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Reliable Topology Design of Wireless Networks under Correlated Failures

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***Abstract*—Inherent vulnerability of wireless backhauling to random fluctuations of the wireless channel complicates the design of reliable backhaul networks. In the presence of such disturbances, network reliability can be improved by providing redundant paths between given source and destination. Many studies deal with modifying and designing the network topology to meet the reliability requirements in a cost-efficient manner. However, these studies ignore the correlation among link failures, such as those caused by rain. Consequently, the resulting topology design solutions may fail to satisfy the network reliability requirements under correlated failure scenarios.**

To address this issue, this paper studies the design of reliable wireless backhaul networks under correlated failures with focus on rain fading. We consider green-field topology design and brown-field topology upgrade scenarios with the objective to minimize the total cost of wireless links added to meet the target reliability requirement in the presence of correlated link failures. We propose a new model to formulate the spatial correlation using pairwise joint probability distribution of rain attenuation between different links. This model is applied to consider the link-wise correlation along individual paths, as well as the correlation among the multiple redundant paths from the source to the destination node of a traffic flow. We formulate the problem as a quadratic integer program, which is NP-hard, and develop a heuristic algorithm to find near-optimal solutions. Performance evaluation shows that correlation-aware design improves the resiliency under rain disturbance at a slightly increased cost.

***Index Terms*—5G, reliability, topology design, correlated failures, rain disturbance.**

I. Introduction

The ever growing mobile network traffic demand requires reliable backhaul solutions to connect different users to the core network providing high capacity and high reliability. As a flexible networking technology, wireless systems continue to play an important part in backhauling of next generation of mobile network referred to as 5G [1]. 5G technology is expected to support high reliability performance, such as the connection availability in order of 99.999 % for certain use cases [2], which corresponds to 5.256 minutes mean downtime per year. Meeting this stringent reliability requirement is challenging due to the nature of wireless communications susceptible to random fading of wireless channels, including multipath fading and rain fading [3], [4]. Thus, the evaluation and improvement of network reliability in the presence of failures becomes essential for the design and maintenance of future highly reliable wireless networks.

Existing backhaul networks typically form a tree topology to ensure connectivity in a cost-efficient manner [5]. However, tree topologies are very sensitive to any kind of link degradation (such as rain attenuation and blockage) as they do not provide any redundant paths, which reduces the network reliability performance. Mesh topologies combined with efficient survivable routing algorithms alleviate this problem by providing alternative communication paths [6], [7], at the expense of higher deployment cost. Knowing that $25-50\%$ of total network cost belongs to backhaul [6], it is of utmost importance to develop cost-efficient backhaul network design approaches capable of guaranteeing high reliability.

A number of studies address network topology design or upgrade to improve the reliability and delay [8]–[11]. In [8], authors evaluate the impact of introducing redundant nodes on the network reliability performance for both static and random wireless multi hop networks. The work in [9] proposes an adaptive multipath provisioning algorithm using multiple disjoint paths to increase the network reliability performance. The authors in [10] study the problem of adding a link which maximally increases connectivity. However, in this case the optimal solution is computationally infeasible. In [11], the topology design problem is considered from a game theoretic perspective, where each node increases its connectivity in a non-cooperative way by adding links to other nodes, constrained by delay and link cost. All aforementioned works apply a common assumption of *uncorrelated link failures*, which does not hold in many scenarios such as weather disturbances, e.g., caused by rain, where a set of links may fail simultaneously and the failures exhibit strong correlation. In this scenario, the approaches of in [8]–[11] may lead to inefficient solutions due to their modeling inaccuracy. Modeling correlated failures for reliability assessment has been studied in [4], [12]. These works consider circular probabilistic failure regions formed by spatially correlated links, where the probability of a link failure outside a given region is zero while inside the region it monotonously decreases with the distance from the failure epicenter. Due to the circular representation of the failure region, such model fails to accurately represent rain attenuation [3].

