How Much TV UHF Band Spectrum is Sufficient for Rural Broadband Coverage?

(*Invited Paper*)

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***Abstract*—Unlike in the developed countries, TV white spaces are abundant in India and rural broadband coverage is negligible. Government of India has an ambitious plan to connect 250,000 rural offices (Gram Panchayat) using optical fiber based point of presence (PoP); this will allay, but not solve the rural broadband coverage problem.**

In this work, a middle-mile multihop mesh network operating in the TV UHF band is presented as a solution to providing seamless connectivity between the Gram Panchayat and village users. This network can coexist with TV broadcasting via the License Shared Access mechanism. The main contribution of this paper is a throughput optimization tool. Given the demography information of rural areas, the desired broadband speed and contention ratio, available frequency, location of fiber PoP, and propagation path-loss models of the TV UHF band—our optimization tool computes optimal power and routing for the multihop mesh network. The analysis is performed at the physical layer. Time division multiple access and spatial reuse of frequency are used for interference management in this work. Simply put, given demography information, our optimization tool determines at what power will broadband coverage will be feasible in the rural areas. This tool's design is separable and it can be utilized in other areas of the world, where demography and path-loss models can be replaced. Our optimization tool will be exemplified using results from one demographic region in India.

I. Introduction

When analog TV channels switched to digital or when broadcasters stopped their transmissions, spectrum bands became available in various channels at different geographic locations. These spectrum holes are called as TV white spaces. The amount of TV white space available in countries such as US, UK, and Japan varies depending on the geographical locations and is fragmented in frequency. Quantitative assessments have shown that the amount of spectrum available as TV white spaces in these countries is limited [1], [2], [3], [4], [5].

Regulators FCC and Ofcom in US and UK, respectively, have permitted devices to make use of "white spaces" on a "secondary" basis, that is, without causing harmful interference to the licensed user or the "primary" [6], [7]. Regulators have allowed low power license-exempt operation on a secondary basis to efficiently utilize the spectrum, which was otherwise utilized earlier by analog transmission, but now is part of TV white spaces due to the *digital dividend*.

In developing countries such as India, Brazil and South Africa, the available TV white space is significant [8], [9]. For example, quantitative assessment in India [8] (where only one incumbent national broadcaster is transmitting at most on two channels!) shows that in the 470-590MHz UHF TV band, a major portion is unutilized. The results show that even while using conservative parameters for assessment, in at least 56.27% areas in India, all the 15 channels (100% of the TV UHF band) are free [8]. *We envisage that this abundant underutilized TV band spectrum can be used for provisioning affordable rural broadband* as discussed next.

One of the major impediments for providing broadband connectivity in rural areas of many developing countries is the lack of robust cost-effective backhaul. Even in the urban areas, one of the major impediments for widespread deployment of Wi-Fi Hotspots is the lack of fiber connectivity to Wi-Fi access points (APs). Fiber connectivity in terms of backhaul is limited in developing countries like India, and may currently reach only at designated points in a town or city. E.g., National Optical Fiber Network (NOFN) is an ambitious plan of Government of India, and it plans fiber connectivity only to village administrative units named Gram Panchayat in the next five years; there are about 250,000 Gram Panchayat administering about 600,000 villages (hamlet clusters) in India. Even this already ambitious plan of the Government of India leaves a big gap in providing connectivity to these hamlet clusters.[1]

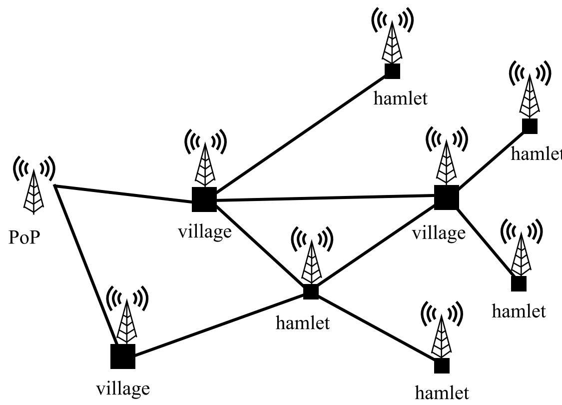

Fig. 1: *A PoP (such as a rural office with NOFN connectivity) is adjacent to villages or hamlet cluster. A TV UHF band multihop mesh network can provide backhaul connectivity between PoP and hamlets.*

[1]Deploying optical fiber at such scale is challenging due to cost issues (feeble return on investment) as well as legal issues such as right of way.

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In this scenario, connecting the core network (such as NOFN) to the access network can be addressed using a *wireless mesh based last-mile or middle-mile network in the TV UHF band*. In detail, our envisaged middle-mile backhaul network is a multihop wireless mesh network that is capable of providing coverage within a radius of one to five kilometers to enable connectivity from the access network such as Wi-Fi zones/APs to an optical fiber point of presence (PoP). Sub-GHz spectrum provides excellent propagation characteristics to reach these distances, and will not require expensive infrastructure such as high towers and strict line-of-sight [10] (see Fig. 1).

In this paper, the throughput achievable through a TV UHF band middle-mile mesh network, as a *fixed service*, is analyzed. The envisaged use is to connect "scattered" broadband hot-spot users (such as APs) [2] in rural or semi-urban areas with the NOFN high-speed optical fiber point. It must be noted that *mobility is not the major consideration* for broadband access, since even fixed broadband access is negligible. The main contribution of our work is a throughput optimization tool for a middle-mile mesh network. Its detail are explained next.

