IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 17, 2018, accepted September 7, 2018, date of publication September 13, 2018, date of current version October 8, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2869917

CHESS-PC: Cluster-HEad Selection Scheme With Power Control for Public Safety Networks

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This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant NRF-2015R1 D1A1A01059473 and Grant NRF-2018R1D1A1B07049043.

ABSTRACT Recently, many wireless network technologies have received impressive attention from public safety networks (PSNs) and public safety communications. Wireless network consists of battery-operated nodes; the power consumption of the network is one of the key issues to carefully address. Several clustering approaches have been adopted in wireless networks to tackle the power consumption issue and they have shown electrifying results. Alongside different clustering approaches, appropriate cluster-head (CH) selection plays a crucial role in making wireless networks more power-efficient. However, in existing studies, clustering was not implemented in PSNs. In this paper, we propose a clustering-based Cluster-HEad Selection Scheme with Power Control (CHESS-PC) for PSN. The proposed scheme utilizes Fuzzy C-Means as a clustering tool. The results show that the proposed scheme significantly reduces the power consumption of the network. The proposed scheme achieved an efficiency improvement of 30.24% and 20.46% compared with the non-clustering based and FCM clustering-based conventional schemes, respectively.

INDEX TERMS Cluster-head selection, FCM clustering, public safety networks, power control.

I. INTRODUCTION

In recent years plenty of research has sought to improve communication in public safety networks (PSN), also referred to as public safety communications. PSN is a type of wireless communications network which is deployed at the disaster site and it is comprised of several nodes called Emergency First Responders (EFRs). EFRs include rescue officers, firefighters, medical staff, and police officers. They need to share voice and data information among themselves as well as with the concerned authorities to timely coordinate situational awareness [1]. EFRs are progressively being furnished with remote tablets, handheld PCs, and versatile camcorders to enhance their effectiveness, sensitivity, and capacity to immediately work together with headquarters, collaborators, and different agencies. Communication is an important parameter during a disaster or emergency. A variety of wireless communications technologies are being increasingly used by EFRs to respond to and avoid incidents [2].

When a disaster situation occurs, the communication network coverage and the power supply system are severely affected, and it is of vital importance that the deployable wireless network i.e. PSN should be power-efficient [3]–[5]. Furthermore, proper information on current situation from disaster site must be delivered effectively and timely to the concerned control center [5]. The use of information and communications technologies for PSN has increased remarkably. Numerous contributions have been made from different disciplines [6], [7]. Many wireless technologies have been utilized for efficient PSN. The applications of Worldwide Interoperability for Microwave Access technology and relay-based communications have been investigated in [8]–[10]. A sort of ad-hoc wireless typology that is especially applicable to PSN is the use of a mobile ad-hoc network [11]. In [12], the use of partial and full mesh networks is described along with their advantages and disadvantages. Wang *et al.* [13], Ferru and Baldini [14], and Akyildiz *et al.* [15] surveyed and described the usage of WLAN applications, cognitive radio and spectrum sharing principles, and cellular communication to enhance public safety communications. This research has proved that public safety services can be improved by adopting these technologies.

Beside these technologies, Long-Term Evolution (LTE) technology has become a strong candidate technology for future public safety networks. A comparison between terrestrial trunked radio and LTE is provided in [16], which shows LTE to be the choice for future PSN. Some working groups of the 3GPP LTE Release 11 and 12 are addressing areas that are tightly coupled to public safety communications to standardize different protocols and technologies for public safety networks, commonly called Public Safety LTE [17]–[19].

Disaster situations lead to remarkably high traffic loads and a lack of network coverage and capacity. To overcome such issues, the cellular network providers allocate some resources to be used by EFRs only. In this paper, we consider a situation in which EFRs will use the resources that are allocated by a cellular network provider during a disaster scenario.

The quality of a wireless communications network is tested by various parameters, of which power consumption is one very important parameter. The wireless network is consisted of battery-operated nodes. In any wireless network, most of the power is consumed by the data transmission. Similarly, a PSN is also comprised of battery-limited nodes i.e. EFRs. Since, the PSN is deployed at a disaster site and it is almost impossible to have battery-recharging capability at a disaster site as the power supply system is degraded or destroyed [20]. Therefore, it is crucial to control the transmission power to make a power-efficient PSN.

