Rural Broadband Access via Clustered Collaborative Communication

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***Abstract*—Broadband penetration in rural areas of the developing countries is significantly low. Unique challenges in enabling rural connectivity are sparsity of population locations and modest income of the villagers, which induce low return on investment to the conventional cellular network providers. In this paper, we propose a novel cluster-based network architecture and protocols for efficient rural broadband coverage which requires minimal infrastructure setup by the service provider. Multiple customer premise equipments (CPEs) in a village form clusters and transmit collaboratively over unused television bands to the base station. A two-tier uplink access protocol is proposed and its performance in terms of network throughput and energy efficiency are obtained analytically. Cluster size is optimized to maximize the uplink network throughput and energy-efficiency. A distributed clustering algorithm is proposed for the CPEs to form clusters, while channels are allocated to the clusters using the proposed channel allocation algorithm to minimize inter-cluster interference. Via network simulation studies we demonstrate that the proposed architecture can be cost-effective and energy-efficient, while being scalable at the same time.**

***Index Terms*—Rural broadband system architecture, TVWS, distributed beamforming, medium access control protocol, distributed clustering algorithm, discrete-time Markov chains**

I. Introduction

Internet has been playing a critical role in uplifting the socio-economic standard of living. Wireless broadband services are used in various communication, monitoring, and control applications [2]. However, broadband access coverage in rural areas of the developing countries is still significantly low (www.trai.gov.in). In rural areas, villages are sparsely located with low population density and a lower per-capita income of the villagers. For instance, rural population in India is about 67% with two-thirds of them are dependent on agriculture for income (www.data.worldbank.org). Though the statistics suggest that the rural population is on the decline, it is still significant, and therefore an efficient IT infrastructure is necessary to prevent further migration from rural to urban places. An efficient and low-cost network set-up is required to make the broadband services available in rural areas.

Cellular broadband services are unavailable in far-flung rural areas because of the low return on investment to the service providers, owing to low demands and high infrastructure cost. Cost in rolling out fiber-optic/copper lines for last mile access is high. Electrical power-line communication (PLC) was proposed in [3] to provide rural broadband connectivity. However, in developing nations, there are still some areas with little or no electricity infrastructure. Thus, rural broadband access (RBA) suffers from *mid-haul and end-haul connectivity*, where establishing communication from point of presence (PoP; Internet gateway) to the rural people is the bottleneck.

With the television (TV) transmission shifted from analog to digital domain, large portions of the UHF (ultra high frequency) TV spectrum remain unused. TV band spectrum measurements reveal that 100% of the TV bands (470 MHz - 590 MHz) are unutilized at almost 36% of the places in India [4]. Studies show that, this spectrum band is unused in other parts of the world as well, e.g., in Kenya [5], and the US [6]. Communication over these unused TV bands or white spaces (TVWS) are being considered for enabling RBA due to its good long-range propagation characteristics.

IEEE 802.22 and 802.11af have been proposed for providing rural coverage via TVWS. IEEE 802.22 standard provides coverage in the range of $17-30$ km from the TVWS base station (BS). This standard specifies an infrastructure-based point-to-multi-point network with the network being formed between a TVWS BS and the user equipments installed at the customer premise. IEEE 802.11af extends the conventional wireless local area networks (WLAN) to the TVWS bands for extended coverage. As noted in [7], user equipments specified in IEEE 802.22 prove to be expensive, and therefore may be unsuitable for deployment in the economically backward regions. In [8], the authors showed that mere usage of TVWS in WLAN communications would not help in range extension due to asymmetric channel conditions in uplink and downlink and high interference range in the UHF band transmissions.

A. Related Works and Motivation

A few experiments have been conducted ([9], [10]) to provide broadband access via TVWS. In these deployments, a TVWS BS is set-up at the PoP (large towns/villages with wireline broadband connectivity). The operator sets up UHF-band nodes in a village which provides Internet access to its nearby users. Backhaul connectivity to the UHF-band node is provided by the PoP BS via transmission over point-to-point TVWS link, while the co-located WiFi access point (AP) at the UHF-band node serves the end-users (e.g., mobile devices, laptops) over the ISM (2.4 GHz) band. Thus, these UHF-band nodes form connection between the village users and the PoP.

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Though the network model employed in various industrial and academic trials [9], [10] works well in a small area, scaling these networks to cover an entire rural area is a challenge. To provide connectivity to a larger and sparser village population, multiple UHF-band nodes need to be installed by the operator that increases the operator's infrastructure cost. Increase in rural population would invite deployment and maintenance of more UHF-band nodes by the operator. Moreover, due to the use of high transmit power over UHF band - to establish reliable communication with PoP BS (also called TVWS BS) as well as over WiFi - to cover a large geographical area, energy efficiency of this network architecture is expected to be low. The end-user devices (e.g., mobile phones, tablets) have to connect to these sparsely-deployed UHF-band nodes, which would require higher transmit power, thereby reducing their battery life. Hence, setting up UHF-band nodes is undesirable.

In order to address these issues, an alternative cluster-based RBA system model is proposed in this paper that does not require the UHF-band nodes to be setup by the operator. Low power customer premise equipments (CPEs) are installed at each house. These CPEs carry out cooperative communication with the PoP BS on the uplink using distributed beamforming (DBF). The network performance is evaluated in terms of network throughput and energy efficiency. Optimal cluster size is obtained to maximize the uplink network throughput and energy efficiency, and a distributed clustering algorithm (DCA) is proposed for the CPEs to form clusters.

Access protocols and clustering algorithms for wireless ad hoc and sensor networks have been well investigated in the literature. In [11], the authors proposed an energy-efficient medium access control protocol for wireless sensor networks (WSNs). The authors in [12] proposed a dynamic clustering algorithm for wireless small-cell networks. An energy-efficient DCA was proposed in [13], where the objective was to maximize the sensor network lifetime. Similar DCA were also presented in [14] and [15].

Main idea of this work is to employ DBF for establishing efficient communication between CPEs and TVWS BS. The access protocols and algorithms proposed in the literature for WSNs cannot be applied to the networks employing DBF. A few works have been reported in the areas of DBF. For example, in [16], the authors presented an optimal node selection scheme for DBF. Communication between two clusters employing DBF was investigated in [17]. Energy-efficient beamforming in clustered networks was studied in [18] and [19]. To the best of our knowledge, there has been no work reported on developing medium access and cluster formation strategies in networks employing DBF.

To this end, this work presents a novel network access strategy and analyze performance of networks employing DBF. *We believe that adaptive distributed clustering and DBF-based uplink access strategies proposed in this work is a paradigm shift from the classical network communication strategies towards achieving low-cost and scalable RBA-solution. The proposed schemes can also be applied to other network scenarios, such as wireless ad hoc networks, low power WSNs, and cooperative device-to-device communications.*

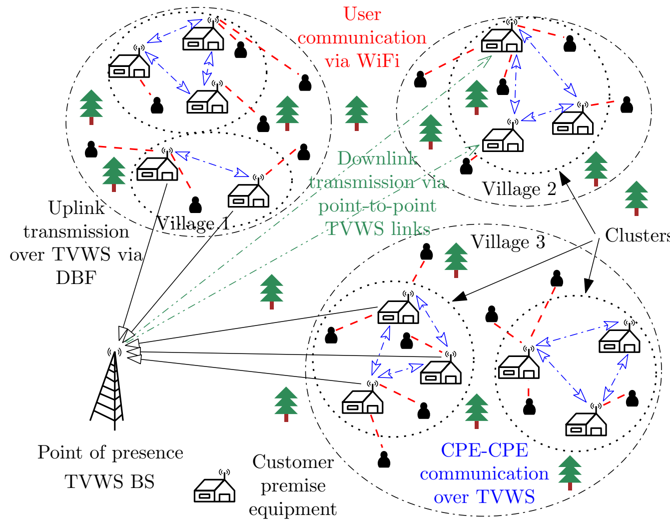


Fig. 1: Proposed clustered RBA system architecture.

B. Contributions and Paper Organization

Key contributions of this paper are summarized as follows:

1) A novel cluster-based architecture for RBA is proposed which does not require additional infrastructure setup by the service provider. Two-tier uplink access mechanism is proposed for the users to transmit their data to the BS (Section II).
2) Distributed clustering and channel allocation algorithms for intra-cluster communication are proposed for CPEs forming clusters with the neighboring CPEs (Section III).
3) Performance of the proposed scheme in terms of uplink network throughput and energy efficiency is derived analytically (Section IV).
4) Optimal cluster size for maximizing the uplink network throughput and energy efficiency is obtained by solving the respective optimization problems (Section IV-F).

Results presented in Section V demonstrate that the proposed architecture achieves on average 20% higher energy efficiency than the conventional RBA scheme. The proposed architecture is also shown to be cost-effective, scalable, and offers a larger coverage due to collaborative transmissions.