Our throughput optimization tool, which has a separable architecture, has the following inputs: (i) a set of sink nodes which designate NOFN nodes or more generally PoP; (ii) a (relatively larger) set of APs which generate network traffic to be sent/communicated to the sink nodes; (iii) demography information (population and geographical locations) of areas served by APs; (iv) amount of available frequency and desired contention ratio (or number of simultaneously active users); and (v) propagation path-loss models. *Using these inputs—with time division multiple access (TDMA), power-control, and spatial reuse of frequencies for interference management—the net output of our optimization tool is sum-power optimal assignment of routes to data 'packets', and achievable throughputs*. Since demography of rural areas and NOFN nodes is used, the mesh network is naturally formed by rural clusters as APs and NOFN nodes as the PoP. The population information from demography naturally determines the data-rate demand. Coupled with calculated achievable power-throughput tradeoff, our optimization tool determines the bandwidth needed for broadband coverage in rural areas. *This tool is modular and its method can be utilized in other areas of the world* (see Fig. 2).

On regulations: The wireless spectrum in the TV UHF band, 470-590MHz being used by the TV broadcasters can be made available in a Licensed Shared Access (LSA) mechanism for enabling the middle-mile mesh network. The LSA mechanism is a complementary approach to the traditional exclusive licensing and the license exempt (unlicensed) approaches. In LSA, additional users (termed as co-primary or LSA licensee) are granted license to operate in a frequency band which is assigned (or will be assigned in the future) to an incumbent user. The incumbent users agree to the terms of the LSA license, which is granted by the regulator. A certain quality of service is guaranteed to both the incumbent users and the LSA licensees. LSA is being considered in 3GPP [11] for deploying

[2]In low income developing countries, affordable access is a primary challenge. Therefore, we contend that affordable access can be provided using unlicensed Wi-Fi APs, which in turn can be connected to a fiber point with a mesh network comprising of TV UHF band devices.

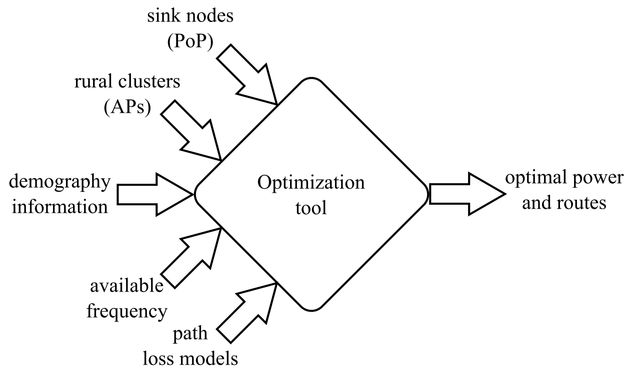


Fig. 2: *Our throughput optimization tool has the following inputs: (i) sink nodes which designate PoPs; (ii) rural clusters (APs) which generate network traffic to be sent to the sink nodes; (iii) demography information (such as population and geographical locations) of areas served by the APs; (iv) amount of available frequency and desired contention ratio; and (v) propagation path-loss models. Using these inputs—with TDMA, power-control, and spatial reuse of frequency for interference management—the output of our optimization tool is sum-power optimal assignment of routes, and achievable throughputs.*

Long Term Evolution technology. It could be considered for deploying middle-mile mesh network for fixed services in TV UHF band where the TV UHF band devices can be considered as co-primary users operating along with the incumbent [12].

Prior art: To the best of our knowledge, this is *the first work* which proposes a middle-mile multihop mesh network for backhaul using the TV UHF band or TV white space. Capacity of TV white space channels for secondary or unlicensed usage has been studied by Hessar and Roy [13]. Backhauling using TV white space and fixed directional antenna has been studied by Gerami, Mandayam, and Greenstein [14]. A review of wireless mesh networks, topologies, and power efficiency in such network is present in the literature [15], [16]. It should be noted that the novelty of this work lies in the exploration of wireless mesh network based solution to the rural broadband problem and the associated design issues.

Organization: System model and assumptions are described in Sec. II. The sum-power optimization and route selection in wireless mesh network is described in Sec. III. The results of power optimization and route selection, when applied to an example topology from western India, are presented in Sec. IV. Finally, concluding remarks are presented in Sec. V.

II. System Details and Modeling Assumptions

A set of M sink nodes (PoP), N transmission nodes (AP), and a population vector $\vec{N}$ form the multihop mesh network. Only uplink scenario from the TV UHF band transmission nodes to the sink nodes is considered.[3] Each transmission node represents a hamlet's TV UHF band transmitter wired with Wi-Fi as an AP for rural population. The TV UHF band transmitter, in essence, backhauls the data gathered from the nearby rural population using local Wi-Fi network. Let $\mathcal{S} := \{S_1, S_2, \ldots, S_M\}$ be the sink nodes and $\mathcal{T} :=$

[3]The downlink is conceptually similar as the transmission nodes as well as the sink nodes are *fixed.*

$\{T_1, T_2, \ldots, T_N\}$ be the transmission nodes. Each node in $\mathcal{T}$, in a mesh topology in Fig. 1, is designated to serve two purposes: (i) serve broadband users connected to itself; and, (ii) forward the data from its neighbors, if any. Let $\vec{N}$ be the population demography, that is, $N_i, i \in \mathcal{T}$ is the population which needs broadband connectivity at node i. It is assumed that each broadband user needs a *guarantee* of R bits/second and α is the fraction of population active (on an average) at a given time.[4] So, $\alpha R N_i$ is the amount of data generated for uplink at transmission node $i \in \mathcal{T}$. The value of α is specified with demography information in the optimization tool in Fig. 2.

