WiLiTV: A Low-Cost Wireless Framework for Live TV Services

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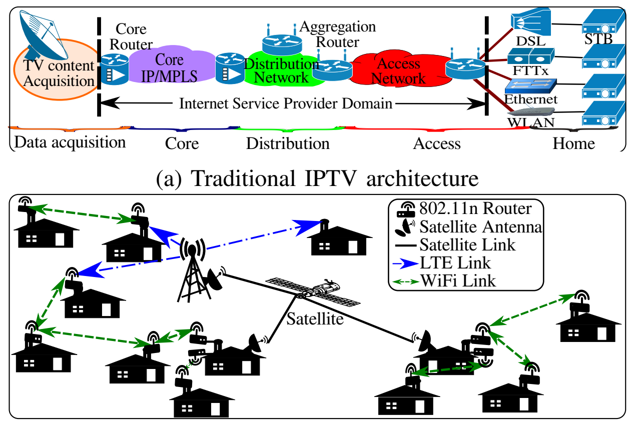
***Abstract*—The bandwidth required for TV content distribution is rapidly increasing due to the evolution of HDTV and Ultra HDTV. Service providers are constantly trying to differentiate themselves by innovating new ways of distributing content more efficiently with lower cost and higher penetration. We propose a cost-efficient wireless framework (WiLiTV) for delivering live TV services, consisting of a mix of wireless access technologies (e.g., Satellite, WiFi and LTE overlay links). In the proposed architecture, live TV content is injected into the network at a few residential locations using satellite antennas. The content is then further distributed to other homes using a house-to-house WiFi network or LTE overlay. Our problem is to construct an optimal content distribution network with the minimum number of satellite injection points, while preserving the highest Quality of Experience (QoE), for different neighborhood densities. We evaluate the framework using time-varying demand patterns and a diverse set of home location data provided from an operational content distribution network. Our study demonstrates that the architecture requires 84–88% fewer satellite injection points, compared to traditional architectures. We have also shown that our proposed WiLiTV architecture is more robust in its support for several TV formats.**

I. Introduction

With the evolution of HDTV, 4K content, and the prevalence of thousands of channels, the need for bandwidth is ever increasing [1]. Even with advanced video compression techniques, each Standard and High Definition TV (SDTV, HDTV) channel requires 2 and 9 Mbps, respectively. Today, the vast majority of houses receive TV content via cable to the home (cable TV), over an IP network (Internet Protocol TV), or through a satellite (satellite TV) [2]. As illustrated in Fig. 1(a), Internet Protocol TV (IPTV) streams live TV content from a few regional hub offices to set-top boxes over either a dedicated private network or over-the-top via the core IP network [3]. To satisfy Quality of Service (QoS) requirements, IPTV must be provisioned with a sufficiently high bandwidth in the distribution network [4]. Thus, the current infrastructure will soon be stressed with this escalating demand.

One solution to the growing demand is to deploy more cables/fibers to scale up the capacity of both backbone and distribution networks; however, this will require additional routing equipment, thus resulting in greater infrastructure cost [5] and greater energy consumption [6]. Satellite TV providers avoid the wired infrastructure cost by broadcasting live TV content to *every* subscriber/house equipped with a satellite dish antenna. However, satellite providers incur a high initial cost to install a dish antenna at each new customer home. In New York, for example, installing a single satellite dish costs approximately $1,000 [7].



(a) Traditional IPTV architecture

(b) *Our proposed WiLiTV architecture:-* content is first delivered to a community through a few selected houses and LTE BSs with satellite antennas, and is then distributed to other houses using WiFi and LTE.

Fig. 1: Comparison of IPTV and our proposed WiLiTV architectures.

To balance lower cost content distribution with higher penetration, we propose a low-cost, Wireless Live TV (WiLiTV) architecture that leverages a range of access technologies (Satellite, WiFi, and LTE) to provide high quality live TV services. As shown in Fig. 1(b), the WiLiTV architecture strategically equips a few houses and/or LTE Base Stations (BSs) with satellite antennas and relays TV content to other homes using WiFi and/or cellular networks. Our proposed architecture offloads TV content from the traditional core IP network or a dedicated wired IPTV infrastructure to long-haul satellite links and local high speed wireless links among houses, with the potential of leveraging recent advances in wireless technologies, such as Massive MIMO and Millimeter Wave. With this novel architecture, our design goal is to satisfy the live TV demands of all houses at the lowest possible infrastructure cost. In order to quantify the savings from such an architecture, we need to solve two sub-problems:

- *Source Provisioning:* which houses are chosen to install satellite antennas and download all live TV channels?
- *Relay Routing:* how should the live TV channels requested by each house be relayed from the sources?

