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Traffic load–based cell selection for APCO25 conventional–based professional mobile radio

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Abstract

Wireless communication between public safety officers is very important to transmit voice or data during emergency crises. When the public communication networks cannot provide services during crises, disasters, and high traffic cases, Professional or private mobile radio (PMR) such as Association of Public Safety Communications Officials (APCO25) conventional systems are needed to improve the service quality and to provide uninterrupted service to the users. In this paper, we propose traffic-based cell selection algorithms for the APCO25 conventional systems to attach users to base stations in a balanced manner to reduce waiting time while establishing a connection. The simulation results of the proposed traffic load–based cell selection algorithms are illustrated in terms of the RSSI measurements counter, the number of connection requests, the average waiting time, and the number of re-selections for the APCO25 conventional systems.

Keywords Cell selection · Cell re-selection · APCO25 · PMR · Traffic aware

1 Introduction

During natural disasters and emergencies, continuous voice and data services play a critical role for communication in public safety networks. In the course of a disaster such as an earthquake or flood, the public network structure can be affected since the base stations (BSs) are damaged. Moreover, major disasters are the greatest contributors to telecommunication traffic load. Public communication networks may fail because of physical damages and traffic load. In case of a natural disaster, their robustness and reliability are very critical. Public networks alone may not be sufficient under these conditions. For reliable, efficient, and uninterrupted communication between wireless radio users, PMR systems are required, and they must work even when the public networks are out of order.

PMR systems refer to a suite of radio mobile network technologies for different emergency services like police forces, fire departments, military forces, transportation (taxi, buses), and health emergency associations. PMR networks are developed for short and fast call setup. They provide radio services for closed user groups, group call and push-to-talk (PTT). Among several digital PMR standards, the well-known systems are Terrestrial Trunked Radio (TETRA) system, APCO25, digital mobile radio (DMR), integrated dispatch radio (IDRA) system, digital integrated mobile radio system (DIMRS), TETRAPOL system, and Enhanced Digital Access Communications (EDACS) system. In this work, we focus on APCO25 conventional systems since they support a large coverage area due to their high transmit power. In the literature, different names of APCO25 such as Project 25, P25, APCO, and APCO Project 25 are used in the standards. APCO25 conventional is an open standard initiated by the Association of Public Safety Communications Officials and developed by the Telecommunications Industry Association (TIA) [1]. APCO25 conventional radio systems are qualified to meet the communication needs in case of disasters and communication traffic generated by different

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wireless radio users at Public Safety and Emergency Support Organizations.

In order to provide uninterrupted services to users during disasters and high traffic intensity cases, it is very important to select the BS efficiently and to ensure that user mobility is supported seamlessly. In this case, selecting the BS to be served through efficient cell selection algorithms has a critical role in overall system performance.

Various studies in the literature have focused on user assignment and cell selection processes. The received power, distance, signal-to-noise ratio (SNR), signal-to-interference-plus-noise ratio (SINR), bit error rate (BER), traffic density, priority, quality of service, and the various combinations of these parameters play a decisive role in cell selection and cell re-selection algorithms.

In heterogeneous networks, the user is attached to the BS with maximum received power. However, this causes unequal cell association. In order to find a solution to this problem and also to attain the throughput gain of multi-tiering networks, the significance of considering both load balancing and interference management in the cell selection process has been investigated in [2]. In [3], a cell selection algorithm has been examined for mobile networks with backhaul capacity constraints. This model analyzes the possibility to exploit load balancing among BSs depending on backhaul capacity utilization. In [4], so as to select the best-serving BS while achieving the highest achievable data rate, a cell selection algorithm has been implemented by utilizing a proportional fair scheduling algorithm. In [5], cell selection criteria based on Reference Signal Received Power (RSRP), Reference Signal Received Quality, and RSRP with offset have been examined. Offloading users' traffic from macrocells to small cells provides load balancing. In the RSRP- and RSRQ-based cell selection algorithms used in the Long Term Evolution (LTE) system, network throughput is maximized. In [6], in order to achieve proportional fairness for all users in BS, a cell selection has been formulated into a network-wide utility maximization problem.

In [7], a cell range expansion (CRE) algorithm in which the received power of a given cell is multiplied by a bias value has been examined. This bias value is adjusted based on the tier and traffic load. Thus, the CRE algorithm attaches the users to the lightly loaded BSs. However, there is a need for optimization of bias values to achieve the desired system utility. To ensure the desired throughput gains, two different biased cell selection algorithms have been examined in [8]. The first algorithm indicates that a serving BS having highest received signal strength with bias is chosen. Another technique selects a serving BS based on maximizing the product of SINR and bias. In [9], a CRE-based cell selection algorithm with an adaptive value considering users' distribution has been given to improve the cell throughput and resource utilization. In [10], a network coordinated cell selection method which employs both RSRP and cell load has been given by allowing users to be offloaded to macrocell or picocell in the range expansion region based on the achievable throughput. In [11], a detailed analysis between RSRP and CRE cell selection methods for different bias values has been given to explore cell selection efficiency in LTE-A heterogeneous systems.

All these cell selection algorithms are mainly applied to heterogeneous networks in order to balance the system load between macro and small BSs. However, due to their complexity and high overhead, these algorithms cannot be directly applied to APCO25 conventional systems classified as a single-tier network.

In APCO25 conventional–based PMR systems, the user groups need to communicate with each other or other user groups without any delay while establishing a reliable transmission link. While satisfying these requirements, the distribution of users among the BSs must be balanced so that overall system performance can be improved. In order to meet these needs, we propose efficient cell selection algorithms for APCO25 conventional systems to manage traffic load at the BSs. Thus, it is possible to decrease the waiting time without sacrificing BER performance. In this work, we determine the traffic load by considering call duration. In our previous work in [12], we calculated the utility value based on the number of active users in the cell and biased SINR values. In [13], the utility value was determined by considering the number of active users and received signal strength indicator (RSSI) values. In [14], the cell load–based cell selection algorithm was applied to TETRA Trunk instead of the DMR system. The main difference between TETRA Trunk and APCO25 conventional systems is that the coverage area of BSs for TETRA Trunk systems is considerably less, which means that more BSs are needed for the same given area. In [15], the cell load–based algorithm was performed to provide a fairer distribution of users among cells while reducing the number of received power measurements for TETRA Trunk system.