II. Proposed Cluster-based Rural Broadband System Architecture

In the proposed cluster-based RBA solution, low-power CPEs installed at user premises form clusters among the neighboring ones and transmit to the PoP BS via DBF to establish the mid-haul uplink connectivity. Utilizing DBF, multiple CPEs simultaneously transmit the same content to the PoP BS in such a manner that multiple signals from different CPEs add up constructively at the PoP BS, resulting in a much higher received signal-to-noise ratio (SNR) [20].

The CPEs are considered to be formed by augmenting the traditional terrestrial TV antennas that may be already installed in many houses in the villages. Thus, a CPE is statically installed at a customer premise (e.g., house rooftop), which is now enabled with low-cost and low-power UHF-band transceiver for TVWS access and low-power WiFi AP for ISM

TABLE I: Cost analysis in setting up a UHF-band node.

Item	Cost (approx.)
UHF band transceiver (30 dBm)	US$ 230
UHF band antenna	US$ 20
Microcontroller	US$ 10
Solar panel (10 W)	US$ 25
WiFi access point (20 dBm)	US$ 15
Total	US$ 300

TABLE II: Cost analysis of a CPE.

Item	Cost (approx.)
UHF band transceiver (10 dBm)	US$ 25
Microcontroller	US$ 10
Solar panel (1 W)	US$ 5
WiFi access point (10 dBm)	US$ 10
Total	US$ 50

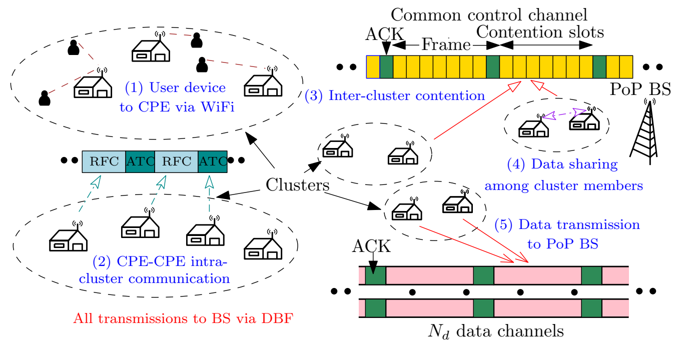


Fig. 2: Different components in uplink communication process for the proposed architecture.

band access functionalities. The end-users connect to these CPEs over WiFi.

Note that, unlike the UHF-band nodes, the CPEs are low-power, low-cost devices, installed by the customers. Because the CPEs are installed in every house, they provide seamless access to the mobile devices. Also, being in close proximity to the CPEs, the user devices would require less power to operate. Cost analysis of a UHF-band node (in [9], [10]) and a CPE (our design) is presented respectively in Tables I and II.

For the uplink communication, a CPE first forms cluster with the neighboring CPEs by coordinating with them and sharing its data over TVWS band. Then, these CPEs transmit to the PoP BS via DBF over the TVWS band so that the uplink data can be reliably communicated at a lower transmit power from each CPE. On the other hand, for downlink communication CPEs independently receive from the PoP BS. Fig. 1 depicts the proposed RBA system architecture.

A. Uplink Access Mechanism

During network initialization, the neighboring CPEs form clusters by implementing DCA proposed in Section III-A. A CPE communicates with the other CPEs in the cluster over a TVWS band. Since the TVWS is in UHF band with low path loss profile, transmission power required for CPE-CPE coordination is small. For intra-cluster contention, the PoP BS notifies apriori the set of UHF sub-bands to be used. Once the clusters are formed, each cluster chooses a UHF sub-band from the notified set for its intra-cluster contention based on a channel allocation algorithm (cf. Section III-B), so as to minimize interference in the intra-cluster communication between neighbouring clusters.

A two-tier uplink access protocol is proposed. In the first tier CPEs in a cluster contend amongst themselves, while in the second tier different clusters contend at the PoP BS. The uplink communication process is detailed below:

1) User devices to CPE: User devices connect to the CPE over WiFi. A user device chooses to connect to that CPE which offers maximum received signal strength indicator (RSSI).

2) CPE - CPE intra-cluster communication: Slotted-Aloha is employed for intra-cluster contention. Time is divided in slots of duration T_1. When a packet arrives at a CPE, that CPE contends over the assigned UHF sub-band by transmitting 'request to collaborate' (RTC) over a slot with a certain probability. An RTC is successful if no other CPE transmits in the same slot. On successful transmission of an RTC, one of the other CPEs (based on random backoff) in the cluster broadcasts 'agree to collaborate' (ATC) to all the cluster members, indicating a successful contention. On receiving ATC, all other CPEs in the cluster stop intra-cluster contention process. Subsequently, the transmitter CPE acts as cluster coordinator (CC) and further coordinates the cluster's contention and data transmission to the PoP BS.

For the cluster contention process (RTC/ATC transmissions), it is considered that sufficiently large number of UHF sub-bands are available for intra-cluster communication. Specifically, in this study as an example, we consider that a 6 MHz TVWS channel is divided into 30 sub-bands of bandwidth 200 kHz each. These channels are considered sufficient for intra-cluster contention. In Section III-B, we propose a channel allocation algorithm for assigning different UHF sub-bands to the different clusters.

3) Inter-cluster contention protocol: Multiple data channels over TVWS bands are available at the PoP BS for the CPEs to transmit their data. PoP BS maintains a common control channel (CCC) over the TVWS band over which different clusters can contend for data channel reservation. Over the CCC, time is divided into frames, which is further subdivided into $m+1$ slots. The CC of a cluster attempts contention by choosing a one of the first m slots uniformly at random. All the CPEs in the cluster are informed of the CC's decision and hence they transmit collectively in DBF mode in the chosen slot in the frame. DBF mechanism is discussed in Section II-C.

The other clusters may also transmit over their respective chosen slots in a frame. The contention process is successful when no other cluster chooses the same slot for transmission. Consider that N_d data channels are available at the PoP BS for the clusters to transmit their content. If the number of successful contentions are more than N_d data channels, N_d clusters are uniformly chosen at random by the PoP BS to allow them transmit their data over the allocated data channels. Clusters are informed about the data channel allocation decision at the end of the frame via acknowledgement (ACK) transmission at the last slot by the PoP BS. Data channels are allocated for a frame duration. The unsuccessful clusters attempt contention in the subsequent frames following the same protocol.

4) Data sharing among cluster members: Once a data channel is allocated to a cluster, in the subsequent frame, the CC shares its data to be transmitted to the PoP BS with the cluster members over the allocated channel. During this data sharing, some other cluster may be transmitting its data to the PoP BS over the same channel. This data sharing is unlikely to interfere with the BS reception, because transmission at low power from a single CPE (CC) to the cluster members may not be reachable to the BS. Conversely, data transmission to the BS does not interfere with the data sharing process, as the DBF mechanism employed for data transmission to the BS (as discussed next) results in high directivity gain along with lower power outside the main beam [21]. Inter-cluster interference is also avoided as in the same frame the BS does not assign the same channel to the neighbors.

5) Data transmission to PoP BS: Once the data is shared among the cluster members, the cluster CPEs in the next frame transmit collectively in their respective data channels using DBF. Uplink reception at the BS is considered successful if its received SNR is above an acceptable threshold. At the end of data transmission, the PoP transmits ACK to indicate successful transmission. In case of NACK transmission by the PoP, the cluster re-contends in the following frame. On successful completion of data transmission, the CPEs in the cluster resume their intra-cluster contention process over the UHF sub-band in the next frame, and the process repeats.

The different contention and operation phases in the uplink communication are presented in Fig. 2.

B. Downlink Access Mechanism

In the downlink, as the PoP BS transmits at a higher power, its transmissions are independently received by the individual CPEs. The BS carries out priority-based resource scheduling, where frames are allocated to different CPEs based on their need. It transmits the data packets to the individual CPEs in their respective allocated frames and data channels. A slot is allocated to the CPE by the BS for ACK transmission, which is conveyed along with the data packet. Once a CPE successfully receives the packet, it sends an *ACK transmission request* packet to the cluster members over the UHF sub-band. This packet contains the time slot and packet ID for ACK transmission. Upon its reception, the CPEs in the cluster transmit ACK to the BS in the allocated slot using DBF.

C. Distributed Beamforming (DBF)

DBF is a key aspect in the proposed RBA, where the CPEs in a cluster collaboratively transmit the data content to the BS. Extensive research has been carried out on the feasibility aspects of DBF [22]. Following are the steps involved in DBF:

1) All the CPEs in the cluster transmit to the PoP BS over the allocated data channel.
2) At regular intervals (say, every 1 ms), BS sends a feedback packet to the CPEs containing its received SNR.
3) On the reception of feedback, all the CPEs correct their frequency offset with respect to the received carrier frequency by obtaining the local oscillator's offset and predicting the carrier frequency using Kalman filter.
4) From the feedback bits containing the BS's received SNR, CPEs adjust their phase.

D. Practical Considerations

Unused TV bands can be made available to the operators in two ways. Firstly, called *licensed shared access* [23], the TV band licensee can lease a part of its unused band to an operator who in turn makes exclusive use of it in a specified geographical region. Second is *unlicensed operation*, where the operators make use of the unused TV bands by either checking for unused spectrum from a geolocation database [24] or by sensing the channel at a given location, or both.