In a typical wireless network, the nodes communicate directly with the control center (CC). This direct communication between nodes and CC makes the network power-inefficient due to the large distances between nodes and CC. The power consumption issue needs a careful concentration, for that, clustering techniques are adopted in wireless networks which showed promising results to overcome the issue [21]–[23]. This means that the network is divided into several clusters and each cluster contains a cluster-head (CH). Every cluster-member communicates with the corresponding CH instead directly with CC. Because the distances between cluster-members and CH are shorter than the distances between cluster-members and CC, there will be a remarkable reduction in the network power consumption.

Several clustering techniques have been adopted in wireless networks and been able to make the network power-efficient. Low-Energy Adaptive Clustering Hierarchy (LEACH) [24], is a decentralized clustering approach with two-hop topology. In LEACH, a node is randomly selected as CH for a cluster. It does not guarantee uniform distribution of CHs in the network. However, it improves network lifetime as compared to the minimum-transmission-energy [25] or direct communication technique; also called non-clustering based technique [26]. An enhancement to LEACH is Low-Energy Adaptive Clustering Hierarchy Centralized [27]. It works similar to LEACH but in a centralized fashion. Other clustering approaches based on LEACH are Power-Efficient GAthering in Sensor Information Scheme [28], the Threshold-sensitive Energy Efficient sensor Network (TEEN) [29], Adaptive Periodic Threshold-sensitive Energy Efficient Network (APTEEN) [30], and Hybrid Energy-Efficient Distributed [31] protocols.

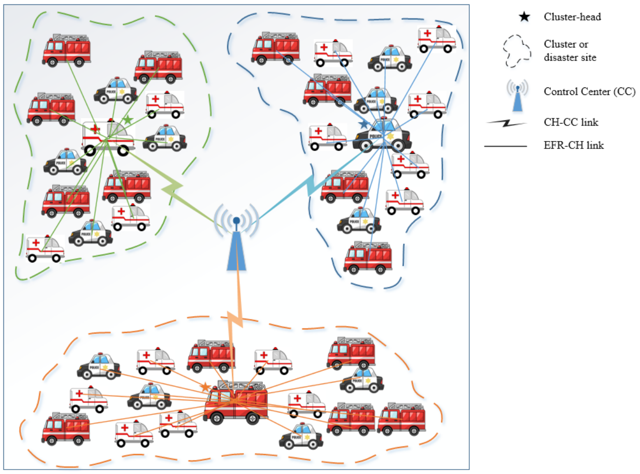

FIGURE 1. **Application of clustering technique for PSN.**

These approaches do enhance the network lifetime by improving the network efficiency, but they do not optimize the formation of clusters.

Moreover, the k-means and Fuzzy C-Means (FCM) are other more-efficient clustering techniques than the LEACH-based approaches. Pachlor and Shrimankar [32] proposed a k-means clustering-based protocol and the comparison results clearly showed that the k-means performs better than LEACH. In [33], FCM is used which outperformed the LEACH-based protocol. These both clustering techniques strive to find the center of a cluster. The techniques initiate with k cluster center points, then other nodes are allotted membership values based on their distance from a cluster-center. These membership values show to what degree a node is a member of a cluster. These two techniques are almost similar. However, k-means makes clusters by hard-partitioning the nodes, whereas FCM uses soft partitioning, which means that one node can be a cluster-member of one or more clusters, based on the degree of membership assigned. In addition to that, the computational complexity of k-means is $O(ndci)$ whereas for FCM it is $O(ndc^2i)$. It means that FCM is more complex than k-means. However, FCM performs better than k-means [34] as it uses soft-partitioning to create efficient clusters. Therefore, in this paper we will adopt FCM to split the public safety network into several clusters. A cluster-based PSN is illustrated in Fig. 1.

Alongside the suitable clustering technique, the CH selection is a critical part of cluster-based wireless communication networks. The position of the CH plays a vital role in network performance, not the least regarding network power consumption. Appropriate position of the CH makes a power-efficient wireless communications network. Kozal *et al.* [35] used the clustering approach to tackle the energy tradeoff and showed that the proposed scheme outperforms the conventional schemes. However, there are a few drawbacks in [27], such as: (i) the authors did not mention the exact clustering approach and (ii) the CH selection is based on the distance

