS calculated using Eq. (5) as follows,

$$P'_{totdBm} = N'_m \times 10\log_{10}(P_{tm}) = 10N'_m\log_{10}(P_{tm}) \quad (23)$$

The number of femtocells covering the urban area (y) is calculated as,

$$N_f = \frac{y}{\frac{3\sqrt{3}}{2}R_f^2} \quad (24)$$

The total transmitted power (in dB) by these femto BSs is obtained by multiplying the number of femtocells covering the urban area (y) calculated using Eq. (24) with the

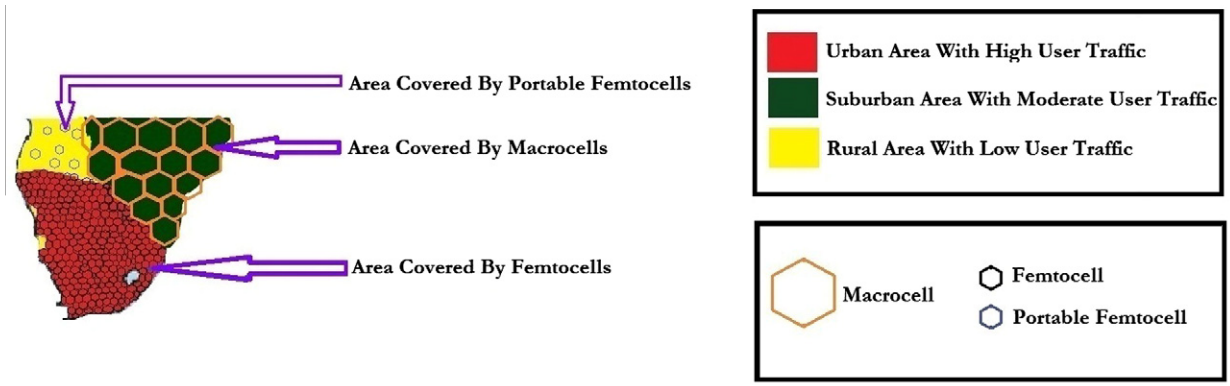

Fig. 2. Allocation of femtocells, macrocells and portable femtocells in urban, suburban and rural areas based on mobile user traffic.

transmission power of each femto BS calculated using Eq. (9) as follows,

$$P_{totdBf} = N_f \times 10\log_{10}\left(P_{tf}^{T_D}\right) = 10N_f\log_{10}\left(P_{tf}^{T_D}\right) \quad (25)$$

Let the number of portable femtocells covering rural area is N_{fp}. It should be less than the maximum number of portable femtocells that can cover the rural area (w) given by,

$$N_{fpmax} = \frac{w}{\frac{3\sqrt{3}}{2}R_f^2} \quad (26)$$

The total transmitted power (in dB) by the portable femto BSs is obtained by multiplying the number of portable femtocells (N_{fp}) covering the rural area (w) with the transmission power of each femto BS calculated using Eq. (9) as follows,

$$P_{totdBfp} = N_{fp} \times 10\log_{10}\left(P_{tf}^{T_D}\right) = 10N_{fp}\log_{10}\left(P_{tf}^{T_D}\right) \quad (27)$$

The total transmitted power (in dB) by the BSs (macro, femto and portable femto) in the total area is given by,

$$\begin{aligned} Pmf_{totdB} &= P'_{totdBm} + P_{totdBf} + P_{totdBfp} \\ &= 10N'_m\log_{10}(P_{tm}) + 10(N_f + N_{fp})\log_{10}\left(P_{tf}^{T_D}\right) \end{aligned} \quad (28)$$

Dividing Eq. (22) by Eq. (17) we obtain,

$$\frac{N'_m}{N_m} = \frac{\frac{z}{\frac{3\sqrt{3}}{2}R_m^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N'_m = \frac{z}{x}\cdot N_m \quad (29)$$

Dividing Eq. (24) by Eq. (17) we obtain,

$$\frac{N_f}{N_m} = \frac{\frac{y}{\frac{3\sqrt{3}}{2}R_f^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N_f = \frac{y}{x}\cdot\frac{R_m^2}{R_f^2}\cdot N_m = \frac{y}{x}\cdot M\cdot N_m \quad (30)$$

where $M = \frac{R_m^2}{R_f^2}$. As $R_m^2 \gg R_f^2 \Rightarrow \frac{R_m^2}{R_f^2} \gg 1 \Rightarrow M \gg 1$.

Subtracting Eq. (28) from Eq. (18) we obtain,

$$\begin{aligned} P_{totdBm} - Pmf_{totdB} &= 10N_m\log_{10}(P_{tm}) - \big(10N'_m\log_{10}(P_{tm}) \\ &\quad + 10(N_f + N_{fp})\log_{10}\left(P_{tf}^{T_D}\right)\big) \\ &= 10N_m\log_{10}(P_{tm}) - \left(10\left(\frac{z}{x}\cdot N_m\right)\log_{10}(P_{tm})\right. \\ &\quad \left. + 10\left(\frac{y}{x}\cdot M\cdot N_m + N_{fp}\right)\log_{10}\left(P_{tf}^{T_D}\right)\right) \end{aligned} \quad (31)$$

As $P_{tm} \gg P_{tf}$, $M \gg 1$, $T_D \leqslant 1$ and, $x \gg y$, $x \gg z$, $x \gg w$, thus,
$10N_m\log_{10}(P_{tm}) - (10(\frac{z}{x}\cdot N_m)\log_{10}(P_{tm}) + 10(\frac{y}{x}\cdot M\cdot N_m + N_{fp})\log_{10}\left(P_{tf}^{T_D}\right)) > 0$ which implies,

$$P_{totdBm} > Pmf_{totdB} \quad (32)$$

From Eq. (32), it is observed that the total transmitted power by the BSs after covering the urban area, suburban area and rural area by femtocells, macrocells and portable femtocells respectively, is less than the transmitted power by the BSs after covering the total area by only macrocells. Thus in case 2, in an area cell sizes are decided depending on the mobile user density and mobile user traffic generated in that area and number of cells to be allocated are decided based on the required coverage area.

3.4. Case 3: Femtocells and picocells used in urban area and microcells used in suburban area and portable femtocells at rural area

In the respective case, an area is divided into four parts: densely populated urban area, sparsely populated urban area, suburban area and rural area. Let the number of users present at densely populated urban, sparsely populated urban, suburban and rural area are U_{du}, U_{spu}, U_{su} and U_r respectively. In the densely populated urban area, due to very high population the number of mobile subscribers is very high. The sparsely populated urban area has high population but comparatively low than the densely populated urban area. Hence in the sparsely populated urban area the number of mobile subscribers is also high but less than the densely populated urban area. Suburban area has medium population and thus medium number of mobile subscribers. Due to low population, number of mobile subscribers in rural area is very low. Hence $U_{du} > U_{spu} > U_{su} > U_r$. The mobile user traffic generated in densely populated urban, sparsely populated urban, suburban and rural area are [44], $(Call \times U_{du})$, $(Call \times U_{spu})$, $(Call \times U_{su})$ and $(Call \times U_r)$ respectively where $Call$ is the average number of call request per user in the network.