These two sub-problems are tightly coupled: source provisioning determines the potential sources that a house can download content from; and if some houses cannot find a relay routing solution to get their desired channels, new sources have to be added to the distribution network. There is a fundamental trade-off between the complexity of relay routing and the cost saving in source provisioning. The current satellite TV providers, such as Dish Network [8], are at one end of the trade-off spectrum, where each house installs a satellite antenna and no relay routing is needed at all. At the other end, one can minimize the number of satellite antennas to be installed by maximally utilizing any possible wireless relay routing among houses to satisfy their live TV demands. However, multihop networks suffer from bandwidth constraints, increasing delay and lower reliability as the number of hops increase. Any practical solution has to find the sweet spot and strike the right balance between complexity and cost-saving.

To systematically evaluate the impact of various relay routing factors on cost saving, we formulate a series of joint provisioning-routing optimization problems to find the lowest costs under a relay hop count limit over a WiFi network, and an LTE overlay. The formulated optimization problems is solved using binary integer programming, or mixed-integer programming for small and medium networks. For large networks, we develop greedy heuristic algorithms to obtain close-to-optimal solutions. The optimization models developed are used to numerically investigate the routing complexity and cost saving tradeoff through case studies with real house topologies and demand data. We consider one topology each for urban, suburban and rural scenarios. There are 22,606, 1,914 and 805 houses in the urban, suburban and rural topologies we considered, respectively. TV content demand is sampled at each hour of the day for every house in all three considered topologies. Our results show that we can save up to 84%-88% of the cost of satellite antennas using WiLiTV, as compared to a pure satellite TV architecture. Further, WiLiTV is robust in its support of different TV formats.

This paper is organized as follows. In Section II we discuss the related work. The system model and assumptions made are described in Section III. The optimization problem formulations are presented in Section IV. Section V and Section VI contain the associated solution techniques and the numerical results, respectively. Section VII concludes the paper.

II. Related Work

An IPTV architecture can be divided into five main parts, (i) a data acquisition network, (ii) a core backbone network containing super hub offices, (iii) a regional distribution network containing video hub offices, (iv) an access network containing DSLAMs, and (v) the customer home network containing residential gateways and set-top-boxes [9]. To decrease bandwidth requirements in the core backbone network and for fast TV channel switching, multicast channels and groups are typically used [10]. However, building and pruning multicast groups puts an extra burden on the network. It is also costly to maintain multicast groups for less popular TV channels [11].

Pure Peer-to-peer (P2P) is another technology that has been investigated for distributing live TV. In P2P IPTV each user is also a potential server, multicasting received content to other users [9]. However, there are challenges associated with P2P for accommodating fast TV channel switching and TV channel recovery, especially when streaming peers leave the system abruptly. This can result in interruption while viewing live TV and eventually a poor QoE. In our proposed WiLiTV architecture, we push TV content close to end users that reduces the delays associated with channel switching. Additionally, unicast flow for requested TV channels makes WiLiTV architecture suitable for less popular channels.

III. System Model and Assumptions

As illustrated in Fig. 1(b), our wireless distribution network for live TV consists of three types of nodes:

1) A subset of houses equipped with satellite antennas act as the injection points for live TV content. They also have WiFi APs for relaying content to WiFi-only houses.
2) LTE BSs equipped with satellite antennas act as additional live TV injection points, and can deliver content to LTE-enabled houses over lightly loaded LTE bands.
3) Houses which do not have satellite antennas, but are equipped with WiFi APs and/or LTE receivers, can receive TV content from houses having satellite antenna over the WiFi network and/or LTE overlay. These houses can also relay traffic for other houses using WiFi.

As a result, a house can receive TV content by the following methods: (i) directly from satellite antenna or, (ii) through WiFi and/or LTE relay. We assume that a house receives content from a *single source/relay* node; that is, we do not allow *fractional flows* from multiple sources. TV traffic demand at house i at a time instant t is denoted by $\delta_i(t)$ (in Mbps). The demand can also be expressed as $\psi_i(t) * b$, where $\psi_i(t)$ is the number of channels being demanded at house i at time t and b is the capacity required per channel in Mbps.