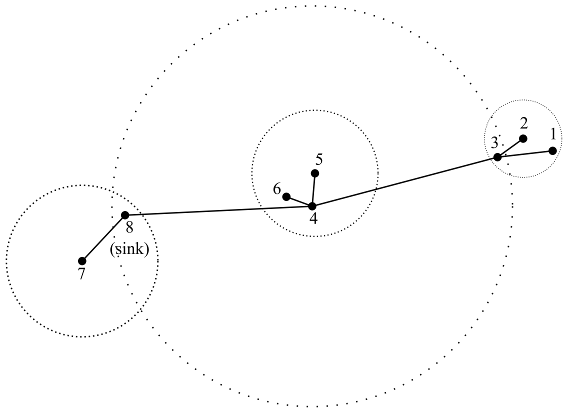


Fig. 3: *An example of mesh topology is shown. Node 8 is the sink while nodes 1 to 7 are transmission nodes. Data from (transmission) nodes 1 to 7 has to be transported to (the sink) node 8. The nodes have populations $N_1, \ldots, N_7$ and each node generates $\alpha R N_i$ number of bits/second to be sent to the sink. The transmission nodes use a power vector $P_1, \ldots, P_7$. Examples of interference regions for node 2, node 4, node 5, and node 7 are illustrated by circles. The links from 5 to 4 and 7 to 8 can operate in parallel due to spatial reuse; but, the link from 4 to 8 interferes with all other nodes. That is, $IZ_{4,8} = \{1, 2, 3, 5, 6, 7\}$ while $IZ_{2,3} = \{1, 3, 4\}$. Observe that node 1 has to send $\alpha N_1 R$ bits/second, while node 3 has to send $\alpha R(N_1 + N_2 + N_3)$ bits/second.*

The network topology is formed as a connectivity graph, depending on the transmit power and the receive sensitivity of the radios. A link exists in the connectivity graph between node i with transmit power P_i (in dBm) and node j, if node j is within the communication range of node i, that is if

$$P_i - PL_{(i,j)} \geq \xi_j; \forall i \in \mathcal{T}, j \in (\mathcal{T} \cup \mathcal{S}) \tag{1}$$

where $PL_{(i,j)}$ is the path-loss in dB, and ξ_j is the receiver sensitivity of radio at node j (in dBm). It is obvious that P_i should be smaller than a maximum limit set by regulations. This limit will be called as maximum equivalent isotropically radiated power (mEIRP) in this paper. For a fixed topology of nodes in $(\mathcal{S} \cup \mathcal{T})$, any node $i \in \mathcal{T}$ will need a minimum power (say $P_{i,\min}$) for connectivity to its nearest node.

Let $\vec{P}$ be the power assigned to the nodes in $\mathcal{T}$. Depending on the choice of $\vec{P}$, there is a connectivity graph that will form as follows. Let $\mathcal{G} \equiv \mathcal{G}(\vec{P}) := (\mathcal{S} \cup \mathcal{T}, \mathcal{L})$. The connectivity graph has nodes from the set $\mathcal{S} \cup \mathcal{T}$, and links (edges) that depend on the chosen power vector $\vec{P}$. The links in $\mathcal{L}$ get determined by the set of links that satisfy the receive power condition in (1). It is assumed that each node in $\mathcal{T}$ is equipped with an omni-directional antenna in the TV UHF band.

[4] A common value of α for $i \in \mathcal{T}$ represents the uniform socio-economic conditions and the broadband Internet requirements of all hamlets.

It is assumed that links in $\mathcal{L}$ are half-duplex and operate on a single 8MHz bandwidth TV UHF band channel. This channel can be made available either by a database query [17], or in the licensed shared access mode [11]. In this work, *only uplink throughput and power* are optimized for simplicity. To address downlink as well as uplink, two (similar) optimization problems need to be solved. No new conceptual insights will be added by two simulations instead of one.

Interference management will be attained by TDMA and spatial reuse. For spatial reuse, interference zone needs to be identified; similarly, for TDMA, activity time (or fraction) or a link needs to be identified. *Interference zone* for a node $i \in \mathcal{T}$ while communicating with a node $j \in \mathcal{S} \cup \mathcal{T}$ is defined as the set of nodes that satisfy the following interference condition:

$$\begin{aligned} IZ_{i,j} = \{k : & P_i - PL_{(i,k)} - N_0 \geq \Delta \text{ or} \\ & P_k - PL_{(k,j)} - N_0 \geq \Delta, k \in \mathcal{S} \cup \mathcal{T}\} \end{aligned} \tag{2}$$

where N_0 is the thermal noise in dBm and Δ is an SNR threshold in dB to determine whether one node is in the interference zone of the other. In this work, $\Delta = -5$dB, which means at the boundary of interference zone, the signal of i is -5dB below the noise floor (or insignificant). The interference zone consists of all the nodes which will either cause interference to the receive node j or will receive interference from node i. At any time, if node i is communicating with node j, then other nodes in $IZ_{i,j}$ are not transmitting or receiving. That is, only one link is used within each interference zone at a time.

For throughput calculations, Shannon's capacity formula for additive white Gaussian noise channel is used. The expression is given in terms of received signal to noise ratio. The capacity C_{ij} is function of $P_i - PL_{(i,j)}$ and is given by [18],

$$C_{ij} = W \log_2 \left(1 + 10^{\left\{ \frac{\left(P_i - PL_{(i,j)} - N_0\right)}{10} \right\}} \right).$$

Transmit power P_i and noise N_0 are in dBm. The bandwidth W is 8MHz for one TV UHF band channel. The TV UHF band affects (only) the path-loss model $PL_{(i,j)}$. The optimization tool, i.e., the main contribution of this work, is discussed next.

III. Optimization setup and methodology

In this section, power allocation to various nodes in a mesh topology and routing will be obtained as the result of a constrained optimization problem. Our optimization tool yields a route between transmission nodes and sink nodes, with optimal power allocation, such that a data-rate of $\alpha R N_i$ can be sustained at each transmission node i in the mesh-topology.