As $U_{du} > U_{spu} > U_{su} > U_r$, then $(Call \times U_u) > (Call \times U_{spu}) > (Call \times U_{su}) > (Call \times U_r)$.

Thus the densely populated urban area has the highest mobile user traffic, sparsely populated urban area has high mobile user traffic, suburban area has moderate amount of mobile user traffic and rural area has very low mobile user traffic. Femtocells are deployed to deal with very high traffic in densely populated urban area because each femto BS can serve 16–32 users in its very small coverage area. Picocells are deployed to deal with high traffic in sparsely populated urban area due to its small coverage area. To deal with moderate amount of traffic, microcells are deployed at suburban area due to its standard coverage area. As the rural area has very low traffic, portable femtocells are deployed at rural area when required. Thus femtocells, picocells, microcells and portable femtocells are allocated at urban, suburban and rural area respectively depending on mobile user density and mobile user traffic as shown in Fig. 3. The numbers of femtocells, picocells, microcells to be deployed are decided based on the coverage area required.

Let the total area = x, the densely populated urban area = y_1, sparsely populated urban area = y_2, suburban area = z, rural area = w, i.e.

$$x = y_1 + y_2 + z + w \quad (33)$$

The number of microcells covering suburban area (z) is calculated as,

$$N_{mi} = \frac{z}{\frac{3\sqrt{3}}{2}R_{mi}^2} \quad (34)$$

The total transmitted power (in dB) by these micro BSs is obtained by multiplying the number of microcells covering

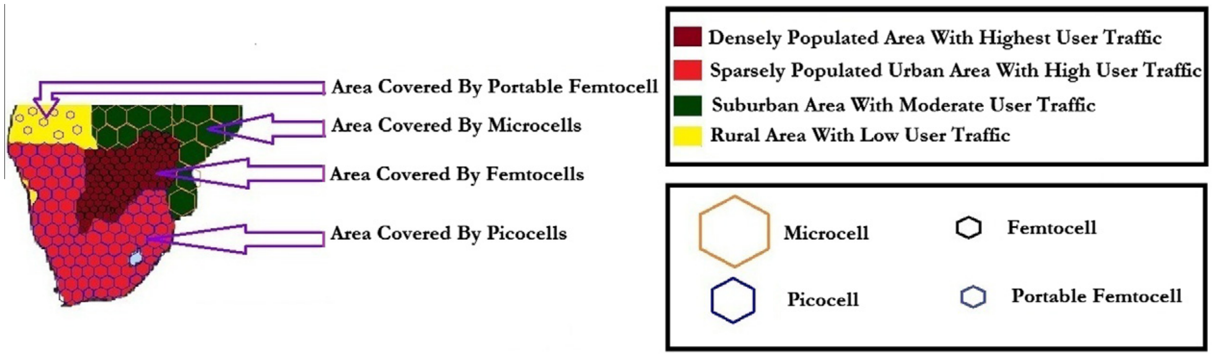

Fig. 3. Allocation of femtocells, picocells, microcells and portable femtocells in densely populated, sparsely populated, suburban and rural area based on mobile user traffic.

suburban area (z) calculated using Eq. (34) with the transmission power of each micro BS calculated using Eq. (6) as follows,

$$P_{totdBmi} = N_{mi} \times 10\log_{10}(P_{tmi}) \tag{35}$$

The number of picocells covering sparsely populated urban area (y_2) is calculated as,

$$N_p = \frac{y_2}{\frac{3\sqrt{3}}{2} R_p^2} \tag{36}$$

The total transmitted power (in dB) by these pico BSs is obtained by multiplying the number of picocells covering sparsely populated urban area (y_2) calculated using Eq. (36) with the transmission power of each pico BS calculated using Eq. (7) as follows,

$$P_{totdBp} = N_p \times 10\log_{10}(P_{tp}) \tag{37}$$

The number of femtocells covering densely populated urban area (y_1) is given by,

$$N_{f1} = \frac{y_1}{\frac{3\sqrt{3}}{2} R_f^2} \tag{38}$$

Total transmitted power (in dB) by these femto BSs is obtained by multiplying the number of femtocells covering densely populated urban area (y_1) calculated using Eq. (38) with the transmission power of each femto BS calculated using Eq. (9) as follows,

$$P_{totdBf1} = N_{f1} \times 10\log_{10}\left(P_{tf}^{T_D}\right) \tag{39}$$

The total transmitted power (in dB) by the portable femto BSs (N_{fp}) in rural area (w) is obtained from Eq. (27).

Dividing Eq. (34) by Eq. (17) we obtain,

$$\frac{N_{mi}}{N_m} = \frac{\frac{z}{\frac{3\sqrt{3}}{2}R_{mi}^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N_{mi} = \frac{z}{x} \cdot M_1 \cdot N_m \tag{40}$$

where $M_1 = \frac{R_m^2}{R_{mi}^2}$. As $R_m^2 \gg R_{mi}^2 \Rightarrow \frac{R_m^2}{R_{mi}^2} \gg 1 \Rightarrow M_1 \gg 1$

Dividing Eq. (36) by Eq. (17) we obtain,

$$\frac{N_p}{N_m} = \frac{\frac{y_2}{\frac{3\sqrt{3}}{2}R_p^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N_p = \frac{y_2}{x} \cdot M_2 \cdot N_m \tag{41}$$

where $M_2 = \frac{R_m^2}{R_p^2}$. As $R_m^2 \gg R_p^2 \Rightarrow \frac{R_m^2}{R_p^2} \gg 1 \Rightarrow M_2 \gg 1$.

Dividing Eq. (38) by Eq. (17) we obtain,

$$\frac{N_{f1}}{N_m} = \frac{\frac{y_1}{\frac{3\sqrt{3}}{2}R_f^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N_{f1} = \frac{y_1}{x} \cdot M_3 \cdot N_m \tag{42}$$

where $M_3 = \frac{R_m^2}{R_f^2}$. As $R_m^2 \gg R_f^2 \Rightarrow \frac{R_m^2}{R_f^2} \gg 1 \Rightarrow M_3 \gg 1$.