A. Relay using WiFi

The WiFi relay network is modeled as an undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of houses and $\mathcal{E}$ is the set of WiFi links between houses. WiFi transmissions between neighboring houses operate on orthogonal channels, and are highly directional by making use of beamforming techniques [12]. Beamforming techniques in IEEE 802.11n reduces collisions by utilizing spatial diversity among houses. Furthermore, the houses are bounded by a degree of connectivity represented by ρ, i.e., a house has a maximum of ρ point-to-point links with neighboring houses.

B. Relay using WiFi and LTE

LTE BSs can be additional injection points of live TV content, subject to the availability of LTE bandwidth at the BS. Let $\mathcal{L}$ indicate the set of LTE BSs having significant spare LTE resources. The network topology is augmented as $\mathcal{G}' = (\mathcal{V}', \mathcal{E}')$, with $\mathcal{V}' = (\mathcal{V} \cup \mathcal{L})$ and $\mathcal{E}'$ consisting of all WiFi and LTE links. We assume that residual capacity is combined using channel aggregation at the LTE BSs and the aggregated capacity is used for WiLiTV. Thus, resources must be shared between houses receiving TV content from the same LTE BS.

Due to the space limit, we discussed details of path loss models (both WiFi and LTE) and link capacity calculation in our technical report [13].

IV. Joint Optimization of Satellite Antenna Placement and Relay Routing

In this section, we develop optimization models to evaluate the design trade-offs between the cost saving on satellite antennas and the complexity of relay routing. Ideally, each connected island of houses only needs one source, and TV content can be relayed to all houses using an arbitrary number of hops. However, live TV services have stringent QoS requirements on delay, bandwidth and reliability. It is well known that multi-hop wireless relays can lead to long delays, low end-to-end throughput, and poor reliability [14]. Therefore, we limit relay routing to be at most two hops. We present a formulation for multi-hour service provisioning that can cover the time-varying video demands of all houses.

A. General Purpose Optimization Formulation

Our proposed WiLiTV architecture has a maximum relay hop count of two. Thus, there are three types of houses in the network: source nodes with satellite antennas, non-source nodes relaying video for other nodes (called relay nodes), and non-source nodes without any relaying traffic (called terminal nodes). Let $X_i \in \{0, 1\}, \forall i \in \mathcal{V}$ be the binary variable indicating whether a node is equipped with a satellite antenna. Let $Y_i \in \{0, 1\}$, $i \in \mathcal{V}$ be another binary variable indicating whether a node relays other nodes' traffic. For a source node we have $X_i = 1$ and $Y_i = 0$, i.e., a source node does not relay other nodes' traffic. Similarly, for a relay node we have $X_i = 0$ and $Y_i = 1$, and for a terminal node, we have $X_i = 0$ and $Y_i = 0$. Fig. 2 illustrates the three types of nodes in the two-hop relay, and how terminal nodes download video content from the source through a common relay node. Further, LTE resources are shared among all the houses that receive TV content from the same LTE BS. Let $0 \le \lambda_{ij} \le 1$ be the time share of the link from LTE BS $i \in \mathcal{L}$ to house $j \in \mathcal{V}$, $\sum_j \lambda_{ij} \le 1$, $\forall i \in \mathcal{L}$. Using the previous variables, we can formulate a mixed-integer programming problem as follows:

$$\underset{\{X_i, Y_i, u_{ij}\}}{\textbf{Minimize:}} \sum_{i \in \mathcal{V}'} X_i \tag{1}$$

Subject to:

$$\sum_{j:\langle i,j\rangle \in \mathcal{E}'} u_{ij} \le \rho(X_i + Y_i), \forall i \in \mathcal{V}'; \tag{2}$$

$$\sum_{i:\langle i,j\rangle \in \mathcal{E}'} u_{ij} = (1 - X_j), \forall j \in \mathcal{V}; \tag{3}$$

$$0 \le X_i + Y_i \le 1, \forall i \in \mathcal{V}'; \tag{4}$$

$$Y_j \le 2 - Y_i - u_{ij}, \forall i, j \in \mathcal{V}'; \tag{5}$$

$$u_{ij} C_{ij} \ge \delta_j(t) u_{ij} + \sum_{k:k \ne i,j} Y_k \delta_k(t) u_{jk}, \forall i, j, k \in \mathcal{V}, \forall t \in \mathcal{T}; \tag{6}$$

$$\lambda_{ij} C_{ij} \ge \delta_j(t) u_{ij} + \sum_{k,k \ne i,j} Y_k \delta_k(t) u_{jk}, \forall i \in \mathcal{L}, \forall j, k \in \mathcal{V}, \forall t \in \mathcal{T}. \tag{7}$$

