Fronthaul Design for Wireless Networks: a Software Tool

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This document details a software tool built from scratch (based on the MATLAB programming language) to evaluate and compare the performance of Microwave Radio Transmission (MRT), Free Space Optics (FSO) and Fiber Optics (FO) technologies when applied to the fronthaul. More specifically, the software tool has the following purposes: (i) to determine the most cost-effective solution to connect two points regarding a link between a Remote Radio Head (RRH) and a Baseband Unit (BBU), under user-specified equipment characteristics and link conditions; (ii) to optimally find a fronthaul topology for wireless networks, given the RRHs location — namely, the required number of BBUs and where they should be positioned in order to minimize the overall network costs. The algorithms associated with these goals, designated as *Link Design Algorithm* and *Network Planning Algorithm*, respectively, are presented next. The software tool, including its source code, is freely available online [1] — hence, besides being a generic tool, because it can be used for a wide range of fronthaul projects, it is also a versatile tool, in the sense that it can be modified by anyone in order to incorporate other features that are specific for a certain project.

0.1. Link Design Algorithm

The Link Design Algorithm determines, out of all the user-specified equipment characteristics associated to one or more of the communication technologies (MRT, FSO and FO), which is the most cost-effective solution to connect two points under user-specified link conditions; for a set of specifications, namely the equipment features and other installation aspects (such as link distance, required bit rate and surrounding environment characteristics), this algorithm computes the cheapest solution that is able to deliver the necessary bit rate, while satisfying certain link margin and error criteria.

With respect to the wireless technologies addressed herein (MRT and FSO), it is important to mention that only single-hop links are considered by the algorithm, because the inclusion of relay stations is not straightforward (e.g., sites for relay deployment may not be available) and leads to more complex business models (e.g., addition of rental expenses for the extra sites). Accordingly, link distance is henceforth regarded as hop distance when MRT and FSO technologies are under consideration.

The following subsections present the details of the Link Design Algorithm, namely the adopted models for the communication technologies, the economic analysis methodology and, finally, the workflow of the algorithm.

0.1.1. Communication Technologies Models

For wireless communication technologies such as MRT and FSO, the received signal power, P_{Rx}, is given by (in logarithmic units)

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - A_0 - A_{equi} - A_{sys}, \quad (1)$$

where P_{Tx} corresponds to the transmitted power (in dBW or dBm), G_{Tx} and G_{Rx} stand for the transmitter and receiver antenna gains (in dBi), respectively, A_0 represents the free-space path loss (in dB), i.e.,

$$A_0 = 92.4 + 20\log_{10}(d_{[\mathrm{km}]}) + 20\log_{10}(f_{[\mathrm{GHz}]}), \tag{2}$$

where d denotes the link distance and f refers to the carrier frequency, A_{equi} denotes the losses (in dB) related to equipment like cables, modulators, etc. (which are typically lower than 3 dB), and A_{sys} corresponds to other losses (in dB) related to specific attenuation factors regarding the considered communication technology.

With respect to MRT systems, the term A_{sys} incorporates the attenuation caused by obstacles in the line-of-sight path (A_{obs}), the attenuation induced by atmospheric gases (A_{gas}), and the attenuation due to rain (A_{rain}). All these attenuation factors can be computed as described in the related literature [2] — a summary is given as follows. The attenuation due to obstacles can be computed as (in dB)

$$A_{obs} = \max\left\{0\ ;\ 6.9 + 20\log_{10}(\sqrt{(\nu-0.1)^2+1}+\nu-0.1)\right\}, \tag{3}$$

where ν is proportional to the amount of the Fresnel ellipsoid that is obstructed by the obstacle, i.e.,

$$\nu = \frac{h_{obs}}{17.32}\sqrt{8\frac{f_{[\mathrm{GHz}]}}{d_{[\mathrm{km}]}}}, \tag{4}$$

where h_{obs} denotes the height of the top of the obstacle above the straight line joining the two ends of the link (if the height is below this line, then h_{obs} is negative). The attenuation due to atmospheric gases (namely uncondensed water vapor and oxygen) can be computed as (in dB)