The total transmitted power (in dB) by the BSs (micro, pico, femto and portable femto) in the total area is given by,

$$\begin{aligned} Pmipf_{totdB} &= P_{totdBmi} + P_{totdBp} + P_{totdBf1} + P_{totdBfp} \\ &= N_{mi} \times 10\log_{10}(P_{tmi}) + N_p \times 10\log_{10}(P_{tp}) \\ &\quad + \left((N_{f1} + N_{fp}) \times 10\log_{10}\left(P_{tf}^{T_D}\right)\right) \\ &= 10N_m\left[\frac{M_1 z}{x}\log_{10}(P_{tmi}) + \frac{M_2 y_2}{x}\log_{10}(P_{tp}) \right. \\ &\quad \left. + \left(\frac{M_3 y_1}{x} + \frac{N_{fp}}{N_m}\right)\log_{10}\left(P_{tf}^{T_D}\right)\right] \end{aligned} \tag{43}$$

Subtracting Eq. (43) from Eq. (18) we obtain,

$$\begin{aligned} P_{totdBm} - Pmipf_{totdB} &= 10N_m\log_{10}(P_{tm}) - 10N_m\left[\frac{M_1 z}{x}\log_{10}(P_{tmi}) \right. \\ &\quad + \frac{M_2 y_2}{x}\log_{10}(P_{tp}) \\ &\quad \left. + \left(\frac{M_3 y_1}{x} + \frac{N_{fp}}{N_m}\right)\log_{10}\left(P_{tf}^{T_D}\right)\right] \\ &= 10N_m\left[\log_{10}(P_{tm}) - \left[\frac{M_1 z}{x}\log_{10}(P_{tmi}) \right.\right. \\ &\quad + \frac{M_2 y_2}{x}\log_{10}(P_{tp}) \\ &\quad \left.\left. + \left(\frac{M_3 y_1}{x} + \frac{N_{fp}}{N_m}\right)\log_{10}\left(P_{tf}^{T_D}\right)\right]\right] \end{aligned} \tag{44}$$

As $P_{tm} > P_{tmi} > P_{tp} > P_{tf}$, $x \gg y_1, x \gg y_2, x \gg z, x \gg w$, and $T_D \leqslant 1$, we can conclude that,

$$10N_m\left[\log_{10}(P_{tm}) - \left[\frac{M_1 z}{x}\log_{10}(P_{tmi}) + \frac{M_2 y_2}{x}\log_{10}(P_{tp}) + \left(\frac{M_3 y_1}{x} + \frac{N_{fp}}{N_m}\right)\log_{10}\left(P_{tf}^{T_D}\right)\right]\right] > 0$$

which implies,

$$P_{totdBm} > Pmipf_{totdB} \tag{45}$$

Hence we can conclude that using this strategy, total transmitted power by the BSs in an area can be reduced. As each of the micro, pico and femto BS has less transmission power than the macro BS, minimum radiation and reduction in energy consumption by each mobile terminal can also be achieved using such microcell, picocell, femtocell and portable femtocell based network as according to Eq. (13) the received power by a MT is directly proportional to the transmitted power by the BS. Thus in case 3, in an area cell sizes are decided depending on the mobile user density and mobile user traffic generated in that area and number of cells to be allocated are decided based on the required coverage area.

3.5. Case 4: Microcells, picocells and femtocells used at border region

In this case we have considered an area that cannot be covered properly using macrocells. Border region of such an area either remains uncovered or causes useless coverage that result in wastage of power. For example, we have considered an island as shown in Fig. 4. To deal with such issue, we have considered allocation of macrocells in the entire area except in the border region and allocation of micro, pico and femtocells at the border region based on the coverage required as shown in Fig. 4. Let consider an area (x) within which br is the border region area. We have divided the border region area (br) into three portions: br_1, br_2, br_3. Depending on the required coverage, br_1, br_2, br_3 contain micro, pico and femtocells respectively. Hence,

$$br = br_1 + br_2 + br_3 \tag{46}$$

The number of microcells covering br_1 area is calculated as,

$$N'_{mi} = \frac{br_1}{\frac{3\sqrt{3}}{2} R_{mi}^2} \tag{47}$$

The total transmitted power (in dB) by these micro BSs is obtained by multiplying the number of microcells covering br_1 area calculated using Eq. (47) with the transmission power of each micro BS calculated using Eq. (6) as follows,

$$P'_{totdBmi} = N'_{mi} \times 10\log_{10}(P_{tmi}) \tag{48}$$

The number of picocells covering br_2 area is calculated as,

$$N'_p = \frac{br_2}{\frac{3\sqrt{3}}{2} R_p^2} \tag{49}$$

The total transmitted power (in dB) by these pico BSs is obtained by multiplying the number of picocells covering br_2 area calculated using Eq. (49) with the transmission power of each pico BS calculated using Eq. (7) as follows,

$$P'_{totdBp} = N'_p \times 10\log_{10}(P_{tp}) \tag{50}$$

The number of femtocells covering br_3 area is calculated as,

$$N'_{f1} = \frac{br_3}{\frac{3\sqrt{3}}{2} R_f^2} \tag{51}$$

The total transmitted power (in dB) by these femto BSs is obtained by multiplying the number of femtocells covering br_3 area calculated using Eq. (51) with the transmission power of each femto BS calculated using Eq. (9) as follows,

$$P'_{totdBf1} = N'_{f1} \times 10\log_{10}\left(\left(P_{tf}^{T_D}\right)\right) \tag{52}$$

If macrocells are used to cover the rest of the region (i.e. $(x - br)$), then the number of macrocells required will be,

$$N_{mr} = \frac{x - br}{\frac{3\sqrt{3}}{2} R_m^2} \tag{53}$$

The total transmitted power (in dB) by these macro BSs is obtained by multiplying the number of macrocells covering the rest of the region $(x - br)$ calculated using Eq. (53) with the transmission power of each macro BS calculated using Eq. (5) as follows,