A. Setup of the optimization problem

Interference-avoidance is incorporated to mitigate interference in the network, i.e., at any given time, at most one transmitter is active in any interference zone as described in (2). Thus, in a given channel, interference is managed. TDMA through a central scheduler will be used to allocate different activity time to various links $(i, j) \in \mathcal{L}$. From Fig. 3, recall that an intermediate transmission node i in the mesh network has two functions: (i) serve its own users with data rate of $\alpha R N_i$; and, (ii) relay the incoming information from other nodes. This relaying differentiates capacity of a link from throughput in the network. For example, in Fig. 3, even though node 3 communicates $\alpha R(N_1 + N_2 + N_3)$ bits/second, its own data-throughput is $\alpha R N_3$.

The constraints for the operation of our proposed mesh network are the following:

1) There are flow-control constraints, which dictate that the outgoing link capacity (together with the activity) from any node should exceed the total data-rate due to relaying and users present at the same node. For example, in Fig. 3, the data-rate multiplied by activity time on link from node 3 to node 4 should exceed the data-rate due to N_3 users at node 3 as well as relaying traffic from node 1 and node 2.
2) There are links in set $\mathcal{L}$ and interference is managed by ensuring that two links in the same interference zone (see (2)) are not active together. This naturally leads to a constraint on the activity time of various links (for example, the activity fraction of links in an interference zone should sum to at most one).
3) There is a maximum power constraint on each node i. Specifically, $P_{i,\min} \leq P_i \leq$ mEIRP.

The formulation of optimization problem also requires the definition of incoming traffic nodes and outgoing traffic nodes. Nodes from which a node i receives relay traffic will be termed as incoming traffic nodes $\mathcal{X}_i$. Similarly, nodes to which a node j sends relay traffic will be termed as outgoing traffic nodes $\mathcal{Y}_i$. For example, in Fig. 3, $\mathcal{X}_3 = \{1, 2\}$ and $\mathcal{Y}_3 = \{4\}$.

Two types of routing will be considered. If the transmission nodes route data through multiple paths, it will be termed as *generalized routing*. If the transmission nodes route data through only a single path, it will be termed as Internet Protocol (IP) routing. While generalized routing can yield better results in terms of power and throughput, IP routing is more desirable from a network layer perspective [19].

Recall that $\vec{P} = \{P_1, P_2, \ldots, P_N\}$ is the power vector allocated at the transmission nodes. The *generalized routing* based optimization problem is as given below:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{i \in \mathcal{T}} a_i P_i \qquad (3)\\
\text{subject to} \quad & \sum_{x \in \mathcal{X}_i} \lambda_{x,i} C_{xi}(P_x) + \alpha R N_i = \sum_{y \in \mathcal{Y}_i} \lambda_{i,y} C_{iy}(P_y) \\
& \qquad \text{for all } i \in \mathcal{T} \\
& \lambda_{x,i} \geq 0 \text{ for all } i \in \mathcal{T}, x \in \mathcal{X}_i \\
& \lambda_{i,y} \geq 0 \text{ for all } i \in \mathcal{T}, y \in \mathcal{Y}_i \\
& \sum_{u \| v \in IZ_{i,j}} \lambda_{u,v} \leq 1, \text{ for all } i \in \mathcal{T}, j \in \mathcal{Y}_i \\
& P_{i,\min} \leq P_i \leq \text{mEIRP}.
\end{aligned}
$$

In (3), the parameters $\lambda_{i,j}$ indicate the fraction of time for which the link between nodes i and j is active. The fractions $\lambda_{i,j}$ will be termed as the *activity* of the link (i, j). The parameters $a_i, i \in \mathcal{T}$ represent activity of node i. Physically, a_i denotes the time for each node i is transmitting in one second. The first constraint in (3) captures the flow-control condition in the above-mentioned list. The second and third constraints just dictate that the activities of various links are positive. The fourth constraint captures the interference management condition in the above-mentioned list. Finally, the last constraint captures the power condition in the above-mentioned list.

All the constraints in (3) are linear in various activity time variables $\lambda_{i,j}$. The optimization, therefore, seems simple via linear programming. However, a change in the power vector $\vec{P}$ can result in the addition or removal of a link in the connectivity graph and interference zones (see (1) and (2)). This can lead to different constraint equations in (3). In our experience, this makes the optimization problem *difficult to solve* using standard techniques.

The *IP routing* based optimization problem is obtained as a slight variation of (3) as given below:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{i \in \mathcal{T}} a_i P_i \qquad (4)\\
\text{subject to} \quad & \sum_{x \in \mathcal{X}_i} \lambda_{x,i} d_{xi} C_{xi}(P_x) + \alpha R N_i = \\
& \qquad \sum_{y \in \mathcal{Y}_i} \lambda_{i,y} d_{iy} C_{iy}(P_y) \text{for all } i \in \mathcal{T} \\
& \lambda_{x,i} \geq 0 \text{ for all } i \in \mathcal{T}, x \in \mathcal{X}_i \\
& \lambda_{i,y} \geq 0 \text{ for all } i \in \mathcal{T}, y \in \mathcal{Y}_i \\
& \sum_{u \| v \in IZ_{i,j}} \lambda_{u,v} \leq 1, \text{ for all } i \in \mathcal{T}, j \in \mathcal{Y}_i \\
& P_{i,\min} \leq P_i \leq \text{mEIRP}.
\end{aligned}
$$

Between (3) and (4), the key difference is introduction of d_{xi} and d_{iy} variables. These variables are explained next.