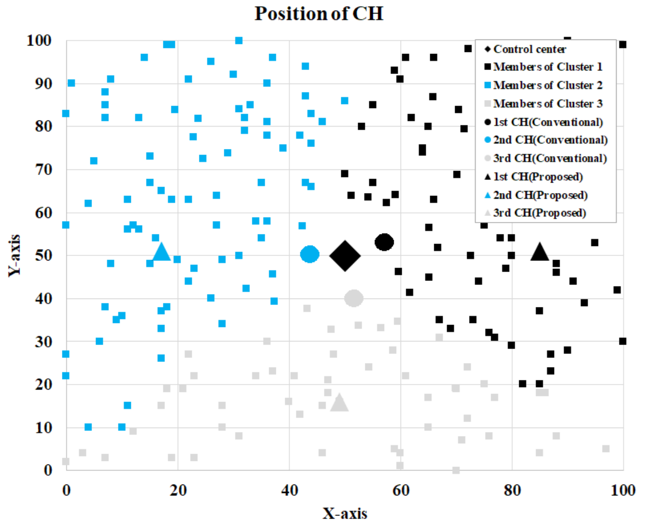

FIGURE 2. System model.

between the node and CC. In this way, the node that is closer to CC will be selected as CH. Maity *et al.* [36] and Kumar *et al.* [37] adopted FCM as a clustering tool. The network is efficiently partitioned into clusters due to FCM. In [36], however, there are some flaws, i.e., (i) even after clustering, each node communicates with CC and (ii) there is no evidence of a CH selection process. In [37], however, CH is selected based only on the residual energy of the node. Due to this selection criterion, there is always the chance that CH may be selected closer to CC or farther from CC. In [35]–[37], the CH is given priority to save its power. However, a significant decrease in the power consumption of the CH-CC communications does not guarantee an overall network power efficiency, because there are more frequent communications between cluster-member and CH than between CH and CC. Therefore, giving priority to cluster-members, i.e., selecting CH near cluster-members, will make the network more power-efficient. To overcome these power-inefficiency issues, we propose a FCM-based CH selection and power control scheme for public safety networks.

II. SYSTEM MODEL

We consider a 100 $m \times 100$ m fully connected network that consists of N randomly distributed nodes, EFRs, and a CC, as shown in Fig. 2. All EFRs have same battery-life. They gather information about the current situation at a disaster site and send this information to CC via a CH. The CH works as a relay from the cluster-members to CC. CC is responsible for collecting location-based information, dividing the network into clusters, selecting appropriate CH, and allocating suitable transmission power to EFRs.

The locations of the i-th and j-th EFRs are denoted by φ_i and φ_j, respectively, whereas their xy-coordinates are denoted by $\varphi_i(x_i, y_i)$ and $\varphi_j(x_j, y_j)$, respectively, while $\varphi_{CC}(x_{CC}, y_{CC})$ represents the xy-coordinates of CC, which is located at the center of the network i.e., $\varphi_{CC}(x_{CC}, y_{CC}) = \varphi_{CC}(50, 50)$.

The network is clustered into M clusters. A CH is selected by CC for each cluster, using the proposed scheme. The cluster members transmit their data to CC via CH. CH collects the data from its cluster members and forwards the data to CC.

All the EFRs send their unique ID and location information, i.e., xy-coordinates, to CC. Once CC collects the location information, it starts clustering the network, selects CHs, and calculates the transmission power. During the calculation of the transmission power, the quality of service (QoS) is also considered.

III. PROPOSED SCHEME

The proposed scheme is carried out into three phases. In the first phase, clustering is performed, and the network is divided into M clusters. In the second phase, an appropriate CH is selected for each cluster. In the final phase, a suitable transmission power is calculated for each cluster. The proposed scheme is described in Scheme 1.