To conclude, the novel contributions of this work compared to previous studies are the consideration of user mobility in the coverage area and the traffic intensity in the BSs. The users are either vehicle users or pedestrian users and can move from one cell to another during the call. In this paper, we apply a cell re-selection procedure for these users through the proposed traffic-based cell selection algorithms. In addition to that, the proposed algorithms examine the traffic intensity by calculating the utility value, whereas the load-based cell selection algorithms consider only the number of active users in the cell. We provide the simulation results compared to the conventional cell selection algorithms in terms of the RSSI measurements counter, the number of connection requests, the average waiting time and the number of re-selections, load fairness index, and outage probability on BER.

The remainder of this paper is organized as follows: Section 2 describes the system model and gives the conventional cell selection methods. Sections 3 and 4 introduce the proposed traffic-based cell selection algorithms. Sections 5 and 6 provide simulation parameters and simulation results. Finally, concluding remarks are drawn in Section 7.

2 System model

There are two methods of organizing frequency/channel usage in a PMR system: trunked and conventional radio systems. Conventional radio systems have dedicated frequencies and channels assigned to individual user groups. When a user makes a call and selects a channel, other user groups cannot use this channel until the end of the call. On the other hand, in trunked mode, there is a separate controller in the infrastructure that manages call setup and channel assignment. A communication link is allocated for the duration of a call and then automatically released to use for other user groups in the system [16].

We consider APCO25 conventional system with U BSs and the total number of N_u users in the area. It is supposed that the users are distributed in a uniform manner in the area. APCO25 conventional standard has been developed in two phases: phase 1 and phase 2. In this work, APCO25 conventional phase 1 is used. Phase 1 radio systems use frequency division multiple access (FDMA) technique with channel spacing at 12.5 kHz and continuous 4 level FM (C4FM) non-linear modulation for digital transmissions. The modulation sends 4800 symbols/sec with each symbol conveying 2 bits of information [17].

In APCO25 conventional systems, the number of available channels M_u regarding the BS u is calculated as

$$M_u = \frac{B_u}{\Delta f} \tag{1}$$

where B_u represents the available bandwidth belonging to the cell u and Δf denotes channel spacing. One of the M_u channels is used for control, and all remaining channels are available for data communications [18].

There are two widely used cell selection algorithms for APCO25 conventional. The common cell selection algorithm is based on RSSI in which a BS with the maximum average RSSI value is selected as

$$u_k^* = \arg\max_{1 \le u \le U} \overline{\delta}_{u,k}, \quad \forall k \in \{1, 2, \ldots, N_u\} \tag{2}$$

where $\overline{\delta}_{u,k}$ represents the average RSSI value. In order to achieve accurate received signal measurements, the average of 9 frames of RSSI values, each 20 ms, is taken. Instantaneous RSSI in dB is given as follows:

$$\begin{aligned}\delta_{u,k} = {} & EIRP_u - PL_{u,k} - Shd_{u,k} + GRA - LB_k - LBU_k \\ & - LRC - F_{u,k}\end{aligned} \tag{3}$$

where $PL_{u,k}$ is path loss; $Shd_{u,k}$ is shadowing, which is modeled by log-normal distribution; and $F_{u,k}$ represents the Rayleigh fading channel, which is generated by using Jakes' model for user k and the BS u. GRA is antenna gain, and LRC is cable loss at the receiver. LB_k denotes body loss, and LBU_k is building loss for the user physically in the building. $EIRP_u$ is the effective isotropic radiated power (EIRP) for BS u which is calculated as

$$EIRP_u = P_u^t + GTA \tag{4}$$

where P_u^t denotes transmit power for BS u and GTA is antenna gain for the transmitter.

In another common cell selection algorithm, based on SINR, each user is assigned to the BS with the maximum average SINR value:

$$u_k^{**} = \arg\max_{1 \le u \le U} \overline{\gamma}_{u,k}, \quad \forall k \in \{1, 2, \ldots, N_u\} \tag{5}$$

where $\overline{\gamma}_{u,k}$ is the average of 9 frames of instantaneous SINR values, each 20 ms. The instantaneous SINR is given as follows:

$$\gamma_{u,k} = \frac{P_{u,k}}{I_k + N} \tag{6}$$

where $P_{u,k}$ is the received power for user k from the BS u, N is the noise power, and I_k represents the interference power for user k caused by other cells with the same frequency and is determined by assuming that the cell planning is known at each user.

Because of simplicity, both RSSI and SINR algorithms are widely applied to APCO25 conventional systems. However, these algorithms do not take into consideration the traffic load while assigning the users to the cells. Since the traffic load is not balanced and the number of available channels, M_u, for each BS is limited in the APCO25 conventional systems, the users have to wait in the queue. Therefore, we propose traffic-based cell selection and re-selection algorithms by taking into account both traffic load and RSSI values.

3 Proposed full set traffic load–based cell selection

Users are divided into groups according to the use cases and the calls. Group calls occur only among users in the same group. Each user belongs to one group, and users can be active and inactive during the day. PTT determines the number of active users in the groups and consequently the traffic load is defined in the system. Active users are attached to a BS and communicate, while inactive users are just attached and do not communicate. In the considered system model, there are G different groups including N_g users in a group.

In the proposed full set traffic-based cell selection algorithm, for each user, the utility value is calculated considering the RSSI value and traffic load information from each BS in the system. Then, the highest utility valued BS with a sufficient number of channels is selected to establish communication for the user.

