Abstract—In this paper we introduce a new strategy for controlling the topology in hybrid RF/FSO mobile ad hoc networks. This strategy is based on adapting and adjusting the transmission power and the beam-width of individual nodes according to Quality of Service (QoS) requirements. Our main focus in this work is to meet QoS requirements in terms of end-to-end delay and throughput. Thus, we propose an Integer Linear Programming (ILP) formulation that accurately characterizes the objective and the constraints of the problem. Lagrangian Relaxation (LR) with iterative repair heuristic is also proposed to provide a feasible solution with upper bound and lower bounds for the optimal solution.

Index Terms—Hybrid RF/FSO, Topology Control, QoS, Linear Programming, Lagrangian Relaxation, MANETs.

I. INTRODUCTION

In mobile Ad hoc networks (MANETs), nodes communicate with each other in the absence of a fixed infrastructure. Currently, such networks are deployed strictly in RF domain because of the broadcast nature of the RF channels. However, technical challenges are preventing MANETs from providing a scalable QoS support, particularly bandwidth scarcity, lack of security, high interference, and high bit error rates of wireless RF channels. Because of these limitations and challenges, researchers started to draw attention to the use of Free Space Optics (FSO) in wireless communications. FSO is a technology that enables the transmission of optical signals through free space or air. Such propagation of optical signals through air requires the use of light. Light sources can be either coherent light (lasers) or non-coherent light (LEDs) [1]. Using LEDs in MANETs is more practical, since LEDs use very little power, have wider beam-width compared with lasers, and overcome the safety issue that is considered as a major concern in laser powers. Recently, high-brightness LED technology is rapidly developed where some LEDs can be deployed with a rate up to 2 Gbps and can reach a distance up to 104 miles [2]. In addition to the high data rate, FSO can provide directional transmissions by adjusting its channel beam-width. This directionality in transmission can reduce the FSO communication interference, and can also provide a secure directional transmission instead of broadcasting to multiple neighbors. However, one of the big challenges of FSO is the need to have line of sight (LOS) between transmitter and receiver during communications. Moreover, FSO link availability can be degraded by adverse weather conditions like fog, rain, snow, and haze. A hybrid approach that uses RF/FSO is needed to overcome the weakness of the individual channel types. Several frameworks have been proposed for such hybrid networks [3, 4, 5, 6] and other prototypes have been implemented [7, 8].

We believe that the hybrid RF/FSO approach is an attractive solution for use in three areas: (i) Battlefield Environment, (ii) Intelligence Transportation Systems (ITS), and (iii) Telemetry and Telesurgery. In battlefield, RF/FSO technology has many applications in the next generation military networks [5] such as:

- Ultra high-capacity cross-links between satellites and potentially space-to-air or space-to-ground platforms.
- Airborne networks.
- Air-to-ground links to increase the high-rate RF links currently used for communication.

In ITS environment, there is a need for vehicles to communicate with one another. The broadcast nature and the low data rate of RF channels make the employment of RF technology, in such dense environments, not a practical solution. We propose the use of hybrid RF/FSO channels to alleviate the limitations of RF channels. In this approach, directionality and high data rate features of FSO channels make it a suitable solution for data communication. Furthermore, RF channels can serve as backup and control channels at the same time.

The other application where hybrid RF/FSO technology can be used is Telemetry and Telesurgery. These technologies provide emergency care to people in remote areas and/or harsh environments, such as war zones, polar regions, or space stations even if a doctor is not available. In this kind of application, the surgeons operate using robotic arms based on a visual feedback that comes from a tiny video camera inserted in the patient. Receiving such video streams requires reliable and high data rate connection that can be achieved using hybrid FSO/RF.
The varying nature of RF and FSO channels makes the topology control in hybrid RF/FSO MANETs a major issue that needs to be addressed. Topology control in traditional MANETs has been extensively studied where the objective is to adjust the power level either to have connected network using the minimum possible power or to reduce interference to meet some specific QoS requirements [9, 10, 17]. Limited research in the area of topology control in hybrid RF/FSO has been done. In [11], the authors proposed a joint topology control and routing framework where the RF links serve to provide instantaneous backup to traffic in a hybrid RF/FSO networks when FSO links are degraded. Proposed algorithms have been provided to maximize path protection using RF links. In [12], the authors extended their work in [11] by proposing algorithms for integrated topology control and single-path or multi-path routing in mesh networks. Also, they proved the problem to be NP-Hard. The main focus of previous work was to obtain a strongly connected topology by providing path protection. Topology control using adaptive power control and beam-width adjustment was not part of their studies. In this paper we propose an adaptive topology control framework where each node can adjust its power level for both RF and FSO channels. Also, it can adjust the beam-width of FSO channels such that we end up with a topology configuration that can meet the needed QoS requirements (end-to-end delay and throughput jointly) while minimizing the total transmission power.