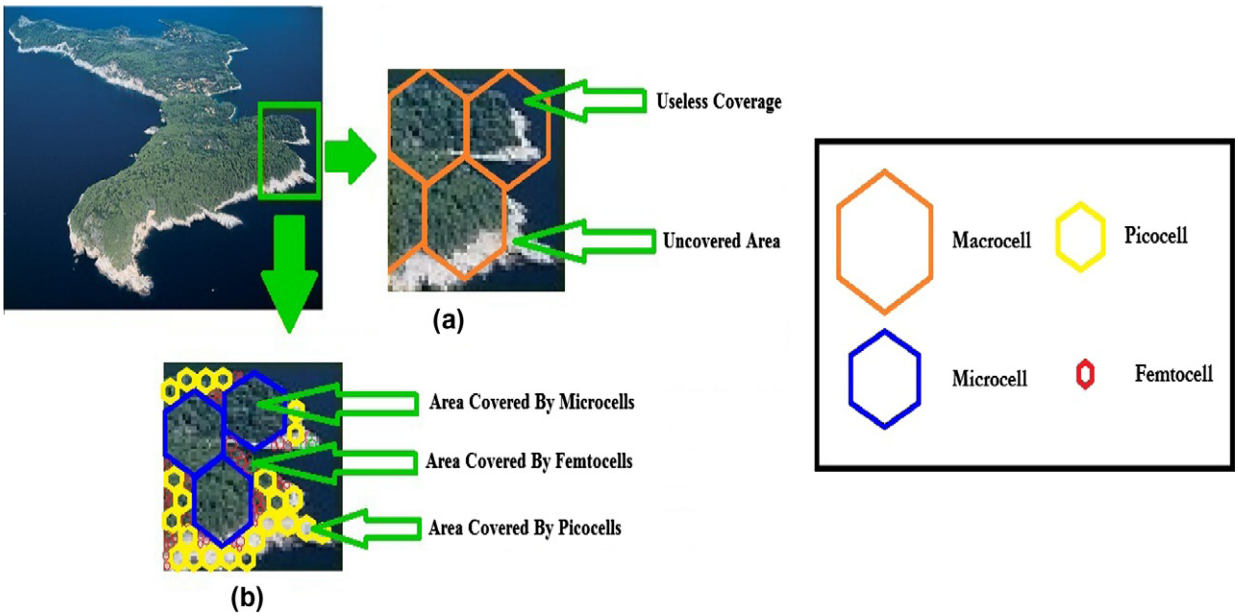

Fig. 4. (a) Border region covered by Macrocells (b) Border region covered by Microcells, Picocells and Femtocells.

$$P'_{totdBmnew} = N_{mr} \times 10\log_{10}(P_{tm}) \tag{54}$$

Dividing Eq. (47) by Eq. (17) we obtain,

$$\frac{N'_{mi}}{N_m} = \frac{\frac{br_1}{\frac{3\sqrt{3}}{2}R_{mi}^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N'_{mi} = \frac{br_1}{x} \cdot M_1 \cdot N_m \tag{55}$$

where $M_1 = \frac{R_m^2}{R_{mi}^2}$. As $R_m^2 \gg R_{mi}^2 \Rightarrow \frac{R_m^2}{R_{mi}^2} \gg 1 \Rightarrow M_1 \gg 1$.

Dividing Eq. (49) by Eq. (17) we obtain,

$$\frac{N'_{p}}{N_m} = \frac{\frac{br_2}{\frac{3\sqrt{3}}{2}R_{p}^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N'_{p} = \frac{br_2}{x} \cdot M_2 \cdot N_m \tag{56}$$

where $M_2 = \frac{R_m^2}{R_{p}^2}$. As $R_m^2 \gg R_{p}^2 \Rightarrow \frac{R_m^2}{R_{p}^2} \gg 1 \Rightarrow M_2 \gg 1$.

Dividing Eq. (51) by Eq. (17) we obtain,

$$\frac{N'_{f1}}{N_m} = \frac{\frac{br_3}{\frac{3\sqrt{3}}{2}R_{f}^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N'_{f1} = \frac{br_3}{x} \cdot M_3 \cdot N_m \tag{57}$$

where $M_3 = \frac{R_m^2}{R_{f}^2}$. As $R_m^2 \gg R_{f}^2 \Rightarrow \frac{R_m^2}{R_{f}^2} \gg 1 \Rightarrow M_3 \gg 1$.

Dividing Eq. (53) by Eq. (17) we obtain,

$$\frac{N_{mr}}{N_m} = \frac{\frac{x-br}{\frac{3\sqrt{3}}{2}R_{m}^2}}{\frac{x}{\frac{3\sqrt{3}}{2}R_m^2}} \Rightarrow N_{mr} = \frac{x-br}{x} \cdot N_m \tag{58}$$

The total transmitted power (in dB) by the BSs in the total area in proposed macro–micro–pico–femtocell based network is given by,

$$\begin{aligned} PBmmipf_{totdB} &= P'_{totdBmnew} + P'_{totdBmi} + P'_{totdBp} + P'_{totdBf1} \\ &= N_{mr} \times 10\log_{10}(P_{tm}) + N'_{mi} \times 10\log_{10}(P_{tmi}) \\ &\quad + N'_p \times 10\log_{10}(P_{tp}) + N'_{f1} \times 10\log_{10}((P_{tf}^{T_D})) \\ &= 10N_m\left[\left(\frac{x-br}{x}\right)\log_{10}(P_{tm}) + \left(\frac{br_1}{x}\cdot M_1\right)\log_{10}(P_{tmi}) \right. \\ &\quad \left. + \left(\frac{br_2}{x}\cdot M_2\right)\log_{10}(P_{tp}) + \left(\frac{br_3}{x}\cdot M_3\right)\log_{10}\left(P_{tf}^{T_D}\right)\right] \\ &= 10N_m\left[\log_{10}(P_{tm})^{\frac{x-br}{x}} + \log_{10}(P_{tmi})^{\frac{br_1}{x}\cdot M_1} \right. \\ &\quad \left. + \log_{10}(P_{tp})^{\frac{br_2}{x}\cdot M_2} + \log_{10}(P_{tf})^{\frac{br_3}{x}\cdot M_3 T_D}\right] \end{aligned} \tag{59}$$

Subtracting Eq. (59) from Eq. (18) we obtain,

$$\begin{aligned} &P_{totdBm} - PBmmipf_{totdB} \\ &= 10N_m\log_{10}(P_{tm}) - 10N_m\left[\log_{10}(P_{tm})^{\frac{x-br}{x}} + \log_{10}(P_{tmi})^{\frac{br_1}{x}\cdot M_1} \right. \\ &\quad \left. + \log_{10}(P_{tp})^{\frac{br_2}{x}\cdot M_2} + \log_{10}(P_{tf})^{\frac{br_3}{x}\cdot M_3 T_D}\right] \\ &= 10N_m\log_{10}\left(\frac{P_{tm}}{\mathrm{P}_{\mathrm{tm}}^{\left(\frac{x-br}{x}\right)}\mathrm{P}_{\mathrm{tmi}}^{\left(\frac{br_1}{x}\cdot M_1\right)}P_{tp}^{\left(\frac{br_2}{x}\cdot M_2\right)}P_{tf}^{\left(\frac{br_3}{x}\cdot M_3 T_D\right)}}\right) \end{aligned} \tag{60}$$

Now, $x \gg br_1$, $x \gg br_2$, $x \gg br_3$, $M_1 \gg 1$, $M_2 \gg 1$, $M_3 \gg 1$, $T_D \leqslant 1$ and $P_{tm} > P_{tmi} > P_{tp} > P_{tf}$.