The overall procedure of the full set traffic-based cell selection algorithm is outlined below.

- The user k measures the received power of all BSs in the system.
- The user k constructs the set of $\mathbb{P}_k$ in which the RSSI values of BSs exceed the receiver sensitivity threshold, denoted by δ_{rec}:

$$\mathbb{P}_k = \left\{\overline{\delta}_{u,k} \geq \delta_{rec}; \quad u \in \{1, 2, \ldots, U\}\right\}. \tag{7}$$

- Each user k calculates a utility value for each BS in the set of $\mathbb{P}_k$ as below:

$$U_{u,k} = w\, r(\overline{\delta}_{u,k}) + (1-w)\, s(UTL_{u,t}), \quad \forall u \in \mathbb{P}_k \tag{8}$$

where w denotes the weight parameter between RSSI and traffic load, the function $r(.)$ converts the RSSI values to the normalized RSSI values, and the function $s(.)$ converts the unmapped traffic load (UTL) to the mapped one based on the predefined table.

The $UTL_{u,t}$ is calculated as follows:

Since there is no call request for initial cell selection ($t = 1$), all users are inactive users and the traffic load of BSs for the initial cell selection is calculated as

$$UTL_{u,1} = \frac{F_{u,g}}{N_g} \tag{9}$$

where $F_{u,g}$ refers to the number of inactive users belonging to group g attached to the BS u initially, as given in Eq. 2.

When a user requests a communication link for a certain period of time, the total duration of calls are taken into account for the BSs. Then, the traffic load of the BS u is calculated as follows:

$$UTL_{u,t} = \frac{T_d}{T_f \times M_g} \quad \forall u \in \mathbb{P}_k \tag{10}$$

where T_d is the total duration of calls in a given time interval, T_f shows the fixed time interval, and M_g is the number of channels per group in the cell.

- For each user, the BS with the maximum utility value is chosen as follows:

$$u_k^* = \arg\max_{u \in \mathbb{P}_k} \; U_{u,k} \quad \forall k \in \{1, 2, \ldots, N_u\} \tag{11}$$

- For active users, check whether the BS u_k^* has enough capacity. If not, all utility values are sorted in descending order. Then, they send a request for the next BS having the highest utility value.
- If an active user cannot attach to any BS, they will be a waiting user in the BS with the highest RSSI value.
- Inactive users register to the BS with the highest utility value.

The proposed cell selection algorithm is presented by the flowchart diagram shown in Fig. 1.

4 Proposed reduced set traffic load–based cell selection

In the reduced set traffic-based cell selection algorithm, the first BS which exceeds the predefined *utility threshold value* is selected to decrease waiting time due to the RSSI measurements belonging to all BSs. Therefore, the utility value is

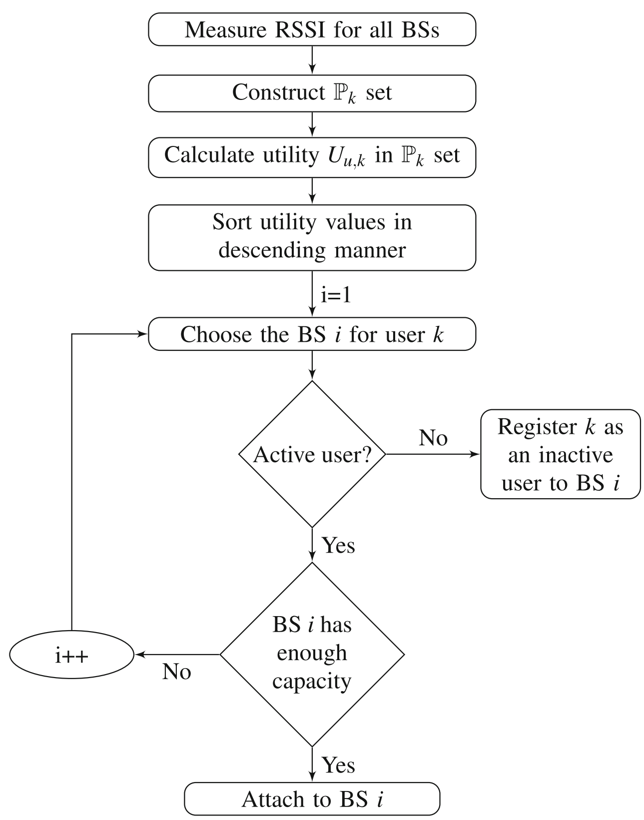

Fig. 1 The flowchart of the proposed full set traffic-based cell selection algorithm

not calculated for all BSs in the system. While determining the utility threshold value, we consider establishing a reliable connection to fulfill the BER requirements of voice communication.

The overall procedure of the proposed reduced set traffic-based cell selection algorithm is outlined below.

1. Neighbor cell set
   - Firstly, with the aid of a GPS system, the neighbor cell set is obtained in terms of distances. The user tries to attach to the closest neighbor cell. The number of neighbor cells can be changed according to the system plan.
2. Utility value calculation
   - The user calculates the utility value of the closest cell until the utility value threshold (U_{th}) is satisfied. The utility value is calculated by taking into account both RSSI values and traffic load information as follows:

$$U_{u,k} = w\ f(\overline{\delta}_{u,k}) + (1-w)\ s(UTL_{u,t}) \qquad (12)$$

   where the function $f(.)$ transforms the RSSI values to the normalized RSSI values for the reduced set–based cell selection algorithm.
3. Connecting to BS
   - The active user is connected to the BS when the utility value for the BS is higher than U_{th} and the RSSI value of this BS is higher than the receiver sensitivity, δ_{rec}, in the case that this chosen BS has enough capacity.
   - The inactive user is registered to the BS when the utility value for the BS is higher than U_{th} and the RSSI of this BS is higher than the receiver sensitivity, δ_{rec}.
   - When the active user does not attach to any neighbor BS because of its capacity or any threshold issues, this user connects to another BS whose utility value is less than U_{th}, indicating that RSSI of this BS is higher than δ_{rec} and that this BS has enough capacity. For the inactive users, in the case there are not any BS satisfying the utility threshold value and receiver sensitivity in the neighbor cells set, the inactive user registers to the BS with the highest utility value.
   - If the active user still does not attach to any BS, another option is to find non-neighbor cells. The same conditions previously described are applied.
   - When an active user does not attach to any BS in the above cases, it will be a waiting user in the BS with the highest utility value.

