Resilient Multicast Routing in CRNs Using a Multilayer Hyper-graph Approach

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***Abstract*—**
Cognitive Radio Networks (CRNs) have a dynamic nature where channels availability changes over time. In this paper, we introduce a strategy to route multicast sessions in CRNs and to protect them against failures or disappearance of channels. We model the network as a Multilayer Hyper-Graph ($MLHG$), such that a group of Secondary Users (SUs) which have a common channel are modeled by a hyper-edge. Also, each layer in the $MLHG$ represents a different channel. Primary paths from a source SU to destination SUs are selected by considering channels' switching delay, and transmission delay. To protect the multicast session, we select a backup path for primary path, if feasible, such that the primary and backup paths are Shared Risk Hyper-edge Groups ($SRHEGs$) disjoint.

We develop an Integer Linear programming (ILP) model, in order to find the multicast primary paths and their backup paths, minmize the maximum path delay, and minimize the number of selected channel links. Our simulation results show that when the number of available channels increases, the number of primary and backup paths that can be routed in the CRN increases, and the maximum path delay decreases almost linearly.

I. Introduction

This paper considers the problem of multicasting in CRNs for SUs group, such that the selected multicast routing tree serves the maximum number of SU destinations. Finding a Multicast Routing Tree (MRT) in CRNs is more difficult than in traditional wireless networks, since more than one channel may be used over the routing path. Also channels switching time delay must be minimized in order to reduce the maximum End-2-End (E2E) MRT delay. The maximum MRT delay is equal to the routing path which has the maximum routing latency. We introduce the following definitions:

Definition I.1: **SUs Group**: is a set of SUs that are within the same geographical locality of each others, have at least one channel common between them, and each SU can communicate with all SUs in its group with one transmission-hop.

Definition I.2: **Routing path**: is a route from an SU source node to an SU destination node, which contains one or more transmission hops along SU groups, such that when two different groups communicate, an SU which has a common channel between them transmits data, while the communication between SUs within the same group occurs over a common group channel.

Definition I.3: **Multicast Routing Tree (MRT) problem**: finding a routing path, if feasible, from the source node to each SU destination, where the destination nodes are a subset of SU nodes in the network.

Routing in CRNs is different from traditional wireless networks, due to many reasons such as follows: First, multi-hop routing requires good sensing techniques. Second, packet routing service is intermittent. Third, route maintenance mechanisms are required, due to PUs activity. Rerouting can be done by only switching to new available channels over the same link(s), or by selecting new SUs nodes. Fourth, selecting channels for links over a route is a challenge, since channels with longer Primary Users' (PUs') idle times should be selected, in order to improve routes stability.

Providing resilient multicast routing in CRNs is crucial, due to the opportunistic spectrum access nature of unlicensed users. The dynamic nature of channels availability may cause an SU to lose one/more of its communication links with its neighboring SUs. There are two approaches for providing survivability, protection and restoration. Usually, protection is preferred to restoration due to its speed of recovery. In this paper, we adopt the reactive protection strategy, which waits until the failure takes place, and then reroute the information over the preplanned backup path.

In CRNs, we protect against channel link(s) failure for one or more SUs nodes, such that these failures occur at the same time over the channel that is common between SUs, and this occurs when the PU of this channel resumes activities again. Our proposed protection strategy will be explained in detail later in this paper. To build a multicast primary routing tree and protect it against single or multiple failures, a set of traditional QoS requirements are considered. These include the E2E transmission delay which includes channels switching time, and minimum channels capacity threshold. In doing this, one must minimize the number of used channels (or resources) over the primary paths and backup paths in the MRT. Some licensed channels, such as VHF and UHF band for TV channels (54 MHz-862 MHz), are not busy all the time, and can be be utilized by SUs when they are idle as proposed in IEEE 802.22 standard [1]. New America Foundation study in [2] shows that the percentage of TV bands spectrum availability after each DTV transmission vary from 30% to 74% for urban and rural cites. In this paper, we assume that when the routing path, primary or backup, is established, it will be sustained for a while.