$$A_{gas} = (\gamma_o + \gamma_w) \times d, \tag{5}$$

where γ_o and γ_w represent, respectively, the attenuation caused by oxygen and water by unit of length — values for these parameters can be extracted from nonlinear curves as a function of the carrier frequency. With respect to A_{rain}, it should be pointed out that since rain is highly variable over time and differs from place to place, the respective attenuation factor depends on the desired time availability for the MRT link. More specifically, the attenuation due to rain has to be computed taking into account the value of rain intensity that is not exceeded in a certain percentage of the time in the location of interest. Accordingly, and having in mind the Service Level Requirements (SLR) — which address service times, maintenance, availability, performance, etc. — an MRT system designer must first stipulate the minimum time availability of the link (e.g., 99.9% of the time); afterwards, by using the method suggested by an ITU-R[1] recommendation [3], the rain attenuation is computed, thus ensuring that the planned MRT link may still suffer from rain outage, but no longer than the maximum percentage of time unavailability of the link (U_{max}), with $U_{max} = 100\% -$ minimum link availability percent. Formally, and given the rain intensity not exceeded in 0.01% of the time ($R_i^{(0.01\%)}$), the rain attenuation for that percentage of the time is given by (in dB)

$$A_{rain}^{0.01\%} = \beta \times \left(R_i^{(0.01\%)}\right)^{\alpha} \times d_{ef}, \tag{6}$$

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where β and α denote coefficients that depend on the carrier frequency and on the considered temperature, and d_{ef} corresponds to the effective distance through a rainy path, which is computed as

$$d_{ef} = \max\left\{2.5\,d\,;\ \frac{d}{0.477\,d_{[\mathrm{km}]}^{0.633} \times \left(R_i^{(0.01\%)}\right)^{0.073\,\alpha} \times f_{[\mathrm{GHz}]}^{0.123} - 10.579\left(1 - e^{-0.024\,d_{[\mathrm{km}]}}\right)}\right\}; \tag{7}$$

finally, the rain attenuation exceeded for a percentage of time U_{max} other than 0.01% is obtained as

$$A_{rain} = A_{rain}^{0.01\%} \times 0.12\,U_{max}^{-(0.546+0.043\log_{10} U_{max})}. \tag{8}$$

Turning now the attention to FSO systems, the term A_{sys} encompasses the attenuation induced by atmospheric absorption (A_{abs}), the attenuation due to atmospheric turbulence (A_{turb}), and the attenuation caused by scattering (A_{sca}). All these attenuation factors can be computed as described in the related literature [4,5] — a summary is given as follows. Considering the atmospheric absorption (which is mainly caused by the presence of gaseous molecules), it can be given by (in dB)

$$A_{abs} = \gamma_{abs} \times d, \tag{9}$$

where γ_{abs} stands for the absorption attenuation coefficient, which depends on the considered temperature and on the relative humidity. The attenuation due to atmospheric turbulence (i.e., small and random variations of the refractive index of the Earth's atmosphere, which are responsible for wave front distortion) can be described by (in dB)

$$A_{turb} = 2\,\sigma_{scin}, \tag{10}$$

where σ_{scin} refers to the scintillation index, which can be expressed as

$$\sigma_{scin} = \sqrt{1.23\,C_n^2 \times \left(\frac{2\pi}{\lambda_{[\mathrm{m}]}}\right)^{\frac{7}{6}} \times d_{[\mathrm{m}]}^{\frac{11}{6}}}, \tag{11}$$

where λ corresponds to the operating wavelength and C_n^2 represents the index of refraction structure parameter, which is computed as (in $\mathrm{m}^{-2/3}$)

$$C_n^2 = 9.8583 \times 10^{-18} + 4.9877 \times 10^{-16} \times e^{-\frac{h_{a[\mathrm{m}]}}{300}} + 2.9228 \times 10^{-16} \times e^{-\frac{h_{a[\mathrm{m}]}}{1200}}, \tag{12}$$