The proposed reduced set cell selection algorithm is presented by the flowchart diagram shown on the cell planning given in Fig. 2.

5 Simulation parameters

Five different scenarios are performed by considering user groups, PTT of the users, distribution of the users in the area, and different types of environments. Since the considered system is conventional, the channels are allocated to a specific user group in the cell.

Three different models are planned according to urban, suburban, and rural environments. Three different distributions of the users in the area depending on their mobility cases are considered. In the first one, 30% of the users are indoor users, 40% of the users are vehicle users, and 30%

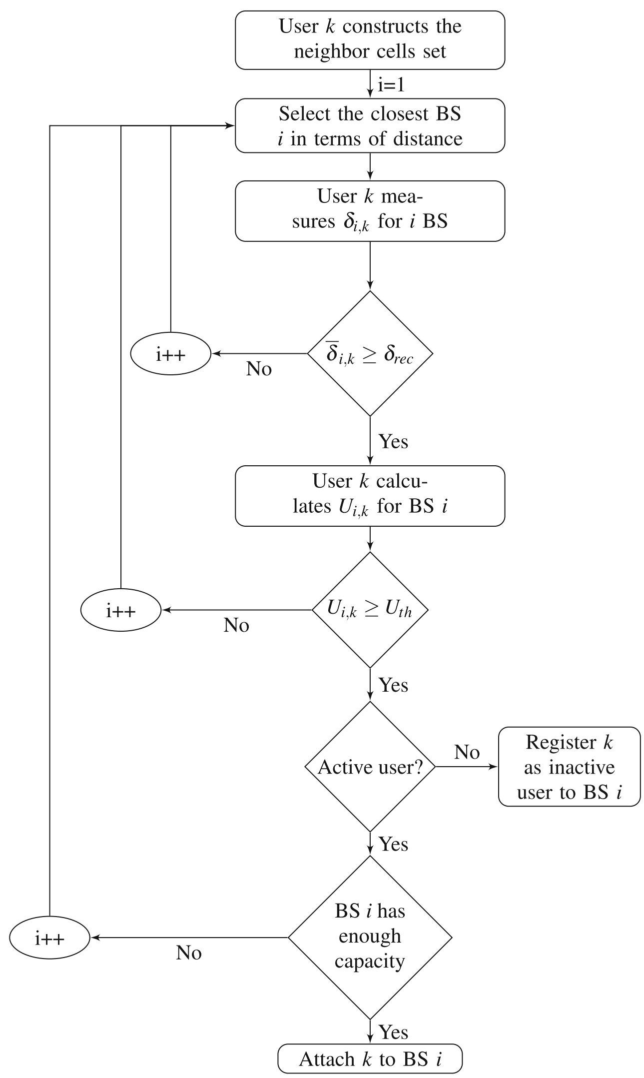

Fig. 2 The flowchart of the proposed reduced set traffic-based cell selection algorithm

Table 1 Normalization of RSSI values with r (.) function

Index for ranked RSSI	r (RSSI)
1	1
2	0.8571
3	0.7143
4	0.5714
5	0.4286
6	0.2857
7	0.1429

Table 3 Mapping of traffic load $UTL_{u,1}$ values for the initial cell selection with s (.) function

Range for $UTL_{u,1}$	s (UTL)	Index
0–0.3	1	1
0.3–0.5	0.86	2
0.5–1	0.71	3
1–1.06	0.57	4
1.06–1.10	0.43	5
1.10–1.20	0.29	6
1.20–upper	0.14	7
No channel	0	8

of the users are pedestrian users. In the second one, all users are vehicle users. In the last one, 50% of the users are indoor and 50% of the users are pedestrian. For all scenarios, the users demand voice application and one physical channel is allocated for each voice user.

The re-selection criterion of the users in mobility is performed according to the measured RSSI values. As a result of 6 measurements from the last 10 RSSI values which are below the re-selection threshold value, the users perform the cell re-selection process with the threshold value of −100 dBm.

Only the active users occupy the channels for the call duration. The active user who is called in a group is assigned to a call duration of $5 - 15$ s randomly within 1 min. The total duration of the simulation is 30 min. If the active user cannot attach to the chosen BS, it waits until there would be available capacity in this BS.

In the proposed algorithms, while calculating the utility values, the mapping procedures are applied according to the predefined $r(.)$, $f(.)$, and $s(.)$ functions. $r(.)$ and $f(.)$ are the mapping functions for the actual RSSI values which range between −65 dBm and −100 dBm in practical systems. The only difference between these two functions is the use of a linear and non-linear normalization, respectively.

The function $r(.)$ is used to map the RSSI values for the full set traffic-based cell selection algorithm. The RSSI values of all BSs in the set of $\mathbb{P}_k$ in Eq. 7 are sorted in descending order and are assigned to the normalized values proportionally to their sorted RSSI indexes given in Table 1. This table shows an example in which there are 7 BSs in the $\mathbb{P}_k$ set. The normalization of RSSI values is applied linearly according to the number of BSs in the set of $\mathbb{P}_k$. Since one of our goals is to attach the user to the BS with the highest RSSI value, the maximum RSSI is assigned to the highest normalized value.