There is some recent work in the literature for CRNs routing protection against PUs appearance which causes one or more channel links to fail. In [3], a protection method is proposed, in order to protect the primary path to the destination against a PU activity, and a backup path is selected using a Bayesian decision. A multicast routing protocol in CR ad-hoc networks is proposed in [4], in order to find multicast routes using Minimal spanning tree-based routing algorithm, such that channels time is slotted and transmission are scheduled. In [5], a multi-session multicast trees construction method is proposed for multi-hop CRNs, in order to minimize the used network resources. Authors in [6], considers channels switching delay besides transmission time for a multicast routing in CR mesh networks. Their solution approach is based on a dynamic programming method. Authors in [7], developed a layered graph model for constructing an efficient routing and channels allocation algorithms to reduce adjacent channels interference. However, channels switching latency is not considered. In conclusion, in all of the above studies, 1-to-M (a route from one source to each destation, such that M is the number of destinations) protection for multicast routing and SUs groups communication together with channel switching delay are not considered. Therefore, we are motivated in this paper to consider these factors.

II. Motivation

We are motivated to develop a model using multilayer hypergraph [8], in order to model the fact that CRNs have multiple available channels. Our motivations are: **First**, constructing multicast primary routes, if feasible, for a source and a set of selected destination SU nodes, such that switching time between channels is considered besides the transmission time delay. **Second**, protecting the multicast routes, if feasible, such that the primary and backup paths do not fail together. Our disjointness notion will be clear in Section V. **Third**, minimizing the maximum path delay for the primary and backup paths, in order to reduce the multicast session delay. **Fourth**, minimizing the number of used channel links that are used in the multicast routing tree, and in the backup paths.

III. System Model

Assume we are given a set of SU nodes, their available channels, the adjacency relations between SUs, which means that two SUs are adjacent on a certain channel, if the channel is available at both SUs and they are within communication range from each other. In order to form a group of SUs, a set of criteria can be considered such as the common channel between SUs with the same locality, the cumulative interference from neighboring nodes, path loss, and BER. Forming SUs' grouping algorithm is part of our future work. In this paper, we assume that the SUs groups are given, while forming their groups mainly is based on the common channel between SUs with the same geographical locality. We model each group of SU nodes as a hyper-edge in a hyper-graph, definition III.1. In order to model more than one licensed channel availability in CRNs, we use a multilayer hyper-graph such that each channel is represented by one layer.

Definition III.1: **Hyper-graph**: It is a graph in which a hyper-edge may connect multiple vertices. In CRNs, the hyper-edge contains SU nodes that have a common channel.

We use a multilayer hyper-graph ($MLHG$), in order to model our network model, as follows:

- A Layer: it represents a frequency band (channel).
- Hyper-Edge[1] (HE): represents one or more SUs nodes which have a common channel between them, and within the transmission range of each others, one-hop links, over this channel, e.g., in Figure 1, HE_1 in layer 1 represents the communication links availability between SUs a, b, c, and d, over channel 1.
- An SU is represented by a node in each layer in the MLHG, such that a node in a layer belongs to a hyper-edge only if the layer corresponding channel is available at the SU. Also, a node in a layer may belong to more than one hyper-edge, when the corresponding SU node belongs to more than one SUs' groups in the same layer, e.g., node f belongs to $HE2$ and $HE3$ in Figure 1.
- Hyper-Edge cost: represents the transmission time delay[2] for SUs group that correspond to the hyper-edge.
- An SU can form an HE in a layer by itself, e.g., the corresponding channel layer is available for this SU only, since other SUs transmission within its locality cause an interference to PUs over this channel, when PU becomes active. Or, there are no other SUs within its transmission range.
- Some SU nodes do not form an HE in a layer, e.g., in Figure 1, SU j in layer 1 does not belong to any HE in its layer, because channel 1 is not available for this SU.
- Inter-layer edge: this is an edge between the same node in two different layers, and corresponds to switching between the two channels corresponding to the two layers.
- Inter-layer edge cost: represents the SU transceivers channels switching time delay between two channels, e.g., in Figure 1, SU b switching time delay from channel 1 to channel 2 where SU b nodes are in HE_1 and HE_4, respectively, is represented by the cost of the inter-layer edge that connects SU b nodes in HE_1 and HE_4.

  In Figure 1, assume the source node is SU b, and it has channels 1 and 2 available. We introduce a dummy node notation, called b_t, in order to represent the source node, such that the dummy node incident edges cost is equal to zero. Using the dummy node guarantees that the source node is tuned to the channel which results in minimum path cost to destination(s), e.g., assume one destination node, SU e, therefore, the source node, SU b should be tuned to channel 2, and not channel 1. Also for the same reason, we use the dummy node notion for all destination nodes, e.g., SU h, that has more than one channel available.