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Scheme 1: Power-Efficient Public Safety Network
Phase1 – Clustering
    • Select number of clusters $M$
    • Initialize membership values $\mu_{i,m}$ and centers of clusters $o_m$
    • Initialize the membership function $\mu_{i,m}^k = \frac{1}{\sum_{l=1}^{M}\left(\frac{\|\varphi_i - o_m\|}{\|\varphi_i - o_l\|}\right)^{\frac{2}{p-1}}}$
    • At the $k$th step: Calculate the centers of the clusters $o_m^k = \frac{\sum_{i=1}^{N} \mu_{i,m}^p \cdot \varphi_i}{\sum_{i=1}^{N} \mu_{i,m}^p}$
    • Update $\mu_{i,m}^k$ to $\mu_{i,m}^{k+1}$
    • If $\max_{i,m}\left\{\left|\mu_{i,m}^{k+1} - \mu_{i,m}^k\right|\right\} < \kappa$ then STOP; else REPEAT
Phase2 – CH Selection
    • Calculate the Euclidean distance between each pair of EFRs $i, j$ in every cluster $m$ using $d_{i,j}^m = \left\|\varphi_i^m - \varphi_j^m\right\|$
    • Calculate $\beta^m$ using $\beta^m = \min_{i',o} d_{i',o}^m$
    • Select $EFRi'$ as $CH$
    • If $d_{i',o}^m = \beta^m$
    • Then $CH \leftarrow EFRi'$
Phase3 – Power allocation
    • Calculate $\gamma^m$ using $\gamma^m = \max_{CH,i} d_{CH,i}^m$
    • Allocate transmission power to every cluster using $P_t^m(dBm) = 10\log_{10}\left(\alpha_{target}\gamma^m\right)$
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A. CLUSTERING

The network is clustered using the FCM clustering algorithm [38], which is commonly used in pattern recognition. It has been adopted to wireless communications and proved effective to enhance the performance. It assigns a degree of membership value to every data point, relating to the relevant cluster center. The sum of all data points' membership values should yield a value of 1. FCM depends on minimization of the objective function

$$\min_{\mu^{k}_{i,m},\, o^{m}_{k}} \left(\Omega_p\right), \tag{1}$$

where $\mu^{k}_{i,m}$ is the membership value of i-th EFR in the m-th cluster after k iterations and o^{k}_{m} is the updated center of the m-th cluster after k iterations. Then

$$\Omega_p = \sum_{i=1}^{N} \sum_{m=1}^{M} \mu^{p}_{i,m} \left\|\varphi_i - o_m\right\|^2, \tag{2}$$

where p is the fuzziness exponent (any real number greater than 1), N and M show the number of EFRs and clusters, respectively, φ_i is the position of the i-th EFR, and o_m the center of the m-th cluster. The membership value of φ_i in cluster m, is denoted by $\mu_{i,m}$ which falls in the range of [0, 1] for each EFR in the network with respect to every cluster-center. $\|*\|$ is the Euclidean norm expressing the distance of EFR from the cluster-center.

Fuzzy clustering is carried out through an iterative optimization of the objective function Ω_p with the update of membership values $\mu_{i,m}$ and the cluster-centers o_m by

$$\mu^{k}_{i,m} = \frac{1}{\sum_{l=1}^{M} \left(\frac{\|\varphi_i - o_m\|}{\|\varphi_i - o_l\|}\right)^{\frac{2}{p-1}}}, \tag{3}$$

and

$$o^{k}_{m} = \frac{\sum_{i=1}^{N} \mu^{p}_{i,m} \cdot \varphi_i}{\sum_{i=1}^{N} \mu^{p}_{i,m}}, \tag{4}$$

where k represents the k-th iterative step. This iteration operation will stop if $\max_{i,m} \left\{\left|\mu^{k+1}_{i,m} - \mu^{k}_{i,m}\right|\right\} < \kappa$, where κ is the termination criterion and lies in [0, 1]. As the clustering operation is finished, the cluster-head selection process starts.

B. CLUSTER-HEAD SELECTION

The CH selection is a crucial phase of the proposed scheme because the next phase i.e., transmission power calculation is based on an appropriate location of CH. If the CH is selected closer to CC, then the cluster-members will consume more power for transmitting their data to CH. However, if CH is located closer to the center of the cluster, then the distance from cluster-members to CH will be reduced significantly and cluster-members will need much lower transmission power for data transmission to CH.

Because the communications between cluster-members and CH are very frequent, we have given priority to the cluster-members during the CH selection procedure. Our target is to select CH near the cluster-center. Even though, by selecting CH closer to the cluster-center, the distance between CH and CC is increased, the overall power-consumption will be reduced drastically, as the cluster-members-CH communications are more frequent than CH-CC communications. This results in a more power-efficient system.

To select appropriate EFR as CH, CC first needs to calculate the Euclidean distance between two EFRs

$$d^{m}_{i,j} = \left\|\varphi^{m}_{i} - \varphi^{m}_{j}\right\|, \tag{5}$$

where $d^{m}_{i,j}$ is the Euclidean distance between the i-th and j-th EFRs in the m-th cluster and φ^{m}_{i} and φ^{m}_{j} are positions of the EFRs i and j in cluster m, respectively.