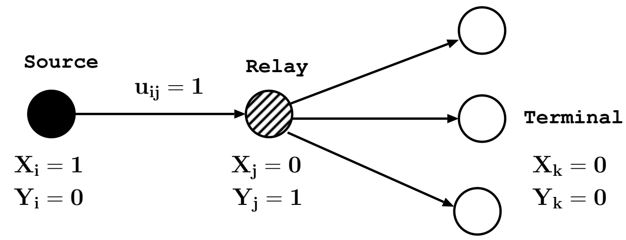


Fig. 2: Two-hop Relay Routing: node i is a source node ($X_i = 1$), node j is a relay ($Y_j = 1$), downloading traffic from i ($u_{ij} = 1$), relaying video to other terminal nodes ($X_k = Y_k = 0$).

The objective (1) is to minimize the number of satellite antennas. Constraint (2) bounds the maximum degree of connectivity at source and relay nodes (both have $X_i + Y_i = 1$), and terminal nodes cannot have outgoing video traffic ($X_i + Y_i = 0$). According to constraint (3), all non-source nodes download their video from exactly one incoming link. Constraint (4) states that a node in the distribution network can only assume one role: source, relay or terminal node. Constraint (5) ensures that a relay node does not receive traffic from another relay node. This is because if node j receives video from a relay node i, then $Y_i = 1$ and $u_{ij} = 1$. Then to make (5) hold, we must have $Y_j = 0$, i.e, j cannot be a relay node anymore. On the other hand, if i is a source node, $Y_i = 0$, even if $u_{ij} = 1$, we can still have $Y_j = 1$ (i.e., j can still relay video to other nodes). Constraint (6) guarantees each outgoing WiFi link from a source or relay has enough bandwidth to carry video traffic assigned to it. Similarly, constraint (7) ensure that each outgoing LTE link has enough bandwidth to carry video traffic assigned to them.

We can observe that the general purpose optimization problem is not a convex optimization problem due to constraints (6) and (7). Also, we want to evaluate the tradeoff of one hop vs two hops relay routing. Thus, we modify the general purpose optimization problem to make it convex and account for different relay routing scenarios.

1) One-hop WiFi Relay: The network graph is given by $\mathcal{G}$, consisting only of houses. Furthermore, there will not be any relay node, i.e., $Y_i = 0, \forall i \in \mathcal{V}$. Thus, the optimization problem reduces to:

$$\underset{\{X_i, u_{ij}\}}{\textbf{Minimize:}} \sum_{i \in \mathcal{V}} X_i$$

Subject to: (2), (3), and (6).

2) Two-hop WiFi Relay: The network graph is given by $\mathcal{G}$, consisting of only houses. The WiFi network contains source nodes, relay nodes, and terminal nodes, i.e., a few of the nodes do not have $Y_i = 0$. Thus, constraint (6) is modified in the equation (8) to make it convex.

$$u_{ij} C_{ij} \ge \delta_j(t) u_{ij} + \sum_{k,k \ne i,j} \delta_k(t) u_{jk} - \Theta(1 - X_i - Y_i), \forall i, j, k \in \mathcal{V}, \forall t \in \mathcal{T}. \tag{8}$$

The first term on the right hand side of equation (8) is the video traffic from the source/relay node to its direct receiver. The second term is non-zero only if i is a source and j is a relay; it represents the traffic of all households downloading video from i through relay j. The last term is zero if i is a source or relay, and if i is a terminal node, Θ is a large number so that the inequality automatically holds. Thus, the optimization problem is modified as:

$$\underset{\{X_i, Y_i, u_{ij}\}}{\textbf{Minimize:}} \sum_{i \in \mathcal{V}} X_i$$
$$\textbf{Subject to: } (2), (3), (4), (5) \text{ and } (8).$$

3) One-hop Relay over WiFi and/or LTE: The network graph is given by $\mathcal{G}'$, consisting of houses and LTE BSs. Further, there will not be any relay node in the network, i.e., $Y_i = 0, \forall i \in \mathcal{V}$. Thus, the optimization problem reduces to:

$$\underset{\{X_i, u_{ij}\}}{\textbf{Minimize:}} \sum_{i \in \mathcal{V}'} X_i$$
$$\textbf{Subject to: } (2), (3), (6) \text{ and } (7).$$

4) Two-hop Relay over WiFi and/or LTE: The network graph is given by $\mathcal{G}'$, consisting of houses and LTE BSs. The network contains source nodes, relay nodes, and terminal nodes, i.e., a few of the nodes do not have $Y_i = 0$. Thus, constraint (7) is modified in the equation (9) to make it convex.

