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Article

Fixed Wireless Access in Flexible Environment: Problem Definition and Feasibility Check

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Abstract

This paper presents a problem definition and feasibility check for an algorithm to select a connection point in an existing fiber-optical access network topology that can be used to connect a new site, the planned location, via an *E*-band millimeter-wave radio link. The newly added fixed wireless access connections must meet end-to-end network requirements for availability, latency, and bandwidth. To accommodate highly dynamic service traffic patterns, requirements are defined with a suitable time granularity. Similarly, dynamic changes in available network capacity affect end-to-end availability, latency, and bandwidth. The proposed algorithm is designed to handle these dynamic changes both in the service requirements and in the available resources.

Keywords: availability; dynamic load; FWA; latency; network topology

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1. Introduction

Fixed Wireless Access (FWA) is commonly used as an alternative for wireline connections in the last mile [1]. The concept has existed for some time, known as integrated Fiber–Wireless (FiWi) broadband access network [2], hybrid Wireless–Optical Broadband Access Network (WOBAN), or broadband wireless access (BWA) [3,4].

Earlier, FWA was mainly considered an undesirable, inferior substitute. In developed countries, wired subscriber access can take years to materialize in certain locations [5], while in emerging countries, fixed broadband is not yet widespread. However, utilizing 5G New Radio (NR) in the millimeter wavelength bands enables the delivery of high-speed broadband services comparable to fixed (copper or fiber) connections.

Accordingly, one of the earliest utilizations of 5G is FWA, which promises to deliver Gigabit internet speeds. To permanently substitute wireline connection in the last mile (both for enterprises and for residential communities), FWA must provide the same (or better) connectivity not only from bandwidth, but from availability perspective as well [6]. Furthermore, FWA can often be brought to homes/businesses for a fraction of the cost of installing a wired connection. Finally, deploying FWA may improve latency (beeline radio hop instead of a meandering optical cable path).

When wired solutions are unavailable, point-to-point radio access (FWA) from/to the existing backhaul network offers a rapid solution [1,6]. Existing methods for designing wireless connections usually focus on achieving the desired throughput and availability for the new radio link only, without considering end-to-end (e2e) availability, throughput, and latency [7]. (For the wireless part, several radio-link planning tools exist e.g., PathLoss [8] and Comsearch IQ-Link [9]). However, no algorithm currently addresses the problem of providing broadband access at a specific location, ensuring that e2e throughput, availability, and latency requirements are met for connections to a data center or to the internet in general, all within a constrained timeframe. In the era of 5/6G networks, the traffic of the specific location is expected to comprise multiple services with diverse requirements. At the same time, the load handled by the existing infrastructure continuously fluctuates. Although selecting the closest connection point in the existing nearby optical network is often the best approach, this lacks algorithmic rigor, and numerous scenarios exist where this approach fails [10,11]. Several factors can prevent the selection of the closest optical point, including:

- Local power supply conditions (e.g., lack of a battery backup unit) may immediately degrade the availability of the traffic running through that connection point below the necessary requirement of service;
- Latency from the closest connection point may not be the best e2e;
- Optical connection could provide the required availability and latency, but all Gbit Ethernet ports may be allocated already (costly hardware upgrade required);
- Expected Line-of-Sight (LoS) problems (e.g., new building or growing trees) may be foreseen at the site of the closest connection point;
- Radio-frequency interference or frequency permitting problems (e.g., high/low sub-band conflict of radio transceivers) may occur.

A single radio link may be insufficient to serve all the service traffic at the new planned location. In these complex scenarios, a potential solution is to assign the traffic of different services to different links. For this problem, a complex search algorithm is needed. This paper presents a rigorous problem description, defining both existing network load and expected traffic at the new site. It also includes a feasibility check of potential connection points. A feasible connection point is defined as one where a radio link can serve all new service traffic and the existing network can handle that traffic to its destination (or from its source). The feasibility check may also identify cases where planned traffic cannot be served, such as when all potential connection points fail to meet latency requirements. The feasibility check can be followed by a search algorithm to find an optimal solution, considering the use of multiple connection points.

This paper is structured as follows: Section 2 introduces the related work; Section 3 defines our assumptions and the input parameters of the problem; Sections 4 and 5 present the proposed feasibility check and an example; Section 6 provides details of the radio-link dimensioning and simulation; and finally, Section 7 concludes the paper and summarizes the planned continuation of the current work.

2. Related Work

The work reported in [3] describes the availability of routes in hybrid networks but does not provide the overall availability of a connection considering possible failover alternatives, no system-level availability provided. While the authors of [10] calculate combined wired–wireless availability, the calculation is limited to primary and secondary paths only, in addition to assuming no redundancy in the wired network. Several research papers discuss the availability of wireless radio and wireless optical links [11–14]. The WOBAN paper [15] considers the availability of wireless mesh networks and studies multipath routing as well. In contrast to these works, the present study considers dynamicity and even the concept of software defined networking (SDN) [16]: the available resources may change in the existing network and the traffic added can be dynamic consisting of multiple streams.