The rest of this paper is organized as follows. In Section II, we define the adaptive topology control problem. In Section III, we describe the system model of our topology control problem using hybrid RF/FSO channel. In Section VI, we propose an integer linear programming (ILP) formulation for the problem. In Section V, we relax our ILP formulation using Lagrangian Relaxation (LR), also a Lagrangian Relaxation (LR) with iterative repair heuristic is provided. In Section VI, we present the experiments and interpret their outcomes. Finally, in Section VII, we present overall conclusions and the future trajectory of our research efforts.

II. PROBLEM DEFINITION

Adjusting the beam-width and the transmission power in MANETs has pros and cons. A node with large beam-width or high transmission power usually has more nodes in the transmission range (higher node degree). This can help to reduce the average number of hops; thus minimizing the end-to-end delay. However, a higher node degree can lead to more channel contentions and an increased amount of interference. In a similar manner, nodes with lower number of nodes in the transmission range tend to have lower connectivity. This results in high average path length which consequently leads to high end-to-end delay.

As such, it appears that there is a trade-off and our objective is to construct a robust topology by minimizing the transmission power, adapting the beam-width, and selecting different channels such that we meet joint throughput and end-to-end delay requirements.

III. SYSTEM MODEL

We consider a hybrid RF/FSO wireless ad-hoc network consisting of $N$ nodes equipped with directional FSO transceivers and omnidirectional RF transceivers with limited transmission range. We assume the light source for FSO channels is non-coherent light LEDs. Also, every FSO transceiver at each node is carrying data on its own unique wavelength. Hence, multiple FSO transceivers can send and receive data at the same time without interfering with each other.

RF and FSO propagations suffer from different losses and attenuations [1, 13]. In our study, we focus on the attenuations that occur due to geometrical loss. If node $i$ transmits with power $P_r$, the power of the signal received by node $j$ $P_r$ is given by [1]:

$$P_r = P_r \left( \frac{D_r}{D_r + 100d\theta} \right)^2,$$

where $D_r$ is the transceiver diameter, $d$ is the distance between node $i$ and node $j$, and $\theta$ is the beam divergence angle.

Each wireless channel has a computable Bit Error Rate (BER) that is the probability of the occurrence of an error during data transfer over that link. The relationship between the BER of a wireless channel and the received power level $P_r$ is a function of the modulation scheme. In RF channel, we will consider the instantaneous channel BER that is given in [14, 15] based on non coherent binary orthogonal Frequency Shift Keying (FSK) modulation scheme.

$$BER = \frac{1}{2} \text{erfc} \left( \frac{-P_r}{2P_{\text{noise}}} \right),$$

where $P_{\text{noise}}$ is the RF noise power.

In the FSO channel, we will consider BER that is given in [16] based On-Off Keying (OOK) modulation scheme.

$$BER = \frac{1}{2} \text{erfc} \left( \frac{-R/P_{\text{noise}}}{\sqrt{2}P_{\text{noise}}} \right),$$

where $R$ is the photo detector responsivity, and $P_{\text{noise}}$ is the FSO noise power.

IV. ILP FORMULATION

We have been able to model our optimization problem as Integer linear programming (ILP) problem.

Assumptions

- The network topology is a mesh with directed links.
- At any given node, we have RF and FSO transceivers.
- RF transceivers are omnidirectional, while FSO transceivers are directional.