Hence we can conclude that,

$$10N_m\log_{10}\left(\frac{P_{tm}}{\mathrm{P}_{\mathrm{tm}}^{\left(\frac{x-br}{x}\right)}\mathrm{P}_{\mathrm{tmi}}^{\left(\frac{br_1}{x}\cdot M_1\right)}P_{tp}^{\left(\frac{br_2}{x}\cdot M_2\right)}P_{tf}^{\left(\frac{br_3}{x}\cdot M_3 T_D\right)}}\right) > 0,$$

which implies,

$$P_{totdBm} > PBmmipf_{totdB} \tag{61}$$

Thus we can conclude that using microcells, picocells and femtocells at the border region depending on the coverage needed and macrocells at rest of the region, instead of covering the total area by macrocells, total transmitted power by the BSs can be minimized as well as coverage can be provided in uncovered area and useless coverage can be avoided.

3.6. Case 5: Femtocells at the boundary of a Macrocell

In the respective case, the femtocells are allocated at the border region of a macro cell as shown in Fig. 5. Between two femtocells at the boundary there is a gap of R_f, where R_f is the radius of a femtocell. As shown in Fig. 6, the radius of a femtocell i.e. the length of one side of the femtocell is R_f. The sides *OA* and *OB* of the triangle OAB are the sides of the hexagonal femtocells as shown in Fig. 6. Thus OA = R_f and OB = R_f.

As the angle of a regular hexagon is 120°, Angle OAF = 120°, therefore angle OAB = 180° − 120° = 60°. Similarly angle OBA = 60°. Thus angle AOB = 180° − (angle OAB + angle OBA) = 180° − (60° + 60°) = 60°. Thus, OAB is an equilateral triangle and so AB = R_f.

From Fig. 6 it is observed that the length of one side of the macrocell is given by,

$$R_m = 2nR_f - R_f \tag{62}$$

where *n* is the number of femtocells residing at that side. In Fig. 6 three femtocells are used at one side and the length of the side of the corresponding macrocell = $5R_f = 2.3 \cdot R_f - R_f$. From Fig. 6 it is also observed that if two femtocells are allocated the length of one side of the corresponding macrocell = $3R_f = 2.2 \cdot R_f - R_f$. Similarly if only one femtocell is used at a side, the length of one side of the corresponding macrocell = $R_f = 2.1 \cdot R_f - R_f$. Let us assume if *k* femtocells are used, the length of one side of the corresponding macrocell = $2kR_f - R_f$. We have to prove that for $k + 1$ femtocells, Eq. (62) is valid. If another femtocell is added at the side, $2R_f$ will be added with the previous length of the side of the macrocell, thus the new length of the side of the corresponding macrocell = $2kR_f - R_f + 2R_f = 2(k + 1)R_f - R_f$. Hence it is proved that Eq. (62) holds for $k + 1$ femtocells. Thus the Eq. (62) is valid for any number of femtocells according to the principle of induction. Solving Eq. (62), the number of femtocells (n) situated at one side of the macrocell is determined as $\frac{R_m+R_f}{2R_f}$.

As each of the femtocells at the corner of the macrocell is common to both sides, the total number of femtocells situated at six sides of the hexagonal macrocell is given by,

$$6 \times \frac{R_m + R_f}{2R_f} - 6 = 6 \times \left(\frac{R_m + R_f}{2R_f} - 1\right) = \frac{3(R_m - R_f)}{R_f} \tag{63}$$

From Eq. (63), the number of femtocells allocated per macrocell is determined. The number of macrocells (N_m) allocated in the total area (x) is calculated using Eq. (17). Thus total number of femtocells allocated in total area (x) is given by,

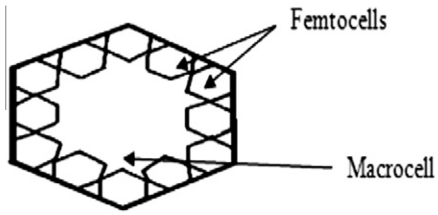

Fig. 5. Femtocells residing at the boundary of macrocell.

$$N_{totfem} = N_m \times \frac{3(R_m - R_f)}{R_f} \tag{64}$$

Total transmitted power (in dB) in that area by all the femto BSs is determined by multiplying the number of femtocells determined from Eq. (64) with the transmission power of each femto BS obtained from Eq. (9) as follows:

$$\begin{aligned} P_{totfemtodB} &= N_m \times \frac{3(R_m - R_f)}{R_f} \times 10\log_{10} P_{tf}^{T_D} \\ &= 10N_m \log_{10}(P_{tf})^{T_D\left(\frac{3(R_m-R_f)}{R_f}\right)} \end{aligned} \tag{65}$$

When all the femtocells are turned on, the macrocell shrinks its coverage area as shown in Fig. 7. Hence in this particular case, we have considered the value of $T_D = 1$. Thus, total transmitted power (in dB) in that area by all femto BSs is given by,

$$P_{totfemtodB} = 10N_m \log_{10}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)} \tag{66}$$

When all the femtocells are switched on, the macrocell reduces its radius by the diameter (2 × radius) of the femtocell as shown in Fig. 7 and the reduced radius is given by,

$$R'_m = R_m - 2R_f \tag{67}$$

Hence the reduced coverage area of the macrocell is calculated as,

$$A'_m = \frac{3\sqrt{3}}{2} R_m'^2 \tag{68}$$

The transmission power (in dB) of the macro BS after reduction in coverage area is given by,

$$P'_{tdBm} = 10\log_{10} \frac{P'_{rm}(4\pi)^2 R_m'^2 L}{G_{tm} G_r \lambda^2} = 10\log_{10} P'_{tm} \tag{69}$$

where P'_{rm} is the minimum received power by a MT in the macrocell after reduction in its coverage area.

Number of macrocells allocated in the total area (x) is N_m calculated using Eq. (17). Thus the total transmitted power (in dB) by all the macro BSs (N_m) after reduction in coverage area is calculated as follows:

$$P'_{totdBmr} = 10N_m \log_{10}(P'_{tm}) \tag{70}$$

Thus the total transmitted power by the BSs considering both macrocells (after reduction in coverage area) and femtocells is determined as follows:

$$\begin{aligned} P_{totdBmf} &= P'_{totdBmr} + P_{totfemtodB} \\ &= 10N_m \log_{10}(P'_{tm}) + 10N_m \log_{10}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)} \\ &= 10N_m \log_{10}\left(P'_{tm}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)}\right) \end{aligned} \tag{71}$$

Subtracting Eq. (71) from Eq. (18) we obtain,

$$\begin{aligned} P_{totdBm} - P_{totdBmf} &= 10N_m \log_{10} \mathrm{P_{tm}} \\ &\quad - 10N_m \log_{10}\left(P'_{tm}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)}\right) \\ &= 10N_m \log_{10}\left(\frac{\mathrm{P_{tm}}}{P'_{tm}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)}}\right) \end{aligned} \tag{72}$$

As $R_m > R'_m \Rightarrow A_m > A'_m \Rightarrow P_{tm} > P'_{tm}[asP_t \propto A]$.

As P_{tf} is a very small quantity and $R_m \gg R_f$, it can be concluded that $(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)} < 1$.