$$\lambda_{ij} C_{ij} \geq \delta_j(t) u_{ij} + \sum_{k, k \neq i, j} \delta_k(t) u_{jk} - \Theta(1 - X_i - Y_i), \quad \forall i \in \mathcal{L}, \forall j, k \in \mathcal{V}, \forall t \in \mathcal{T}. \tag{9}$$

Similar to (8), this constraint ensures that the link from BS i to household j carries video demands of household j and all other households using j as a relay. The optimization problem reduces to:

$$\underset{\{X_i, Y_i, u_{ij}\}}{\textbf{Minimize:}} \sum_{i \in \mathcal{V}'} X_i$$
$$\textbf{Subject to: } (2), (3), (4), (5), (8) \text{ and } (9).$$

V. Approximation Algorithms

In Section IV, one-hop and two-hop scenarios are modeled as binary programming problems. When the network size is small, one can use various optimization tools, such as CVX in MATLAB [15], to get the exact optimal provisioning and relay routing solutions. However, when the network size is large, the computation time becomes prohibitive. In this section, we develop heuristic approximation algorithms to obtain close-to-optimal solutions for large networks.

The one-hop problem formulation in Section IV-A1 is similar to the classic set cover problem. Our objective is to determine the minimum number of nodes that can cover all other nodes in a given directed graph $\mathcal{G}$ with limited link capacity. Let $\mathcal{A}$ denote the relay matrix, where $\mathcal{A}[i, j] = 1$ if, and only if, there is a wireless relay link from node i to j, and the capacity of link $\langle i, j \rangle$ is larger than δ_j, the total video demand of j. Let $\mathcal{B}(i) \triangleq \{j \in \mathcal{V} : \mathcal{A}[i, j] = 1\}$ be the set of nodes that can potentially download their TV demands from node i. Then call $\mathcal{B}(i)$ the bin of node i.

The one-hop relay routing problem formulated in Section IV-A1 can be approximately solved using the greedy heuristic algorithm defined in Algorithm 1. Let $\mathcal{S}$ be the set of chosen source nodes, and $\mathcal{T}$ the set of terminal nodes that receive their TV channels from some source node in $\mathcal{S}$. At each iteration, the node i with the largest bin size is selected as a new source node. All nodes in node i's bin are added to the terminal node set $\mathcal{T}$. If i's bin has more than ρ nodes, then we randomly select ρ nodes to be covered by i. All links from i to its receivers are added to the relay topology. Our problem is different from the traditional set cover problem as each element of a bin has its own bin. Thus, after selecting a node as source, the nodes in its bin are not removed from the network, because they can still act as sources for other nodes in future iterations. As a result, when we select a new source, it might have been covered by some source node and added to the terminal set in previous iterations. We need to remove it from the terminal node set (line 10), and also remove its incoming video link from the relay topology (line 11). After we update the source and terminal node sets, all links going to source and terminal nodes no longer need to be considered, and thus are removed from the relay matrix. After the iterations, nodes that are not marked as either source or terminal nodes are isolated nodes that need satellite antennas.

Algorithm 1: Greedy algorithm for one-hop non-splittable relay

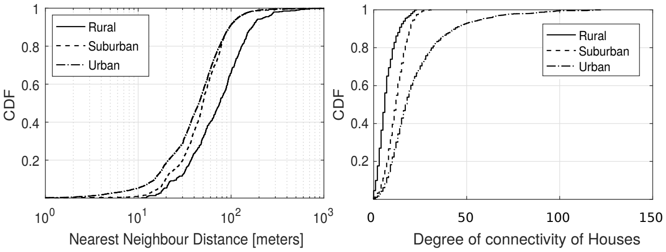
Input: Relay matrix ($\mathcal{A}$)
Output: Satellite antennas positioning and one-hop relay topology