Knowing the specific characteristics of rain attenuation, this paper proposes a new model to consider the spatial correlation under rain, and investigates the related topology design prob-

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lem. The objective is to add links in the backhaul network such that their total cost is minimized and the required reliability under rain disturbances is satisfied. We address this problem in several steps of increasing complexity. We first formulate an integer linear program (ILP) of the problem aimed at minimizing the total link cost under reliability constraints for a given pair of source and destination nodes. Then, we modify the formulation to include the spatial correlation of rain attenuation. To do so, we propose a new model to consider correlation based on the joint failure probability distribution between different links under rain. Our model considers two correlation aspects, *i)* link-wise, which deals with correlation between links along a path and computes the path failure probability using pairwise joint probability distribution of rain attenuation between different links along that path and, *ii)* path-wise, which deals with spatial correlation among multiple paths and generates a path correlation matrix using pairwise link correlation coefficients. We formulate the topology design problem considering both link- and path-wise correlation as a quadratic integer program (QIP), which is NP-hard. Hence, we develop an efficient heuristic algorithm based on the continuous relaxation of the problem, which is shown to find near-optimal solutions.

The rest of the paper is organized as follows. Section II presents the considered system model. The problem formulation considering independent failures is described in Section III. In Section VI, the topology design formulation is modified for correlated failure scenarios and the heuristic algorithm for link addition is presented. The performance of our proposed approach is evaluated in Section V and concluding remarks are given in Section VI.

II. System Model

In this section, we first explain the network and channel model and then describe the link failure probability under rain.

A. Network Model

We consider a wireless mesh network connecting multiple macro base stations (BSs) where each BS serves its associated user data or relays the traffic of other BSs. The BSs are interconnected with point-to-point line-of-sight links realized by highly directional antennas placed at each BS with negligible mutual interference [13]. A subset of BSs generates traffic while a subset of BSs serves as gateways and is connected to the core network segment through high capacity links (e.g., fiber). The network is modeled by a graph $H(\mathcal{V}, \mathcal{E})$, where each vertex $v \in \mathcal{V}$ represents a BS, and each edge $e_i \in \mathcal{E}$ denotes a wireless communication link.

B. Channel Model

We consider a network that is partially or completely affected by rain. Depending on the weather conditions, each link may experience different channel attenuation: multipath fading in clear sky or rain attenuation during rain. Let us denote the rain fading on link e_i by a_i. a_i follows a Lognormal distribution [14]:

$$a_i \sim \ln N\left(m_i, \sigma_i\right) , \tag{1}$$

where m_i and σ_i are mean and standard deviation of $\ln(a_i)$, respectively. The average rain attenuation on link e_i affected by rain is $m_i = \gamma \rho^{\eta} d_i$, where d_i is the length of the link, ρ [mm/hour] shows the rainfall intensity, γ and η are constants that depend on carrier frequency [15]. These rain statistics can be derived from long-term measurements during several years or estimated from Recommendations ITU-R P.530 [16].

Rain attenuation on different links exhibits strong spatial correlation, which is modeled by combining the independent white Gaussian signals for each link with a spatial correlation matrix R. The element (i, j) of the correlation matrix, denoted by r_{ij}, shows the correlation coefficient between links e_i and e_j and is calculated as

$$r_{ij} = \frac{s_{ij}}{\sqrt{s_{ii} s_{jj}}} , \tag{2}$$

where s_{ij} denotes the spatial correlation between links e_i and e_j, and s_{ii} refers to the spatial correlation of link e_i with itself. To calculate s_{ii}, we first compute the rainfall rate correlation between two points along the link as:

$$\varphi = \exp\left(-\alpha d\right) , \tag{3}$$

where d expresses the distance between two points and α^{-1} is the de-correlation distance, defined as the distance at which $\varphi = e^{-1}$ [14]. Spatial correlation between two links is calculated by integrating the rainfall rate correlation between any two points along the lengths ℓ_i and ℓ_j of the links:

$$s_{ij} = \int_0^{\ell_i} \int_0^{\ell_j} \varphi dl_i dl_j . \tag{4}$$

Similarly, s_{ii} for each link, is calculated as a double integral (3) along length ℓ_i of link e_i.