The function $f(.)$ is used to map the RSSI values for the reduced set traffic-based cell selection algorithm. The RSSI values are divided into some intervals considering a non-linear mapping. Thus, the high RSSI values can be assigned to the high normalized values. The mapping of RSSI values with $f(.)$ function is given in Table 2.

For each BS, the $UTL_{u,t}$ value which represents the traffic intensity has a critical importance to calculate the utility value at the user side. All relevant information consisting of the total number of channels, the number of active and inactive users, and the total number of BSs to calculate $UTL_{u,t}$ are available at the BS u. Each BS calculates the $UTL_{u,t}$ value at every second and averages over the fixed time interval, T_f. Then, each BS broadcasts its traffic load value, $UTL_{u,t}$, at every T_f by using 3 bits. Based on these $UTL_{u,t}$ values, mapping is done considering the $s(.)$ function as in either Tables 3 or 4. When

Table 2 Mapping of RSSI values with f (.) function

RSSI values (dBm)	f (.)	Index
RSSI $\geqslant -65$	1	1
$-65 >$ RSSI $\geqslant -70$	0.88	2
$-70 >$ RSSI $\geqslant -75$	0.75	3
$-75 >$ RSSI $\geqslant -80$	0.63	4
$-80 >$ RSSI $\geqslant -85$	0.50	5
$-85 >$ RSSI $\geqslant -90$	0.38	6
$-90 >$ RSSI $\geqslant -100$	0.25	7
RSSI < -100	0.13	8

Table 4 Mapping of traffic load $UTL_{u,t}$ values with s (.) function

Range for $UTL_{u,t}$	s (UTL)	Index
0–0.2	1	1
0.2–0.3	0.86	2
0.3–0.4	0.71	3
0.4–0.5	0.57	4
0.5–0.6	0.43	5
0.6–0.8	0.29	6
0.8–1	0.14	7
No channel	0	8

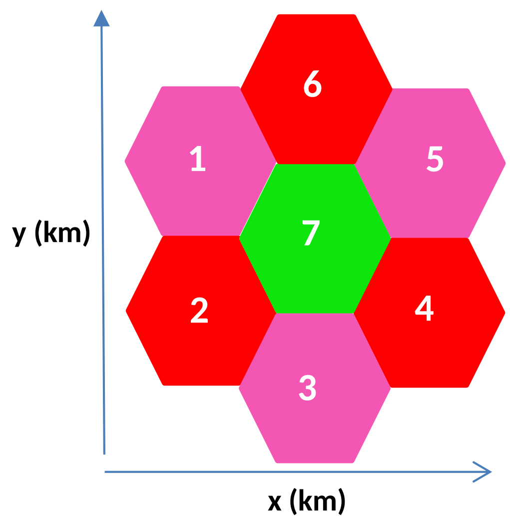

Fig. 3 System model for APCO25 conventional system in the urban area

there is no available channel, the BS broadcasts a zero value so that the user does not try to connect to this BS.

ITU Hata model [19, 20] is used, and extra building loss is added to the indoor users.

The path loss model for *urban environment* is given as follows:

$$PL_{u,k} = 69.55 + 26.16\log_{10} f_u - 13.82\log_{10} h_b \\ -(3.2(\log_{10}(11.75h_m))^2 - 4.97) + (44.9 - 6.55\log_{10} h_b) \\ \log_{10} R_{u,k} \quad [dB] \tag{13}$$

where f_u is the carrier frequency, the BS u, h_b represents the antenna height at the BS side, h_m is the antenna height at the user side, and $R_{u,k}$ is the distance between the user k and the BS u.

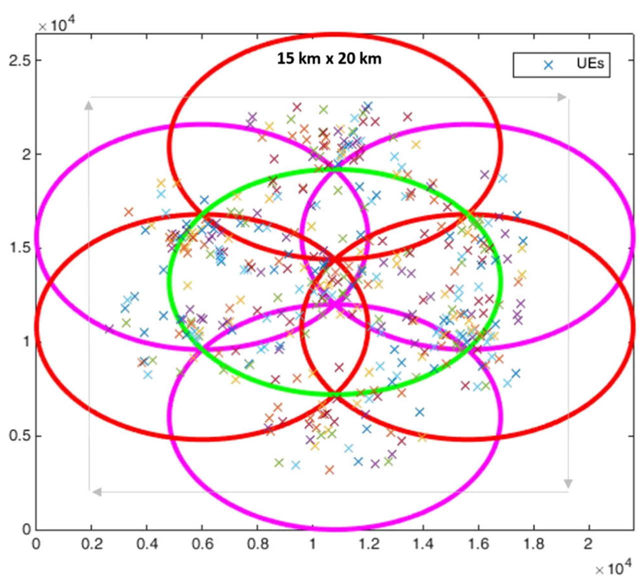

Fig. 4 Cell planning for APCO25 conventional system in the urban area

Table 5 Traffic-based urban area simulation parameters

Environment	Parameter	Setting
Urban	Area	15 km × 20 km
	Total number of groups	5
	Total number of users	400
	Total number of cells	7
	PTT	0.25
	Cell radius	6 km

The path loss model for *suburban environment* is given as follows:

$$PL_{u,k} = 69.55 + 26.16\log_{10} f_u - 13.82\log_{10} h_b \\ +(44.9 - 6.55\log_{10} h_b)\log_{10} R_{u,k} \\ -2(\log_{10}(\tfrac{f_u}{28}))^2 - 5.4 \quad [dB] \tag{14}$$

The path loss model for *rural environment* is given as follows:

$$PL_{u,k} = 69.55 + 26.16\log_{10} f_u - 13.82\log_{10} h_b \\ -(1.1\log_{10} f_u - 0.7)h_m + (1.56\log_{10} f_u - 0.8) \\ +(44.9 - 6.55\log_{10} h_b)\log_{10} R_{u,k} - 4.78(\log_{10}(f_u))^2 \\ +18.33\log_{10} f_u - 40.94 \quad [dB] \tag{15}$$

The system model of the urban area is shown in Fig. 3, and cell planning is given in Fig. 4. The same color represents the same frequency. In this model, the frequency reuse factor is 3.