Input

- $V$: Set of mobile nodes. For each node $i \in V$, we have:
  - Location
  - Number of RF and FSO transceivers
• $T_i$: Set of transceivers. For each transceiver $t$ at node $i$, we have:
  a. C_MAX: Maximum capacity
  b. S: Sensitivity
  c. D: Diameter
  d. Max Beam-Width
  e. Max Power level
• $SD$: Set of requested source-destination connections.
  For each $(s, d) \in SD$, we have:
  a. $H_{i,s}$: Maximum delay
  b. $Th_{i,s}$: Minimum Throughput
• $P$: Transmission power set
• $\Phi$: Beam opening set

In the preprocessing step, we construct a possible network topology $G = (V, E)$, where our objective is to select an optimal construction based on our ILP formulation. The links in a given graph can be enumerated as:

• $l_{i,j,t}^{p,i,j}$: For a given transmission power $p$, transmitter beam-width $\theta_t$, and receiver beam-width $\theta_r$, $l_{i,j,t}^{p,i,j} = 1$ if there is a link$(i,j,t)$ from node $i$ to node $j$ using transceiver $t$; otherwise $l_{i,j,t}^{p,i,j} = 0$.

link $(i,j,t)$ is available if the following two conditions are met:
1) If node $j$ is inside the coverage area of node $i$ using transceiver $t$. This can be verified easily by calculating the transmitter’s maximum range. After that, we can determine the coverage area based on the sector shape area for FSO channels or the circle shape area for RF channels.
2) If there is a line of sight between the transmitter and the receiver. This condition applies on FSO channels only, because RF channels have omnidirectional antennas based on our assumptions stated before.

• $BER_{i,j,t}^{p,i,j}$: For a given transmission power $p$, transmitter beam-opening $\theta_t$, and receiver beam-opening $\theta_r$, $BER_{i,j,t}^{p,i,j}$ represents the bit error rate on link$(i,j,t)$.

• $B_{i,j,t}^{p,i,j}$: For a given transmission power $p$, transmitter beam-opening $\theta_t$, and receiver beam-opening $\theta_r$, $B_{i,j,t}^{p,i,j}$ represents the bandwidth of link$(i,j,t)$:
$$B_{i,j,t}^{p,i,j} = \sum_{p,i,j}^{B_{max}} \theta_t.$$ Where $B_{max}$ is the bandwidth of transceiver $t$ at node $i$.

Variables
• $l_{i,j}^{s,d}$: Boolean variable, $l_{i,j}^{s,d} = 1$ if the path of $(s,d)$ connection pair uses link$(i,j,t)$; otherwise $l_{i,j}^{s,d} = 0$.
• $g_{i,j,t}^{p,i,j}$: Boolean variable selector, $g_{i,j,t}^{p,i,j} = 1$ if $l_{i,j,t}^{p,i,j}$ is selected to construct the topology; otherwise $g_{i,j,t}^{p,i,j} = 0$.
• $x_p$: Boolean power indicator variable. $x_p = 1$ if transceiver $t$ at node $i$ is transmitting using power $p$; otherwise $x_p = 0$.

Objective
$$\text{Min} \left( \sum_{i \in P} p \cdot x_p \right)$$ (1)

Constraints
• Routing Constraints:
  1) To ensure that the $(s,d)$ connection pair is routed correctly.
$$\sum_{i \in V, t \in T_s} \sum_{j \in V, d \in T_d} l_{i,j,t}^{s,d} \cdot g_{i,j,t}^{p,i,j} = \begin{cases} 1 & \text{if } s = i \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in V \text{ and } (s,d) \in SD$$ (2)
  2) To ensure that only a single route can be assigned for a given $(s,d)$ pair.
$$l_{i,j,t}^{s,d} \leq \sum_{p,i,j}^{g_{i,j,t}^{p,i,j}} g_{i,j,t}^{p,i,j} \quad \forall i \in V, t \in T_s \text{ and } (s,d) \in SD$$ (3)

• Delay Constraint: To ensure that the number of hops in the selected route doesn’t violate the delay requirement.
$$\sum_{i \in V} l_{i,j,t}^{s,d} \leq H_{i,s} \quad \forall (s,d) \in SD$$ (4)

• Throughput Constraints: To ensure that the throughput requirements are met.
$$\sum_{i \in V} l_{i,j,t}^{s,d} \cdot Th_{i,s} \leq \sum_{i \in V} B_{i,j,t}^{p,i,j} \cdot (1 - BER_{i,j,t}^{p,i,j}) \cdot g_{i,j,t}^{p,i,j}$$ (5)

• Power Constraint: To ensure that power indicator $x_p$ is 1 when transceiver $t$ at node $i$ is transmitting using power $p$.
$$\sum_{i \in V, t \in T_s} g_{i,j,t}^{p,i,j} \leq N \cdot x_p \quad \forall p \in P, \forall t \in T_s, \forall i \in V$$ (6)