The joint probability distribution between the rain attenuation of link i, a_i and link j, a_j, also follows a lognormal distribution that can be expressed as [14]:

$$f\left(a_i, a_j\right) = \frac{1}{2 a_i a_j \sigma_i \sigma_j \pi \sqrt{1 - {r'_{ij}}^2}} \exp\left(-g(a_i, a_j)\right), \tag{5}$$

where

$$g\left(a_i, a_j\right) = \frac{1}{2\left(1 - {r_{ij}}'^2\right)} \left[\frac{(\ln a_i - m_i)^2}{\sigma_i^2} + \frac{(\ln a_j - m_j)^2}{\sigma_j^2} - \frac{2 r'_{ij} (\ln a_i - m_i)(\ln a_j - m_j)}{\sigma_i \sigma_j} \right] \tag{6}$$

where m_i and σ_i are mean and standard deviation of $\ln(a_i)$, and r'_{ij} shows the correlation coefficient between two links that depends on r_{ij} computed from (2) as follows:

$$r'_{ij} = \frac{\ln\left(r_{ij} \sqrt{\exp(\sigma_i^2) - 1} \sqrt{\exp(\sigma_j^2) - 1} + 1 \right)}{\sigma_i \sigma_j} . \tag{7}$$

C. Link Failure Probability Model

Link failure probability parameter abstracts the ability of the physical layer of wireless systems to reliably transmit packets [8]. A link is considered to fail when its received power falls below a certain threshold necessary to achieve a certain bit error rate (BER) that is required to maintain a given quality of service level.

Let us define a_{th} as the rain attenuation threshold corresponding to a link failure event. Therefore, the link failure probability of link e_i is equal to the probability that its attenuation denoted by a_i is higher than a_{th}:

$$\Pr\left(a_i \geq a_{\text{th}}\right) = \frac{1}{2} - \frac{1}{2}\operatorname{erf}\left(\frac{\ln(a_{\text{th}}) - m_i}{\sigma_i\sqrt{2}}\right) \tag{8}$$

III. Topology Design under Independent Failures

In this section, we formulate the problem of topology design under independent link failures (TD-IF). Let $\mathcal{Q}$ be the set of all possible paths $q_k \in \mathcal{Q}$ between source $s \in \mathcal{S}$ and gateway $g \in \mathcal{G}$. We define a binary path selection variable z_k, which is equal to 1 if path q_k is selected to be established between (s, g) and 0 otherwise. Knowing the set of all possible paths $\mathcal{Q}$, we define matrix C where element $c_{ik} = 1$ if path q_k contains link e_i. Let $\mathcal{D}_k$ be the set of links included in path q_k which can be extracted from matrix C, and p_f^k be the failure probability of path k. As we consider independent link failure events in this section, p_f^k can be computed as:

$$p_f^k = 1 - \prod_{e_i \in \mathcal{D}_k} \left(1 - \Pr\left(a_i \geq a_{\text{th}}\right)\right) \ , \tag{9}$$

where $\Pr\left(a_i \geq a_{\text{th}}\right)$ is the failure probability of link e_i computed from Eq. (8).

Let us consider w_i as the cost of establishing link e_i, which is assumed to be zero for links that are already established in the network in a brown-field scenario. The objective of our approach is to minimize the total cost of links necessary to obtain a reliability level between s and g under rain condition higher than a predefined threshold ϵ. In this paper, we define the reliability metric as the probability of having a successful transmission between s and g, possibly using multiple paths. To meet the reliability constraint, as in [12], we consider multiple disjoint paths. Although this assumption simplifies our formulation, it may overestimate the number of links required to meet the reliability constraint and provides an upper bound on the cost. However, under correlated failure scenarios such as rain, the bound gets tight as the optimal solutions prefer paths without joint links due to their lower spatial correlation under rain condition. The TD-IF problem with consideration of disjoint paths is formulated as follows:

$$\text{TD-IF}: \ \min_{Z} \quad \sum_{k \in \mathcal{Q}} \sum_{i \in \mathcal{E}} c_{ik} w_i z_k \tag{10a}$$

$$\text{s.t.} \quad \sum_{k} c_{ik} z_k \leq 1, \quad \forall i \in \mathcal{E}, \tag{10b}$$

$$\sum_{k} z_k \ln(p_f^k) \leq \ln(1 - \epsilon), \tag{10c}$$

$$z_k \in \{0, 1\} \ , \quad \forall k \ . \tag{10d}$$

Equation (10a) expresses the total cost of links in the network, whose minimization is the objective of our approach. Constraint (10b) enforces that the selected paths do not share any common link, and constraint (10c) ensures the reliability requirement. It should be noted that we use $\ln(.)$ operator to derive a linear constraint in (10c).