In the urban environment, there are 5 different user groups and the PTT of users is 0.25. The number of available channels per cell, M_u, is determined as 6, and one of these channels is used as a control channel. The simulation parameters for the urban area are given in Table 5.

The system model of the suburban area is given in Fig. 5, and cell planning is given in Fig. 6. In this model, the frequency reuse factor is 3.

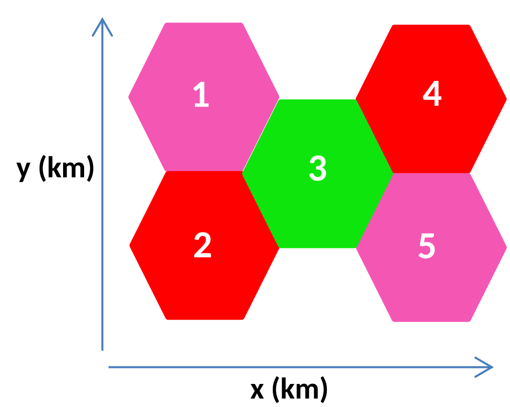

Fig. 5 System model for APCO25 conventional system in the suburban area

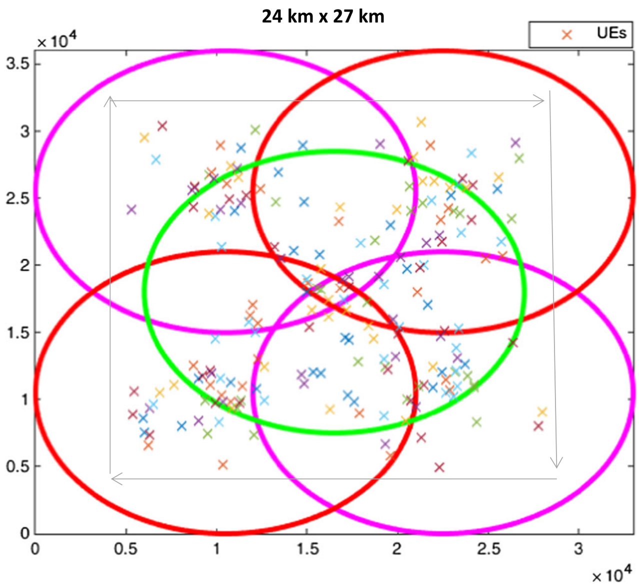

Fig. 6 Cell planning for APCO25 conventional system in the suburban area

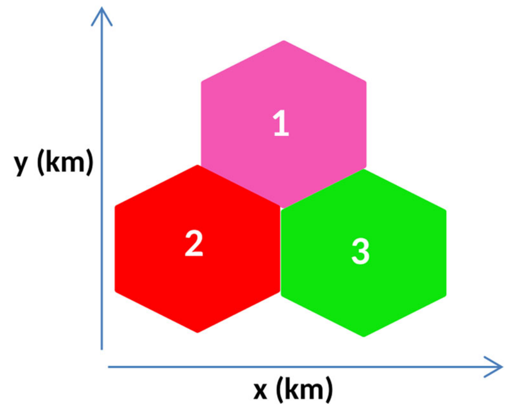

Fig. 7 System model for APCO25 conventional system in the rural area

In the suburban environment, there are 3 different user groups, and the PTT of users is 0.21. The number of available channels per cell is determined as 4, and one of these channels is used as a control channel. There are 3 channels in each BS, and if channel one is given in one group, channels two and three might be assigned to other groups. The simulation parameters for the suburban area are given in Table 6.

The system model of the rural area is indicated in Fig. 7, and the cell planning is given in Fig. 8. In this model, the frequency reuse factor is set to 3.

In the rural environment, there are 4 different user groups, and the PTT of users is 0.32. The number of available channels per cell is determined as 5, and one of these channels is used as a control channel. The simulation parameters for the rural area are given in Table 7.

The simulation parameters for APCO25 conventional system are given in Table 8.

The simulation results of the proposed traffic-based cell selection algorithms with different weights are compared

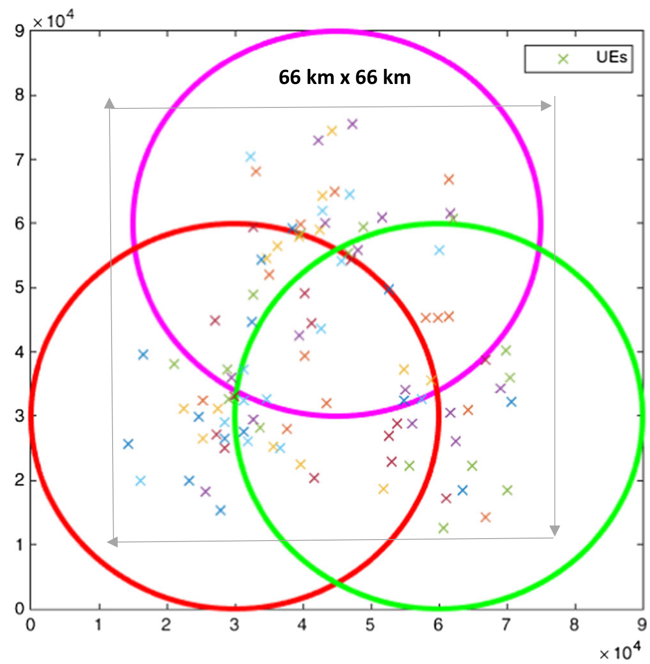

Fig. 8 Cell planning for APCO25 conventional system in the rural area

Table 6 Traffic-based suburban area simulation parameters

Environment	Parameter	Setting
Suburban	Area	24 km × 27 km
	Total number of groups	3
	Total number of users	200
	Total number of cells	5
	Push-to-talk (PTT)	0.21
	Cell radius	10.5 km