1: **Initialization:** $\mathcal{S} \leftarrow \phi$, $\mathcal{T} \leftarrow \phi$, $\mathcal{A}_{tmp} \leftarrow \mathcal{A}$, $\mathcal{A}_{opt} \leftarrow \phi$
2: **while** $\mathcal{A}_{tmp}$ is not empty **do**
3: *Calculate* the bin of each node based on $\mathcal{A}_{tmp}$, and find node i with the largest bin.
4: $\mathcal{S} = \mathcal{S} \cup \{i\}$
5: **if** $|\mathcal{B}(i)| \leq \rho$ **then**
6: $\mathcal{R}(i) = \mathcal{B}(i)$
7: **else**
8: randomly select ρ nodes in $\mathcal{B}(i)$ to $\mathcal{R}(i)$.
9: **end if**
10: $\mathcal{T} = \mathcal{T} \cup \mathcal{R}(i) - \{i\}$
11: $\mathcal{A}_{opt} = \mathcal{A}_{opt} \cup \{\langle i, k \rangle, \forall k \in \mathcal{R}(i)\} - \{\langle k, i \rangle, \forall k \in \mathcal{V}\}$
12: $\mathcal{A}_{tmp} = \mathcal{A} - \{\mathcal{A}(m, n) : m \in \mathcal{V}, n \in \mathcal{S} \cup \mathcal{T}\}$
13: **end while**
14: **return** relay topology $\mathcal{A}_{opt}$ and source set $\mathcal{S}_{opt} = (\mathcal{V} - \mathcal{S} - \mathcal{T}) \cup \mathcal{S}$

The heuristic algorithm for *two-hop WiFi relay* is discussed in the technical report [13].

VI. Performance Evaluation

We evaluate the proposed WiLiTV architecture using real house topology and user demand data from a major USA-based ISP. We focus on data from three representative residential areas: urban (San Diego), suburban (Valencia–California), and rural (Canyon Country–California). The corresponding topologies consist of 22,606, 1,914, and 805 houses, respectively. The details of the three considered topologies are presented in the Fig. 3. Fig. 3(a) plots the Cumulative Distribution Function (CDF) of the distance of the nearest



(a) (b)

Fig. 3: (a) CDF plot of the distance of the nearest neighbor to houses, (b) CDF plot of degree of connectivity to houses.

neighboring house to each house. We can observe from the figure that in rural scenarios around 60% of the houses have their nearest neighboring house located within 100 meters. By contrast, for suburban and urban areas approximately, 90% of the houses have the nearest neighboring house within 100 meters. However, using an Effective Isotropic Radiated Power (EIRP) of 36 dBm and 20° phase-array antennas, we can achieve a range of 230 meters for WiFi in the 5 GHz band using a 802.11n radio [12]. Fig. 3(b) presents the CDF plot of the degree of connectivity of houses in rural, suburban, and urban areas according to the IEEE 802.11n path loss model. From the figure, we can observe a high degree of connectivity to houses for the urban scenario. In the rural scenario, around 5% of houses are standalone houses given their sparse connectivity.

Using the optimization formulations in Section IV, we find the optimal source provisioning and relay topologies under different relay routing complexity constraints. We first conduct an evaluation with static video demands, where each house's demand is its peak TV content demand over all time periods. We then conduct an evaluation with time varying demands. Due to the increased computation complexity, the evaluation is done on a randomly selected sub-area of 1.76 square km in each scenario. We further explore the use of *parallel streams* supported in IEEE 802.11n. Using parallel streams, data can be split and transmitted via multiple independent data streams. Thus, with spatial separation of signals by antennas using beam-forming and Multiple Input, Multiple Output (MIMO) antenna techniques, up to four parallel streams can be supported in IEEE 802.11n.

Fig. 4 shows a typical TV traffic demand pattern over a day in urban scenario. In the rural and suburban scenarios, we obtain a similar pattern for demand. From the real demand data of TV channels for each house at each hour of a day, obtained from a service provider, we computed the capacity required. We assume that each house has only HDTV and the data rate of each HDTV channel is 9Mbps. Further, for small topologies in rural, suburban, and urban, we evaluated the required number of satellite antennas with different TV formats (SDTV, HDTV, and 4K) considering peak demand at each houses. The data rate of each TV channel for SDTV and 4K format TV is 2Mbps and 15.6Mbps, respectively. The carrier frequency for 802.11n radios are 5GHz and the channel bandwidth used is 20MHz. For simplicity of the topology, we assumed that a house can connect to a maximum of 5

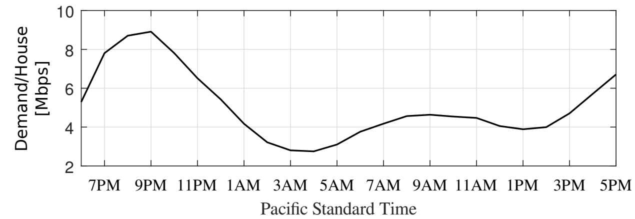
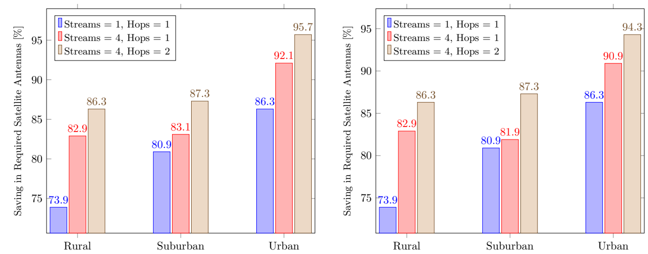


Fig. 4: Typical TV traffic demand



(a) Time-varying demand (b) Static peak demand

Fig. 5: Small topologies and time-varying demand: saving in required number of satellite antennas for live TV services.