Recent papers and actual network deployments have shown that fixed radio links operating in *E*-band (71–86 GHz) [17] can reach 'fiber-like' throughputs of 10 Gbps and even beyond. Available wide radio-frequency (RF) bandwidths combined with new technologies (e.g., dual-band and cross-polarization links, adaptive code rates using Quadrature Amplitude Modulation (*n*-QAM), Automatic Transmit Power Control (ATPC) and error correction coding) make even 20 Gbps throughputs available for short links [6,7,18]. There is already intensive research in the domain of sub-THz radio communication [19,20]. As *E*-band is used more and more frequently, it is expected that with the launch of 6G this band may also become saturated. Additional wireless communication alternatives are also required. Perspective wireless candidates are in the radio *D*-band (130–175 GHz) and free space optics (FSO) [19–25]. Note that the term bandwidth refers to the spectrum that a signal occupies at radio frequencies (in MHz), and at the same time also often used for the maximum amount of data transmitted (in Mbps) in networks over a digital connection. To avoid confusion, for the rest of the paper the term throughput will be used for bandwidth in networks.

Finally, we mention that several microwave planning tools exist, e.g., PathLoss, IQ-Link, Aircom/Asset [8,9,26]; they are limited to radio link design, typically calculating frequencies up to the *E*-band only; *D*-band is discussed only in research papers [20–23]. In general, radio planning tools do not support e2e availability calculation for meshed networks including FSO and fiber-optical sections. Excellent optical design tools exist (e.g., Optiwave/OptiSystem, Synopsys/OptSim, etc., [27,28]), but they lack radio link calculation capabilities. Generic optical system design tools support mainly power budget calculations and geographic visualization for fiber-optical networks, such as PON (Passive Optical Network) or FTTH (Fiber-to-the-Home) systems. Furthermore, optical software tools focus mainly on fiber-link design and rarely handle FSO links. Only a few tools can handle both fiber-optic and radio technologies, e.g., Spider (non-commercial tool), Forsk/Atoll [29]. According to the authors' current information, there is no commercially available planning tool that supports combined optical and radio anyhaul planning, including e2e availability calculations and the same time considering dynamic traffic load.

3. Assumptions and Inputs

It is assumed that setting up a direct wired connection to the planned location (PL) is either impossible (e.g., local rules/laws in a "built heritage environment" does not allow cabling), or too expensive (difficult or harsh ground environment), or simply the construction and cabling works would be too expensive and slow (e.g., due to local administrative rules of the authorities). However, since broadband connectivity is available nearby, FWA presents a viable alternative. The dynamically changing traffic in existing networks results in varying resource availability [30–32]. Similarly, the added traffic changes dynamically and includes the traffic of multiple services with diverse requirements and different endpoints to be connected to. It is assumed that these dynamic changes are defined with identical time granularity to enable the traffic design. Finally, it is assumed that SDN control of the network traffic in the existing network is available to enable the dynamically changing traffic conditions [16,33].

The planned algorithm aims to determine the optimal way to provide a FWA for a specific location that meets (i) bandwidth requirements, (ii) e2e availability expectations, and (iii) e2e latency limits. Optionally other requirements can be added, e.g., limit on maintenance cost [34]. A review of related works revealed no existing solution or algorithm that rigorously examines potential connection point option(s) that meet these requirements. The inputs of the proposed algorithm are grouped as follows.

3.1. Parameters of the Planned Location

The parameters for the PL fall into three main groups: geo-location information, radio link parameters, and LoS information. Geo-location information includes proper coordinates, exact ground and building heights at potential antenna locations. Radio link parameters encompass proper rainfall and rain intensity statistics for the geo-location of the PL (see e.g., [7,11,35–37]), possible frequencies (including band, channel raster, and bandwidth of the radio channel) for the radio link(s) [6,17,19,38], and available radio equipment options, such as outdoor unit and antenna sizes (considering construction limitations like wind load), along with the parameters of the transceiver units and their antennas (e.g., transmitted power, receiver threshold level, supported modulation modes, antenna gain for the selected antenna size, see e.g., [18,39–41]). Finally, LoS information is needed for the potential optical access connection points from the PL [11].

3.2. Time Granularity for Traffic Design

Assuming both dynamic service usage and existing dynamic traffic in the network [30–32], the required and available connection parameters are defined for a series of timeslots (e.g., for every hour of the day/week, or even for every 15 min) as provided by the Communications Service Provider (CSP) and service definitions. This granularity must be synchronized in advance. If no timeslots are defined, a single value is used. If timeslots are defined for every 15 min of the week, it is a $4 \times 24 \times 7 = 672$-dimensional vector and requirements must be fulfilled for all 672 timeslots.