In IP routing, the forwarding tables of all intermediate nodes are updated such that all packets having a source-destination address pair follow the same path. To account for this, the optimization problem (3) is modified such that packets having the same destination must follow the same route at each node. Suppose decision set $\{d_{xi}, x \in \mathcal{X}_i\}$ represents the state of incoming links to node i. Each element of the set must satisfy the condition,

$$
d_{xi} = \begin{cases} 1 & \text{if node } x \in \mathcal{X}_i \text{ routes traffic via node } i, \\ 0 & \text{otherwise.} \end{cases} \qquad (5)
$$

Essentially, active links that forward traffic to node i are represented by 1 and inactive links by 0 via d_{xi}. Similarly, there are outgoing links. Each node in $\mathcal{Y}_i$ is a potential candidate for node i to route traffic towards the sink node. Since IP routing selects only one link to route packets at node i, so only one node in $\mathcal{Y}_i$ should be selected. The decision set $\{d_{iy}, y \in \mathcal{Y}_i\}$ represents the state of outgoing links. And $d_{iy} \in \{0, 1\}$ and $\sum_{y \in \mathcal{Y}_i} d_{iy} = 1, \forall i \in \mathcal{T}$.

The IP routing optimization problem is a mixed-integer programming problem, with possible addition or removal of links due to change in transmit powers. It is well known that mixed-integer programs are difficult to solve [20]. Using random hill climbing, and some relaxation, this problem is solved as well by our optimization tool. The solution may be suboptimal and is compared for one topology in this work. The details of this relaxation is omitted for brevity.

B. Optimization using random hill climbing

There are various optimization algorithms available in the literature to solve the non-convex optimization problem [20]. In this work we use a random hill climbing algorithm inspired from the literature [21], [22]. The random hill climbing algorithm will be used to solve the optimization problems for generalized and IP routing (see (3) and (4)).

For initialization of random hill climbing algorithm, a vector $\vec{P}[0]$ is searched in the solution space, such that $P_i \in [P_{i,\min}, \text{mEIRP}]$, and for which the constraint set in (3) is satisfied. In successive iterations, $\vec{P}[0]$ is perturbed randomly as described next. Let $\{\eta_k\}$ be a sequence of positive parameters, where k denotes a positive integer. At first, the power vector $\vec{P}[0]$ will be perturbed to obtain a random (equally likely) point in the cube $[P_i[0]-\eta_1, P_i[0]+\eta_1]$ for each $i \in \mathcal{T}$. Let $\vec{P}_{\text{temp}}$ be the power vector obtained by this perturbation process. The constraints in (3) are evaluated for $\vec{P}_{\text{temp}}$. If all the conditions are satisfied, then it is checked whether

$$\sum_{i=1}^{N} a_{i,\text{temp}} \vec{P}_{\text{temp},i} < \sum_{i=1}^{N} a_i[0] P_i[0]. \tag{6}$$

If this check is also met then $\vec{P}[1] = \vec{P}_{\text{temp}}$. Otherwise, $\vec{P}[1] = \vec{P}[0]$. Observe that

$$\sum_{i=1}^{N} a_i[1] P_i[1] \leq \sum_{i=1}^{N} a_i[0] P_i[0], \tag{7}$$

that is, $\vec{P}[1]$ is smaller in cost compared to $\vec{P}[0]$. And $\vec{P}[1]$ satisfies the constraints in (3). Thus, $\vec{P}[1]$ is (probabilistically) superior compared to $\vec{P}[0]$. Similarly, $\vec{P}[2]$ is (probabilistically) superior compared to $\vec{P}[1]$. This process can be repeated and the parameter η_k is reduced as k (the number of iteration) increases. Reduction in the (step-size like) parameter η_k obtains a power allocation vector closer to the (locally) optimal value. To terminate the random search procedure for a more optimal point, a limit is kept on the number of attempts at finding a new power allocation vector. The parameter η_k is reduced if new power allocation vector is not found. In this work, η_k was kept at a constant level for ω number of random searches in random hill climbing, and then reduced by a factor of $\exp(-\zeta), \zeta > 0$ where ζ is another parameter to be chosen.

IV. Simulation Results

The result of our optimization tool will be exemplified using a topology from the western region of India. One sink node or PoP is planned at Dhuktan (India), and there are 10 hamlets in its vicinity. The maximum distance between Dhuktan and these hamlets is 2km. The total population of Dhuktan and the 10 hamlets is around 2500. The geographical topology is illustrated in Fig. 5(a). The distances from Dhuktan PoP for various hamlets and their are indicated in the third and first coordinates. For example, 143 is the population while 1.59Km is the distance of of Sutarpada from Dhuktan PoP. It is assumed that each hamlet has only one TV UHF band radio available for backhaul connectivity and the connection between hamlets and Dhuktan PoP forms a multihop mesh network using a single 8MHz channel. Only uplink simulations are illustrated. The fraction of active users (α) at all transmission nodes $i \in \mathcal{T}$ will be varied. The total load in the network can be determined as $\sum_{i \in \mathcal{T}} N_i \alpha R$. A MATLAB program suite was written to determine the power allocation vector and corresponding (generalized or IP) routing for the topology. In the optimization tool, the Okumara-Hata path loss model [23] has been used. In principle, the ITU-R path loss model [24] or any other path loss model can also be included. Additional parameters used for the simulations are provided in Table I.