where h_a denotes the transmitter altitude. With respect to A_{sca}, which is caused by the occasional presence of fog (including mist and haze) and rain, it is important to stress that fog is the major contributor regarding the attenuation due to scattering; hence, and noticing that the respective attenuation coefficient is computed as a function of the visibility, this type of attenuation also depends on the desired time availability for the FSO link. More specifically, one has to take into account the value of the visibility that is not exceeded for a given percentage of the time in the location of interest. Since the ITU-R recommendations for FSO systems design do not provide a metric to compute the visibility distribution, one alternative is to use one of the visibility distribution models presented in a related work [6] — e.g., the simplified model introduced therein and adopted in this methodology — which rely on the average number of foggy days (per year) and the average duration of fog events (in hours). Accordingly, the visibility value can be obtained and used to compute the respective attenuation that ensures that the planned FSO link may still suffer from fog outage but no longer than the maximum percentage of the time regarding tolerated link unavailability, thus enabling to fulfill the SLR — it is important to mention that, in order to ensure the fulfillment of the same SLR regardless of the specific adopted wireless technology, the software tool considers the same percentage of the time for link unavailability regarding the attenuations related to both rain and fog. Formally, the attenuation caused by scattering is given by (in dB)

$$A_{sca} = (\gamma_{fog} + \gamma_{rain}) \times d, \tag{13}$$

where γ_{fog} and γ_{rain} represent, respectively, the attenuation caused by fog and water by unit of length. The former parameter can be expressed as (in dB/km)

$$\gamma_{fog} = \frac{3.91}{V_{[\text{km}]}} \times \left(\frac{\lambda_{[\text{nm}]}}{550}\right)^{-q}, \tag{14}$$

where V stands for the visibility and q refers to a coefficient that is dependent on the size distribution of the scattering particles, which is given by

$$q = \begin{cases} 1.6 & V > 50 \text{ km} \\ 1.3 & 6 \text{ km} < V < 50 \text{ km} \\ 0.16\, V_{[\text{km}]} + 0.34 & 1 \text{ km} < V < 6 \text{ km} \\ V_{[\text{km}]} - 0.5 & 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & V < 0.5 \text{ km} \end{cases}. \tag{15}$$

With respect to the visibility, it can be computed as (in km)

$$V = \frac{U_{max}}{100} \times \frac{365.25}{\overline{N_{fog}}_{[\text{days/year}]}} \times \frac{24}{\overline{D}_{[\text{h}]}}, \tag{16}$$

where $\overline{N_{fog}}$ and $\overline{D}$ refer to average number of foggy days and average duration of fog events, respectively. Finally, the parameter related to the attenuation caused by water can be expressed as (in dB/km)

$$\gamma_{rain} = 1.076 \left(R_i^{(0.01\%)}\right)^{0.67} \times 0.12\, U_{max}^{-(0.546+0.043\log_{10} U_{max})}. \tag{17}$$

After computing the received signal power, the wireless link margin, W_{link}, is obtained as (in dB)

$$W_{link} = P_{Rx} - S_{Rx}, \tag{18}$$

where S_{Rx} refers to the sensitivity of the receiver. In order to consider a wireless connection as viable, and since the higher the link margin, the more robust the wireless link will be, as it will be prepared for potential extra attenuations, W_{link} must be greater than a user-specified minimum accepted link margin (e.g., 3 dB).

Once the link margin requirement is satisfied, another requirement, namely the Bit Error Rate (BER), must be fulfilled in order to ensure that the wireless link is feasible. The BER can be extracted from mapping curves as a function of the Signal-to-Noise Ratio (SNR) of the MRT link [2] or the FSO link [7]. With respect to the SNR of an MRT link, it can be given by (in dB)

$$\text{SNR}^{(\text{MRT})} = P_{Rx} - N_f - N_0, \tag{19}$$

where N_f corresponds to the noise figure of the receiver and N_0 denotes the thermal noise, which can be computed as (in dBW)

$$N_0 = -204 + 10\log_{10}(b_{w[\text{Hz}]}), \tag{20}$$

where b_w represents the noise equivalent bandwidth of the receiver and it can be expressed as

$$b_w = \frac{B_{link}}{\log_2(M)}, \tag{21}$$

where B_{link} and M stand for the link bit rate and the QAM[2] signal constellation size, respectively. Considering an FSO link, and making the typical assumption of a shot-noise-limited operation with On-Off Key (OOK) modulation, the SNR can be obtained as (in dB)

$$\mathrm{SNR}^{(\mathrm{FSO})} = P_{Rx} - \frac{P_{Rx} + A_{turb}}{2} - 5\log_{10}\left(2\,h \times \frac{c}{\lambda} \times B_{link}\right), \tag{22}$$

where h and c refer to the Planck constant and the speed of light, respectively.