IV. Topology Design under Correlated Failures

In this section, we modify the (TD-IF) problem, formulated in (10) to take into account the spatial correlation of rain attenuation. To do so, the first step is to modify the path failure probability p_f^k to consider the spatial correlation of the rain. Then, we consider spatial correlation between different paths by adding extra cost for selecting correlated paths.

A. Path Failure Probability

The spatial correlation of rain attenuation among different links causes correlated failures along each path. In this case, the failure probability of a path is computed as the joint probability of failure of each traversed link, which depends on the spatial correlation of rain attenuation. Let us consider a path q_k with the set of link D_k, $D_k = (e_i, e_{i+1}, ..., e_{i+L})$, and their corresponding attenuation $(a_i, a_{i+1}, ..., a_{i+L})$ between a given source and destination. Considering the spatial correlation between different links along path q_k, the failure probability p_f^k is calculated as:

$$\begin{aligned} p_f^k =& 1 - p_s^k \\ =& 1 - \Pr\left(a_i \leq a_{th}, a_{i+1} \leq a_{th}, .., a_{i+L} \leq a_{th}\right) \ , \end{aligned} \tag{11}$$

where p_s^k is the success probability of path q_k, i.e., the probability that all links along that path are available. To compute the exact value of the success probability, the joint probability distribution of their corresponding attenuation $a_i, ..., a_{i+L}$, should be known. However, only the pairwise joint probability distribution of rain attenuation between different links has been formulated in the literature (see Eq. (5)). Therefore, we approximate the success probability p_s^k using pairwise distribution of all consecutive link pairs included in the path:

$$p_s^k \approx \Pr\left(a_i \leq a_{\text{th}}\right) \prod_{i \in D_k} \Pr\left(a_{i+1} \leq a_{\text{th}} | a_i \leq a_{\text{th}}\right) \ . \tag{12}$$

The marginal $\Pr\left(a_i \leq a_{\text{th}}\right)$ and pairwise probability distribution $\Pr\left(a_{i+1} \leq a_{\text{th}}, a_i \leq a_{\text{th}}\right)$ can be computed from (1) and (5), respectively. It can be shown that $\Pr(a_{i+1} \leq a_{\text{th}} | a_i \leq a_{\text{th}})$, i.e., the conditional success probability between link e_i and e_{i+1}, depends on the correlation factor $r_{i(i+1)}$ and increases when the angular separation between links e_i and e_{i+1} decreases [17].

To model the spatial correlation among different paths connecting source s to gateway g, we define a new correlation matrix, T that uses the correlation coefficient between pairs of links included in the paths. Let $[T]_{kl} = t_{kl}$ quantify the correlation between path q_k and path q_l. We define:

$$t_{kl} = \frac{1}{|D_l| \, |D_k|} \sum_{i \in D_l} \sum_{j \in D_k} r_{ij} \ , \tag{13}$$

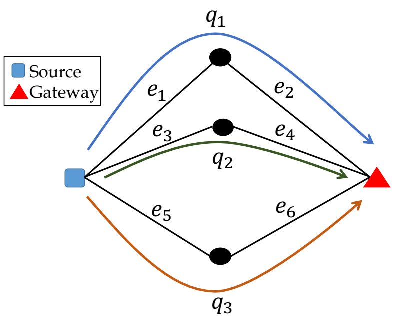

Figure 1: An illustrative example of spatial correlation among paths.

where D_l and D_k are link sets included in path q_l and q_k, resp., and r_{ij} is defined by Eq. (2). Note that T is a correlation matrix, and therefore it should be positive definite. If the computed correlation matrix definite in (13) does not satisfy this constraint, we replace it by the closest positive definite matrix T' that has a minimum distance to T and T' [18].

Illustrative example: The concept of spatial correlation between different paths from a source node to a gateway is illustrated in Fig. 1. We consider three paths (q_1, q_2 and q_3) that use links $D_1 = (e_1, e_2)$, $D_2 = (e_3, e_4)$, and $D_3 = (e_5, e_6)$. The spatial correlation between two paths depends on the correlation factor among the links they traverse. Note that $\theta_{13} < \theta_{15}$, where θ_{ij} shows the angular separation between links e_i and e_j. Consequently, the correlation factor between links e_1 and e_5 is smaller than between e_1 and e_3 (i.e., $r_{15} < r_{13}$). With similar logic, the correlation between links e_2 and e_6 is smaller than e_2 and e_4 (i.e., $r_{26} < r_{24}$). Hence, path q_1 is less correlated to q_3 than to q_2 and choosing paths q_1 and q_3 provides a more reliable solution under rain disturbance compared to selecting q_1 and q_3.