In Figure 1, channel 1 is not available for SUs i and j, channel 2 is not available for SUs a, f, and g. SUs a, b, c, and d have channel 1 available and they are within the same transmission range of each others. Therefore, these SUs are grouped together and are represented by a hyper-edge. SU e in the first layer cannot communicate with SU h within one-hop although both SUs have channel 1 common, because they are not within the transmission range of each others. Therefore, SU e transmits its data to SU f, and then SU f relays it to SU h (2-hop communication without channel switching for SUs e, f, and h).

In order to construct the Multicast Primary Routes from a source to a set of destination SUs nodes in the multilayer hyper-

[1] We use super-node, hyper-edge, and group terms interchangeably.

[2] For simplicity, we assume the transmission time delay for an SU node to other SUs nodes within any hyper-edge is the same for all SUs.

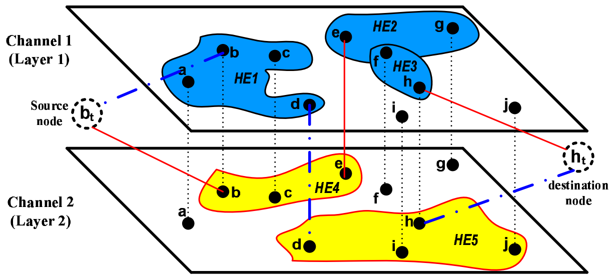

Fig. 1. A multilayer hyper-graph representation.

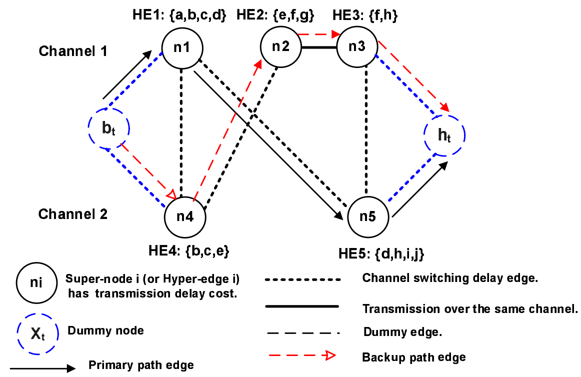

Fig. 2. The mapped graph for the multilayer hyper-graph shown in Figure 1, by using the super-node notation.

graph that is shown in Figure 1, first we convert or map it to a simple graph as shown in Figure 2. The conversion process is based on the following concepts:

- Each hyper-edge is converted to one node, call it super-node, e.g., in Figure 2, super-node n_1 corresponds to SUs a, b, c, and d nodes that belong to HE_1 in layer 1 shown in Figure 1.
- When two HEs in the same layer have some common SUs nodes, the two HEs are connected by a link such that its cost is zero. For example, in Figure 1, HE_2 and HE_3 are represented by super-nodes n_2 and n_3, respectively, and are connected by a zero cost link. When SU f relays data between these two HEs, it does so without switching channels. Therefore, this link cost is equal to 0.
- Each super-node has cost equal to transmission time delay[3].
- If two hyper-edges belong to different layers and are connected by at least one inter-layer edge (vertical dashed edge in the MLHG), convert it to one simple link only, in order to connect the pair of super-nodes in the simple graph which correspond to these two hyper-edges.

Our goal is to find a resilient multicast routing with minimum E2E delay in terms of channels switching times and transmission times. As an illustrative example, the primary and backup paths from the source node, SU b, to destination node, SU h, are shown in Figure 2, where the primary path is represented by the solid lines path, b_t-$n1$-$n5$-h_t. The backup path is represented by the dashed lines path, b_t-$n4$-$n2$-$n3$-h_t. The primary and backup paths are a Shared Risk Hyper-Edge Group ($SRHEGs$), (see definition III.3), disjoint. After the primary and backup paths are selected in the simple graph, Figure 2, this graph can be mapped back to its original multilayer hyper-graph as illustrated in Figure 1 such that the dashed-dotted and solid links represent the selected edges for primary and backup paths, respectively, between hyper-edges.