Considering now FO systems, the associated technology differs from the two wireless communication systems previously discussed (MRT and FSO) as it does not use the atmosphere as propagation medium. More specifically, since the beam is confined to the fiber, there are no outside weather conditions that need to be taken into consideration when planning point-to-point transmission using the FO technology. Accordingly, evaluating a link budget for FO is equivalent to computing the total loss, suffered by a transmitted signal across various components and along the optical fiber, with reference to the minimum receiver power required to maintain normal operation.

In mathematical terms [8], the FO link budget, L_B, is given by (in dB)

$$L_B = Tx_{min} - Rx_{min}, \tag{23}$$

where Tx_{min} and Rx_{min} correspond to the minimum transmit power (at the transmitter) and minimum received power required (at the receiver), respectively (both in dBW or dBm). The total loss suffered by the transmitted signal along the link, T_L, is given by (in dB)

$$T_L = L + (d \times F_L), \tag{24}$$

where L stands for the losses in optical connectors (in dB), d denotes the link distance, and F_L corresponds to the normalized fiber loss (in dB per units of distance) — typical values for these parameters can be found in the related literature [8]. Finally, an FO link is assumed to be feasible if the FO link margin, i.e., $L_B - T_L$, is greater than a user-specified minimum accepted link margin (e.g., 3 dB), and if the link bit rate $\times$ distance product (i.e., the required bit rate times the link length) does not exceed the maximum bit rate $\times$ distance product of the fiber [9].

0.2. Link Costs Analysis

When planning a link, the costs associated with the project will always go beyond the costs of the equipment itself — it is important to mention that when referring to the equipment of a certain technology (MRT, FSO or FO), it includes all the necessary items for installing and operating the respective link. In particular, two different types of costs have to be considered in the scope of these projects:

- Capital Expenditures (CAPEX) — these include the fixed costs related with the network infrastructure, such as equipment and respective deployment, spare parts, and project studies. With respect to wireless technologies, one has to consider emitter and receiver costs, as well as the costs of cables, stands and, in the case of FSO systems, an auto-tracker that allows the receptor to align with the received signal (in order to reduce the impact of atmospheric turbulence). Moreover, the costs associated to CAPEX for MRT and FSO technologies do not depend on the link distance (if no repeaters are considered), unlike FO links. Accordingly, CAPEX related to FO systems can be divided into a fixed term, which accounts for Optical Line Terminations (OLTs), Optical Network Units (ONUs) and other miscellaneous electronics, plus a variable term that

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[2] Quadrature Amplitude Modulation

corresponds to the costs of the fiber itself and the costs of deploying it, which varies with the length of the link, d.

- Operational Expenditures (OPEX) — these do not contribute to the infrastructure itself, since they include operational expenses, such as maintenance costs, energy consumption, government taxes, and repayments. Accordingly, any economical analysis regarding OPEX is usually performed taking into account the lifetime of the communication link — e.g., a period of 10 years.

After gathering the values for both CAPEX and $\text{OPEX}_{\text{lifetime}}$ (for a given lifetime) regarding the use of a certain equipment, the total costs of the link project are given by the summation of these values, i.e.,

$$\text{Total Costs} = \text{CAPEX} + \text{OPEX}_{\text{lifetime}}. \tag{25}$$

It is also important to mention that MRT systems operate in licensed frequency bands, hence individual MRT systems are subject to license (on a case-by-case basis to avoid interference between adjacent systems) by the respective national regulatory authority for communications, which normally entails the payment of an annual fee (an operational cost that is usually square-root dependent on the link length) [10,11]. Based on what was previously mentioned, the total costs depend on the link length in the case of MRT and FO systems, whereas the total costs can be regarded as a fixed value (i.e., independent of the link length) for FSO systems; thus, expression (25) can be rewritten with respect to the different technologies as

$$\text{Total Costs}^{(\text{MRT})} = \text{F.Costs}^{(\text{MRT})} + \text{V.Costs}^{(\text{MRT})} \times \sqrt{d}, \tag{26}$$

$$\text{Total Costs}^{(\text{FSO})} = \text{F.Costs}^{(\text{FSO})}, \tag{27}$$

$$\text{Total Costs}^{(\text{FO})} = \text{F.Costs}^{(\text{FO})} + \text{V.Costs}^{(\text{FO})} \times d, \tag{28}$$

where F.Costs and V.Costs stand for fixed costs and variable costs, respectively, with respect to the associated technology (MRT, FSO or FO) — please note that these costs (i.e., $\text{F.Costs}^{(\text{MRT})}$, $\text{F.Costs}^{(\text{FSO})}$, $\text{F.Costs}^{(\text{FO})}$, $\text{V.Costs}^{(\text{MRT})}$, and $\text{V.Costs}^{(\text{FO})}$) also represent user-specified inputs of the Link Design Algorithm.