B. Problem Formulation

To capture the spatial correlation in the presence of weather disruptions, we must consider the correlation between *i)* links along one path and *ii)* among different paths. The first step is performed by recalculating the path failure probability p_f^k from (10c) using Eqs. (11) and (12). The second step, considering the correlation among different paths, is challenging. The reliability constraint in (10c) sums the logarithms of failure probabilities for each path, which is not valid under correlated failure scenarios. To make this constraint more realistic under rain, it would be necessary to compute the accurate value of reliability taking into account the spatial correlation among all links, which is not possible knowing only the pairwise link correlation. Therefore, we penalize the selection of correlated paths by adding a corresponding extra cost in the objective function. Let $c_{1,2,..,m}$ show the cost of choosing paths $\{q_1, q_2, ..., q_m\}$ simultaneously. We define it based on pairwise correlation coefficient between different paths $[T']_{kl} = t'_{kl}$, as follows:

$$c_{1,2,\ldots,m} = \sum_k \sum_l t'_{kl}. \tag{14}$$

Algorithm 1 Heuristic algorithm of problem TD-CF based on continuous relaxation: TD-CF-H

Given: Source and destination pair (s, g), Set of all paths $\mathcal{Q}$ and the reliability threshold ϵ.
Initialization: Set $S^* = \{\}$; $r_{\text{dif}} = 1$.
Compute failure probability of all paths $\{p_f^k\}_{k=1}^{|\mathcal{Q}|}$ using Eq. (12).
Solve the continuous relaxation of problem TD-CF to compute the optimal solution Z^*.
Compute $S = [V, U]$, where V is the set of all non-zero elements of optimal vector Z^* and U is the set of their corresponding indices.
Sort S based on V.
while $r_{\text{dif}} > 0$ **do**
  Set $S^* \leftarrow S^* \cup S(1)$.
  Compute $r_{\text{dif}} = \sum_{j \in U*} \ln(p_f^j) - \ln(1-\epsilon)$.
  Update S by removing $S(1)$.
end while
Solution: S^*

Based on the above equation and knowing that z_k is used to choose path q_k, the penalty function is given by $c_{1,2,\ldots,m} z_1 z_2 \ldots z_m$. Using this model makes the optimization problem computationally prohibitive due to the multiplication of m variables. Therefore, we use a simplified version of the cost that sums all possible path pairs as follows:

$$c_{1,2,\ldots,m} z_1 z_2 \ldots z_m = \sum_k \sum_l t'_{kl} z_k z_l. \tag{15}$$

To minimize the total deployment cost and penalty function, formulated in Eqs. (10) and (15), respectively, we define the objective of TD-CF optimization problem as a convex combination of (10) and (15):

$$\text{TD-CF}: \min_{Z} \quad \lambda \sum_{k \in \mathcal{Q}} \sum_{i \in \mathcal{E}} c_{ik} w_i z_k + (1-\lambda) \sum_{k \in \mathcal{Q}} \sum_{l \in \mathcal{Q}} t'_{kl} z_k z_l \tag{16}$$

$$\text{s.t.} \quad \text{(10b), (10c), and (10d)}$$

where t'_{kl} is (k,l)-th element of path correlation matrix T' computed in (13), and λ is a constant in $[0,1]$. The problem shown in (16) is a mixed integer quadratic programming which is NP-hard [19]. Therefore, we propose a lightweight heuristic algorithm for finding near-optimal solutions.

C. Heuristic Algorithm for TD-CF

We develop a heuristic algorithm based on continuous relaxation of problem (16). By relaxing variable $0 \leq z_k \leq 1$, the problem (16) is solved in polynomial time as the correlation matrix T' is positive definite [19]. It should be noted that by relaxing $0 \leq z_k \leq 1$, constraint (10b) does not necessarily ensure disjoint paths anymore. However, due to the correlation penalty term in the objective function of problem (16), whose value becomes large for paths with shared links, the optimal solution may automatically include disjoint paths if they exist.