Thus it is observed, $\mathrm{P_{tm}} > \mathrm{P'_{tm}}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)}$.

Hence, $10N_m \log_{10}\left(\frac{\mathrm{P_{tm}}}{P'_{tm}(P_{tf})^{\left(\frac{3(R_m-R_f)}{R_f}\right)}}\right) > 0$, which implies,

$$P_{totdBm} > P_{totdBmf} \tag{73}$$

Hence it is observed that the total transmitted power by the BSs considering macrocell at the center and femtocells at the boundary region of each macrocell in an area, the total transmitted power by the BSs can be reduced than if only macrocells are used to cover the total area.

4. Results and discussions

In this section we have studied the performance of the proposed five cases discussed in the previous section. MATLAB is used for simulation purpose. The performance

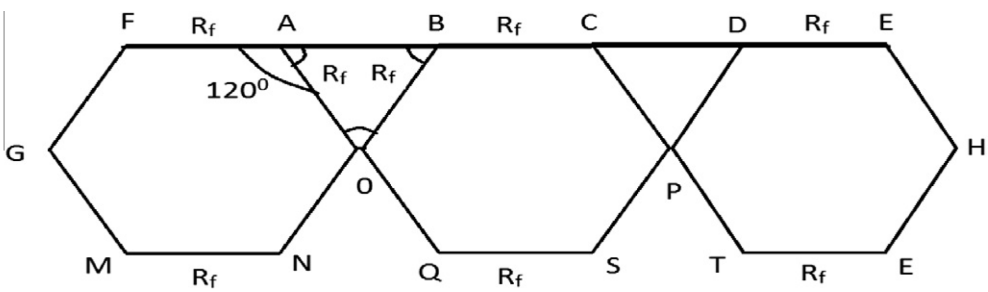

Fig. 6. Length of one side of a macrocell containing three femtocells at that side.

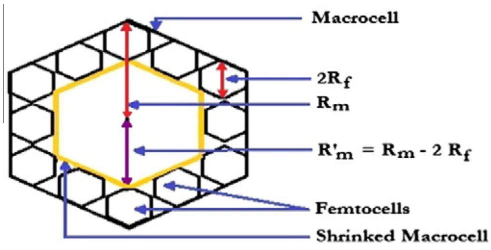

Fig. 7. Macrocell after reduction in coverage area.

Table 2
Parameter values [6,45,46].

Parameter	Value
P_{rm}	10–20 mW
P_{rmi}	5–10 mW
P_{rp}	1–5 mW
P_{rf}	0.35–1 mW
R_m	1–10 km
R_{mi}	0.2–1 km
R_p	0.05–0.2 km
R_f	0.01–0.02 km
G_{tm}	16–18 dBi
G_{tmi}	7 dBi
G_{tp}	5 dBi
G_r	1 dBi
G_{tf}	2 dBi

of each scheme is evaluated depending on different data set. The assumed values of the parameters are presented in Table 2.

To analyze the performance of our proposed five strategies, we have considered different type of regions having different surface area and different shapes. Then we have applied our proposed five schemes one by one on these regions.

Fig. 8 analyzes the performance of case 1. Fig. 8 represents the total transmission power (in dB) of the macrocell base stations in each of the region if each of them is covered by only macrocells i.e. only macrocell based network.

Fig. 8 also represents the total transmission power (in dB) of the femto base stations if instead of macrocells, only femtocells are used to cover each of the region i.e. only femtocell based network. Total transmission power of the macrocell base stations is calculated using Eq. (18). Total transmission power of the femtocell base stations is calculated using Eq. (16). Fig. 8 presents that using only femtocell based network instead of only macrocell based network, 82.72–88.37% reduction in power consumption by the BSs can be achieved.

Fig. 9 analyzes the performance of case 2. In case 2, femtocells are used at urban area with high mobile user traffic, macrocells are used at suburban area with moderate mobile user traffic and portable femtocells are allocated to rural area with low mobile user traffic. As the mobile user density and mobile user traffic differ depending on the number of mobile subscribers present in a particular area, using macrocell throughout the total area results in high power consumption by the BSs and poor QoS at indoor environments but useless coverage especially at rural area. Thus in our proposed strategy, femtocells and macrocells are deployed in each of the region depending on mobile user density, mobile user traffic and coverage to offer low power consumption. Fig. 9 presents the total transmission power (in dB) of the BSs in each of the region covered by macrocells, femtocells and portable femtocells i.e. in macrocell, femtocell and portable femtocell based network, calculated using Eq. (28). Fig. 9 also presents the total transmission power (in dB) of the BSs in each of the region covered by only macrocells i.e. macrocell based network calculated using Eq. (18). Fig. 9 demonstrates that using macrocell, femtocell and portable femtocell based network 78.53–80.19% reduction in total transmission power of the BSs can be achieved as compared to only macrocell based network.

Fig. 10 analyzes the performance of case 3. In case 3, femtocells, picocells, microcells and portable femtocells are deployed at densely populated urban with highest mobile user traffic, sparsely populated urban with high mobile user traffic, suburban area with moderate mobile user traffic and rural area with low mobile user traffic respectively.

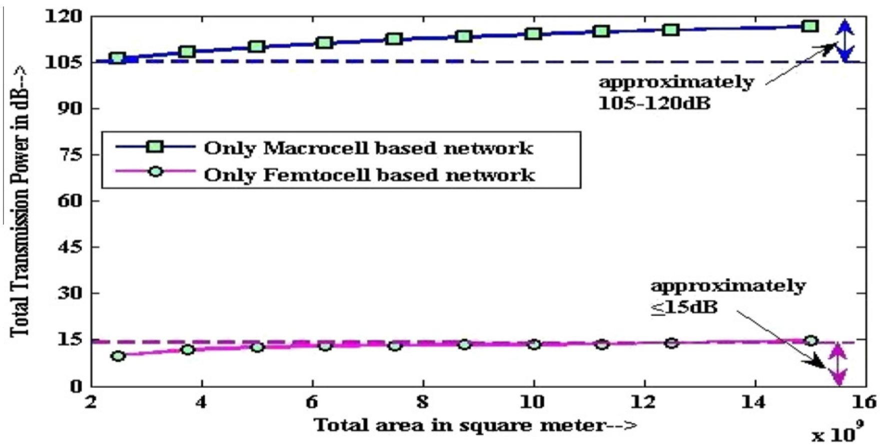

Fig. 8. Total area (square meter) of each region vs. total transmission power (dB) of the BSs in that region in case 1.