0.3. Link Design Algorithm Workflow

Figure 1 depicts the flowchart of the Link Design Algorithm. The first step is to read and store the information contained in the “MRT.dat”, “FSO.dat” and “FO.dat” files. These “.dat” files are text files that contain data about the user-specified equipment being tested, as well as about the respective associated costs — in general, these necessary inputs are provided by the equipment manufacturers and, concerning costs, by taking into account the CAPEX and OPEX items listed in the previous section. The user can test and compare, at the same time, as many different equipment as desired, as the algorithm is able to process a variable amount of equipment — in this manner, the user can, for example, test and compare different solutions from different providers in a single run of the algorithm. More specifically, each line of the “.dat" file associated to the respective communication technology (MRT, FSO and FO) corresponds to a different equipment of that technology. The structure of each line of these “.dat” files, namely the required inputs for each communication technology equipment (which should be separated by commas), is given in Table 1, where ID refers to the identifier (number or word) of an equipment, B stands for the maximum bit rate that an equipment can offer for the specified inputs, whereas BxD corresponds to the maximum bit rate $\times$ distance product of an optical fiber.

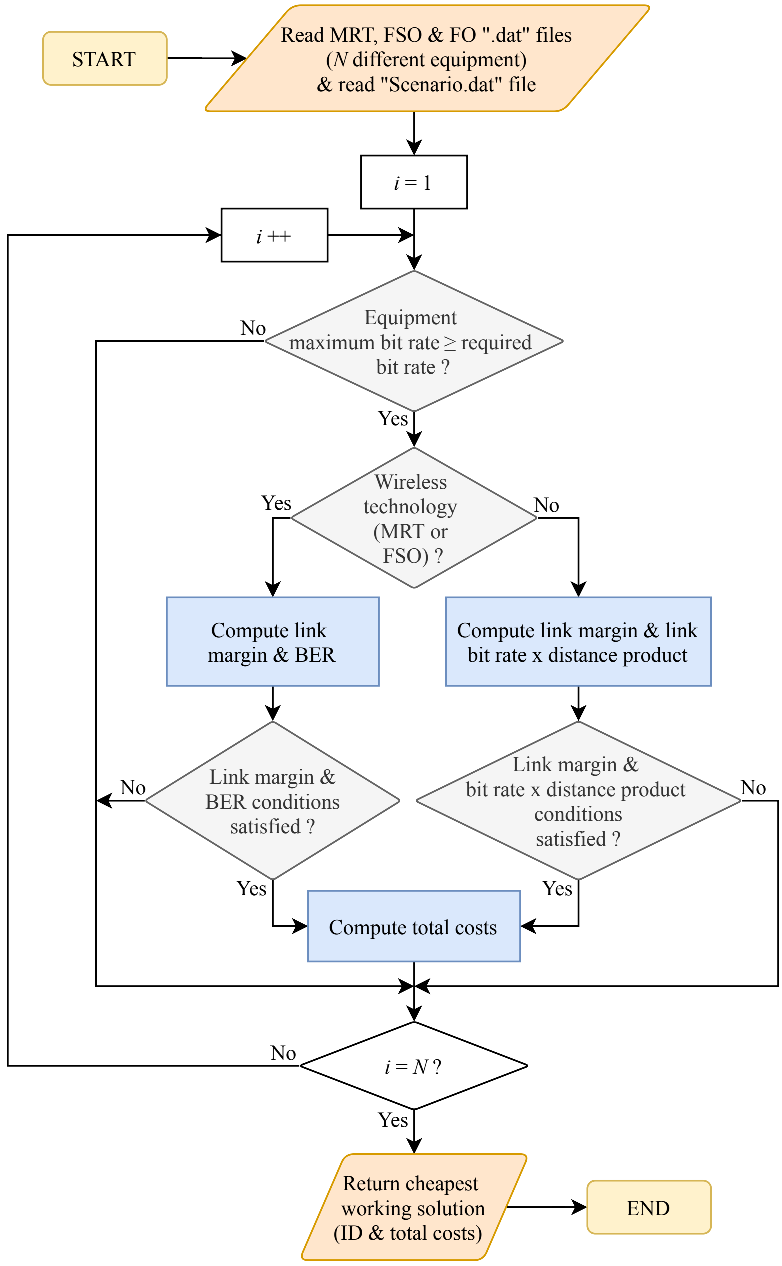

Figure 1. Flowchart of the Link Design Algorithm.