The pseudocode of the proposed TD-CF heuristic (TD-CF-H) algorithm is shown in Algorithm 1. The set of all possible paths between a given pair of source and destination (s, g) as well as the reliability threshold ϵ are given. The set of

Table I: Simulation parameters.

Parameters	Description	Value
γ	Rain-related parameter	0.15
η	Rain-related parameter	1.04
ρ	Rain rate	20 [mm/hour]
β	Temporal variation	1/9 min^{-1}
σ	Variance of rain attenuation	1.14
α	De-correlation factor	0.46 km^{-1}

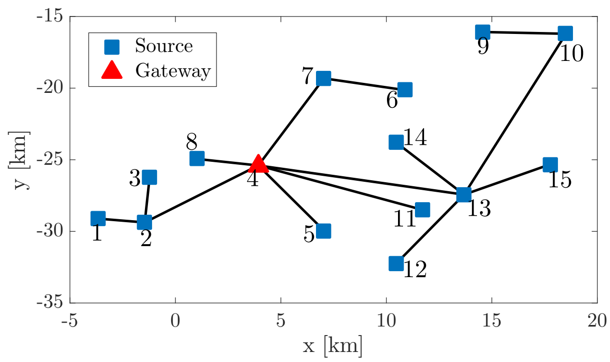

Figure 2: The network topology used in the simulations.

paths to be established in the network represents the solution of TD-CF-H, and is denoted with S^*, initially empty. The failure probability of each path is computed using Eq. (12) *(Line 3)*. TD-CF-H first solves the continuous relaxation of the TD-CF problem by setting the value of Z between $[0,1]^{|Q|}$, and computing the optimal path selection vector Z^* *(Line 4)*. The algorithm creates vector $S = [V, U]$, where V contains the non-zero elements of vector Z^* and U holds their corresponding indices *(Line 5)*. To select the best paths, the elements in vector $S = [V, U]$ are first sorted based on the value of V *(Line 6)*. The algorithm then checks the reliability requirement and iteratively adds the first element from S to the solution set S^* until the reliability threshold is satisfied *(Lines 7-11)*. Variable r_{dif} is used to express the difference from the reliability of the current solution and the required threshold, validating whether constraint (10c) is satisfied *(Line 9)*. The selected path candidate is removed from S *(Line 10)* before proceeding to the next iteration.

V. Simulation Results

The performance of our topology design approach was evaluated through simulations in four different scenarios:

- Green-field uncorrelated (GUC): no existing links are established in the network and the link failures are assumed to be uncorrelated.
- Green-field correlated (GC): no existing links are established in the network and the spatial correlation between different link failures is considered.
- Brown-field uncorrelated (BUC): certain links are already deployed in the network (with zero cost), and the link failures are assumed to be uncorrelated.
- Brown-field correlated (BC): certain links are already deployed in the network (with zero cost), and the spatial correlation between different link failures is considered.

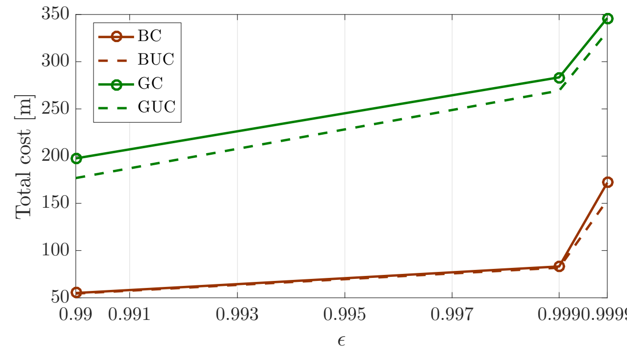

Figure 3: Total cost for different reliability thresholds in GUC, GC, BUC, and BC scenarios.

The network considered in the simulation is a part of a currently deployed wireless backhaul network [7], comprising 15 BSs communicating with one gateway, as shown in Fig. 2. We consider a scenario where rain attenuation is the only cause of failures, and the link failure probability is obtained from Eq. (8). The carrier frequency and transmitted power from each BS are 38 GHz and 21 dBm, respectively [20]. We generate the time series of rain samples considering the temporal and spatial correlation based on the model from Section II-B using the parameters gathered in Table I. Throughout the simulation, the cost of establishing a link is equal to its distance. All results are generated with MATLAB as simulation platform.