3.3. Potential Connection Targets

The set of potential connection targets (CT) is indicated by

$$pCT = \{pCT_1, pCT_2, \ldots, pCT_k\}. \tag{1}$$

This set can include any nearby datacenter (if the host placement for the service is flexible), internet exchange point(s) for general internet connectivity, and the home server of the CSP for telephony services [34,42].

3.4. Service Traffic of the Planned Location

The connectivity requirements can be split to multiple service traffic for different services [30,31]. Let us mark these service traffic as $(st_1, st_2, \ldots, st_m)$. Each service traffic st_i is defined by:

1. the planned connection target(s): as a subset of pCT in timeslot t_j: $pct(i, j)$,
2. the connection parameters between PL and $pct(i, j)$ in timeslot t_j, including
    a. the required throughput, $TP_{PL}(st_i, t_j)$, defined as a quadruple of:
        - guaranteed bitrate for uplink, $GBR_{UL}(i, j)$,
        - guaranteed bitrate for downlink, $GBR_{DL}(i, j)$,
        - maximum bitrate for uplink, $MBR_{UL}(i, j)$, and
        - maximum bitrate for downlink, $MBR_{DL}(i, j)$.

    In general, available throughput meets the requirements if all guaranteed bitrate parameters are fulfilled. The handling of maximum bitrate parameter can be defined by policy (either ignored or considered in an objective function when selecting a radio link if multiple solutions are found). It is assumed that the throughput parameters do not represent average figures but include overhead to serve traffic spikes that may happen as part of normal deviations in traffic. Extreme traffic spikes can be served if capacities are available (without impacting other services) as best effort services, or traffic is dropped/delayed (reducing service availability).

b. the required availability, $A_{\mathrm{PL}}(st_{\mathrm{i}}, t_{\mathrm{j}})$; and
c. the tolerated latency, $L_{\mathrm{PL}}(st_{\mathrm{i}}, t_{\mathrm{j}})$.

3.5. Parameters of the Existing Network

The parameters of the existing network infrastructure are:

1. the set of the potential connection points (CP):

$$pCP = \{pCP_1, pCP_2, \ldots, pCP_{\mathrm{p}}\}. \tag{2}$$

These points are locations (sites) around the PL suitable for a new radio link, with either a direct wired or radio access to the existing network. Unused transmission capacity is assumed available at each point.

2. For each link in the existing network with available throughput (to be assigned to traffic from PL), the following parameters are required: available throughput in each timeslot, link availability, and link latency. Note that these are the parameters used by the SDN controller of the existing network as well.

4. Feasibility Check

The feasibility check comprises three main steps.

Step 1. Identify the feasible neighborhood, i.e., the potential connection points that are technically viable. Details are provided below.

Let A_{max} represent the highest availability, L_{min} the lowest latency, and TP_{max} the maximum throughput required at the PL by any service traffic. Formally:

$$A_{\mathrm{max}} = \max\{A_{\mathrm{PL}}(st_{\mathrm{i}}, t_{\mathrm{j}}) \mid \text{for all } st_{\mathrm{i}} \text{ and for all } t_{\mathrm{j}}\}, \tag{3}$$

$$L_{\mathrm{min}} = \min\{L_{\mathrm{PL}}(st_{\mathrm{i}}, t_{\mathrm{j}}) \mid \text{for all } st_{\mathrm{i}} \text{ and for all } t_{\mathrm{j}}\}, \tag{4}$$

$$TP_{\mathrm{ULmax}} = \max\left\{\sum_{k=1}^{m} GBR_{\mathrm{UL}}(\mathrm{k,j})\middle|\text{for all } t_j\right\}, \tag{5}$$

$$TP_{\mathrm{DLmax}} = \max\left\{\sum_{k=1}^{m} GBR_{\mathrm{DL}}(\mathrm{k,j})\middle|\text{for all } t_j\right\}, \tag{6}$$

$$TP_{\mathrm{max}} = \max(TP_{\mathrm{DLmax}}, TP_{\mathrm{ULmax}}). \tag{7}$$

Note that (7) assumes a symmetric connection for the new radio link (i.e., equal uplink and downlink bandwidths), as typically mandated by local or national regulators (e.g., based on ETSI [38]). Therefore, the required maximum capacity is the maximum of the overall uplink and downlink GBR parameters at any given time. Since these represent the extreme values for e2e connectivity, the radio link itself must offer superior performance (higher availability, lower latency). These values serve as an upper limit for the length of feasible radio links. A link throughput estimation LT_{est} can be calculated for any link length based on the parameters of the available antennas and the rain intensity statistics of the planned location, as shown in Figures 1–3.