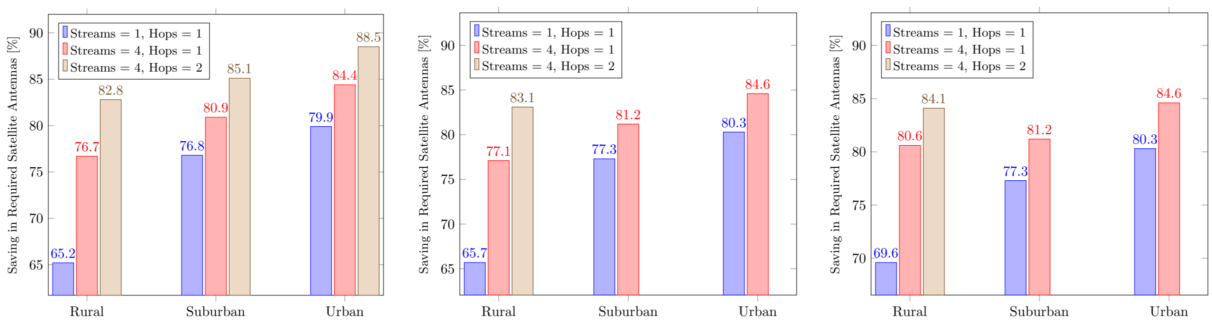
neighboring houses. We assumed that 10%, 20%, and 30% of total LTE bandwidth is available for WiLiTV architecture in the rural, suburban, and urban scenarios, respectively.

A. Time-varying Demand

For time-varying demand, we randomly selected a small sub-topology of 1.76 km^2 in San Diego, Valencia, and Canyon Country. Fig. 5 presents the percentage savings in the required number of satellite antennas for small topologies with time-varying demand as well as the static peak demand. Theoretically, multi-hour provisioning using time-varying demand should be more cost-effective than provisioning using the peak demand. Fig. 5(a) plots saving in required satellite antennas for the multi-hour formulation. We can observe that for smaller topologies the required satellite antennas can be reduced to 5%-14%. Fig. 5(b) plots the results for provisioning with static peak demand at each house. We can observe from the figure that we require approximately the same number of satellite antennas for both static peak demand and multi-hour provisioning. This suggests that provisioning with static peak demand is sufficient to achieve most of the cost saving. We do not need to solve the multi-hour provisioning problem which has much higher computation complexity. Thus, we consider peak demand for all further work in this paper.

B. Static Peak Demand

Fig. 6 plots the percentage saving in the required number of satellite antennas for live TV content distribution in different scenarios for different topologies. With one IEEE 802.11n stream and a single hop over the WiFi network, 65%, 77%, and 80% of required satellite antennas can be saved for the rural, suburban, and urban scenarios. With one IEEE 802.11n stream and a single hop over WiFi, and an LTE network, 69%, 77%, and 80% of required satellite antennas can be saved for the rural, suburban, and urban scenarios. Similarly for four streams using WiFi links over two hops, savings in the



(a) WiFi Network: Heuristic algorithm (b) WiFi Network: Branch and bound (c) WiFi and LTE: Branch and bound

Fig. 6: Large topologies and static peak demand: saving in the required number of satellite antennas for live TV services.

required number of satellite antennas increases to 82%, 85% and 88% for the rural, sub-urban, and urban scenarios. *This suggests that additional WiFi link capacities resulting from more streams directly translate into cost savings in satellite antennas, especially with two-hop relays.* From Fig. 6(c), we can observe some saving in the required satellite antennas in the rural scenario due to the large amount of available LTE bandwidth. However, we do not observe any gain in saving in the required satellite antennas for suburban and urban scenarios due to the congested LTE bandwidth assumption.

Fig. 6(a) and 6(b) compares the results of branch-and-bound with our proposed heuristic algorithm. Using branch-and-bound over a single hop, we obtain the optimal solution for the rural,sub-urban, and urban topologies. However, with two-hop communication, we failed to obtain solutions for urban and suburban topologies in a reasonable time due to high computational complexity. Our proposed heuristic algorithm can always get approximate solutions for all three scenarios. From the two figures, we can observe that the solutions obtained by the heuristic algorithm are close to the optimal solutions obtained by branch-and-bound.