TABLE I: Simulation Parameters

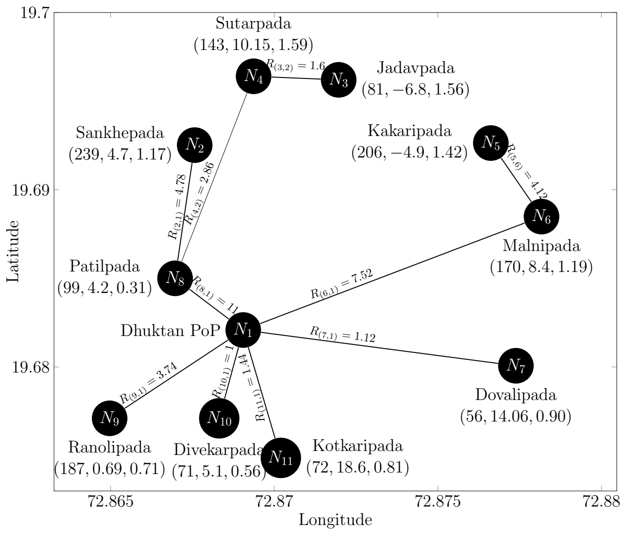
Parameter	Description	value
f_C	Carrier frequency	500MHz
W	Bandwidth of the channel	8MHz
R	Targeted per user broadband speed	2Mbps
h_i	Sink node antenna height	40m
h_j	Transmission node antenna height	40m
G_{Tx}	Transmitter antenna gain	10dBi
ξ_j	Receiver sensitivity of transmission node radios	-86dBm
N_0	Thermal noise for 8MHz bandwidth	-104.75dBm
Δ	SNR threshold to determine whether a node is in the interference zone	-5dB

The optimal power allocation for a given network load is determined using the simulation methodology described earlier for the Dhuktan PoP. Fig. 4 and Fig. 5 provide the results of power allocation and routing diagram. Fig. 4(a) plots the average and maximum value of power allocation vector for percentage users active varying from 1 to 3. It can be observed from the figure that the average power in dBm increases linearly with increasing load on the network. This can be inferred from the fact that load on the network is linearly related to the percentage of users served at the hamlets, while capacity of the links rises logarithmically with increasing transmitted power.

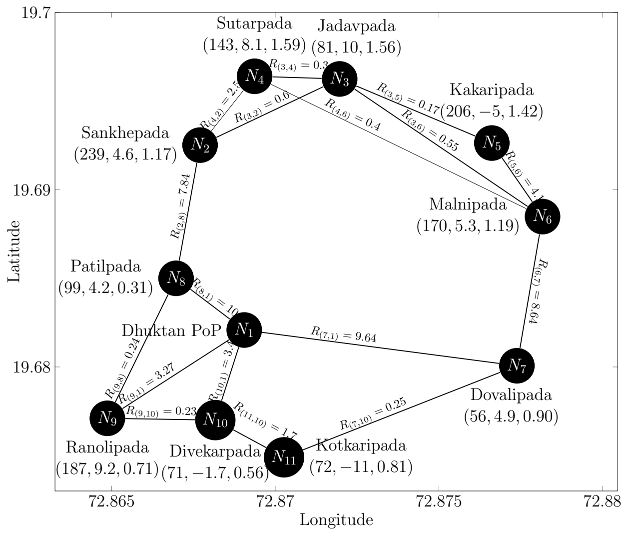
The corresponding power allocation vector and routing for three different values of the network load for ($\alpha = 0.01$, $\alpha = 0.0125$, and $\alpha = 0.02875$) for generalized routing and IP routing is presented in Fig. 5. The values of α are chosen such that different topologies are formed in case of generalized routing and IP routing. $\alpha = 0.02875$ corresponds to the maximum percentage of active users for given $P_{\max} = \text{mEIRP}$. From Fig. 5, in the IP routing scenario, each node tries to minimize the number of hops to the sink node by skipping the intermediate nodes, if there is no significant impact on Quality of Service. On the other hand, in case of generalized routing with low load, traffic is divided at nodes and sent to the sink node. However, with increase in traffic direct path towards sink is preferred.

Correctness of algorithm is evaluated using various performance parameters. Fig. 4(b) shows the convergence of the algorithm with number of simulation iterations for different percentage of users, which are active at any given instance.

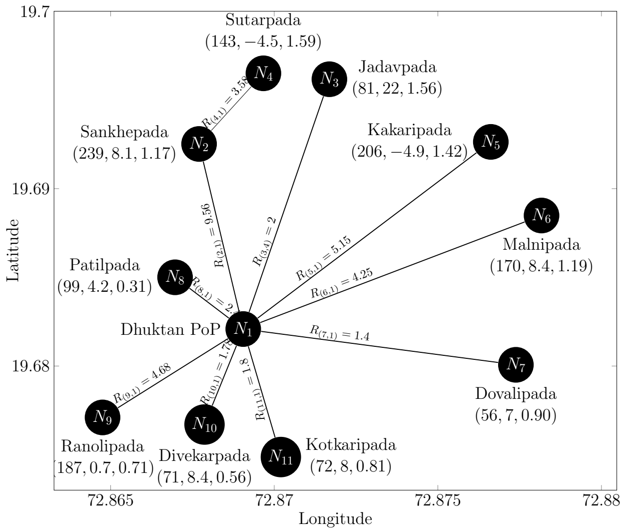
The above results hold at the physical layer. In prac-