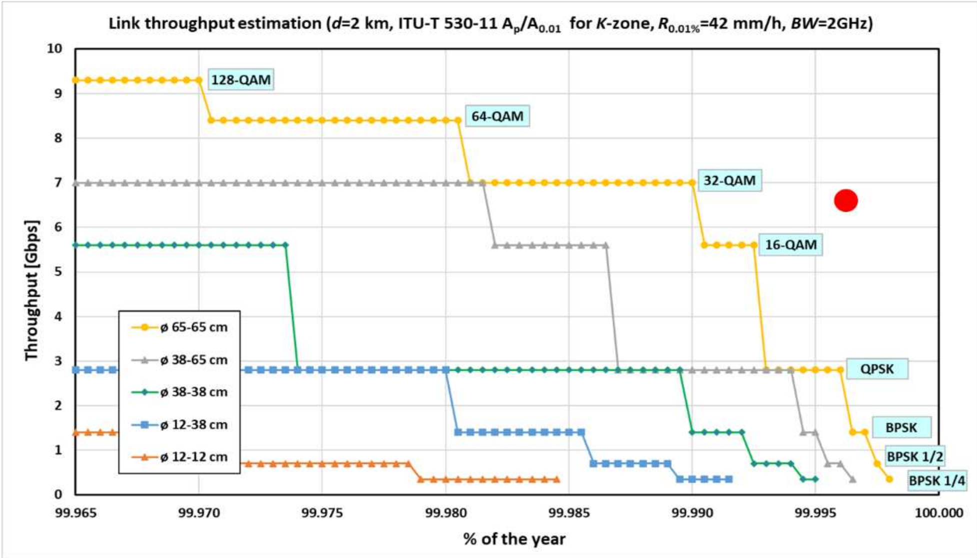


Figure 1. Link throughput estimation, LT_{est}, for 2 km radio hop length.

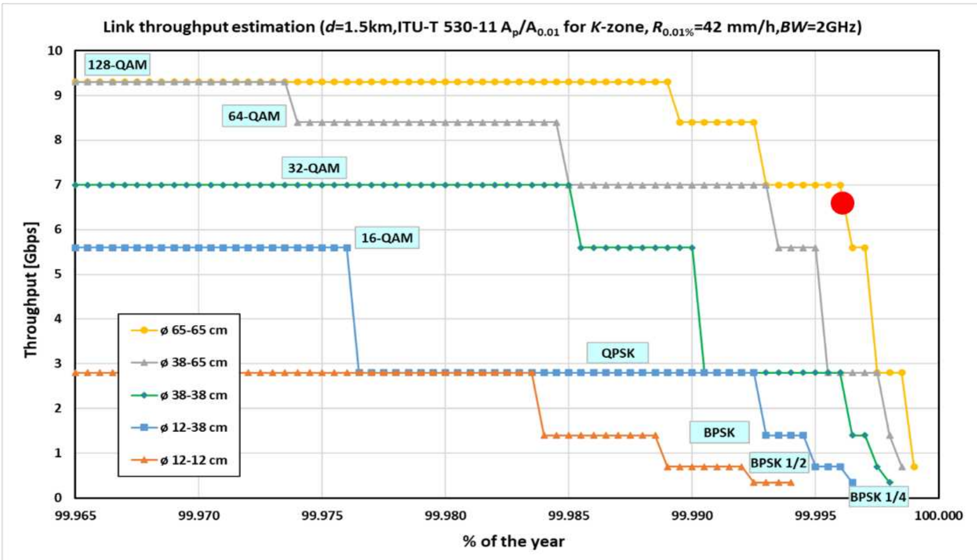


Figure 2. Link throughput estimation, LT_{est}, for 1.5 km radio hop length.

LT_{est} is a function that determines the maximum throughput, $LT_{\text{est}}(d, A)$, achievable for a distance d with availability A. The maximum length, d_{max}, where the link throughput estimation meets the maximum availability and throughput requirement is defined as:

$$LT_{\text{est}}(d_{\text{max}}, A_{\text{max}}) = TP_{\text{max}}. \tag{8}$$

Details of link throughput estimation are provided in Section 6, including throughput simulations for various antenna size combinations (i.e., TX and RX), modulation modes, availability results, and experimental results. Figures 1–3 illustrate this; the red dot represents the availability and throughput requirements. In Figure 1 (d = 2 km), the red dot is beyond the capabilities of the 2 km long radio link; therefore, a 2 km radio link at PL cannot meet availability and throughput requirements. In Figure 2 (d = 1.5 km), the red dot is at the limit of the 1.5 km long radio link's capabilities. While this link fulfills the requirements, it is unlikely to be part of a feasible e2e solution, because the requirements are e2e requirements. (However, if the pCP is the pCT for all services, the 1.5 km radio link should be considered. See Figure 4, which simplifies to a single connection target, but any *pCP* could host a service and thus could be a *pCT*.) In Figure 3 (d = 1 km), the red dot falls within the capabilities of the 1 km link, exceeding the requirements and making it easily part of a feasible e2e solution. Figure 3 also shows that different antenna pairs (e.g., 1- or 2-foot diameters) can satisfy the requirements; larger antennas may provide higher throughput.