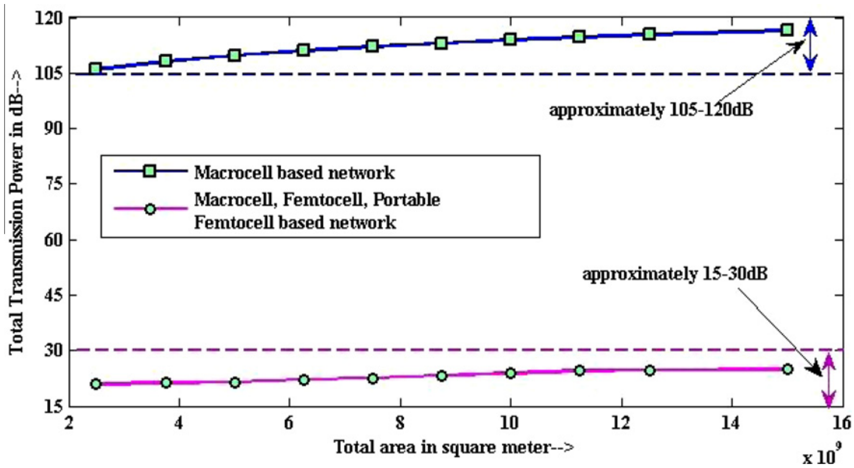

Fig. 9. Total area (square meter) of each region vs. total transmission power (dB) of the BSs in that region in case 2.

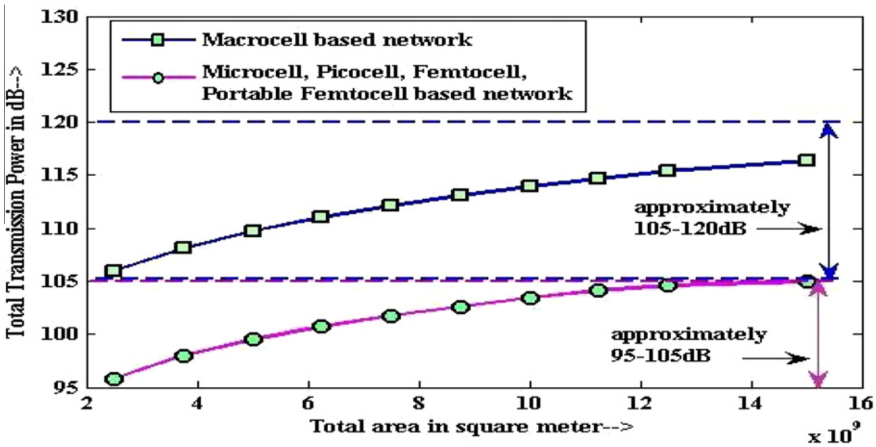

Fig. 10. Total area (square meter) of each region vs. total transmission power (dB) of the BSs in that region in case 3.

As the mobile user density and mobile user traffic differ with the number of mobile subscribers present in that area, using macrocell throughout the total area results in high power consumption by the BSs and poor QoS at indoor environments but useless coverage especially at rural area. Thus in our proposed scheme, microcells, picocells and femtocells are deployed in each of the region depending on mobile user density, mobile user traffic and coverage to offer low power consumption. Fig. 10 presents the total transmission power (in dB) of the BSs in each of the region covered by microcell, picocell, femtocell, portable femtocell i.e. in microcell, picocell, femtocell and portable femtocell based network calculated using Eq. (43). Fig. 10 also presents the total transmission power (in dB) of the BSs in each of the region covered by only macrocell i.e. macrocell based network calculated using Eq. (18). Fig. 10 also demonstrates that using microcell, picocell, femtocell and portable femtocell based network, 9.19–9.79% reduction in total transmission power of the BSs can be achieved as compared to only macrocell based network.

Fig. 11 analyzes the performance of case 4. In case 4, we have already observed that using femtocells, picocells and microcells at border region and macrocells at rest of the region, total transmitted power can be reduced than covering the total region by macrocells. As the mobile user density at border region for example a seaside, as in Fig. 4 is very low, using macrocell throughout the total border region results in useless coverage. Thus in our proposed scheme, microcells, picocells and femtocells are deployed at border area of each of the region depending on the coverage required and rest of the region is covered by macrocells. Fig. 11 presents the total transmission power (in dB) of the BSs while microcells, picocells, femtocells are used at border area and macrocells at rest of the area of each region calculated using equation (59). Fig. 11 also presents the total transmission power (in dB) of the BSs if only macrocells are used throughout each region and this is calculated using Eq. (18). Fig. 11 demonstrates that using microcells, picocells, and femtocells at border area depending on the requirement and macrocells at rest of the area in each region, 5.52–5.98% reduction in total transmission

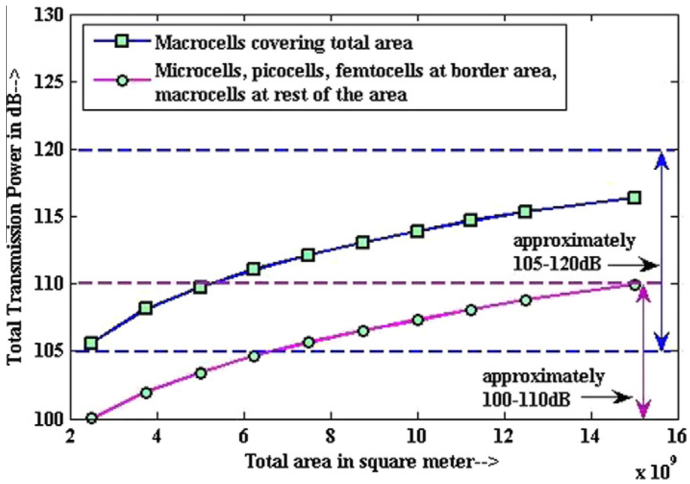

Fig. 11. Total area (square meter) of each region vs. total transmission power (dB) of the BSs in that region in case 4.

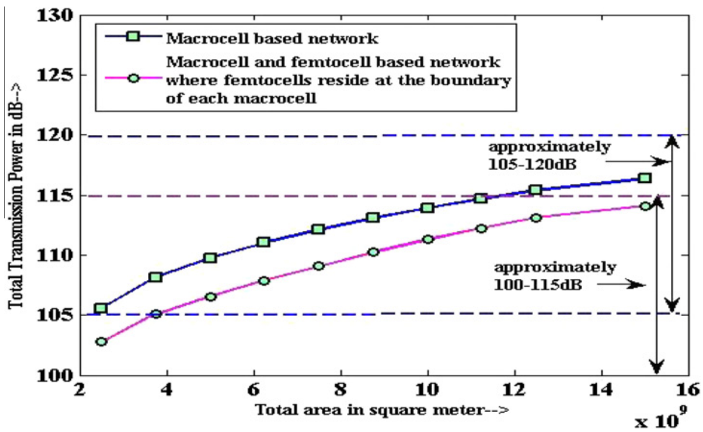

Fig. 12. Total area (square meter) of each region vs. total transmission power (dB) of the BSs in that region in case 5.

power of the BSs can be achieved as compared to using macrocells throughout the total area of each region.