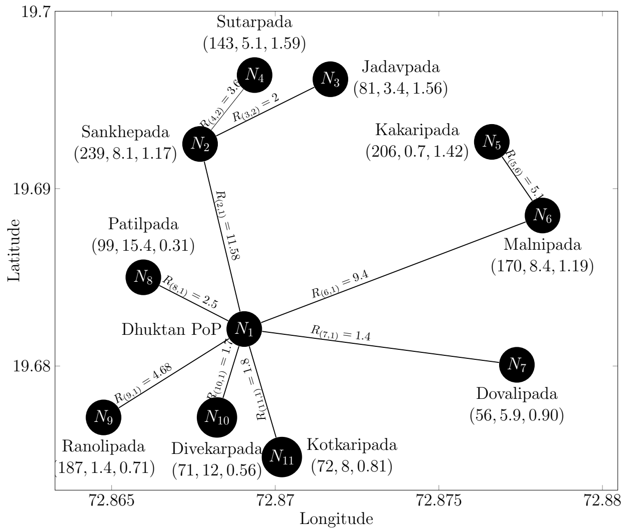
(a) IP routing: 1% users active



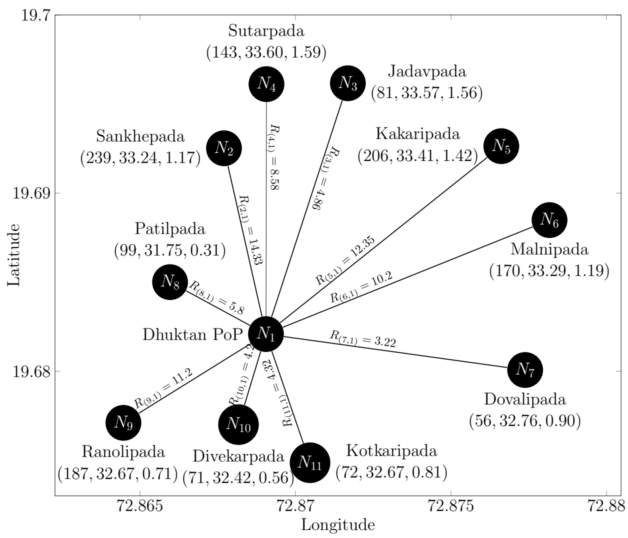
(b) Generalized routing: 1% users active



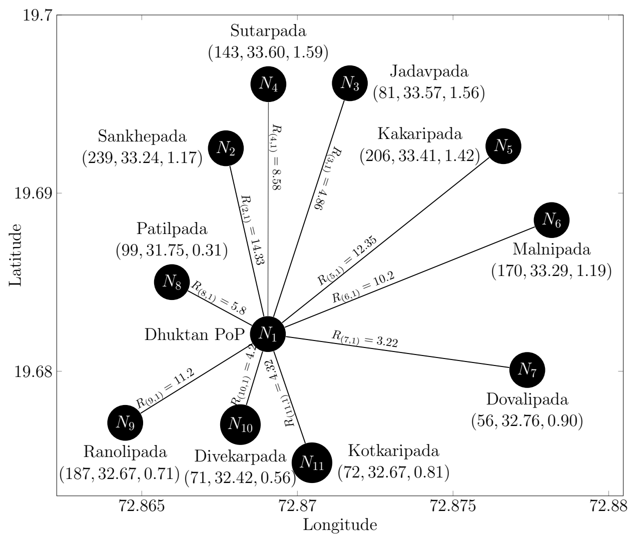
(c) IP routing: 1.25% users active



(d) Generalized routing: 1.25% users active



(e) IP routing: 3% users active



(f) Generalized routing: 3% users active

Fig. 5: Optimal routes and power allocations for both generalized routing and IP routing for Dhuktan PoP and associated hamlets are illustrated for $\alpha = 0.01, 0.0125, 0.03$. The hamlets are geographically laid out, and their names are adjoined with the (population, power, distance from PoP) triad. For example, Sutarpada has 143 population, 10.15dBm power for IP routing and $\alpha = 0.01$, and 1.59Km distance from Dhuktan PoP. The $R_{(i,j)}$ numbers on each link labels the link's *total* throughput. Various links have throughputs that facilitate $R = 2$Mbps for α fraction of users in *all* the hamlets. Observe that for smaller α, the network exhibits a mesh topology, and becomes point to multipoint as throughput demands increase on each link with α.

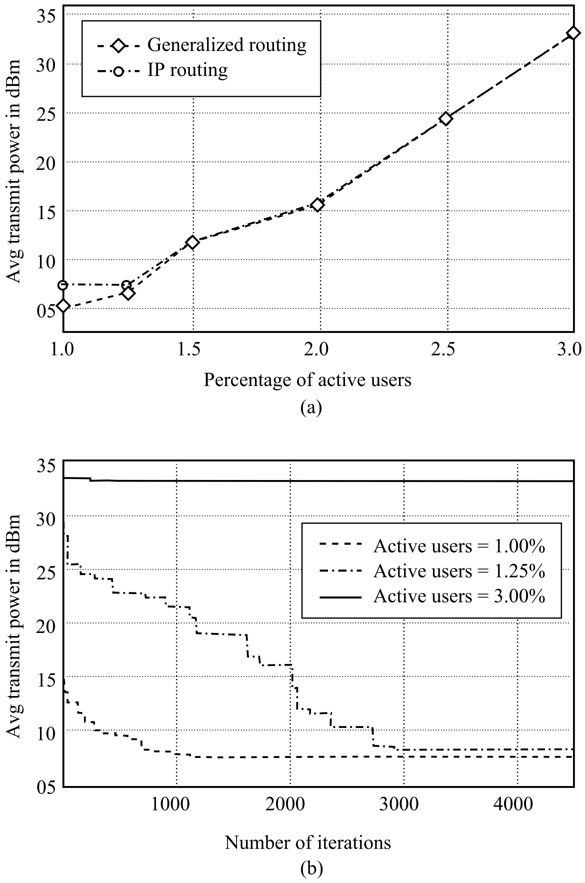


Fig. 4: (a) The average power needed by transmission nodes to provide $R = 2$Mbps data-rate to α fraction of users in the Dhuktan (India) region is plotted for IP routing and generalized routing. The graph is nearly linear in the dB scale. (b) The convergence of random hill climbing algorithm against the number of trials is illustrated. A few thousand random iterations are sufficient for a large range of transmit power.

tice, the delay, throughput analysis, and jitter analysis can also be considered at the network layer. Network simulator-3 (ns-3) simulations were performed as described next for the multihop mesh network designed illustrated for Dhuktan, India (see Fig. 5). Like in TDMA, time axis is divided into successive frames of equal length consisting of fixed number of slots. Let s_i be the number of slots assigned to node $i \in \mathcal{T}$, in a frame. The number of slots assigned to a transmission node from $\mathcal{T}$ in a single frame depends on its traffic. For simulations, the buffer size at all transmission nodes was fixed to 500 packets. If $b_i[n]$ is the number of packets in the buffer for node i at the n^{th} time slot, and $y_i[n]$ is the number of packets entering the buffer of node i during time interval $(n, n+1]$, then the following equations hold

$$b_i[n+1] = \begin{cases} b_i[n] - u(b_i[n]) + y_i[n] & \text{if node } i \text{ transmits;} \\ b_i[n] + u(b_j[n]) + y_i[n] & \text{if node } j \text{ transmits} \\ & \text{and node } i \text{ receives} \\ & \text{packet from node } j; \\ b_i[n] + y_i[n] & \text{otherwise.} \end{cases}$$

The function $u(l)$ is defined as $u(l) = 1, l > 0$ and $u(0) = 0$.