Table I presents the savings in the required satellite antennas for different TV formats (SDTV, HDTV, and 4K format TV) for the one hop and one stream scenario. We can observe from the table that we require a few more satellite antennas for the 4K format TV. However, the increment in the required satellite antennas is not significant. Further, for a higher number of streams and more hops, the required number of satellite antennas were same for all three TV formats. The results are consistent in all three topologies. *The analysis shows that our proposed WiLiTV architecture is robust even with an increase in required data rates.*

TABLE I: Savings for different TV formats [%]

Scenario	**SDTV**	**HDTV**	**4K**
Rural	73.9	73.9	69.6
Suburban	80.9	80.9	79.7
Urban	86.3	86.3	85.1

VII. Conclusion

In this paper, we propose an all-wireless solution to deliver live TV services. Some service providers now have the option of leveraging a combination of varied access technologies to distribute live TV content (e.g., satellite, 4G LTE, and WiFi). We capitalize on this opportunity to create a distribution infrastructure that is optimized to serve large residential neighborhoods with a minimal number of TV content injection points. We developed multicommodity optimization flow problems to model various scenarios. Using real data from a national TV service provider, we show that our proposed architecture can save provisioning costs by between 84% to 88%. Our results cover three different representative residential neighborhoods with time-varying traffic demands. Our investigation shows that there is an optimum strategy for placing the satellite dish antennas, combined with an appropriate selection of WiFi relay routes, to meet the TV content demand of subscribers/houses.

References

[1] K. Brunnström, B. Ahlgren, C. Lagerstedt, M. Kihl, and A. Novak, "Future media distribution : An innovation agenda for digital media distribution," Tech. Rep., Feb. 2015.

[2] J. Ulin, *The business of media distribution: Monetizing film, TV and video content in an online world.* CRC Press, 2013.

[3] X. Hei, C. Liang, J. Liang, Y. Liu, and K. W. Ross, "A measurement study of a large-scale P2P IPTV system," *IEEE Trans. Multimedia*, vol. 9, no. 8, pp. 1672–1687, Dec. 2007.

[4] K. Kerpez, D. Waring, G. Lapiotis, J. B. Lyles, and R. Vaidyanathan, "IPTV service assurance," *IEEE Commun. Mag.*, vol. 44, no. 9, pp. 166–172, Sep. 2006.

[5] Clarke Richard N., "Costs of neutral/unmanaged IP networks," *Review of Network Economics*, vol. 8, no. 1, pp. 61–89, Mar. 2009.

[6] J. Baliga, K. Hinton, and R. S. Tucker, "Energy consumption of the Internet," in *Proc. IEEE COIN-ACOFT*, June 2007.

[7] homewyse, "Cost to install a satellite dish," http://www.homewyse.com/services/cost_to_install_satellite_dish.html, accessed: 2016-07-28.

[8] M. Wittig, "Satellite onboard processing for multimedia applications," *IEEE Commun. Mag.*, vol. 38, no. 6, pp. 134–140, Jun. 2000.

[9] Y. Liu, Z. Liu, X. Wu, J. Wang, and C. C. Y. Yang, "IPTV system design: An ISP's perspective," in *Proc. IEEE CyberC*, Oct. 2011.

[10] P. Paul and S. V. Raghavan, "Survey of multicast routing algorithms and protocols," in *Proc. of ACM ICCC*, Aug. 2002.

[11] A. Abdollahpouri, B. E. Wolfinger, and J. Lai, "Unicast versus multicast for live TV delivery in networks with tree topology," in *Proc. ACM WWIC*, June 2010.

[12] U. Paul, R. Crepaldi, J. Lee, S. J. Lee, and R. Etkin, "Characterizing WiFi link performance in open outdoor networks," in *Proc. IEEE SECON*, June 2011.

[13] R. Kumar, R. Margolies, R. Jana, Y. Liu, and S. Panwar, "WiLiTV: A low-cost wireless framework for live TV services," Tech. Rep., Jan. 2017. [Online]. Available: https://arxiv.org/pdf/1701.02669v1.pdf

[14] L. Gouveia, "Multicommodity flow models for spanning trees with hop constraints," *EUR J OPER RES*, vol. 95, no. 1, pp. 178 – 190, 1996.

[15] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.1," http://cvxr.com/cvx, Mar. 2014.