There have been a few experiments conducted to establish the practicality and effectiveness of DBF concept. The authors in [22] demonstrated DBF transmission using commodity off-the-shelf radios. They performed DBF over 900 MHz band and claimed that the number of distributed nodes can be easily scaled to a large value. From these experimental findings we believe that DBF considered in our system model is feasible and can be easily implemented using commercial radios.

E. Assumptions

The following are the main assumptions that are made in the system model and in the proposed solution:

A.1 Noting that villages may not have adequate power line infrastructure for enabling PLC, the CPEs are considered equipped with wind/solar panels for harvesting sufficient energy for their needs [25].

A.2 Number of UHF sub-bands available for intra-cluster contentions are sufficient to cater to the cluster demands in a village. As the bandwidth requirement for contention is small, this assumption is realistic.

A.3 CPE density in a village is considered such that the clusters of desired size can be formed. As the CPE-CPE communication takes place over UHF bands which have higher transmission range, this assumption is practical in real world setting.

A.4 For analytical tractability, we assume that a CPE can have at most one packet at a time. Otherwise, multiple packet arrivals at a CPE would require maintaining queues at various CPEs, which would eventually lead to an overwhelmingly-large number of states in the resulting Markov chain. This assumption has been considered in seminal works on Slotted-ALOHA [26].

III. Clustering and Channel Allocation Algorithm

In this section, we propose a DCA for the CPEs in a village to form clusters of desired size. Once the clusters are formed, channel allocation algorithm is proposed for intra-cluster communication.

A. Distributed Clustering Algorithm (DCA)

The clustering algorithm is developed for a single village scenario, where multiple CPEs are considered spread across the village. We consider that the distance between two villages is large enough such that the CPEs of one village can not communicate with the CPEs of the other village. The CPEs are stationary. For cluster formation, all the CPEs transmit over a common UHF channel with the same transmit power. Links are considered symmetric, i.e., two CPEs can communicate with each other using the same power. We consider that the CPEs know their neighboring CPEs by exchanging broadcast messages. Cluster size plays a key role in performance of the network. Based on the network performance optimization (maximizing the uplink network throughput and energy efficiency, cf. Section IV-F), the PoP BS broadcasts the optimal cluster size l^* for a village. The aim of DCA is to form clusters of size at least l^* (preferably l^*). The actual cluster size is permitted to be slightly larger than l^* so as to provide reliable communication between the cluster and the PoP BS.

CPEs in a village can be considered as vertices in a graph. An edge between the two vertices indicates that the two CPEs can directly communicate with each other. Various distributed algorithms have been proposed in the literature to cater to a wide range of problems spanning graph coloring, maximal independent set (MIS), and maximal cliques in a graph. In [27], the authors proposed a min-max cut algorithm for graph partitioning and data clustering. The objective was to minimize similarity between clusters and maximize similarity within a cluster. A polynomial time clustering algorithm was presented in [28] to partition the graph based on similarity score. The authors in [29] studied the sensory organ precursor cells in the fly's nervous system and derived a fast algorithm for MIS selection. In [30], the authors proposed a clubs algorithm for aggregating processors into groups in an amorphous computer. They also derived an upper bound on the number of groups formed and the density of the groups. The clubs algorithm was extended to solve MIS and graph coloring problems.

Information dissemination in wireless networks was studied in [31]. Here, an algorithm was proposed to enhance information dissemination by using self organization phenomena, such as, lateral inhibition, flocking, and beamforming. The authors in [32] and [33] presented algorithms to form a geographically uniform clusters in a WSN with an aim to maximize connectivity and minimize the number of clusters formed. The issue of locality in distributed processing was studied in [34], where the degree to which a global solution can be obtained from local interactions in a graph was discussed. They investigated MIS and graph coloring problems.

Clique partitioning problem aims at obtaining maximal clique in a graph. This problem has been well studied in [35], [36], and [37]. It is well known that the clique partitioning problem is NP-hard [38]. In contrast, the objective of the present problem is to form equal size cliques in the graph. This objective cannot be achieved using the existing algorithms in the literature. In the following, our proposed DCA is presented.

In the proposed DCA, some of the CPEs act as cluster initiator (CI) to initiate cluster formation. These CIs invite other CPEs to join its cluster. A utility is associated with each cluster which depends on its size. Each CPE aims at maximizing its utility by joining a cluster that would result in the highest utility (i.e., creating clusters closer to l^*). In the process, CPEs (either CI or members) may leave their present cluster and join other clusters as members. In case a CI leaves its cluster, another CPE from the cluster is chosen at random and appointed as CI. Utility of a cluster with x cluster members (including the CI) is defined as:

$$\mathcal{U}(x) = \begin{cases} x & x < l^*, \\ l^* + e^{-(x-l^*)} & x \geq l^*. \end{cases} \tag{1}$$

Cluster's utility increases with the increase in number of CPEs in the cluster and is maximum for cluster of size l^*. Utility decreases for cluster size $> l^*$. However, $\mathcal{U}(x) > \mathcal{U}(l^* - 1), x > l^*$ so as to encourage cluster formation of size at least l^*. Note that utility of cluster and its members are the same.

Time is divided into slots with each slot further subdivided into three mini-slots. Specific operation is carried out in each mini-slot. In the first mini-slot, CIs invite other CPEs to join its cluster by broadcasting `Invite` message. CI broadcasts `Invite` message with certain probability p_{inv} which is fixed by the network operator to allow CIs to join other clusters. `Invite` message contains details about cluster members and the degree (number of neighbours) of the CI.

In the second mini-slot, other CPEs (CPEs (including CIs) which did not transmit `Invite` message) evaluate multiple `Invite` messages received from different CIs and choose the one they want to join. From the `Invite` message, firstly, the CPEs evaluate whether all the members of a cluster are its neighbors. Among the clusters with common members/neighbors, the CPE chooses the one which, when joined, would result in the highest utility. If the utility of the CPE is lower than the highest utility, the CPE indicates its interest to join that cluster by sending a `Join` message. Ties are broken by choosing the one with its CI having minimum degree. `Join` message contains CPE ID and a list of its neighbors.

In the third mini-slot, CIs evaluate the multiple `Join` messages received and permit a single CPE to join its cluster by transmitting a `Permit` message to the CPE. CI chooses the CPE with minimum degree, because these CPEs are more vulnerable to be left out. Among the CPEs with minimum degree, CI chooses the one with the highest number of common neighbors between the CPE and the cluster to ensure good connectivity between the cluster members and the newly joined CPE. If the CPE is part of another cluster, it leaves its present cluster and joins the new one. CPE transmits a joined ACK `J-Ack` message to the new CI to indicate its joining the cluster, while same `J-Ack` notifies its former CI that it has left the cluster. CSMA/CA protocol is used to avoid collisions between multiple transmissions in each mini-slot.

The algorithm works in three stages. During network initialization, there are no CIs. **In the first stage**, some of the CPEs become CI according to certain probability called CI probability, which is determined based on the number of neighbors of the CPE. If a CPE's degree is low, it initiates to form cluster with a high probability. Otherwise it may be left out if all its neighboring CPEs join other clusters. In our approach, we employ the following CI probability model:

$$P_{CI} = \min\left\{P_{max}, \max\left\{P_{min}, \frac{\chi N_e}{l^*|N_{nbr} - l^* + \zeta|}\right\}\right\}, \quad (2)$$

where P_{min} and P_{max} are respectively the minimum and maximum probability, decided by the network operator, N_{nbr} is the degree of the CPE, N_e is the total number of CPEs spread across multiple villages, χ is a positive constant, and ζ is a positive constant close to zero. This probability is higher for CPEs with lower number of neighbors. With the passing of each time slot, if a CPE is not a member of a cluster then it increments its $P_{CI} \leftarrow \min\{1, 2P_{CI}\}$. In the first stage, only clusters of size $\leq l^*$ are allowed to be formed to ensure that maximum clusters of size l^* are formed. Stage 1 concludes when there are no change in the cluster members for η consecutive slots. η is chosen proportional to l^*, because $l^* - 1$ CPEs are required to join a cluster. A higher value of η results in a more accurate algorithm convergence, but it also increases the convergence time. A lower value of η may result in poor performance in a lesser time. In this work, we consider $\eta = 50l^*$, as the performance saturates beyond this value while convergence time increases. At the end of this stage, either a CPE is a CI or a cluster member with cluster size of $\leq l^*$.

In the second stage, CPEs are allowed to form clusters of size $> l^*$ to ensure that maximum clusters are of size at least l^*. This stage concludes when there is no change in the CPE members for η (considered same as before) consecutive slots.