Table 7 Traffic-based rural area simulation parameters

Environment	Parameter	Setting
Rural	Area	66 km × 66 km
	Total number of groups	4
	Total number of users	100
	Total number of cells	3
	PTT	0.32
	Cell radius	30 km

Table 8 Simulation parameters

Parameters	System APCO25 conventional
Transmit power (P_u^t)	50 dBm (100 W)
Channel spacing (Δf)	12.5 kHz
Modulation bandwidth	10 kHz
Carrier frequency	415 MHz
Transmitter antenna gain (GTA)	8 dB
Transmitter cable loss	2 dB
Receiver antenna gain (GRA)	–2 dBi
BS antenna height (h_b)	30 m
MS antenna height (h_m)	1.5 m
Building loss (LBU_k)	16.5 dB
Body loss (LB_k)	10 dB
Receiver sensitivity (δ_{rec})	–116 dBm
Noise spectral density (N_0)	–174 dBm/Hz
Weight (w)	0.1, 0.5 and 0.7
Utility threshold (U_{th})	0.5
Fixed time interval (T_f)	1 min
Shadowing standard deviation	6 dB

to the conventional cell selection algorithms in the urban, suburban and rural areas. The simulation results are provided based on different metrics including the average waiting time, the number of re-selections, the number of connection requests, the RSSI measurements counter, load fairness index, and outage probability on BER.

- *The average waiting time* represents the average delay for the active users that cannot attach to any BS due to capacity.
- *The number of re-selections* refers to the average number of changing attached BSs for the pedestrian and vehicle users due to the cell re-selection process.
- *The number of connection requests* shows the average number of BSs that the user sends to a connection request during the simulation time.
- *The RSSI measurements counter* is the average number of RSSI values that the user measures to be connected to the BS.
- *Load fairness index* shows the fairness of the users' association among BSs and is calculated by

$$LFI = \frac{(N_u)^2}{U\sum_{j=1}^{U}(A_u^2 + F_u^2)}. \quad (16)$$

  where A_u and F_u are the number of the active and inactive users attaching to the BS u, respectively.
- In addition, *BER performances* of all algorithms under Rayleigh fading channels for different traffic cases are examined. BER is required to be below 0.05 for the voice users to guarantee service quality.

6 Simulation results

Table 9 gives the simulation results in the urban environment for the first distribution of the users. According to the results, the proposed reduced set traffic-based cell selection algorithm attaches to a BS having less number of RSSI measurements. In particular, the reduced set with $w = 0.1$ traffic-based algorithm has the lowest RSSI measurements counter and is reduced by 85% compared with the full set traffic- and SINR-based cell selection algorithms. In addition, the reduced set with $w = 0.1$ traffic-based algorithm has the lowest average number of re-selections. The average waiting time is decreased by 12.97% with the full set $w = 0.1$ and 15.28% with the reduced set $w = 0.1$ traffic-based algorithms compared to the RSSI-based cell selection. The results on load fairness index show well-balanced user distribution among the cells for the full and the reduced set traffic-based algorithms.

Table 9 Traffic based simulation results for the urban area with 30% indoor users, 40% vehicle users and 30% pedestrian users

Algorithms	Load fairness index	RSSI measurements counter	Number of connection requests	Average waiting time (sec)	Number of Re-selections	Outage probability
SINR BASED	0.51923	7	1.0324	5.8975	38.3	0.031
RSSI BASED	0.95592	6.8962	1.0252	4.6382	18.2825	0.040
FULL SET, $w = 0.1$	0.9819	**7**	**1**	**4.0368**	**24.09**	0.046
FULL SET, $w = 0.5$	0.96871	7	1	4.3232	18.99	0.038
FULL SET, $w = 0.7$	0.95783	7	1	4.4133	18.3487	0.035
REDUCED SET, $w = 0.1$	0.95422	**1.0507**	**1**	**3.9295**	**14.73**	0.023
REDUCED SET, $w = 0.5$	0.97356	1.6912	1	4.1378	18.5613	0.036
REDUCED SET, $w = 0.7$	0.97806	3.6254	1	4.328	20.7062	0.043

The best ones are in bold in each metric

Table 10 Traffic based simulation results for the suburban area with 30% indoor users, 40% vehicle users and 30% pedestrian users

Algorithms	Load fairness index	RSSI measurements counter	Number of connection requests	Average waiting time (sec)	Number of re-selections	Outage probability
SINR BASED	0.72839	5	1.0166	4.0917	21.8975	0.005
RSSI BASED	0.96785	4.9588	1.018	3.8734	11.505	0.022
FULL SET, $w = 0.1$	0.98127	**5**	**1**	**3.3607**	**16.59**	0.045
FULL SET, $w = 0.5$	0.97275	5	1	3.531	12.505	0.027
FULL SET, $w = 0.7$	0.96851	5	1	3.6591	11.525	0.022
REDUCED SET, $w = 0.1$	0.97385	**1.075**	**1**	**3.4266**	**9.5175**	0.020
REDUCED SET, $w = 0.5$	0.98024	1.8584	1	3.5179	12.4925	0.027
REDUCED SET, $w = 0.7$	0.96812	3.6359	1	3.5635	12.4375	0.032

The best ones are in bold in each metric

Table 11 Traffic based simulation results for the rural area with 30% indoor users, 40% vehicle users and 30% pedestrian users