For example, in Figure 2, if SU a needs to transmit a packet to SU h, these consecutive steps are required:

1) SU a (belongs super-node n_1) broadcasts the packet to SUs within its group nodes (or hyper-edge), SUs b, c, and d, over channel 1.
2) When SU d (belongs to super-node n_1) receives the packet over channel 1, switches to channel 2 (therefore becomes a node in super-node n_5).
3) SU d transmits the received packet to SUs within its group nodes over channel 2, in order to be received by SU h.

[3]We assume all hyper-edges have the same transmission time delay, for simplicity.

The channel switching time is the required time for an SU's transceiver to switch between two channels (typically, it is on the order of 1 ms per 10 MHz [9]). The transmission time refers to the required time for an SU in a group to broadcast a packet to other SUs within its group. Also, let us assume that channel rate is $10 Mbps$, and packet size is 1500 bytes, therefore, packet transmission time is $1.2\ ms$. For the above example, we find the E2E delays for the primary and backup path that we discussed earlier for the source and destination nodes, SUs b and h, respectively. Based on our proposed algorithm, the primary path is b_t, HE_1, HE_5, and h_t, while the backup path is b_t, HE_4, HE_2, HE_3, and h_t, as shown in Figure 2. The primary path E2E delay is equal to ($1.2 + 1 + 1.2 = 3.4$ ms), while the backup path E2E delay is equal to ($1.2 + 1 + 1.2 + 1.2 = 4.6$ ms). Notice that edges that are connected to dummy nodes, e.g., b_t, have zero cost.

In our proposed model, we assume a super-node becomes unavailable (or fails) when a PU(s) of this channel becomes active. Since the transmission power of SU nodes which belongs to this super-node causes an interference to the PU(s) receivers protection area, therefore, SUs stop using this channel, call it SU channel link failure, (see definition III.2). Therefore, when a PU becomes active, at least one super-node failure occurs. Let's call the set of HEs that fail together in the network a $SRHEG$. For example, in Figure 1, assume HE_4 and HE_5 transmission areas are contained within a PU receiver protection area such that its corresponding PU transmitter transmits data over channel 2. If the PU becomes active these two HEs fail at the same time. Hence, HE_4 and HE_5 form a $SRHEG$.

Definition III.2: **Channel-link (or Hyper-edge) failure**: means that all SU nodes in the hyper-edge can no longer transmit data over their common channel, when this channel's PU becomes active.

Definition III.3: **Shared Risk Hyper-edge Group** ($SRHEG$): a group of one or more hyper-edges in one layer in the MLHG that use the same PU channel. The transmission ranges for SUs in these hyper-edges overlap with the protection range of the PU(s) corresponding receiver(s). When this PU becomes active, these SUs can no longer access their corresponding channel.

IV. Multicast Primary Routes

We assume the Multicast Primary Routes (MPRs) have one source node and multiple destination SU nodes. The source and the destination nodes are a set of SUs where each destination may belong to one (or more) hyper-edges in different layers, e.g., SU b belongs to two hyper-edges in layers 1 and 2 as shown in Figure 1. Our objectives for constructing an MPR in CRNs are as follows: a) Maximizing the number of selected primary paths that are feasible. b) Minimizing the E2E delay including transmission times and switching delays, by minimizing the maximum path E2E delay for the primary paths. The MPR solution consists of: 1) A set of primary paths between the source SU node and the destination SU nodes, such that each destination SU node is associated with only one primary path, if feasible. These paths form a tree graph structure, call it Multicast Routing Tree (MRT), Definition I.3. 2) The MRT solution determines the channel over which any pair of SUs along the primary routing paths must transmit and receive their data, in order to minimize the E2E delay including the transmission and switching delays.

V. Protection Model

We consider a single failure model which occurs when PU, affecting a number of hyper-edges forming an SRHEG, becomes active. Therefore, none of the SUs that correspond to the SRHEG can transmit data using the PU's channel. In order to increase the network resiliency in CRNs, our protection assumptions are as follows:

- For each destination SU's node, there is a primary path and a backup path. Transmission are switched from primary to backup paths once there is a failure affecting primary paths.
- The backup paths between the source SU node and the destination SU nodes, guarantee that each destination SU node is protected by only one backup path, if feasible, where the primary and the backup paths for a SU destination are SRHEGs disjoint.