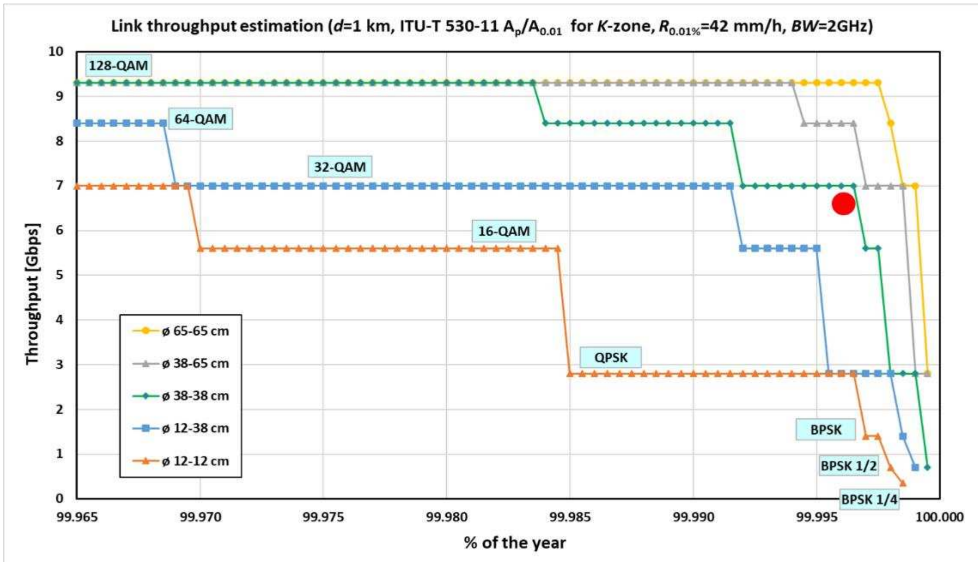


Figure 3. Link throughput estimation, LT_{est}, for 1 km radio hop length.

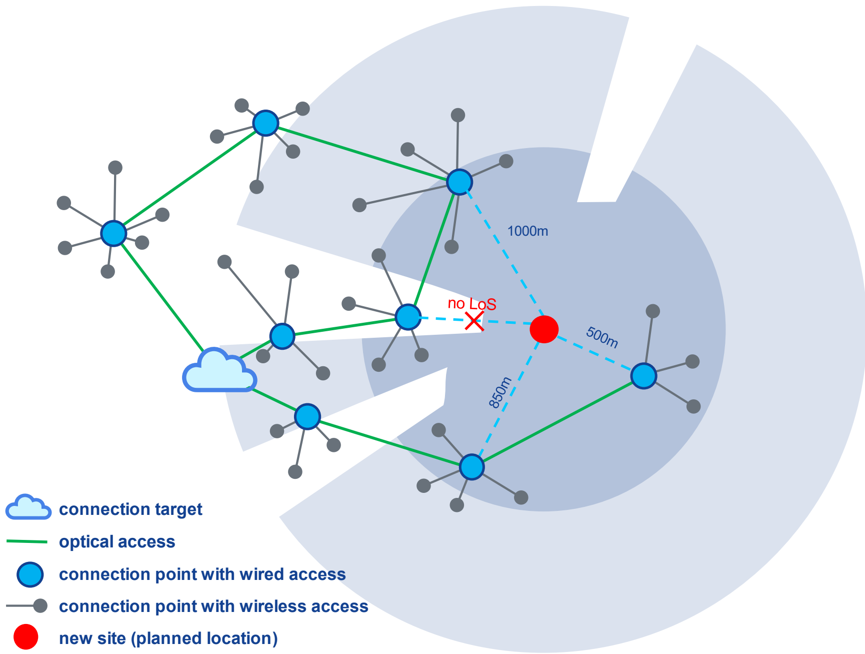


Figure 4. Topology showing the existing network and the search area of the potential connection points, *pCPs*.

Besides combined availability/throughput limitations, more relaxed criteria (e.g., latency only) can be used if a single connection point cannot meet all service connectivity requirements. Figure 4 illustrates these limitations, the darker grey area shows where both availability and throughput requirements can be met for all services. The lighter grey area represents where latency requirements are met. Obstacles in the LoS further reduce these feasible regions.

Step 2. Determine the feasibility of each connection point. These sub-steps (2A–2D) are executed for all *pCP*s. Let us consider pCP_p as an example.

Step 2A. Based on the distance between PL and pCP_p (dist(PL, pCP_p):

Determine the latency of the radio link L_p (timeslot independent), the availability of the radio link for each time slot: if TP(i) is the throughput used in timeslot t_i,

$$TP(\mathrm{i}) = \max\left(\sum_{k=1}^{m} GBR_{\mathrm{UL}}(\mathrm{k},\mathrm{i}),\ \sum_{k=1}^{m} GBR_{\mathrm{DL}}(\mathrm{k},\mathrm{i})\right). \tag{9}$$

then the availability for timeslot t_i is A_p(i), the maximum availability value, where the LT_{est} function is above TP(i).

$$A_p(\mathrm{i}) = \max\{A \mid LT_{est}(\mathrm{dist}(\mathrm{PL}, pCP_p), A) > TP(\mathrm{i})\}. \tag{10}$$

Note that in timeslots where the maximum throughput is lower, the availability is higher.