• Selector Constraint:
$$\sum_{i \in V} g_{i,j,t}^{p,i,j} \leq 1 \quad \forall i, t \in T_s$$ (8)
where $t$ is an FSO transceiver
$$\sum_{i \in V} g_{i,j,t}^{p,i,j} \leq 1 \quad \forall i \in V, t \in T_s$$ (9)
\[
\sum_{(p,t,i,j)} g_{p,t,i,j}^r \leq 1 \quad \forall i, j \in V, t \in T, \quad (10)
\]

where \( t \) is an RF transceiver

- Beam opening Constraints: To ensure that transceiver \( t \) at node \( i \) is using the same beam opening during transmission and reception.

\[
\sum_{(p,t,i,j)} g_{p,t,i,j}^r + \sum_{(p,t,i,j)} g_{p,t,i,j}^r \leq 1 \quad (11)
\]

when \( \theta_t \neq \theta_i, j \in V, t \in T, \forall \theta_t \in \Phi \)

- Alignment Constraints

\[
\sum_{(p,t,i,j)} g_{p,t,i,j}^r + \sum_{(p,t,i,j)} g_{p,t,i,j}^r \leq 1 \quad \forall t \in T, \forall \theta_t \in \Phi, \forall i, j, k = i \text{ or } k \text{ in line of sight of } i \text{ and } j.
\]

The complexity of any ILP problem depends on the number of variables and constraints in that problem. In the proposed formulation, the factors that determine the number of variables and constraints are the number of nodes (\( N \)), the number of transceivers (\( T \)), the number of source destination pairs (\( SD \)), the transmission power granularity (\( P \)), and the beam width granularity (\( \theta \)).

The following two equations provide the number of variables and constraints involved in the ILP problem.

\[
W = N[(N-1)(SDT + P(1 + T\theta^2)) + TP],
\]

where \( W \) is the number of variables

\[
Z = N(N-1)(SDT + 2T + (T-1)\theta^2) + N[SDT + 2PT + 2(T-1)] + SD,
\]

where \( Z \) is the number of constraints.

V. LAGRANGIAN RELAXATION

Our ILP problem is an NP-C problem that its degree of difficulty depends on the number of variables and constraints. For example, a scenario with \( N=10 \), \( SD=10 \), \( T=4 \), \( P=4 \), and \( \theta=4 \) has 25740 variables and 5890 constraints. Finding an optimal solution for such a large size problem is computationally inhibited. Thus, finding good suboptimal solutions is more practical.

In this section, we propose a Lagrangian relaxation (LR) approach that performs constraint relaxations by using Lagrangian multipliers. In the relaxation process, our problem is transformed into a dual problem as given below by adding the power constraints (6, 7) and the beam opening constraints (11) which are the complicating constraints in the original primal problem.

\[
\begin{aligned}
\text{Min} \quad & \sum_{p,t,i,j} p_{i,j} x_{i,j}^p \\
& + \lambda_1 ( \sum_{(p,t,i,j)} g_{p,t,i,j}^r + \sum_{(p,t,i,j)} g_{p,t,i,j}^r - 1) \\
& + \lambda_2 ( \sum_{(p,t,i,j)} g_{p,t,i,j}^r - N x_{i,j}^p) \\
& + \lambda_3 (x_{i,j}^r - \sum_{(p,t,i,j)} g_{p,t,i,j}^r )
\end{aligned}
\]

subject to the remaining constraint equations.

Updating Lagrangian Multipliers

Lagrangian multipliers are updated using the method provided in Figure 1 which is based on the LR method [6].

Feasible solution Construction

Despite the fact that Lagrangian relaxation usually generates infeasible solutions, these solutions can be used as a starting point for a repair strategy to generate feasible ones. We propose a lagrangian relaxation with iterative repair heuristic to modify infeasible solutions into feasible solutions. The strength of the proposed heuristic stems from its simplicity and its ability to achieve a solution that is close to optimal. In our proposed heuristic, we minimize the complexity of duality problem by deleting unnecessary constraints that don’t contain violated variables in their equations. Also, we fix variables that are not violated. We define violated variables, as the variables that exist in violated constraints. A high level description of the proposed heuristic is provided in Figure 2.