Our model protects against one SRHEG failure for each destination, such that if the primary path fails the traffic is rerouted over the backup path, if it exists. When the backup path is used to carry data, the source node protects this backup path by finding a new backup path to the destination, if feasible, which is $SRHEG$ disjoint from the currently used backup path. Our objectives for constructing the backup paths are similar to MPRs, these objectives are as follows:

- Maximizing the number selected backup paths that are feasible.
- Minimizing the E2E delay including transmission times and switching times delays, by minimizing the maximum path E2E delay for the backup paths.
- It should be noted that the priority will be given to finding MPRs over finding protection paths.

VI. Optimal Solution

In this Section, we present the Integer Linear Program (ILP) Formulation solution for the multicast primary routes and its protection model. The solution contains a primary and backup path for each SU destination, if feasible, such that this pair of paths is SRHEG disjoint. There are multiple objectives of the ILP. Maximizing the number of selected primary paths is the first priority, to maximize the number of selected backup paths is the second priority, and the third priority is to minimize the maximum path delay for the primary and the backup paths. The fourth objective is to minimize the number of used channels links in the network.

A. Notations:

Let us define the following notations:

- PT: is the number of selected primary paths from the source node to different destinations.
- BT: is the number of selected backup paths from the source node to different destinations.
- T: is the maximum path delay between the primary and backup paths.
- LT: is the number of selected channel links in the multicast tree.
- $\mathcal{A}$: the set of links between super-nodes.
- N: is number of vertices (hyper-edges or super-node) in the simple undirected graph.
- α, β, γ, and μ are the weighting factors for the objectives PT, BT, T, and LT, respectively.
- s: is the source node index.
- d: is a variable for the index of a destination super-node.
- D: the set of destination super-nodes indices that contain destination SU nodes.
- g: is a variable for the index of a SRHEG.
- X_m^d: a boolean variable equals to 1, if the primary path from source super-node to destination super-node d passes through super-node m.
- Y_m^d: a boolean variable equals to 1, if the backup path from source super-node to destination super-node d passes through super-node m.
- P_{mn}^d: a boolean variable equals to 1, if the primary path from source super-node to destination super-node d uses link (m, n).
- B_{mn}^d: a boolean variable equals to 1, if the backup path from source super-node to destination super-node d uses link (m, n).
- T_d^p: is the primary path delay from the source node to destination d.
- T_d^B: is the backup path delay from the source node to destination d.
- L_{ij}: a binary variable that equals to 1, if link (i, j) is selected. Otherwise, 0.
- d_{ij}: it is the time for channels switching delay over link (i, j), and the transmission delay within the set of SUs in super-node j in the simple graph (transformed from the hyper-graph). We assume the transmission time in all super-nodes have the same transmission delay, for the sake of simplicity, but it can be easily extended to asymmetric transmission times.
- M_i^g: is an input binary parameter that equals 1, if super-node i belongs to SRHEG g, assuming we are given the set of super-nodes for each SRHEG.

- R_d^g: a binary variable which equals 1, if the primary path for destination super-node d passes through SRHEG g. Otherwise, 0.
- U_d^g: a binary variable which equals 1, if the backup path for destination super-node d passes through SRHEG g. Otherwise, 0.

B. ILP formulation:

For the ILP shown in Figure 3, equations (1) and (2) find the primary paths and backup paths E2E delays, respectively. Constraints (3) and (4) find the maximum path delay between the primary and backup paths. Constraints (5) and (6) guarantee that the super-node in which the SU source node has one unit of flow demand, if selected, and zero unit for the outgoing and incoming flows, respectively, that corresponds to the primary path to each destination. Constraints (7) and (8) guarantee that the destination super-nodes (which contains the destination SU nodes) have one unit of flow demand, if selected, and zero unit for the incoming and outgoing flows, respectively, that corresponds to the primary path. Constraints (9) and (10) guarantee flow conservation for the intermediate super-node except the source and the destination super-nodes have exactly one unit of incoming flow and one unit of outgoing flow. Constraint (11) guarantees that an undirected edge is selected at most once. Constraints (12) $-$ (18) are similar to the aforementioned constraints, except that they correspond to the backup paths. Constraints (19) and (20) ensure the flow conservation such that if the super-node that contains the SU source node is selected in the ILP solution, therefore, its corresponding destination super-node that contains the SU destination node must be selected which are associated with the primary paths and backup paths, respectively. Equations (21) and (22) find the number of selected primary and backup paths. Constraints (26) set the binary variable, R_d^g, that corresponds to the $SRHEG$ to 1, if one or more of its corresponding super-nodes belong to the primary (where c is a large constant value, e.g., N). Constraint (27) sets R_d^g to zero. Constraints (28) and (29) are similar to constraints (26) and (27), however, they correspond to the backup paths. Constraint (30) ensures that the SRHEGs disjointness condition for the selected pair of the primary and backup paths for each destination. Constraint (23) is used to find the total number of selected channel links for the multicast tree. Constraints (24) and (25) are used to set the corresponding binary variable for a link to 1, if it is selected either in the primary or/and the backup paths.