Step 2B. Use available SDN controller algorithms to determine whether all service traffic (st_1, st_2, . . ., st_m) can be served in all timeslots. To meet e2e service requirements the connection parameters are adjusted: the required throughput remains $TP_{PL}(st_i, t_j)$; the required availability is $A_{PL}(st_i, t_j)/A_p(i)$; and the maximum tolerated latency is $L_{PL}(st_i, t_j) - L_p$.

Step 2C. If there is a feasible solution, then pCP_p is marked as a candidate connection point to set up a FWA connection to serve the PL. The solution found by the SDN controller of the existing network combined with the radio link between pCP_p and PL will meet the connectivity requirements of all service traffic e2e.

Step 2D. If there is no feasible solution, then for pCP_p the algorithm stores what requirements were not met: for which service traffic, at which time interval, and what requirement (throughput and/or availability and/or latency).

Step 3. At this point the feasibility of all *pCP*s is checked.

If multiple candidate connection points are found, then CSP may select one based on:

- cost parameters (not considered in this algorithm),
- the marketability of unused additional capacities at the PL,
- flexibility (e.g., selecting a connection point such that, after introducing the PL load, the minimum of the unused capacities will be maximal), or
- a further search algorithm to check if a lower cost solution with multiple links exists. The single radio link solution provides a cost limit for this search.

If there is no feasible solution, check failed requirements. If a common latency failure occurs for all potential connection points, then no feasible solution exists (even with multiple radio links). If a throughput requirement fails, using multiple radio links to different *pCP*s—assigning different service traffics to different radio links—is advisable. Similarly, failed availability requirements can be addressed with multiple radio links. However, the availability of multiple radio links is a more complex calculation, see the following note. The search algorithm for multiple radio links is beyond the scope of this paper.

The complexity of dual-link solutions arises from the abundance of technical options, including common path (e.g., dual-band, dual- or multiple-channels, dual-polarization radios or combinations thereof); radio links over different paths; and hybrid solutions combining radio with FSO links (again, either via common or different routes). Note that the combined availability of two radio links cannot be simply calculated from the individual availabilities. If the angle between two radio links is small, the probability of intense rain affecting both is much higher than if the angle is near 180 degrees.

5. Planned Location Example

Figure 5 shows a single radio link solution fulfilling stringent latency and throughput requirements through the deployment of a large antenna. The red line indicates the selected solution, meeting all requirements for all served traffic. The shortest (500 m) radio link, while seemingly trivial, would have higher latency due to an extra hop in the optical network (rightmost green line). Therefore, the algorithm did not select it. If availability is not a feasibility constraint, the algorithm can be applied for double radio link deployments.

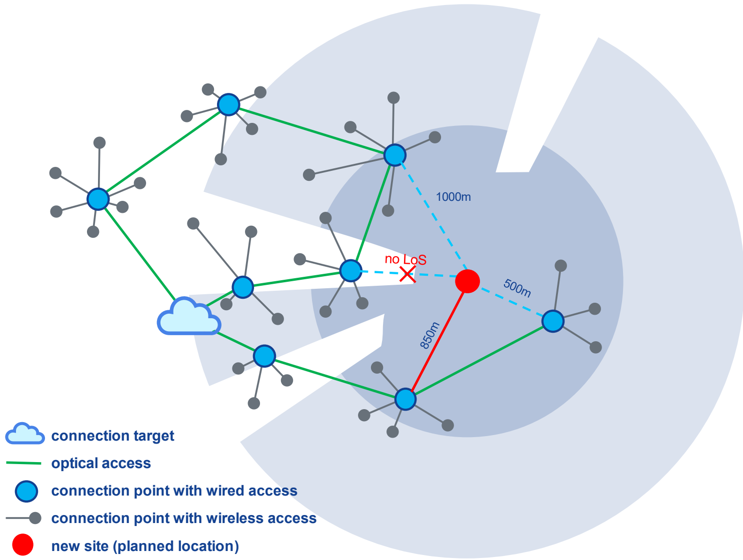


Figure 5. Single radio link solution.

The algorithm does not guarantee a cost-optimal solution. For example, depending on antenna and installation costs, a solution utilizing two smaller antenna pairs might be cheaper than one using a single, larger antenna pair. Consider a scenario where FWA must serve diverse service types simultaneously: one with stringent latency but low throughput requirements, and another needing high throughput but tolerating high latency. Figure 6 illustrates a solution using two radio links: low-throughput, low-latency traffic is sent directly to the *pCT*, while the remaining traffic uses the shortest wireless link.