It should be noted that some of the CPEs may not be able to form clusters of size at least l^* at the end of stage 2. This is possible as its neighbors might have joined other clusters with distant members. **In the third stage**, these CPEs are allowed to join clusters without having all the cluster CPEs in its one-hop neighbors. Such CPEs choose the cluster with maximum number of cluster members in its one-hop neighbors. In such a cluster, a CPE which cannot reach all other CPEs in the cluster in one-hop is marked metastable. Such CPEs in this cluster have utility $= \mathcal{U}(l^*-1)$. This utility is less than the utility of a cluster with cluster size $\geq l^*$. Thus, in further slots, metastable CPEs would attempt to join other clusters and become stable. In this stage, the CI role is circulated among cluster members in each slot such that maximum number of CPEs can listen to the `Invite` messages. This is carried out as follows. At the start of CI rotation, a default list of CI rotation order is formed by the current CI. The list includes only those CPEs which are reachable to all other CPEs in the cluster. As per the list, next CPE is handed over the CI responsibility by the current CI. In the process, the default list from the present CI along with connectivity information is passed down to the next CI. At the end of a slot, depending on if a CPE has joined or left the cluster, the next CI makes amendments to the order by adding/deleting CPE. This stage terminates when there is no cluster with less than l^* number of cluster members.

Once this stage concludes, all the CPEs form clusters of size at least l^*. CI rotation halts at this point and the CPE acting as CI during the stage termination acts as the CI for rest part of the process. Some of the CPEs can be metastable depending on the connectivity of the CPEs in the village. At this stage, the clusters with metastable CPEs communicate with other cluster members using multi-hop communication protocol [39].

Algorithm 1: Proposed distributed clustering algorithm.

1. CPEs know their neighbors by broadcasting messages;
2. Each CPE computes the probability P_{CI} based on its number of neighbors;
3. **Stage 1:** CPEs are allowed to form clusters of size $\leq l^*$; stage terminates when there is no change in cluster members for η consecutive slots;
4. **Stage 2:** CPEs are allowed to form clusters of any size; stage terminates when there is no change in cluster members for η consecutive slots;
5. **Stage 3:** CPEs are allowed to form metastable clusters; utility for metastable CPEs $= \mathcal{U}(l^* - 1)$; CI role is circulated among cluster members; stage terminates when there is no cluster of size $< l^*$.

Algorithm 1 presents an outline of the proposed DCA.

Lemma 1. *Given assumption A.3, the proposed DCA converges in finite steps and forms clusters of size at least l^*.*

Proof. A CPE would become either a member of a cluster or a CI. If a CPE does not hear `Invite` message or it does not receive `Permit` message from a cluster, it increments its CI probability P_{CI}. In finite number of slots, this probability reaches 1 which guarantees that the CPE would act as CI and invite other CPEs to join its cluster. Applying assumption A.3, stage 3 of the algorithm ensures that the CPEs form clusters of size at least l^*. Thus, the algorithm converges in finite steps and it forms clusters of size at least l^*. □

Performance of this algorithm is presented in Section V-B.

B. Cluster Channel Allocation

As stated in Section II, contention in intra-cluster communication involves exchange of RTC and ATC messages. The PoP BS broadcasts a set of UHF sub-bands that can be used for intra-cluster communication. The aim of the channel allocation algorithm is to assign sub-bands to the clusters formed such that the interference in intra-cluster communication is minimal. This decision is made by the clusters distributively. As interference range in UHF bands is much higher that the reception range [8], it is important that the clusters choose sub-band with minimal interference.

Sub-bands are numbered 1 through SB. Each cluster starts by operating over a default sub-band, say sub-band 1. For cluster channel allocation, each CI chooses a random backoff between 1 to BO_{max}. Upon backoff expiry, the CI chooses a random sub-band from the set of available sub-bands (bands with minimal activity sensed) and notifies it to all the members in the cluster. This notification is carried out over the cluster's current sub-band. Each of the cluster members listens to the chosen sub-band for next t_{max} time. If the nodes do not experience any activity in this sub-band, they choose this sub-band for their intra-cluster communication by sending a message to the CI. Each member of the cluster in turn transmits a `Signature` message consisting of the cluster ID and CPE

ID. While a member transmits, the other cluster members listen to the message and record any interference in their reception (in case there is another cluster transmitting at the same chosen sub-band). If there is no interference, the cluster fixes this sub-band for its operation. Otherwise, it chooses another suitable sub-band following the same procedure. CI transmits a beacon signal every t_{max} interval to intimate the sub-band usage to other clusters.

Lemma 2. *All the clusters are allocated a sub-band at the end of this algorithm.*

Proof. Choice of sub-band depends on the number of clusters formed, cluster sparsity, and the number of sub-bands available. If the number of sub-bands are more than the number of clusters in the village, all the clusters choose a different sub-band for their operation. Instead, if the number of sub-bands are comparable or less than the number of clusters, clusters choose sub-bands in such a way that the interference between the two clusters is minimal. Thus, all the clusters choose a suitable sub-band where the interference is minimal. □

Over time, new CPEs may join or leave the network. If a CPE joins/leaves the network, the other CPEs need to re-organize themselves into clusters to maintain reliable communication with the PoP BS. To enable this, the cluster CI regularly maintains a record of the CPEs active in the cluster. If some of the CPEs are detected inactive by the CI, it broadcasts a `Re-run` message. On reception of this message, the neighboring CIs initiate transmission of `Join` message to all the CPEs and DCA is re-implemented.

On the other hand, when a CPE becomes active in the network, it transmits a `Re-run` message. On reception of this message by the neighboring CIs, they re-initiate the DCA and the process repeats.

After DCA execution, the channel allocation algorithm is implemented to allocate channels to the modified clusters.

IV. Network Performance Analysis

Performance of the proposed network model is analyzed in terms of the following metrics:

Definition 1. ***Normalized uplink throughput*** *is the amount of uplink data successfully transmitted by a user to the PoP BS per unit time.*

Definition 2. ***Normalized uplink energy efficiency*** *is the ratio of the normalized uplink throughput to the total energy consumption of the network.*

Normalized downlink throughput and energy efficiency are similarly defined.

Consider that there are N_e CPEs spread across multiple villages. Users are connected to the CPEs via WiFi over the ISM band. Consider, on average, ξ users are associated with a CPE. CPEs form clusters within one-hop range. Consider that there are N_c clusters. Denote for the ith cluster, l_i is the number of CPEs in the ith cluster. Thus, $\sum_{i=1}^{N_c} l_i = N_e$. In the following, the normalized uplink throughput and energy efficiency of the CPE-PoP BS communication system are studied. Downlink throughput and energy efficiency computations are straightforward. Hence, they are not analyzed in this work. However, simulation results in Section V capture downlink performance as well. Before proceeding further, outage probability of a CPE cluster is discussed next.

A. Cluster Outage Probability

Consider that K CPEs in a cluster transmit collaboratively via DBF to the PoP BS. All CPEs experience independent Rayleigh fading. Let the ith CPE in a cluster at a distance of r_i from the PoP BS transmits at power $P_{t,i}$, and has Rayleigh fading channel gain h_i with mean zero and variance $2\sigma_r^2$. The received signal power at the PoP BS from the ith CPE is $P_{r,i} = P_{t,i} r_i^{-\varepsilon}$, where ε is the path loss coefficient. The total received signal at the PoP BS due to DBF transmission by all the CPEs transmitting the same content x is $y = \sum_{i=1}^{K} w_i h_i \sqrt{P_{r,i}} x + n$, where the ith CPE preprocesses its transmission by a factor w_i, n is the additive white Gaussian noise with variance $2\sigma_n^2$, and $\mathbb{E}[|x|^2] = 1$. Received signal is maximized for $w_i = h_i^*/|h_i|$. Accordingly, the received SNR γ is:

$$\gamma = \frac{(\sum_{i=1}^{K} |h_i| \sqrt{P_{r,i}})^2}{2\sigma_n^2}. \tag{3}$$

Hence, the instantaneous capacity of the CPE cluster to the PoP BS link is $I = B \log_2(1+\gamma)$, where B is the channel bandwidth. The outage probability of the cluster with K CPEs transmitting at rate R is $Pr(I < R) \triangleq P_{out}(R, K)$. As the CPEs within a cluster are closely located from each other but far from the PoP BS, $r_i^{-\varepsilon}$ can be considered approximately the same for all CPEs within a cluster and is replaced by $r^{-\varepsilon}$, where r is the mean distance of the CPEs in a cluster to the PoP BS. Thus, the received signal power $P_{r,i}$ from all CPEs are the same, denoted as P_r. Denoting $\rho = P_r/2\sigma_n^2$ and $W = (\sum_{i=1}^{K} |h_i|)^2$, cdf of W is given as [40]:

$$G_W(z,K) = 1 - e^{-\frac{z}{2Kb}} \sum_{i=0}^{K-1} \frac{(\frac{1}{2Kb})^2}{i\,!} - \sqrt{\frac{z}{K}} \frac{a_0(\sqrt{\frac{z}{K}} - a_2)^{2K-1} e^{-\frac{a_1(\sqrt{\frac{z}{K}}-a_2)^2}{2b}}}{2^{K-1}(\frac{b}{a_1})^K (K-1)\,!}, \tag{4}$$

where $b = \frac{\sigma_r^2}{K}[(2K-1)!!]^{1/K}$, $(2K-1)!! = (2K-1)\cdot(2K-3)\cdots 3\cdot 1$, and a_0, a_1, and a_2 are error correction coefficients dependent on K provided in [40]. Finally, the outage probability is given as $P_{out}(R,K) = G_W(\frac{2^{R/B}-1}{\rho}, K)$.