The EFR i' that is located at $\varphi_{i'}\left(x_{i'}, y_{i'}\right)$, is selected as a CH if

$$d^{m}_{i',o} = \beta^{m}, \tag{6}$$

where

$$\beta^{m} = \min d^{m}_{i',o}, \tag{7}$$

and β^{m} is the distance-offset factor, which is used to find the minimum distance $d^{m}_{i',o}$ between node i' and the center of the m-th cluster. This leads us to select an appropriate EFR that is closer to the center of cluster as CH, such that $\varphi_{CH}\left(x_{CH}, y_{CH}\right) \leftarrow \varphi_{i'}\left(x_{i'}, y_{i'}\right)$. Based on this information, the transmission power will be calculated for each cluster.

C. TRANSMISSION POWER CALCULATION

The position of CH plays an important role in calculating a suitable transmission power for cluster-members as well as for CH. The quality of service (QoS) is also kept in mind while calculating the transmission power.

To calculate the transmission power, CC uses

$$P^{m}_{t} = \alpha_{target}\gamma^{m}, \tag{8}$$

where α_{target} is the target received signal strength (RSS) that is used to guarantee QoS. γ^{m} is the maximum distance from a CH to a cluster-member in the m-th cluster, i.e.,

$$\gamma^{m} = \max d^{m}_{CH,i}. \tag{9}$$

In terms of dBm, the transmission power is

$$P^{m}_{t}\,(dBm) = 10\log_{10}\left(\alpha_{target}\gamma^{m}\right). \tag{10}$$

In the end, CC has information that contains the location of CH for each cluster and the transmission power for each cluster. That information will be broadcasted by CC to all EFRs in the network.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed scheme, we first calculate the network power, i.e., the power consumed by the network. The network power is calculated using

$$P_{network} = P_{cluster} + P_{CH}. \tag{11}$$

$P_{cluster}$, which is the total power consumed by the clusters, can be calculated as

$$P_{cluster} = \sum_{m=1}^{M} \sum_{i=1}^{I} P_{i,m}, \tag{12}$$

where M and I represent the total number of clusters and the number of EFRs in a cluster, respectively, and $P_{i,m}$ is the

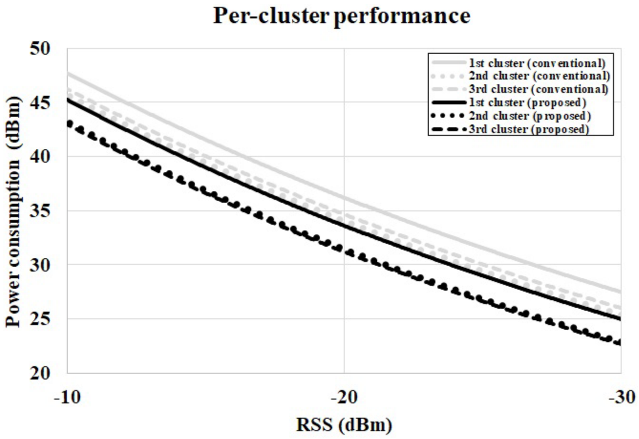


FIGURE 3. Comparison of power consumed by individual cluster when clusters = 3 and the number of EFRs = 200.

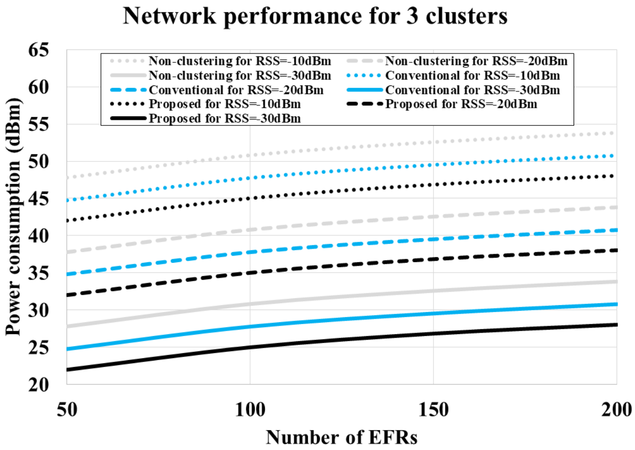


FIGURE 4. Power consumption when the number of EFRs is increasing, i.e. 50, 100, 150, and 200.

power consumed by the $i$thm EFR in cluster m. P_{CH} denotes the power consumed by all CHs, i.e.,

$$P_{CH} = \sum_{m=1}^{M} P_m, \tag{13}$$

where P_m is the power consumed by a CH for its data transmission to CC.