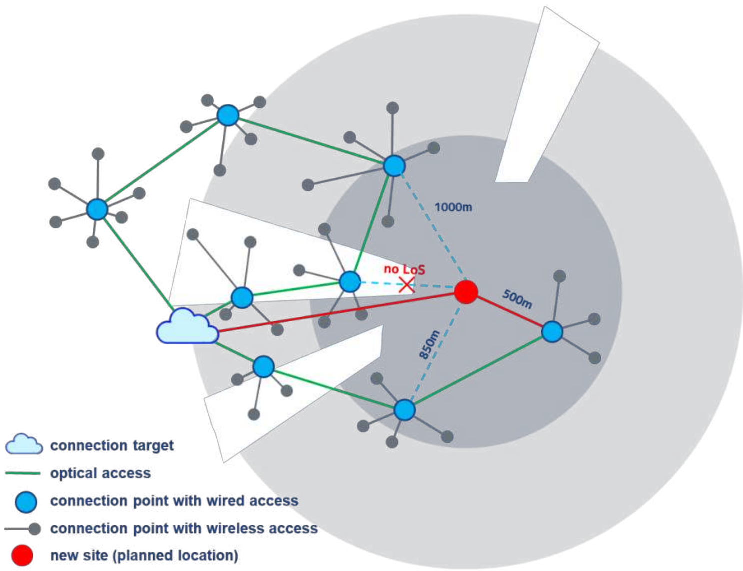


Figure 6. Possible double radio link solution.

6. Radio Throughput Simulations and an Experimental Link

For throughput estimation, it is assumed that advanced microwave and millimeter-wave digital radio links using adaptive modulation are deployed [43–45]. In case of strong fading events, adaptive modulation radios automatically switch to simpler modulation formats. Simpler modulation modes transmit fewer bits per symbol, making them less sensitive to attenuation. Thus, the radio connection remains operational, and transmission is maintained [6]. However, when fewer symbols are transmitted, the digital throughput is reduced to lower bitrates [7,46]. The main factors causing fading in the radio link are intensive rainfall, atmospheric attenuation, and obstacle losses [47–50]. When FWA links are designed, it is not sufficient to know only the maximum capacity of the radio equipment from the technical specifications, it is also necessary to determine the expected link throughput and its availability taking the fading events into account. The applicability of the different modulation modes (resulting in different link throughputs) can be estimated using local meteorological data for the rain intensities and atmospheric attenuation data from ITU-R recommendations [35,47]. Starting with the system gain values (equipment specific for each modulation mode available in the selected RF channel) it is possible to determine the link Fading Margin (FM) values for each modulation mode [11]. The radio link operates at a given modulation mode and throughput, as long as its $FM_{n\text{-mod}}$ is higher than the sum of the link losses [7,14]:

$$FM_{n-\mathrm{mod}}^{[\mathrm{dB}]} > A_{\mathrm{rain}}^{[\mathrm{dB}]} + A_{\mathrm{atm}}^{[\mathrm{dB}]} + A_{\mathrm{obst}}^{[\mathrm{dB}]}, \tag{11}$$

where

$$n\text{-mod} \in \{\text{BPSK } ¼, \text{BPSK } ½, \text{BPSK}, \text{QPSK}, \text{16-QAM}, \text{32-QAM}, \text{64-QAM}, \text{128-QAM}, \text{256-QAM}, \text{512-QAM}, \ldots\}. \tag{12}$$

In (11) and (12), n-mod represents the allowed modulation modes that the radio transceivers can use adaptively. Note that QPSK and 4-QAM are often used interchangeably, while BPSK ½ and BPSK ¼ represent Binary Phase Shift Keying (BPSK) modulation in half and in quarter RF bandwidths, respectively. Narrowing the radio bandwidth (BW) to its half or to its quarter results in 3 dB or 6 dB less noise, respectively, with the same transmit power, thus, the Signal-to-Noise Ratio (SNR) can still be increased, even when using the lowest possible number of symbols (i.e., two). In practical deployments, a clear LoS condition is ensured by proper link design. Therefore, in (11) and (12), obstacle losses can be ignored (or minimized if the antenna is hidden behind a cover or glass window), resulting in $A_{\mathrm{obst}} \cong 0$ dB. The fading margin, $FM_{n\text{-mod}}$, is then determined by the two main factors: rain attenuation (A_{rain}) [35] and atmospheric attenuation (A_{atm}) [47]. For millimetric wavelengths, such as the V-band (57–66 GHz) or E-band, heavy rainfall severely affects transmission quality. In the V-band, atmospheric attenuation can exceed 10 dB/km, enabling denser access networks because mutual interference between links is reduced [25,47]. Rainfall statistics are characteristic for each geographical region [11]. Our simulations used $R_{0.01\%}$ = 42 mm/h, representing the K-rain-zone of ITU-R P.837, where rain intensities can reach or exceed 42 mm/h in 0.01% of the time [35]. The K-rain-zone is typical for Central Europe, including Austria, Hungary, and Slovenia [11,14,37].