Next, we model the intra-cluster communication process.

B. Intra-Cluster Contention

Slotted Aloha is employed for intra-cluster contention. A discrete time Markov chain (DTMC) is formed to represent the state of a cluster in each slot. State in DTMC is defined as a combination of the number of CPEs having packet to transmit and the operation phase of the cluster. Operation phase of a cluster is whether a CPE is successful in intra-cluster contention process ('S'), or the CPEs are contending for intra-cluster contention ('C'). Fig. 3 represents the DTMC model for the jth cluster with l_j CPEs.

A transition from state ‘C’ to ‘S’ happens when there is a successful contention. Once the cluster’s operation phase is ‘S’, it remains in ‘S’ in that communication cycle. Deferred first transmission mode of slotted-Aloha is employed, where a new packet is transmitted with probability one and a backlogged packet is retransmitted with probability p. Thus, a transition from state ‘$0|C$’ to ‘$1|S$’ happens when a new packet arrives at a CPE, while a transition from state ‘$k|C$’ to ‘$k+x|C$’ occurs when a new packet arrives at each of the x CPEs and none of the $k+x$ CPEs successfully contended. A transition from state ‘$k|S$’ to ‘$k+x|S$’ occurs when one of the CPE has already successfully contended and x new CPEs have a new packet arrival.

Let the packet arrival probability for a user in a slot be α_u. Considering q users accessing a CPE, packet arrival probability at the CPE per slot is $\alpha_c = 1-(1-\alpha_u)^q$. If a CPE has a backlogged packet, another packet cannot arrive at the CPE. Thus, at a time, a CPE can have at most one packet.

Consider that k out of l_j CPEs in the cluster have a backlogged packet. Let $Q_a(x,k)$ be the probability that x unbacklogged CPEs transmit a packet in a slot. Also, let $Q_r(x,k)$ be the probability that x backlogged CPEs transmit in a slot. These probabilities are given as:

$$Q_a(x,k) = \binom{l_j-k}{x}(1-\alpha_c)^{l_j-k-x}\alpha_c^x \quad (5)$$

$$Q_r(x,k) = \binom{k}{x}(1-p)^{k-x}p^x. \quad (6)$$

Denote one-step transition probability matrix of the DTMC as $\mathbf{P}_{c,j}$. The state transition probabilities of the DTMC can be written as (note that $k>0$ for all cases):

$$\mathbf{P}_{c,j}(k|C,k|C) = Q_a(0,k)(1-Q_r(1,k)), \quad (7a)$$

$$\mathbf{P}_{c,j}(k|C,k+1|C) = Q_a(1,k)(1-Q_r(0,k)), \quad (7b)$$

$$\mathbf{P}_{c,j}(k|C,k+i|C) = Q_a(i,k), i \geq 2, \quad (7c)$$

$$\mathbf{P}_{c,j}(0|C,1|C) = 0 \quad (7d)$$

$$\mathbf{P}_{c,j}(0|C,1|S) = Q_a(1,0) \quad (7e)$$

$$\mathbf{P}_{c,j}(k|C,k|S) = Q_a(0,k)Q_r(1,k), \quad (7f)$$

$$\mathbf{P}_{c,j}(k|C,k+1|S) = Q_a(1,k)Q_r(0,k), \quad (7g)$$

$$\mathbf{P}_{c,j}(k|S,k+i|S) = Q_a(i,k). \quad (7h)$$

Here, the probability $\mathbf{P}_{c,j}(k|C,k|C)$ that a cluster in intra-cluster contention phase with k backlogged CPEs remain in the same state in the next slot is the probability that none of the backlogged CPEs are successful in channel contention in the next slot (with probability $(1-Q_r(1,k))$) and none of the other CPEs have a packet arrival in the slot (with probability $Q_a(0,k)$). The probability $\mathbf{P}_{c,j}(k|C,k+1|S)$ that the cluster in intra-cluster contention phase with k backlogged CPEs transits to the successful contention phase with $k+1$ backlogged CPEs in the next slot is the probability that one of the unbacklogged CPE has a packet arrival in a slot (with probability $Q_a(1,k)$), while none of the k backlogged CPEs transmit in the slot (with probability $Q_r(0,k)$). Similarly, the other probabilities are obtained.

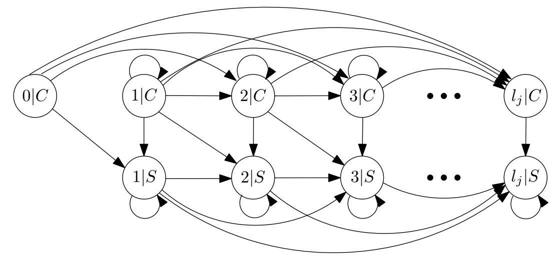


Fig. 3: DTMC model for the intra-cluster contention process.

The DTMC model presented is used in the network performance computation in the subsequent subsections. Below, we model the inter-cluster contention process.

C. Inter-Cluster Contention

PoP BS has N_d data channels and a CCC. These channels are divided into frames of duration T. Over the CCC, a frame is further subdivided into $m+1$ slots of duration T_2 each. The clusters can contend over the first m slots, while the last slot is reserved for ACK transmission by the PoP BS.

Consider that, at a given frame v clusters attempt contention. The probability of κ successful contentions in a frame is computed. Probability that a cluster chooses the ith slot out of m slots is $1/m$. Probability of successful contention in the ith slot is the probability that only a single cluster chooses that slot. This probability is $\frac{v(1-1/m)^{v-1}}{m}$. Probability that a slot is unutilized is $1-\frac{v(1-1/m)^{v-1}}{m}$. The probability $\beta(\kappa,v)$ that a given cluster is successful among κ successful clusters in a frame with v clusters contending is given as:

$$\beta(\kappa,v) = \frac{\kappa}{v}\binom{m}{\kappa}\left\{1-\frac{v}{m}\left(1-\frac{1}{m}\right)^{v-1}\right\}^{m-\kappa}\left\{\frac{v}{m}\left(1-\frac{1}{m}\right)^{v-1}\right\}^{\kappa}. \quad (8)$$

Probability that the given cluster from κ clusters is allocated a data channel is:

$$Pr(\text{User allocated data channel}|\kappa) = \begin{cases} 1 & \kappa < N_d \\ \frac{N_d}{\kappa} & \kappa \geq N_d \end{cases}. \quad (9)$$

Thus, the probability that a data channel is allocated to a given cluster with v clusters contending is given as:

$$P_{suc}(v) = \sum_{\kappa=1}^{\min(v,m)} \beta(\kappa,v)Pr(\text{Data channel allocated}|\kappa). \quad (10)$$

Utilizing the above developments, the uplink network throughput and energy efficiency are computed next.

D. Normalized Uplink Throughput

DTMC is used to obtain the uplink throughput. For the jth cluster, a DTMC is constructed with $3l_j+1$ states. Time slot duration of the DTMC is considered the same as a frame duration T. States are defined by a duplet. The first one

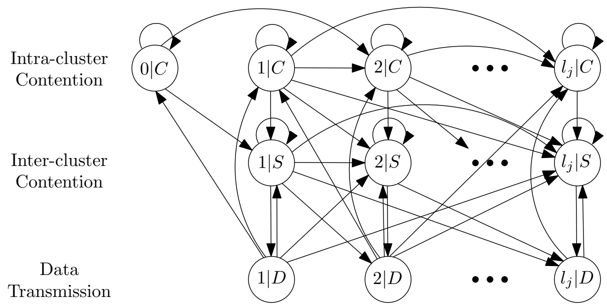


Fig. 4: DTMC model depicting different states of the jth cluster.

depicts the number of CPEs in the cluster having a packet to transmit. The second one depicts the operating phase of the cluster. A cluster can be in one of the three states, namely, in the intra-cluster contention phase ('C'), in the inter-cluster contention phase ('S'), or in the data transmission phase ('D'). Fig. 4 depicts the different states in the DTMC for the jth cluster. A cluster enters the inter-cluster contention phase and subsequently the data transmission phase only when a CPE in the cluster has a packet to transmit.