Table 1. Required inputs for the "MRT.dat", "FSO.dat" and "FO.dat" files.

MRT .dat	ID	B [Mbps]	f [GHz]	P_{Tx} [dBW]	G_{Tx} [dBi]	G_{Rx} [dBi]	A_{equi} [dB]	S_{Rx} [dBW]	N_f [dB]	M [M-QAM]	F.Costs$^{(MRT)}$ [¤]	V.Costs$^{(MRT)}$ [¤/$\sqrt{\text{km}}$]

FSO .dat	ID	B [Mbps]	λ [nm]	P_{Tx} [dBW]	G_{Tx} [dBi]	G_{Rx} [dBi]	A_{equi} [dB]	S_{Rx} [dBW]	F.Costs$^{(FSO)}$ [¤]

FO .dat	ID	B [Mbps]	BxD [Mbps·km]	Tx_{min} [dBW]	Rx_{min} [dBW]	L [dB]	F_L [dB/km]	F.Costs$^{(FO)}$ [¤]	V.Costs$^{(FO)}$ [¤/km]

In addition, the user must provide data (such as link length, required bit rate and climate information) regarding the link deployment scenario. This information is given in the "Scenario.dat" text file and follows a line structure (separated by commas), where the required inputs are indicated in Table 2 — these correspond respectively to link length (d), required bit rate (B_{min}), maximum percentage of the time regarding tolerated link unavailability (U_{max}), temperature (T), rain intensity not exceeded in 0.01% of the time ($R_i^{(0.01\%)}$), relative humidity (H), transmitter altitude (h_a), height difference between the top of an obstacle and the line-of-sight (h_{obs}), average number of foggy days ($\overline{N_{fog}}$), average duration of fog events ($\overline{D}$), and minimum accepted link margins for MRT, FSO and FO links ($Ml_{min}^{(\mathrm{MRT})}$, $Ml_{min}^{(\mathrm{FSO})}$ and $Ml_{min}^{(\mathrm{FO})}$, respectively).

Table 2. Required inputs for the "Scenario.dat" file.

Scenario.dat	d [km]	B_{min} [Mbps]	U_{max} [%]	T [°C]	$R_i^{(0.01\%)}$ [mm/h]	H [%]	h_a [m]	h_{obs} [m]	$\overline{N_{fog}}$ [days/year]	$\overline{D}$ [h]	$Ml_{min}^{(\mathrm{MRT})}$ [dB]	$Ml_{min}^{(\mathrm{FSO})}$ [dB]	$Ml_{min}^{(\mathrm{FO})}$ [dB]

From here, the algorithm becomes independent from the user. It will go through all the N different user-specified equipment and, for each one, the algorithm first checks if the required bit rate of the link is met by the equipment; if that condition is satisfied, then it is evaluated if the link is feasible with that equipment (taking into account the communication technologies models) — in other words, if the required link distance is shown to be too long to be accommodated in a single-hop by the equipment that is under consideration in each iteration, then that equipment is ignored in the remaining analysis. Finally, the algorithm returns the cheapest working solution (taking into account the link costs analysis), namely the respective equipment ID and total costs. Please note that if none of the N different user-specified equipment meet the link requirements, then the algorithm returns (positive) infinity for the total costs and no ID.

1. Network Planning Algorithm

The Network Planning Algorithm has the goal of finding the optimal number of BBUs to be deployed for a certain environment, and where to place them, given the positions of the RRHs and their bit rate needs. Using the previously described Link Design Algorithm and considering the costs associated with a BBU, this algorithm is able to compute fronthaul topologies that minimize the total costs of the network.

The following subsection details the Network Planning Algorithm, namely the considered economic aspects and the algorithm workflow.