We have compared the performance of our scheme with non-clustering-based and conventional clustering-based approaches [35]–[37].

A. PER-CLUSTER POWER CONSUMPTION

To calculate the total power consumed by the network, we first calculate the total power consumed by the individual cluster. It is assumed that the number of EFRs is 200, randomly distributed in 3 clusters, while the RSS values are set to −10, −20, and −30 dBm to guarantee QoS. Figure 3 shows the performance of our proposed scheme compared with conventional clustering-based approaches. It is clear from the figure that the proposed scheme performs better than the conventional schemes in terms of per-cluster power consumption. The figure also shows that the power consumed by the 1st cluster using conventional clustering-based approaches to guarantee an RSS of −10 dBm, is 51.6 W, whereas the proposed scheme consumes only 28.9 W. This means that the proposed scheme saves 22.7 W for the 1st cluster of the network. Similarly, the proposed scheme saves 14 and 19.7 W for the 2nd and 3rd clusters, respectively.

B. NETWORK POWER CONSUMPTION

To evaluate the network performance, we show the influences on the network power consumption by the number of EFRs, number of clusters, and RSS values. For that purpose, we consider different setups.

1) SETUP 1: DIFFERENT NUMBER OF EFRs

In this setup, to show the effect the number of EFRs has on the network performance, we consider 50, 100, 150, and 200 EFRs, and the number of clusters to be 3. The results are shown for different values for the target RSS. As shown in Fig. 4, the difference in power consumption using the proposed scheme when compared with the non-clustering scheme and conventional schemes is noticeable. For 50 EFRs the proposed scheme saves 44.7 and 14.2 W against the non-clustering scheme and conventional schemes, respectively, to guarantee −10 dBm. However, as the number of EFRs increases, the proposed scheme saves more power. For 200 EFRs, to guarantee the same RSS value, we save 178.3 W and 54.5 W compared with the non-clustering and conventional schemes, respectively. This proves that the proposed scheme is suitable even for a large number of EFRs.

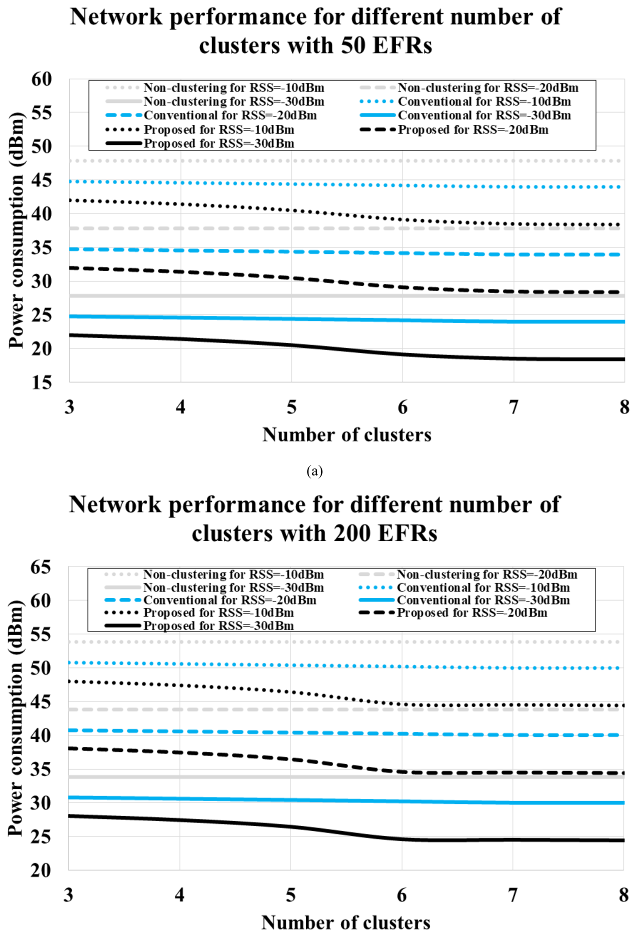
2) SETUP 2: DIFFERENT NUMBER OF CLUSTERS

In this setup, to show the effect the number of clusters has on the performance, we consider the number of clusters to be 3, 4, 5, 6, 7, and 8. Furthermore, this setup is carried out for two different settings: a) with low density of EFRs, i.e., 50 EFRs as shown in Fig. 5(a), and b) with high density of EFRs, i.e., 200 as shown in Fig. 5(b).