Denote the one-step state transition probability matrix of the DTMC as $\mathbf{P}_{d,j}$. Transition from phase 'C' to 'S' occurs when a CPE is successful in intra-cluster contention over a frame duration. This transition probability is given as $\mathbf{P}_{c,j}^{m_c}$, where $m_c = T/T_1$ is the number of intra-cluster contention slots over a frame duration. $\mathbf{P}_{c,j}^{m_c}$ is the m_c-th step state transition probability matrix of the DTMC in Fig. 3. Thus, $\mathbf{P}_{d,j}(a|C, b|S) = \mathbf{P}_{c,j}^{m_c}(a|C, b|S)$. Transition from phase 'S' to 'D' occurs when the cluster is successful in obtaining the data channel (with probability $P_{suc}(n_c)$), where, n_c is the expected number of clusters contending over the CCC. Concurrently, multiple CPEs can have a packet arrival over a frame. Thus,

$$\mathbf{P}_{d,j}(a|S, b|D) = P_{suc}(n_c)\binom{l_j - a}{b - a}\alpha_c^{b-a}(1-\alpha_c)^{l_j-b-a}. \tag{11}$$

Data packet transmission from the jth cluster is successful with probability $(1 - P_{out}(R, l_j))(1 - P_{int})$, where R is the transmission rate and P_{int} is the transmission failure probability due to interference from CPE transmission in intra-cluster data sharing. After successful data transmission, the cluster again returns to the intra-cluster contention phase.

Similar DTMC is formed for each cluster. The unknown here is n_c. To obtain this, let us start with an arbitrary value of n_c in the initial step. Using this n_c, the steady state probability of each state in the DTMC for each cluster is obtained. For the jth cluster it is given as $\pi_j = \pi_j \mathbf{P}_{d,j}$. Steady state probability $\pi_j(S) = \sum_{i=1}^{l_j} \pi_j(i|S)$ of being in phase 'S' corresponds to the cluster's probability of contending over the CCC. This steady state probability for each cluster is added up to obtain the next better iterate of $n_c = \sum_{j=1}^{N_c} \pi_j(S)$. This process is repeated until n_c converges to a steady state value n_c^*.

Once the steady state n_c^* is obtained, the cluster's steady state probability of being in phase 'D' corresponds to its data transmission probability. Probability of successful data transmission for the jth cluster is $(1-P_{out}(R, l_j))(1-P_{int})$. Hence, for the jth cluster uplink throughput is $\pi_j(S)P_{suc}(n_c^*)(1 - P_{out}(R, l_j))(1-P_{int})$. Uplink network throughput is the ratio of the sum of uplink throughput of all clusters to the total number of users, which is given as:

$$\mathcal{T} = \frac{P_{suc}(n_c^*)\sum_{j=1}^{N_c}\pi_j(S)(1-P_{out}(R, l_j))(1-P_{int})}{N_e \xi}. \tag{12}$$

E. Normalized Uplink Energy Efficiency

For uplink energy efficiency, we compute the energy consumption in each state of the DTMC in Fig. 4. Energy consumption in the intra-cluster contention phase depends on the number of CPEs having a packet to transmit. Average energy consumption in a frame duration starting from each state of this contention phase is computed next.

For the jth cluster, energy consumption in transiting from one state to another in the Markov chain in Fig. 3 is obtained. Transition from state '$k|C$' to '$k|S$' would incur an energy consumption of $\phi_{tx} + (l_j - 1)\phi_{rx}$, as a single CPE transmits over a slot and other CPEs in the cluster listen. Here, ϕ_{tx} is the CPE's RTC/ATC contention packet transmission energy consumption for intra-cluster contention and ϕ_{rx} is the contention packet reception energy consumption. Similarly, a transition from state '$k|C$' to '$(k+2)|C$' would incur an energy consumption of $\phi_{tx}(2+kp)+\phi_{rx}(l_j-2-kp)$, where, k backlogged users attempt contention with probability p and the two new arrivals attempt contention. One-step transition probability matrix of the DTMC ($\mathbf{P}_{c,j}$) for the jth cluster is modified as ($\mathbf{P}_{c,j,\phi}$) to include the energy consumption in each transition. This is done by multiplying a factor z^{ϕ} to each transition probability, where ϕ is the energy consumption in a particular transition and z is a variable. Average energy consumption in a frame with m_c slots is given by utilizing the m_c-step state transition probability matrix $\mathbf{P}_{c,j,\phi}^{m_c}$ and is given as:

$$\mathbf{\Psi}_j = \left.\frac{d\mathbf{P}_{c,j,\phi}^{m_c}}{dz}\right|_{z=1}. \tag{13}$$

where, differentiation is carried out for each element of the matrix $\mathbf{P}_{c,j,\phi}^{m_c}$ with respect to the variable z. To obtain the energy consumption during a frame starting with state $i|C$, we sum up the columns in $\mathbf{\Psi}_j$ for that corresponding row (state). Denote $\Phi_j(i|C)$ as the average energy consumption in a frame with the system state starting with state $i|C$.

In the inter-cluster contention phase (i.e., states '$i|S$'), all the CPEs in the cluster contend at the BS, and the BS transmits the ACK at the end of the contention phase. The energy consumption in this phase is $\Phi_j(S) = l_j\phi_{S,cpe} + \phi_{S,bs}$, where $\phi_{S,cpe}$ is the contention and reception energy consumption of a CPE over a frame, while $\phi_{S,bs}$ is the transceiver energy consumption at the BS in this phase. Similarly, for each of the state in the data transmission state, a data packet is transmitted by the CPE along with an ACK transmission by the BS at the end of the frame. Both the CPE and the BS receive in their respective slots. Thus, the energy consumption in this state is $\Phi_j(D) = l_j\phi_{D,cpe} + \phi_{D,bs}$, where $\phi_{D,cpe}$ is the transceiver energy consumption of a CPE in the cluster and $\phi_{D,bs}$ is the energy consumption by the BS in the data transmission phase.

From the steady state probabilities of the states in the Markov chain in Fig. 4, the expected energy consumption of the cluster is $\sum_{\forall i} \pi_j(i)\Phi_j(i)$. Thus, the normalized uplink network energy efficiency $\mathcal{E}$ is given as the ratio of the uplink throughput to the total energy consumption of the network and is given as follows:

$$\mathcal{E}=\frac{P_{suc}(n_c^*)\sum_{j=1}^{N_c}\pi_j(S)(1-P_{out}(R,l_j))(1-P_{int})}{N_e\xi\sum_{j=1}^{N_c}\sum_{k=1}^{3l_j+1}\pi_j(k)\Phi_j(k)}. \quad (14)$$

F. Cluster Size Optimization

Cluster size plays a pivotal role in the performance of the proposed network model. Different villages may have different optimal cluster size, which depends partly on the distance of village from the PoP BS and partly on the distribution of CPEs in other villages. A smaller cluster size would result in a lower transmission gain, leading to high data transmission losses, whereas a large cluster would introduce high delays in successful contention in the intra-cluster communication. To this end, the optimal cluster size for a given set of CPEs in a village is obtained by solving the optimization problems to maximize the uplink throughput and energy efficiency.

Consider N_v villages with jth village having $N_{e,j}$ CPEs. Thus, $\sum_{j=1}^{N_v} N_{e,j} = N_e$. All the CPEs in a village form clusters of same size as they are at approximately the same distance from the PoP BS and experience similar channel conditions. Consider that the jth village forms clusters with l_j CPEs per cluster. Optimization problem for uplink throughput and energy efficiency maximization is formulated as $\max_{l_1,\cdots,l_{N_v}} \mathcal{T}$ and $\max_{l_1,\cdots,l_{N_v}} \mathcal{E}$, respectively.

Note that, these are integer optimization problem as the cluster size l are integers. Closed-form expressions for P_{suc} and $\pi(S)$ are difficult to compute because their steady state values are obtained after iterations as shown in Section IV-D. Further, the number of states in the DTMC is dependent on the cluster size. Thus, obtaining integer relaxed equivalent problem is not possible. These optimization problems can be solved using the pattern search method [41]. It starts with an initial set of points, and depending on the function value at these points a new better set of points are obtained. Convergence is achieved when the function values at the obtained set of points are close.

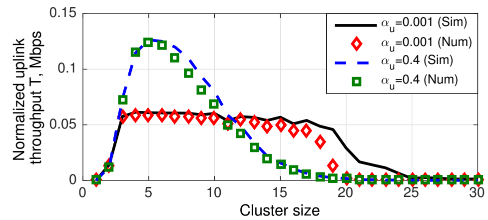
V. Results

In the first part of this section, analysis validation is presented. Thereafter, DCA performance is discussed in the second part of this section. In the final part of this section, performance of the proposed architecture is compared with the existing one considered in [9], [10].

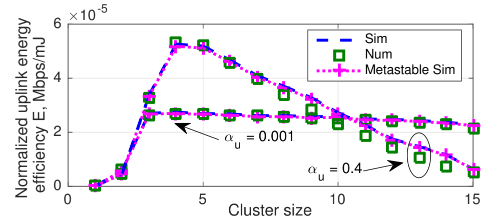
A. Validation of the Analysis

An example scenario of a single village is considered with 600 users accessing the PoP BS which is at a distance of 6 Km. Number of CPEs in the village is 120.

In the existing conventional rural broadband architecture [9], [10], PoP BS and UHF-band nodes transmit over the



(a) Normalized uplink throughput



(b) Normalized uplink energy efficiency

Fig. 5: Variation in normalized uplink throughput and energy efficiency of the cluster-based RBA with the change in cluster size. Sim: simulation, Num: numerical analysis.