Algorithms	Load fairness index	RSSI measurements counter	Number of connection requests	Average waiting time (sec)	Number of re-selections
SINR BASED	0.99072	3	1.0184	3.3599	1.615
RSSI BASED	0.99072	2.8968	1.0184	3.3599	1.615
FULL SET, $w = 0.1$	0.98883	**3**	**1**	**2.7313**	**4.875**
FULL SET, $w = 0.5$	0.99362	3	1	3.1214	1.96
FULL SET, $w = 0.7$	0.99143	3	1	3.1599	1.62
REDUCED SET, $w = 0.1$	0.99093	**1.3603**	**1**	**2.8406**	**1.575**
REDUCED SET, $w = 0.5$	0.9923	1.9369	1	2.8953	2.485
REDUCED SET, $w = 0.7$	0.99278	2.3175	1	3.0281	2.005

The best ones are in bold in each metric

Table 12 Traffic based simulation results for the rural area with only vehicle users

Algorithms	Load fairness index	RSSI measurements counter	Number of connection requests	Average waiting time (sec)	Number of re-selections
SINR BASED	0.9831	3	1.0208	2.9323	4.6924
RSSI BASED	0.9831	2.9412	1.0208	2.9323	4.6924
FULL SET, $w = 0.1$	0.98563	**3**	**1**	**2.8263**	**9.0284**
FULL SET, $w = 0.5$	0.98437	3	1	2.8997	4.9224
FULL SET, $w = 0.7$	0.98311	3	1	2.9307	4.6964
REDUCED SET, $w = 0.1$	0.9839	**1.1393**	**1**	**2.8425**	**3.748**
REDUCED SET, $w = 0.5$	0.98614	1.833	1	2.858	5.5104
REDUCED SET, $w = 0.7$	0.98509	2.512	1	2.8938	5.0632

The best ones are in bold in each metric

Table 10 shows the simulation results in the suburban environment for the first distribution of the users. The average waiting time is reduced by 13.24% with the full set $w = 0.1$ and 11.54% with the reduced set $w = 0.1$ traffic-based algorithms compared to the RSSI-based cell selection. Moreover, the reduced set with $w = 0.1$ traffic-based algorithm decreases RSSI measurements counter by 78.5% compared to the full set traffic- and SINR-based algorithms.

The rural environment results for the first distribution of the users are given in Table 11. The average waiting time is reduced by 18.71% for the full set $w = 0.1$ and 15.46% for the reduced set $w = 0.1$ traffic-based algorithms compared to the RSSI- and SINR-based cell selection. In addition, RSSI measurements counter is reduced by 54.7% with the reduced set $w = 0.1$ traffic-based algorithm compared to the full set traffic- and SINR-based algorithms. The reduced set with $w = 0.1$ traffic-based algorithm provides the lowest number of re-selections. Thus, the BSs perform the cell re-selection process without any delay. Since there is no interference in the rural system, the SINR-based cell selection gives the same performance as the RSSI-based algorithm.

Table 12 indicates the simulation results for the second distribution of the users in the rural environment. For all cell selection algorithms, the number of re-selections is increased because the vehicle users can frequently require cell re-selections compared to the other scenarios. The reduced set with $w = 0.1$ traffic-based algorithm gives the lowest number of re-selections. The average waiting time is reduced by 3.61% with the full set $w = 0.1$ and 3.06% with the reduced set $w = 0.1$ traffic-based algorithms compared to the RSSI- and SINR-based cell selection. Moreover, RSSI measurement counter is reduced by 62% with the reduced set $w = 0.1$ traffic-based algorithm compared to the full set and SINR-based cell selection algorithms.

The simulation results in Table 13 are those of the third distribution of the users in the urban environment. For all cell selection algorithms, the number of re-selections is decreased because the low mobility case is provided compared to the previous scenarios. The reduced set with $w = 0.1$ traffic-based algorithm has the lowest average number of re-selection and the lowest RSSI measurement counter which is reduced by 83.95% compared to the full set traffic- and SINR-based algorithms. The average waiting time is decreased by 6.54% with the full set $w = 0.1$ and 5.97% with the reduced set $w = 0.1$ traffic-based algorithms compared to the RSSI-based algorithm.

The proposed full set and the reduced set traffic-based algorithms with their corresponding weights achieve the lowest number of connection requests. This means that the user is registered to the BS on the first trial on average for all scenarios. Moreover, the required outage probability on BER is satisfied by all cell selection algorithms.

7 Conclusion

PMR systems are designed for the communication between public safety users for the voice and data transmission in emergency situations. We have proposed two efficient traffic-based cell selection and re-selection methods for APCO25 conventional–based PMR systems. We have evaluated the simulation results in urban, suburban, and rural areas. For the proposed cell selection algorithms, the utility values are calculated based on RSSI values and traffic load to reduce the waiting time while establishing reliable transmission. It has been shown that the proposed full set and reduced set traffic-based cell selection algorithms significantly outperform the conventional ones in terms of the average waiting time, the number of connection requests, and the number of re-selections, which are the critical parameters to design efficient APCO25 conventional–based PMR systems.

Table 13 Traffic based simulation results for the urban area with 50% indoor and 50% pedestrian users

Algorithms	Load fairness index	RSSI measurements counter	Number of connection requests	Average waiting time (sec)	Number of re-selections	Outage probability
SINR BASED	0.72487	7	1.0239	5.2316	5.8124	0
RSSI BASED	0.9741	6.3701	1.0064	4.0967	0.3796	0
FULL SET, $w = 0.1$	0.98943	**7**	**1**	**3.8288**	**1.6511**	0.0067
FULL SET, $w = 0.5$	0.98262	7	1	3.923	0.5309	0.0003
FULL SET, $w = 0.7$	0.97602	7	1	4.0404	0.4153	0.0001
REDUCED SET, $w = 0.1$	0.98496	**1.1235**	**1**	**3.8522**	**0.254**	0.0019
REDUCED SET, $w = 0.5$	0.98432	1.5699	1	3.8901	0.4373	0.0039
REDUCED SET, $w = 0.7$	0.97887	2.0865	1	3.9925	0.4263	0.0017

The best ones are in bold in each metric

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