The performance evaluations are carried out for different values of the target RSS. As shown in Fig. 5(a), when the network is clustered into 8 clusters the power consumed by the network using a non-clustering scheme to guarantee a target RSS of −20 dBm is 6.94 W, whereas the proposed scheme consumes only 693 mW. This proves that the proposed scheme can save 6.247 W.

Thus, the proposed scheme consumes 693 mW to guarantee −20 dBm, which is only 88 mW more than the power consumed using the non-clustering scheme to guarantee −10 dBm. This means that the proposed scheme can guarantee better RSS values with only slightly higher power consumption.

Figure 5(b) shows that the proposed scheme saves 596.6 mW to guarantee −30 dBm against conventional schemes when the network is clustered into 4 clusters,



(a)

(b)

FIGURE 5. Power consumption for increasing number of clusters, i.e., 3, 4, 5, 6, 7, and 8, when the number of EFRs are a) 50 and b) 200.

whereas it saves 718.8 and 724.4 mW when the network is clustered into 7 and 8 clusters, respectively.

This evaluation proves that as the number of clusters increases the power consumed by the network decreases. It also helped us find the optimal number of clusters for the given settings. This number is 8.

The power saving for 50 EFRs is marginal against non-clustering and conventional schemes. However, as the number of EFRs increases the power saving is increased drastically.

C. POWER EFFICIENCY

The power efficiency, η, of the proposed scheme in comparison with non-clustering scheme is given by

$$\eta_1(\%) = \left(\frac{P_{non-clustering} - P_{proposed}}{P_{non-clustering}} \right) * 100, \qquad (14)$$

where $P_{non-clustering}$ is the total network power using the non-clustering scheme and $P_{proposed}$ denotes the total network power using the proposed scheme.

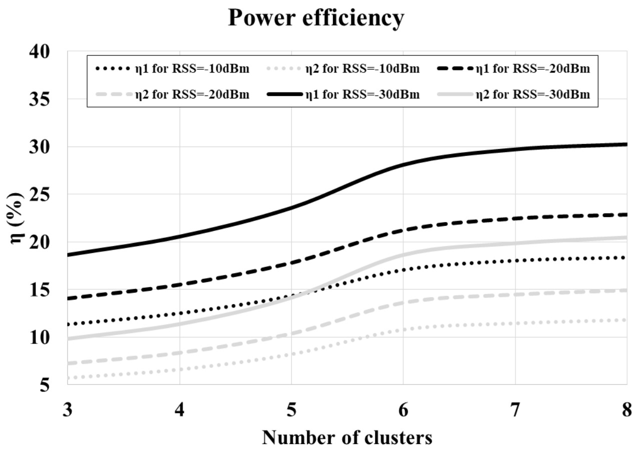


FIGURE 6. Comparison of power efficiency.

The power efficiency of the proposed scheme with respect to conventional schemes is calculated using

$$\eta_2(\%) = \left(\frac{P_{conventional} - P_{proposed}}{P_{conventional}} \right) * 100, \qquad (15)$$

where $P_{conventional}$ is the total network power using conventional schemes.

For the power efficiency, we averaged all the power efficiencies produced when there were 50, 100, 150, and 200 EFRs. Figure 6 shows the power efficiency of the proposed scheme when compared with non-clustering based and conventional clustering-based schemes. The figure clarifies that the proposed scheme can achieve an efficiency increase of 30.24% and 20.46%, respectively, compared with the non-clustering based and conventional clustering-based schemes.

V. CONCLUSION

In this paper, we propose a cluster-head selection scheme with power control for power-efficient PSNs. We adopt a famous clustering technique, i.e., fuzzy C-means, to partition the network into several clusters. Then, a cluster-head selection process is defined to find an appropriate CH for each cluster. In the end, a power control procedure is applied to limit the transmission power. This makes the network more power-efficient. We have shown by performance evaluation that our proposed scheme outperforms both non-clustering-based and clustering-based conventional approaches. We will work on implementing other clustering approaches and power control schemes to further improve the performance of PSN in the future. In addition, we will also utilize other wireless communications technologies.

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