TVWS at 30 dBm, while the WiFi transmission by the UHF-band nodes is carried out at 20 dBm. The UHF-band nodes being sporadically located, the user-end devices associated with UHF-band nodes transmit at 20 dBm. In contrast, in the proposed cluster-based architecture, the CPEs transmit over both TVWS and ISM band at 10 dBm. CPEs consume around 16mW power for reception over UHF bands [42]. Having low-power CPEs at closer proximity, the associated user-end devices transmit at 10 dBm. Transmission is carried out at 16 Mbps over a channel of bandwidth 8 MHz. There are 5 data channels available at the PoP BS. Frame duration over CCC is 2 ms while the slot duration over CCC and for intra-cluster communication is 0.1 ms. Okumura-Hata model is used for propagation path loss model. Rayleigh channel fading is considered with unit variance.

Figs. 5(a) and (b) present the normalized uplink throughput and energy efficiency of the proposed cluster-based RBA system architecture versus cluster size at different user packet arrival probability α_u. We observe that the analytical and simulation results match closely, which validates the analysis. With a higher cluster size, numerical results are slightly lower than the simulation results. This is because, with a higher cluster size there are lesser number of clusters in the network. When the number of clusters contending at PoP BS are less than the number of slots available, the probability $\beta(\kappa, v)$ computed in (8) provides an approximation to the actual value resulting in mismatch between simulation and numerical results. This effect is more pronounced at lower α_u, where the number of clusters contending is even lower. We also observe that, there exists an optimal cluster size for which the uplink throughput and energy efficiency is maximum.

In metastable clusters, the uplink throughput remains unchanged, as the cluster contention and data transmission mechanisms remain unaffected. However, two-hop communication is required for data sharing among the cluster members. This additional data transmission activity slightly degrades energy

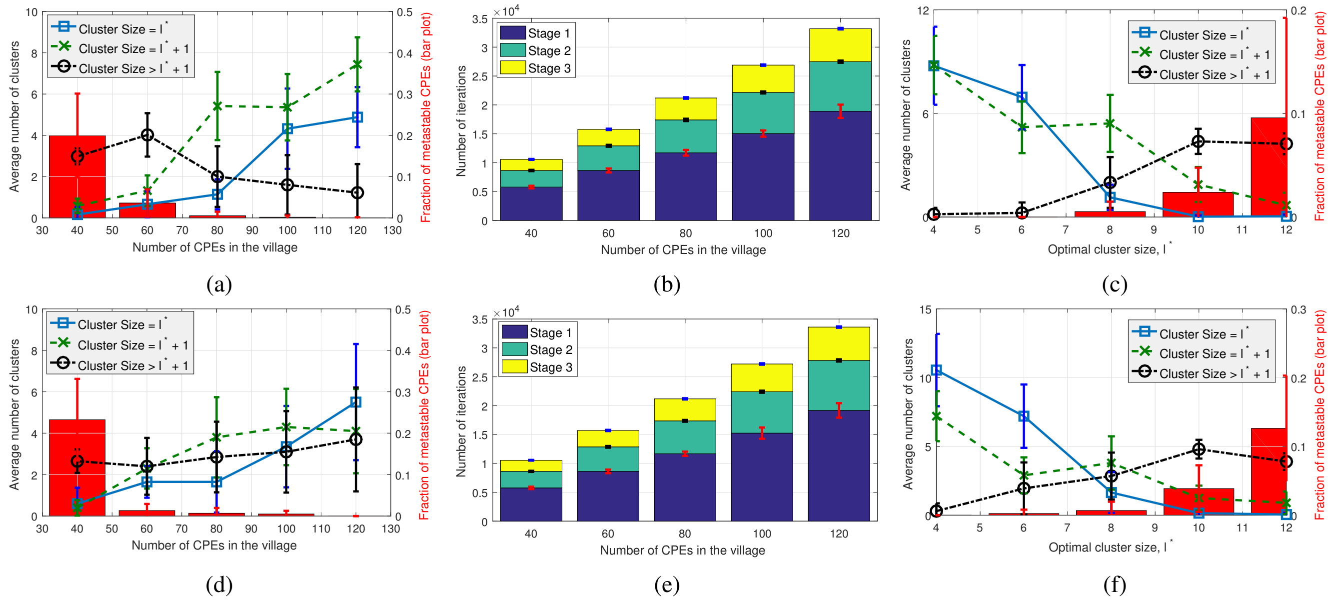


Fig. 6: Uniform deployement scenario: (a)-(c); Non-uniform deployement scenario: (d)-(e). (a),(d) Average number of clusters and fraction of metastable clusters versus number of CPEs for $l^* = 6$; (b),(e) number of iterations required versus number of CPEs; and (c),(f) average number of clusters and fraction of metastable clusters versus optimal cluster size with 80 CPEs. Standard deviation bars are also shown.

efficiency performance of the metastable CPEs (cf. Fig. 5(b)).

B. DCA Performance

Performance of the proposed DCA is investigated in this section. We consider a single village scenario with an area of 0.25 Km^2. CPEs communicate with each other over the TVWS band with transmission power of 10 dBm. Both uniform and non-uniform scenarios are considered and the results are presented by averaging over 20 random scenarios.

1) Uniform Scenario: Multiple CPEs are assumed located in the village according to the Poisson point process. Fig. 6(a) presents the number of clusters of different sizes formed after the execution of DCA with the variation in number of CPEs. Optimal cluster size is set to $l^* = 6$. We observe that, as the number of CPEs increases, the number of clusters formed of size l^* and $l^* + 1$ increases because a high CPE density results in a higher node degree and thus higher chance of forming optimal clusters. The fraction of metastable CPEs also reduces as the degree of the nodes increases. High variance bars indicate that though the trend remains the same, cluster formation is CPE placement dependent. Fig. 6(b) presents the average number of iterations required in different stages of the algorithm. Here, we observe that for higher number of CPEs, higher iterations are required because, at each iteration one CPE connects to a cluster. To form optimal number of clusters, large number of iterations are required. First stage of DCA requires a higher number of iterations compared to the second and third stages, indicating that optimal number of clusters (of size l^*) can be formed in the first stage itself. Here, the variances are low across different stages which indicates that the DCA takes almost constant execution time for different scenarios, but depends on the number of CPEs in the village.

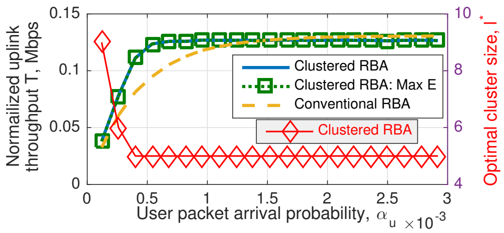
Fig. 6(c) presents the number of clusters formed with the variation in optimal cluster size for 80 CPEs in the village. We observe that as the optimal cluster size l^* increases, higher number of metastable clusters are formed as higher degree of the CPEs is required. Thus, with the increase in l^* more clusters with size $> l^*+1$ are formed. There is a high variance in fraction of metastable CPEs for higher cluster size l^*, as the CPE connectivity plays a key role when cluster size is large.

2) Non-uniform Scenario: In this case, CPEs are located in a village according to non-homogeneous Poisson point process with Gaussian intensity function having center of the village as its mean and unit variance. The plots obtained are presented in Figs. 6(d)-(f); the trends are similar to the ones obtained for uniform distribution scenario. However, we note that the number of clusters formed of size $> l^* + 1$ and number of metastable CPEs are higher in this case as the CPE density is higher at the village center and it decreases as we move away from it. Thus, due to lower connectivity of the distant CPEs, more metastable clusters are formed, which results in higher number of clusters with size $> l^* + 1$.

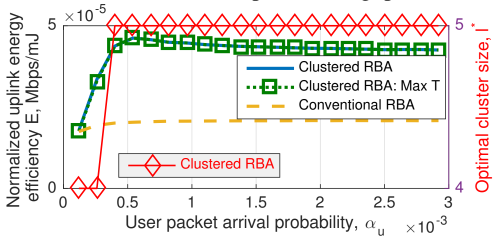
C. Relative Performance Comparison

A single village scenario (as considered earlier) is considered to present the relative performance comparison in the first part. Additionally, relative performance in two real-world scenarios are studied in the second part of this subsection.