1.1. Network Costs Analysis

With respect to the total costs of the network, there are two main aspects to take into consideration: the costs of each RRH–BBU link and the costs of a BBU. Accordingly, the network total costs are given by the sum of the global costs of the RRH–BBU links plus the costs of the total number of BBUs used in the network.

The costs of each RRH–BBU link can be obtained with the Link Design Algorithm. It is important to notice that when dealing with the acquisition of equipment, as is the case when designing the fronthaul network, some vendors might be able to provide substantial discounts on their prices for purchases involving larger amounts of equipment. Accordingly, these discounts could make one technology preferable to another, cost-wise. Nevertheless, even though this is an important consideration, it is extremely difficult to quantify these discounts as constraints within the algorithm in a universal manner. Therefore, it will be assumed that the unitary price of the equipment remains unaltered for large quantities, which means that the global costs of the RRH–BBU links considered by the Network Planning Algorithm can be regarded as an upper limit for this type of costs — nonetheless, please bear in mind that since the source code of this algorithm is freely available online, it can be modified by anyone, namely by a system designer, in order to incorporate other features such as particular costs computations according to specific terms of the vendors.

It is worth to point out that when deciding to add or remove a BBU from the network, the BBU costs play a major role when determining the total costs of the network. More specifically, if the BBU costs were considered negligible, the optimal solution (although unrealistic) would be given by the total number of BBUs equaling the number of RRHs, with colocated placements, as this would mean close to zero distances between the RRHs and the corresponding BBU, thus yielding the minimum possible costs regarding RRH–BBU links. Accordingly, one of the virtues of the Network Planning Algorithm is that the BBU costs are not disregarded when determining the optimal number of BBUs to be deployed for a certain environment.

1.2. Network Planning Algorithm Workflow

Figure 2 depicts the flowchart of the Network Planning Algorithm. The first step is to read and store the information contained in the "RRH.dat" file, which is a text file that contains (in each line and separated by commas) the cartesian coordinates (X, Y) of the RRHs under consideration, along with the required bit rate for each RRH — Table 3 presents the structure of each line regarding the "RRH.dat" file. In addition, the user must provide data regarding the BBUs in the "BBU.dat" text file; once more, a line structure is followed (separated by commas), where the required inputs are the ones indicated in Table 4 — these correspond respectively to maximum number of RRHs supported by a BBU ($RRHs_{max}$), maximum bit rate supported by a BBU for each RRH–BBU link (B_{max}), costs of a BBU (Costs_{BBU}), minimum and maximum number of BBUs to be considered in the analysis (min_BBU and max_BBU, respectively), and number of different initializations regarding the network costs optimization procedure (D_{init}).