Using the defined progression of the queue in the above equation, the delay, jitter and actual user throughput are evaluated using ns-3 simulations. For ns-3 simulations, the traffic at node is assumed to be constant bit rate with data-rate equal to load at that node. Packets would not be retransmitted if receiver fails to receive the packet. Interval of time slot is formulated in such a manner that a node can transmit maximum one packet in its assigned schedule. Fig. 6 plots comparison of obtained user throughput versus target user throughput and end-to-end average delay and jitter received by packets in the network for topology. Fig. 6(a) compares the target user throughput (2Mbps) with average User Datagram Protocol (UDP) throughput received.

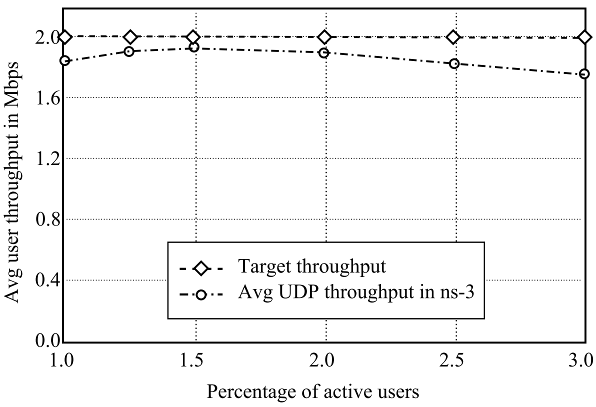
It can be seen from Fig. 5 that for a lower load there exists multiple hops in the network. In low load scenario, when traffic is sent on multiple hops (for $\alpha = 0.01$) slightly less average user throughput is achieved compare to when traffic is sent on direct paths from node to the sink (for $\alpha = 0.015$). This is because transmission nodes forwarding other node's data encounter significant packet drops, and it gets worse when network is heavily loaded. A similar observation is found in Fig. 6(b) for end-to-end average packet delay experience by packets in the network. Error bar at a point in delay plot indicates 95% confidence interval calculated using different seed values in ns-3.

The Telecom Regulatory Authority of India (TRAI) has proposed a contention ratio of 50, which corresponds to $\alpha = 0.02$, for household [25]. In summary, using Fig. 4(a), *we assert that using mEIRP* $= 25$*dBm and* 10*dBi of transmit antenna gain and transmit power allocation vector corresponding to* $\alpha = 0.02$*,* 100% *of the users can be served in Dhuktan, India.* Of course, by using multiple channels (more bandwidth) at each hamlet, more broadband throughput can be achieved. In an upcoming work, we plan to examine our obtained results by in-field test-bed in Dhuktan, India.

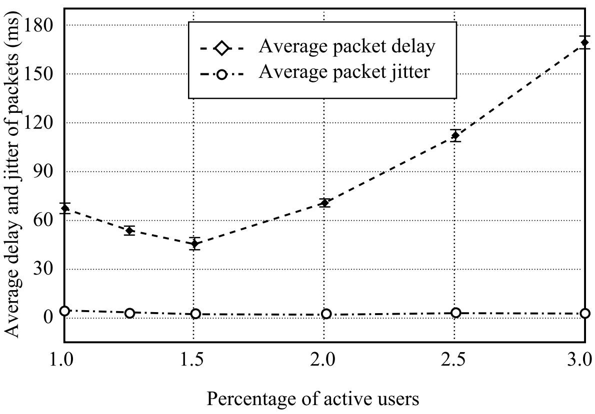
V. Conclusions

In this work, a middle-mile multihop mesh network operating in the TV UHF band has been presented as a solution to providing rural broadband coverage between optical fiber PoP at designated points and (rural) broadband users. The paper explained a throughput optimization tool, which utilizes demography information to determine a power optimal route between PoP (sink nodes) and access points (transmission nodes). The analysis has been performed at the physical layer; and, TDMA and spatial reuse of frequency are used for interference management. Power optimization has been addressed by a random hill climbing algorithm. The proposed optimization tool's design is separable and its methodology can be utilized in other areas of the world, where demography and path-loss models can be changed suitably.

For region around Dhuktan, India, it is observed that 25dBm transmit power with 10dBi antenna gain is sufficient for providing 2Mbps throughput to the entire population with a contention ratio of 50. In the future, we plan to examine our obtained results by in-field test-bed in Dhuktan, India.



(a)



(b)

Fig. 6: ns-3 simulations for the Dhuktan region are illustrated. (a) The target throughput for α fraction of users is $R = 2$Mbps. The achieved throughput in ns-3 simulations is compared for the Dhuktan region against the target. The results at network layer are coherent with the physical layer design. (b) The average packet delay in ms is plotted. The packet delay becomes larger when $\alpha = 0.03$. At $\alpha = 0.03$, all the transmission nodes have assigned power near mEIRP in their respective time slots. As a result, the delays are higher. The observed jitter is fairly low in our deterministic traffic model.

ACKNOWLEDGMENT

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