$Maximize\ \alpha\, PT + \beta\, BT - \gamma\, T - \mu\, LT$

subject to:

$$T_d^p = \sum d_{ij} P_{ij}^d,\ \forall i,j \in \{1,...,N\}, \forall d. \quad (1)$$
$$T_d^B = \sum d_{ij} B_{ij}^d,\ \forall i,j \in \{1,...,N\}, \forall d. \quad (2)$$
$$T \geq T_d^P, \forall d. \quad (3)$$
$$T \geq T_d^B, \forall d. \quad (4)$$
$$\sum_{i=1, i\neq s}^{N} P_{si}^d = X_s^d,\ \forall d. \quad (5)$$
$$\sum_{i=1, i\neq s}^{N} P_{is}^d = 0,\ \forall d. \quad (6)$$
$$\sum_{i=1, i\neq d}^{N} P_{di}^d = 0,\ \forall d. \quad (7)$$
$$\sum_{i=1, i\neq d}^{N} P_{id}^d = X_d^d,\ \forall d. \quad (8)$$
$$\sum_{i=1}^{N} P_{mi}^d = X_m^d,\ \forall d, \forall m \notin s,d. \quad (9)$$
$$\sum_{i=1}^{N} P_{im}^d = X_m^d,\ \forall d,\ \forall m \neq s,d. \quad (10)$$
$$P_{ij}^d + P_{ji}^d \leq 1,\ \forall i,j \in \{1,...,N\},\ \forall d. \quad (11)$$
$$\sum_{i=1, i\neq s}^{N} B_{si}^d = Y_s^d,\ \forall d. \quad (12)$$
$$\sum_{i=1, i\neq s}^{N} B_{is}^d = 0,\ \forall d. \quad (13)$$
$$\sum_{i=1}^{N} B_{di}^d = 0,\ \forall d. \quad (14)$$
$$\sum_{i=1}^{N} B_{id}^d = Y_d^d,\ \forall d. \quad (15)$$
$$\sum_{i=1}^{N} B_{mi}^d = Y_m^d,\ \forall d,\ \forall m \neq s,d. \quad (16)$$
$$\sum_{i=1}^{N} B_{im}^d = Y_m^d,\ \forall d,\ \forall m \notin s,d. \quad (17)$$
$$B_{ij}^d + B_{ji}^d \leq 1,\ \forall i,j \in \{1,...,N\},\ \forall d. \quad (18)$$
$$X_s^d = X_d^d,\ \forall d. \quad (19)$$
$$Y_s^d = Y_d^d,\ \forall d. \quad (20)$$
$$PT = \sum X_s^d, \forall d. \quad (21)$$
$$BT = \sum Y_s^d, \forall d. \quad (22)$$
$$LT = \sum_{(i,j)\in\mathcal{A}} L_{ij}. \quad (23)$$
$$L_{mn} \geq P_{mn}^d, \forall m,n,d. \quad (24)$$
$$L_{mn} \geq B_{mn}^d, \forall m,n,d. \quad (25)$$
$$\sum_{i=1}^{N} M_i^g X_i^d \leq c.R_d^g,\ \forall g,\ \forall d,\ i \notin s \cup \mathcal{D}. \quad (26)$$
$$R_d^g \leq \sum_{i=1}^{N} M_i^g X_i^d,\ \forall g,\ \forall d,\ i \notin s \cup \mathcal{D}. \quad (27)$$
$$\sum_{i=1}^{N} M_i^g Y_i^d \leq c.U_d^g,\ \forall g,\ \forall d,\ i \notin s \cup \mathcal{D}. \quad (28)$$
$$U_d^g \leq \sum_{i=1}^{N} M_i^g Y_i^d,\ \forall g,\ \forall d,\ i \notin s \cup \mathcal{D}. \quad (29)$$
$$R_d^g + U_d^g \leq 1,\ \forall g,\ \forall d. \quad (30)$$