Fig. 3 shows the total cost versus the reliability threshold for the four considered scenarios. As can be expected, the total cost for achieving the same reliability performance in brown-field scenario is significantly lower than green-field as it uses previously established links as much as possible. In brown-field scenarios, the average extra cost of BC due to considering correlated failures is only 2% higher than for BUC at low reliability threshold, while it increases to 10% for higher reliability requirement. In green-field scenarios, the GC has 10% higher cost than GUC for all reliability threshold. This is explained by the necessity of using more paths to compensate for the correlated failure events and meet the same reliability requirement, compared to an uncorrelated scenario. However, the benefits of considering failure correlation manifest themselves in higher reliability in the presence of rain.

Fig. 4 shows the performance of our topology design approach under different rain rates. The optimal network topology was obtained for $\rho = 20$ $[\text{mm/hour}]$ on all links, which was then changed to evaluate the average path availability of the design on a wider rain rate scale. The results show that the topology design considering correlated failures (GC and BC) is consistently more resilient than the independent scenarios (GUC and BUC). The green-field topology design considering correlation are less sensitive to the rain rate than its corresponding brown-field, as the BC typically uses the already established links which may not be necessarily uncorrelated. Moreover, increasing rain rate decreases the average path availability in all scenarios, showing further necessity of extending topology design with online adaptation such as routing.

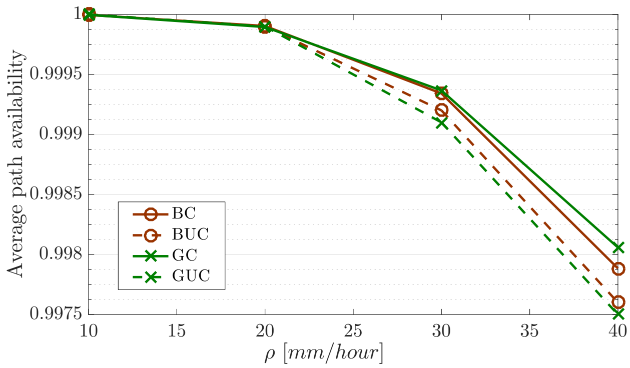

Figure 4: Average path availability under different rain rates.

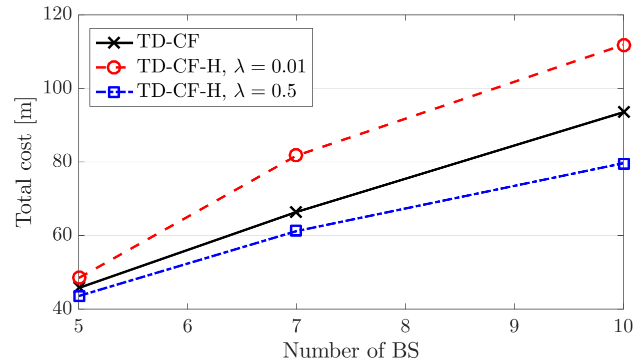

Figure 5: Total cost for random network using TD-CF and TD-CF-H for different λ.

Fig. 5 compares the total cost of the topology obtained by our heuristic algorithm TD-CF-H with the value achieved from solving the quadratic integer programming (TD-CF). The results were collected by generating 100 random network instances with 5, 7, and 10 BSs and a randomly selected gateway. We then design the topology for each random network so that the reliability threshold ϵ from each source to the randomly selected gateway is satisfied. We compute the cost for each network and find the average cost over all 100 networks. The results show that with higher λ, TD-CF-H provides a lower bound for TD-CF problem since the penalty of choosing correlated paths is not high enough, and consequently the solution of our heuristic algorithm may not necessarily include disjoint paths. On the other hand, decreasing λ increases the penalty of selecting correlated paths and TD-CF-H favors disjoint paths, which causes a higher cost due to sub-optimality of our proposed heuristic algorithm.