Fig. 12 analyzes the performance of case 5. Fig. 12 represents the total transmission power (in dB) of the BSs in each of the region if covered by only macrocells determined using Eq. (18). Now if femtocells are deployed at the boundary of each macrocell and turned on, each of the macrocell shrinks, eventually covering the same area as a whole, the total transmission power of the BSs in each of the region is calculated using Eq. (71) and presented in Fig. 12. Fig. 12 demonstrates that using femtocells at the boundary of each macrocell, 1.94–2.66% reduction in power consumption by the BSs can be achieved as compared to only macrocell based network.

We have considered different values for different parameters and different areas having different shapes and sizes to evaluate the performance of the proposed five cases. In each of these five cases, total transmitted power by the BSs contained in the area gets reduced than that of only macrocell based network. No increase or equality will occur and thus in each of these five figures (Figs. 8–12), two lines presenting power consumption by the BSs in proposed five schemes and in macrocell based network will never intersect according to the simulation results.

Depending on the total transmission power of the base stations, we can classify these five cases i.e. the five proposed schemes into five classes of networks where each class contains different combinations of base stations.

By replacing a macrocell by a number of femtocells, transmission power of the base stations can be reduced to less than or equals to approximately 15 dB in an area of range 2000–16000 km^2. This network in case 1 is categorized as class A network (see Table 3).

By allocating femtocells at the urban area having high mobile user traffic, macrocells at suburban area having moderate mobile user traffic and portable femtocells at rural area with low mobile user traffic as in case 2, transmission power of the base stations can come down within the range of approximately 15–30 dB in an area of range 2000–16000 km^2. This network in case 2 falls under class B network (see Table 3).

By allocating femtocells at the densely populated urban area having highest mobile user traffic, picocells at the sparsely populated urban area having high mobile user

Table 3
Comparison of power consumption (in an area of 2000–16000 km^2) in five proposed schemes and categorization of the proposed networks into classes.

Case no.	Cell types used in mobile network	Total transmission power of the base stations (dB)	Reduction in power consumption than only macrocell based network (%)	Class
Case 1	Only femtocell	$\leqslant$15	82.72–88.37	Class A
Case 2	Femtocells at urban area with high mobile user traffic, macrocells at suburban area with moderate amount of mobile user traffic and portable femtocells at rural area with low mobile user traffic	15–30	78.53–80.19	Class B
Case 3	Femtocells at densely populated urban area with highest mobile user traffic, picocells at sparsely populated urban area with high mobile user traffic, microcells at suburban area with moderate amount of mobile user traffic and portable femtocells at rural area with low mobile user traffic	95–105	9.19–9.79	Class C
Case 4	Microcells, picocells and femtocells at border region of an area depending on coverage requirement after covering rest of the area by macrocells	100–110	5.52–5.98	Class D
Case 5	Femtocells at the boundary of each Macrocell	100–115	1.94–2.66	Class E

traffic, microcells at suburban area having moderate mobile user traffic and portable femtocells at rural area with low mobile user traffic as in case 3, transmission power of the base stations comes down within the range of approximately 95–105 dB in an area of range 2000–16000 km^2. This network in case 3 is categorized as class C network (see Table 3).

Deploying microcells, picocells and femtocells at border area and macrocells at rest of the area of a region, transmission power of the base stations falls within a range of approximately 100–110 dB in an area of range 2000–16000 km^2. This network in case 4 falls under class D network (see Table 3).

In the fifth case, the femtocells are allocated at the boundary region of each macrocell which results in the power transmission by the base stations within the range of approximately 100–115 dB in an area of range 2000–16000 km^2. This network in case 5 is categorized as class E network.

From the above five figures (Figs. 8–12) it is also observed that using only macrocell based network transmission power of the base stations falls within the range of approximately 105–120 dB in an area of range 2000–16000 km^2. Thus in this way, based on the total transmission power of the base stations, we can compare and divide our five proposed cases into five classes of cellular networks as presented in Table 3.

All of the figures of this section present that using our proposed schemes (case 1, case 2, case 3, case 4, case 5) transmitted power by the base stations in an area can be minimized. As in Section 3, we have observed that the received power by a MT is directly proportional to the transmission power of the BS, power consumption by each MT can also be minimized using our proposed approaches.

Hence using our proposed five classes of networks, transmission power by the base stations can be minimized than that of only macrocell based network. Macrocells, microcells, picocells or femtocells are deployed in the proposed five classes of networks depending on the mobile user traffic or the coverage and power consumption by the base stations can be minimized which leads to the achievement of green mobile network.

5. Conclusion

In this paper the analytical models of power consumption in macrocell, microcell, picocell and femtocell based networks have been proposed. Five classes of networks are presented in this paper. In the class A network, we have considered femtocell based network where instead of macrocells, an area is fully covered by femtocells. Simulation results show that using only femtocell based network, 82.72–88.37% reduction in power consumption by the base stations can be achieved as compared to the only macrocell based network. The class B network divides the whole area into three parts: urban, suburban and rural area. Depending on mobile user density, mobile user traffic and required coverage, the urban area, suburban area and rural area are covered by femtocells, macrocells and portable femtocells respectively. Simulation results demonstrate that using macrocells, femtocells and portable femtocells, 78.53–80.19% reduction in total transmitted power by the BSs can be achieved as compared to the only macrocell based network. In the class C network, an area is divided into four parts: densely populated urban area, sparsely populated urban area, suburban area and rural area. Depending on mobile user density, mobile user traffic and required coverage, femtocells, picocells, microcells and portable femtocells are allocated in densely populated urban area, sparsely populated urban area, suburban area and rural area respectively. Simulation results show that using microcell, picocell, femtocell and portable femtocell based network, 9.19–9.79% reduction in total transmitted power by the BSs can be achieved as compared to the only macrocell based network. In the class D network, microcells, picocells and femtocells are allocated to border region and macrocells at the rest of the region in an area. Simulation results demonstrate that using microcells, picocells and femtocells at border region and macrocells at rest of the region, 5.52–5.98% reduction in total transmitted power by the BSs can be achieved as compared to the use of only macrocells throughout the total region. In the class E network, femtocells are allocated at the boundary region of the macrocell and turned on as in that region the received signal from the macrocell base station is too low to successfully receive or generate a call. When all the femtocells are kept on, the macrocell shrinks its coverage area. Simulation results present that using femtocells at the boundary of each macrocell, 1.94–2.66% reduction in power consumption can be achieved as compared to the only macrocell based network. As the received power by a mobile terminal is directly proportional to the transmission power of the base station, radiation and energy consumption by the mobile terminals can also be reduced. Hence it can be concluded that using our proposed schemes, power consumption by the base stations as well as mobile terminals can be minimized than that of the only macrocell based network, thus approaching towards a greener cellular network.

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