Fig. 3. ILP Formulation

VII. Performance Results

In this section, we evaluate our proposed protection model for CRNs. We study four performance metrics: 1) The number of primary paths (first priority); 2) The number of backup paths (second priority); 3) The maximum primary and backup paths delay (third priority); 4) Minimizing the number of used channels links (fourth priority). The highest priority is assigned for maximizing the number of primary paths, because our focus is to increase the network connectivity. In our evaluation, the network parameters are as follows; the total number of SUs in the network is 25, and the number of hyper-edges (super-nodes) in each layer $= 10$, there is one source node and 8 destination SU nodes. The $SRHEGs$ size is set to one, such that each hyper-

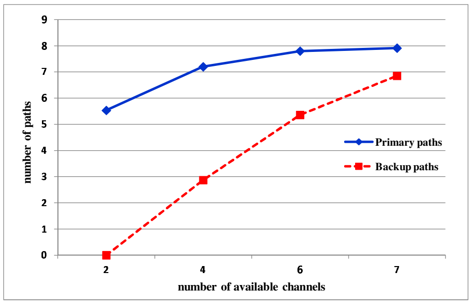

Fig. 4. The average number of primary and backup paths, with respect to the number of available channels.

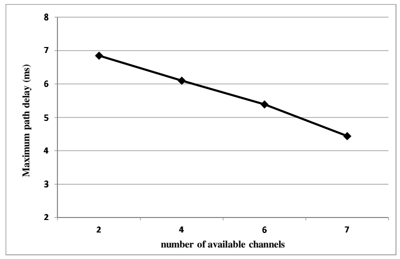

Fig. 5. Maximum path delay to the destinations for the primary and backup paths, with respect to the number of available channels.

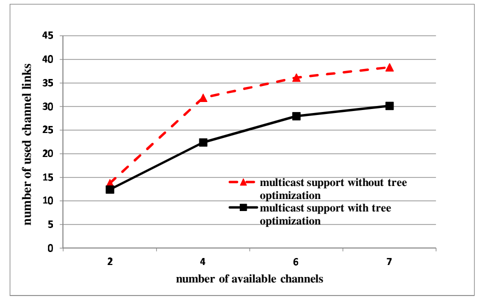

Fig. 6. Number of used channel links in the selected multicast Steiner tree with and without tree optimization.

edge represents a $SRHEG$. In our simulation scenario, we assume the SUs groups that are located within transmission range of each other, called super-nodes, are randomly distributed. The ILP weighting factors α, β, γ, and μ are set to 1000, 100, 10, and 1, respectively. We chose these values after we ran some simulation experiments and studied the results, and we found out these values meet our performance metrics priority rank. In our simulation results in this section, each point is the average of 100 randomly generated network topologies. In each run the source node and the destination nodes are randomly and uniformly selected. Also, the number of available channels, and their IDs for each SU node are randomly and uniformly selected from the available channels.

A. *Number of available channels effect:*

In order to study the effect of the number of available channels, n, on the network performance, under the simulation scenario parameters that are described above, the probability for PU being active is set to 0.3. Figure 4 shows that increasing n increases both the number of primary and backup paths. Increasing n on the number of primary paths has little effect if n is greater than 6. However, the number of backup paths that can be accommodated keeps increasing. Figure 5 shows that the maximum path delay decreases by increasing the number of available channels in the network, which is almost linear.

B. *Minimizing the number of used channels links:*

We also study the effect of adding the fourth objective to the ILP in Section VI, which optimzes the number of used channels resources in the constructed multicast routing tree. Figure 6 shows that the selected links in the multicast Steiner tree is minimized by up to about 30% compared to the optimal solution without the fourth objective. Also in this case study, it is worth mentioning that when the fourth objective is applied the number of primary and backup paths, and the maximum path delay do not change. Only the number of used channel links is reduced since the weight, μ, is small.

VIII. Conclusions

In this paper, we proposed a novel modeling approach for CRNs using a multi-layer hyper-graph. We use this model to develop an Integer Linear programming (ILP) model, in order to find the multicast primary paths and their backup paths, and to also minimize the maximum path delay for primary and backup paths. The number of selected channel links in the construced tree was also minimized. Our simulation results show that when the number of available channels increases, the number of primary and backup paths increases and the maximum path delay decreases almost linearly. Also, the results show that when the number of selected channel links is not minimized, its usage increses by about up to 30%.

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