VI. Conclusion

In this paper, we proposed the cost-efficient design of wireless network topology capable of providing high reliability under rain disturbance. In such conditions, link failures are highly correlated and the reliability requirements cannot be guaranteed by simply assuming uncorrelated failures. To address this issue, we developed a new model to consider the spatial correlation of rain attenuation among links on each path, and among different paths from the source to the gateway node. The evaluation results of the proposed topology design approach show that considering failure correlation significantly improves the network reliability performance under heavy rain at a slightly increased cost. As a port of future work, we will develop tailored online adaptation approaches to meet the reliability requirements under rain disturbance.

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References

[1] J. G. Andrews and *et al.*., "What will 5G be?" *IEEE Journal on Selected Areas in Communication*, vol. 6, no. 32, pp. 1065–1082, Jun. 2014.

[2] R. E. Hattachi and J. Erfanian, "NGMN 5G white paper," *NGMN Board*, vol. 1, Feb. 2015.

[3] J. Rak and *et al.*, "Future research directions in design of reliable communication systems," *Telecommun. Systems*, vol. 60, no. 4, pp. 423–450, 2015.

[4] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Reliability assessment for wireless mesh networks under probabilistic region failure model," *IEEE Trans. on Vehicular Technology*, vol. 60, no. 5, pp. 2253–2264, 2011.

[5] Y. Li and *et al.*, "Multi-objective topology planning for microwave-based wireless backhaul networks," *IEEE Access*, vol. 4, pp. 5742–5754, 2016.

[6] F.-C. Kuo, F. A. Zdarsky, J. Lessmann, and S. Schmid, "Cost-efficient wireless mobile backhaul topologies: An analytical study," in *Proc. Conference GLOBECOM*, 2010, pp. 1–5.

[7] F. Yaghoubi, J. Chen, A. Rostami, and L. Wosinska, "Mitigation of rain impact on microwave backhaul networks," in *Proc. ICC*. IEEE, 2016, pp. 134–139.

[8] G. Egeland and P. E. Engelstad, "The availability and reliability of wireless multi-hop networks with stochastic link failures," *IEEE Journal on Selected Areas in Commun.*, vol. 27, no. 7, 2009.

[9] W. Zhang, J. Tang, C. Wang, and S. de Soysa, "Reliable adaptive multipath provisioning with bandwidth and differential delay constraints," in *Proc. INFOCOM*. IEEE, 2010, pp. 1–9.

[10] H. Wang and P. Van Mieghem, "Algebraic connectivity optimization via link addition," in *Proc. Conference on Bio-Inspired Models of Network, Information and Computing Sytems*, 2008, p. 22.

[11] A. Nahir and *et al.*, "Topology design and control: A game-theoretic perspective," in *Proc. Conference INFOCOM*, 2009, pp. 1620–1628.

[12] H.-W. Lee, E. Modiano, and K. Lee, "Diverse routing in networks with probabilistic failures," *IEEE/ACM Trans. on Networking*, vol. 18, no. 6, pp. 1895–1907, 2010.

[13] T. S. Rappaport, G. R. MacCartney, M. K. Samimi, and S. Sun, "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design," *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3029–3056, Sept. 2015.

[14] M. Cheffena, L. E. Braten, and T. Ekman, "On the space-time variations of rain attenuation," *IEEE Trans. on Antennas and Propagation*, vol. 57, no. 6, pp. 1771–1782, 2009.

[15] S. Lin, "A method for calculating rain attenuation distributions on microwave paths," *Bell System Technical Journal*, vol. 54, no. 6, pp. 1051–1086, 1975.

[16] ITU Recommendation P. 530-12, "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems." *Geneva, Switzerland*, 2007.

[17] G. Hendrantoro, R. J. Bultitude, and D. D. Falconer, "Use of cell-site diversity in millimeter-wave fixed cellular systems to combat the effects of rain attenuation," *IEEE Journal on Selected Areas in Commun.*, vol. 20, no. 3, pp. 602–614, 2002.

[18] N. J. Higham, "Computing the nearest correlation matrix—a problem from finance," *IMA journal of Numerical Analysis*, vol. 22, no. 3, pp. 329–343, 2002.

[19] M. K. Kozlov and *et al.*, "The polynomial solvability of convex quadratic programming," *USSR Computational Mathematics and Mathematical Physics*, vol. 20, no. 5, pp. 223–228, 1980.

[20] A. Bolle and A. Nascimbene, "Microwave transmission in mobile networks," *Ericsson Review*, no. 3, pp. 124–131, 2002.