For a binary linear minimization problem, with all constraints in canonical form

1. Begin with each \( \lambda \) at 0, with step size \( k \) (problem dependent value)
2. Solve the Lagrangian dual to get current solution \( x \).
3. For every constraint violated by \( x \), increase corresponding \( \lambda \) by \( k \).
4. For every constraint with positive slack relative to \( x \), decrease the corresponding \( \lambda \) by \( k \).
5. If \( m \) iterations have passed since the best relaxation value has increased, cut \( k \) in half.
6. Go to 2

Figure 1: Base line Lagrangian relaxation technique [18] adapted for binary linear minimization problems.

Definitions:

- allConstraintsMet: Boolean variable which is true if there is a feasible solution, otherwise it’s false.
- violatedVar[]: Array holds violated variables.
- STOP: maximum iterations to stop looking for a feasible solution
- solveLR(): Function that solves the dual problem using Lagrangian relaxation. It returns true if all constraints are met, otherwise it returns false.
- getViolatedvariables(): Function returns violated variables.
- updateDualProblem(violatedVar): Function updates dual problem based on the provided violated variable from previous Lagrangean solution.

\[
\text{allConstraintsMet} = \text{solveLR}() \\
\text{for}(\text{allConstraintsMet=} \text{false OR i=} \text{STOP})
\]

\[
\text{getViolatedvariables}() \\
\text{updateDualProblem(violatedVar)} \\
\text{allConstraintsMet} = \text{solveLR}() \\
i = i+1
\]

if(\text{allConstraintsMet})

Print Solution
else

No Feasible Solution

Figure 2: Lagrangian relaxation with iterative repair heuristic
VI. RESULTS

In this section we provide some experimental results based on the proposed ILP formulation and the Lagrangian relaxation with iterative repair heuristic. For our experiments, we assume that the capacity of FSO channel is 500 Mbps, the capacity of RF channel is 50 Mbps, the FSO receiver sensitivity is -43dBm, the RF receiver sensitivity is -84dBm, and the maximum beam opening is 240 mrad.

The first experiment compares the results obtained by ILP versus LR heuristic for the requested connections given in Table 1. It’s clear from Table 2, Table 3, Figure 3, and Figure 4 that the solution quality obtained by LR is close to optimal. In this experiment, the topology generated and the power consumed based on the requested connections given in Table 1 are almost the same, except that node 1 established an extra link with node 5 using FSO transceiver. In addition to the feasible solution, the LR provides a tight bound such that the lower bound = 28 and the upper bound= 45.

<table>
<thead>
<tr>
<th>S</th>
<th>D</th>
<th>Throughput (Mbps)</th>
<th>Delay</th>
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<tr>
<td>1</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>5</td>
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<td>100</td>
<td>2</td>
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<td>4</td>
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<td>5</td>
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<td>3</td>
<td>5</td>
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<td>7</td>
<td>2</td>
<td>5</td>
<td>2</td>
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<tr>
<td>8</td>
<td>4</td>
<td>100</td>
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</table>

Table 1: Traffic used to design the topology

The second experiment investigates the impact of changing the source-destination pairs on the generated topology using the LR heuristic. We conducted an experiment similar to the one used in [17] and we reached the same conclusion where the network topology is determined mainly by traffic demand when node locations are given. Figures 5.a, Figure 5.b, and Figure 5.c demonstrate how the number of links in the topology increases when the traffic demand is increased. Figure 6 investigates how LR reduces the complexity of our problem in terms of the number of constraints compared to the original ILP formulation. In this experiment we computed the improvement in five scenarios where N=10, SD=5, P=4, θ=4. To have a fair comparison, we conducted our experiment by varying the number of transceivers (T) because T is a common variable between relaxed constraints and other constraints.

![Topology generated by ILP solution](image-url)
VII. CONCLUSION AND FUTURE WORK

We provided a mathematical model (ILP) for the adaptive topology control by adjusting transmitted power and beam opening in hybrid RF/FSO networks. This model is very powerful and is very flexible. However, because the topology control problem is known to be NP-Complete, we proposed a heuristic solution for mid-scale networks. We proposed a Lagrangian relaxation based on a repair heuristic to extend the applicability of our model to large networks. We were able to find a feasible solution using Lagrangian Relaxation and provided lower and upper bounds. Moreover, our experiments provided more insight into how changing source-destination pairs determined the topology when node locations are given. Using Lagrangian Relaxation is a good approach to provide a tight bound solution, but the amount of computation time is high. In our future work, we will propose a new heuristic solution based on game theory and use the bounds provided by the Lagrangian Relaxation as a baseline to assess the relative performance of the proposed heuristic.
REFERENCES