1) Single Village Scenario: Fig. 7(a) presents the normalized uplink throughput performances of the clustered RBA and conventional RBA. Optimal cluster size to maximize uplink throughput in the cluster-based RBA is obtained via simulations. It is noted that a lower user packet arrival probability, α_u induces a higher optimal cluster size. Large cluster reduces the cluster outage probability. Thus, at lower α_u, large cluster can be accommodated without incurring significant contention delays. However, as α_u increases, a larger cluster would result is higher contentions reducing throughput. Thus,

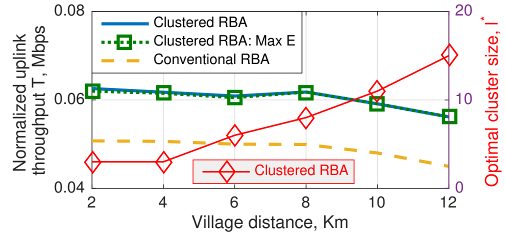


(a) Normalized uplink throughput

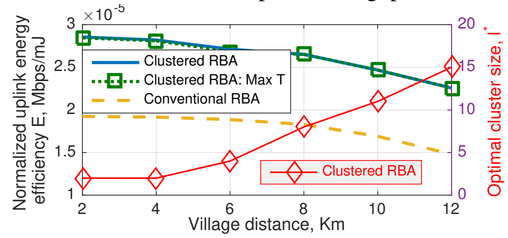


(b) Normalized uplink energy efficiency

Fig. 7: Normalized uplink network throughput and energy efficiency along with optimal cluster size in a single village scenario. Max T/E: network operates at maximized throughput/energy efficiency.



(a) Normalized uplink throughput



(b) Normalized uplink energy efficiency

Fig. 8: Normalized uplink network throughput and energy efficiency along with the optimal cluster size versus distance of the village from the PoP BS with $\alpha_u = 2\text{x}10^{-4}$. Max T/E: network operates at maximized throughput/energy efficiency.

cluster size decreases with increasing α_u. Uplink throughput in the proposed clustered RBA scheme is seen to be better than the conventional RBA at lower α_u, because TDMA induces low throughput at lower traffic intensity. Compared to conventional RBA, in clustered RBA throughput saturates at lower α_u, providing maximum network resource utilization at lower traffic intensity. However, the saturation throughput in clustered RBA is slightly lower than that in conventional RBA, due to contention overhead in clustered RBA.

Fig. 7(b) presents the normalized uplink energy efficiency of the two schemes and the optimal cluster size in the proposed RBA scheme for uplink energy efficiency maximization. Contrary to the uplink throughput case, here the cluster size increases as α_u increases. A larger cluster incurs a higher energy consumption in intra-cluster contention and in data transmission to the PoP BS. As α_u increases, number of clusters contending over the CCC increases reducing throughput and increasing energy consumption. Thus, to reduce the number of cluster contentions at the BS, cluster size increases. Energy efficiency in cluster-based RBA is better than the conventional RBA, as the UHF-band nodes in the conventional RBA consume high energy in data transmissions. Conversely, the proposed RBA uses DBF which reduces energy consumption significantly. On average, clustered RBA offers 105% better energy efficiency than the conventional RBA scheme.

Uplink throughput achieved when the network operates for maximized energy efficiency and vice versa are also shown in Fig. 7. We observe that even when the network operates at maximized energy efficiency, the throughput remains close to maximal. At lower α_u, optimal cluster size for maximizing throughout and energy efficiency are significantly different. However, as noted from Fig. 5, throughput remains constant with cluster size at lower α_u, which provides close to the maximal throughput. At higher α_u, optimal cluster size is same for both the cases, giving maximal performance in both. Similar observations are noted for energy efficiency when the network operates for maximized throughput.

Network performance versus PoP BS-village distance is presented in Fig. 8. It is observed that the cluster size increases with increasing distance, because larger distance communication requires a higher cluster size. We also observe that the performance of the proposed RBA scheme is better than the conventional RBA scheme due to the use of collaborative communication in our proposed clustered RBA.

In the following performances of the two RBA schemes in two real-world scenarios are presented.

2) Real-world Scenarios: Two real-world scenarios are considered. The first one is taken from Dhuktan, Maharashtra, India [9]. There are 10 adjoining villages located within 2 Km from Dhuktan, with total population being approximately 1400. The second scenario is from Zomba, Malawi, Africa [43]. The authors in [43] have implemented a communication system by establishing TVWS connection between PoP and three neighboring places. The network structures for the two scenarios are presented in Figs. 9 (a) and (b).

Fig. 9(c) presents the normalized uplink throughput of the two schemes in the two scenarios. Network throughput increases with the increase in packet arrival rate and saturates at higher rate. As observed from the previous example, lower throughput in conventional RBA scheme is observed due to the use of TDMA access mechanism. However, saturation throughput in clustered RBA is slightly lower due to contention overheads. Fig. 9(d) shows the uplink energy efficiency in the two schemes for the two scenarios. Similar observations are made here as well, where the energy efficiency of the clustered RBA is better than the conventional RBA. On an average, clustered RBA offers 20% higher energy efficiency as compared to the conventional RBA scheme.

Similar conclusion is drawn here as well: when the network operates for maximized energy efficiency, it achieves maximal

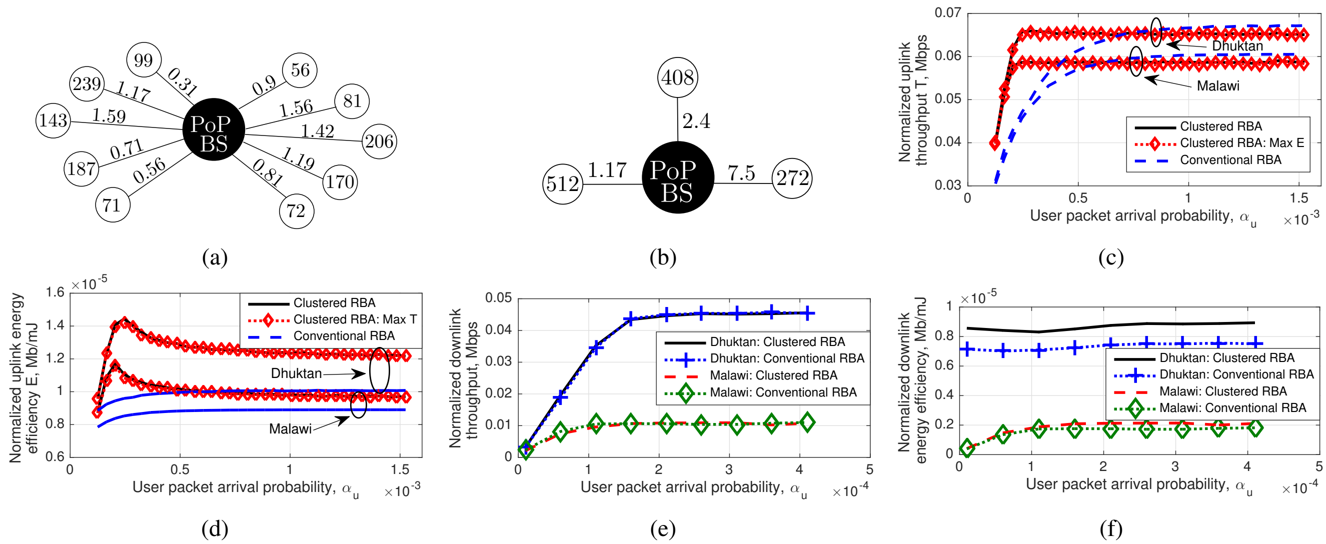


Fig. 9: Network architecture for (a) Dhuktan, (b) Malawi (value in circle represents the population of the village and the weight of the connecting line represents the distance (Km) from PoP BS to the village); (c) - (d) Normalized uplink network throughput and energy efficiency (Max T/E: network operates at maximized throughput/energy efficiency); (e) - (f) Normalized downlink network throughput and energy efficiency.

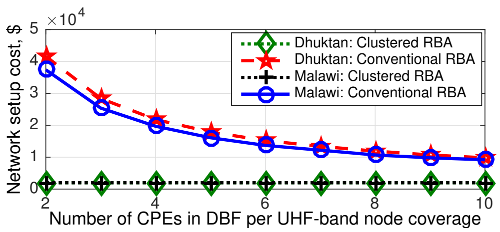


Fig. 10: Network setup cost in the two schemes.

throughput simultaneously, and vice versa.

Normalized downlink network throughput and energy efficiency are plotted in Figs. 9(e) and (f). Here, throughput of the two schemes are nearly equal. However, due to low transmission power requirements in the proposed cluster-based RBA, its energy efficiency is better than the conventional RBA.

Network setup cost of the two schemes is shown in Fig. 10. Number of UHF-band nodes required in a village depends on the village population density. It is observed that, as the number of CPEs per UHF-band node increases the network setup cost of conventional RBA model decreases. However, the operator setup (infrastructure) cost in conventional RBA model remains significantly higher, because the operator has to install higher number of UHF-band nodes which incurs significant deployment as well as operational costs.

VI. Conclusion

The proposed RBA architecture is a small initiative towards breaking the socio-economic barrier between the rural and urban population in developing countries. This work has studied the state-of-the-art strategies on RBA and proposed a cluster-based RBA model. Uplink throughput and energy efficiency of the cluster-based RBA have been obtained analytically using DTMC. Optimization problems to maximize uplink throughput and energy-efficiency have been formulated. A distributed clustering algorithm has also been proposed for the CPEs to form clusters of optimal size and a channel allocation algorithm is proposed to minimize the inter-cluster interference. Results show that the proposed clustered RBA eliminates the need of UHF band nodes in the conventional RBA, which reduces the network deployment and maintenance cost along with making the network energy-efficient and scalable.

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