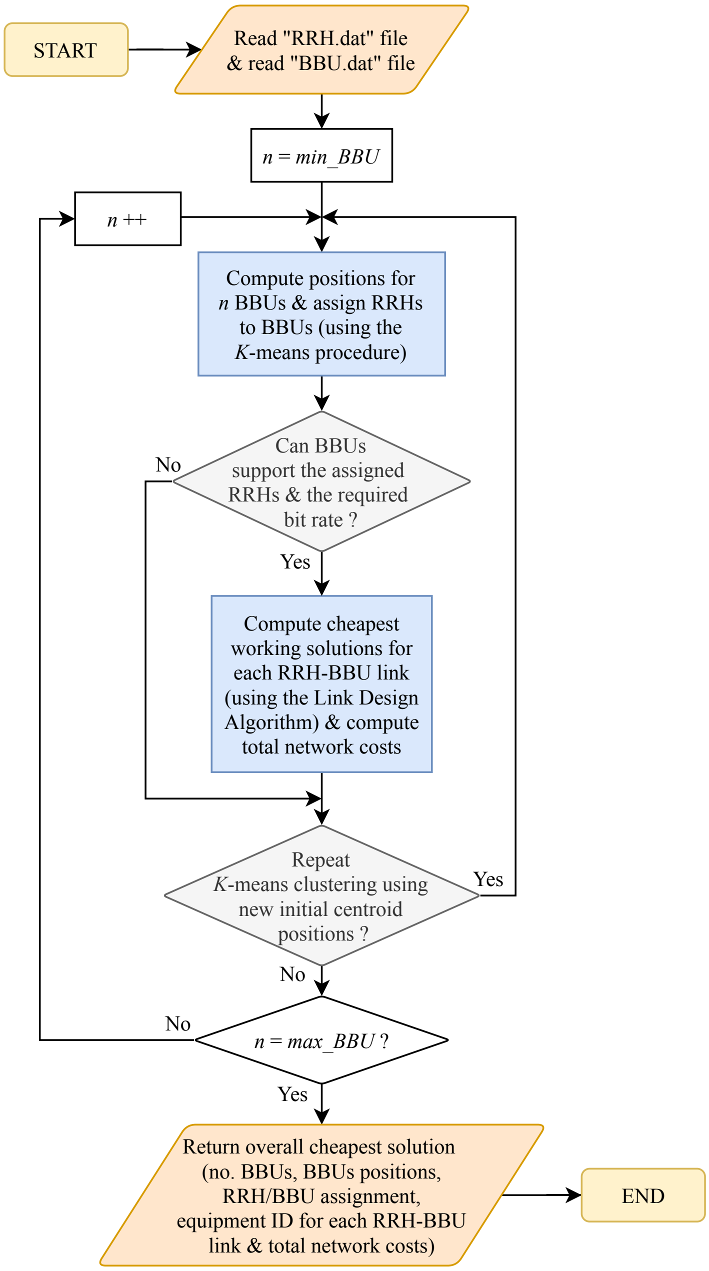

Figure 2. Flowchart of the Network Planning Algorithm.

Table 3. Required inputs for the "RRH.dat" file.

RRH.dat	X [m]	Y [m]	B_{min} [Mbps]

Table 4. Required inputs for the "BBU.dat" file.

BBU.dat	$RRHs_{max}$	B_{max} [Mbps]	Costs_{BBU} [¤]	min_BBU	max_BBU	D_{init}

Afterwards, and given the starting number of BBUs (min_BBU), the algorithm computes the positions of the BBUs. This step, combined with the assignment of each RRH to a BBU (where multiple RRHs can be connected to a single BBU), can be regarded as solving a clustering problem. Since smaller RRH–BBU link distances not only increase the likelihood of adopting single-hop wireless communication technologies (which are simpler to install), but also lead to cheaper FO links, as well as lower fronthaul latencies can be achieved, the adopted criterium for clustering is based on minimizing the distances between RRHs and BBUs. Accordingly, and by applying the K-means clustering algorithm (as suggested in [12]), the positions of the BBUs are determined. More specifically, the K-means procedure groups the RRHs into K different subsets, where K equals the considered number of BBUs (hence $K \leq$ RRHs), by minimizing the sum of squared distances between the RRHs belonging to a cluster and the corresponding cluster centroid, i.e., the associated BBU position.

Next, the algorithm verifies if the BBUs can support the number of RRHs assigned to each one of them, as well as the required bit rate of each RRH–BBU link; if this is the case, then the Link Design Algorithm is used to determine the cheapest working solution satisfying each RRH–BBU link requirements (such as link distance and required bit rate) for the deployment scenario (the scenario characteristics, except link distance and required bit rate, are extracted from the "Scenario.dat" file) — cf. Section 0.1. Subsequently, the total costs of the network are computed taking into account the network costs analysis, i.e., by summing up the costs of all RRH–BBU links and the costs of the considered number of BBUs.

Noticing that the K-means approach is an iterative algorithm that relies on an initial random choice of centroid positions, this procedure may yield different clustering results on different runs of the algorithm, which, in turn, may lead to different network costs — note that there are $K^{N(RRHs)}$ ways to partition N RRHs into K clusters. Therefore, the previous two steps (computation of BBUs positions and determination of the total costs of the network) are repeated multiple times — namely a total of D_{init} times, which is a user-specified value that ideally should be close to $K^{N(RRHs)}$, although this number may be too time consuming to be practical — in order to search for the cheapest network topology regarding the number of BBUs that is under consideration (e.g., min_BBU).

The Network Planning Algorithm then computes again the total costs of the network, but now considering a different number of BBUs, in order to find the cheapest alternative. More specifically, the procedure is repeated, sequentially, from the minimum (min_BBU) to the maximum number of BBUs (max_BBU) defined by the user, and the algorithm will finally return which number of BBUs yields the overall cheapest solution along with other outputs: BBUs positions, RRHs assigned to each BBU, equipment ID for each RRH–BBU link, and total network costs.

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