The following steps determine link throughput and availability estimations for a specific radio hop length (shown in Figures 1–3 for distances of 2, 1.5, and 1 km):

1. The K-rain-zone of ITU-R P.837 is selected (this simulation method is general and applicable for other rain-zones too). Radio equipment throughputs for a given bandwidth and modulation mode are obtained from technical specifications (see the horizontal dot series in Figures 1–3). Our example calculations use Nokia E-band Wavence adaptive code modulation radio transceivers [18,33] (again, the presented simulation

method is general, and applicable for other digital radios too, e.g., [39]). A 2 GHz RF bandwidth is selected (other bandwidth options are also supported, e.g., 62.5, 125, 250, 500, 750, 1000, 1250 and 1500 MHz). With the 2 GHz bandwidth, modulation modes range from BPSK ¼ to 128-QAM, yielding throughputs from 350 Mbps to 9.3 Gbps.

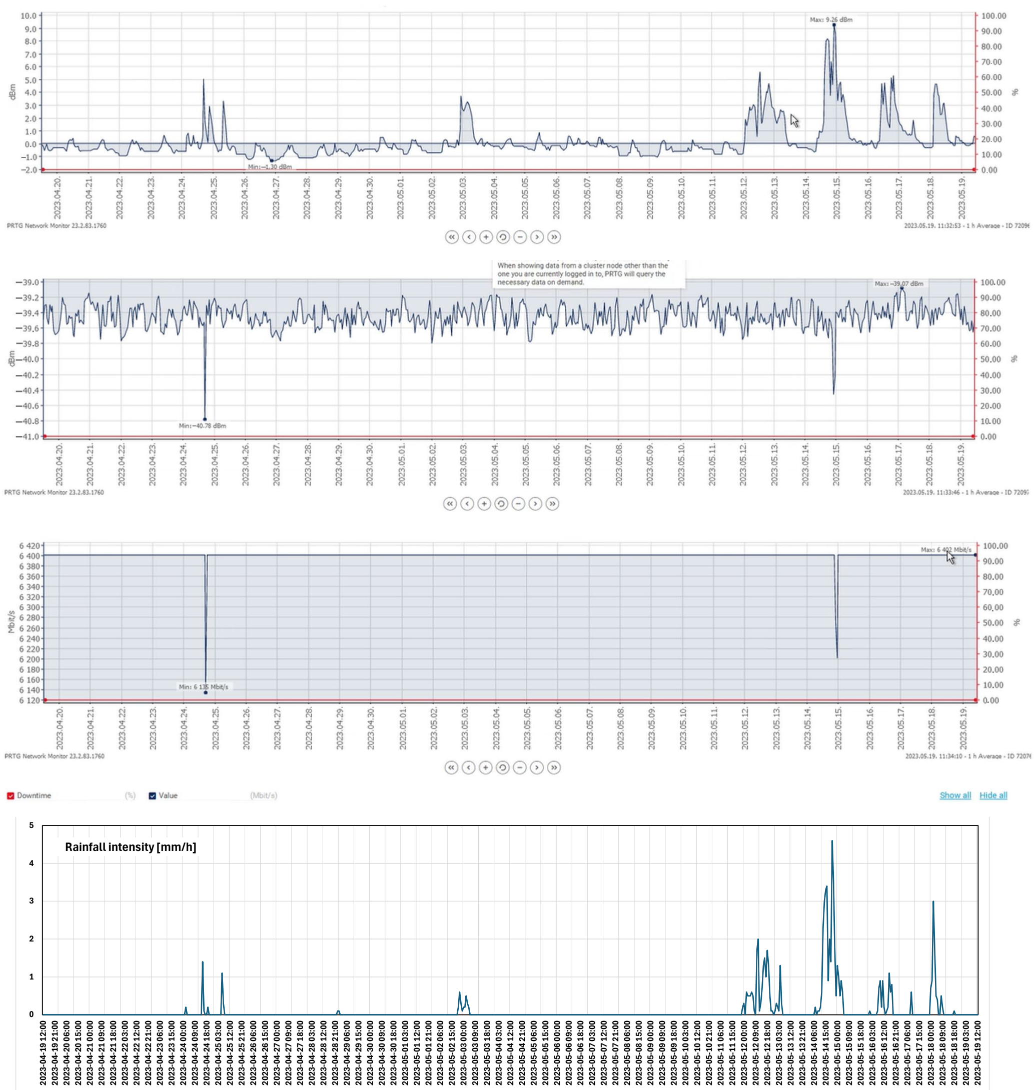
2. Availability for each throughput is calculated iteratively. For a given antenna pair and link length, the simulation begins with the most advanced modulation mode (128-QAM in this example). Using the ITU-R P.837 defined $R_{0.01\%}$, the value $A_{0.01\%}$ (rain attenuation exceeded 0.01% of the time) is calculated [35]. ITU-R P.530 [51] extrapolates this to calculate $A_{p\%}$ (rain attenuation exceeded *p*% of the time). For *E*-band, atmospheric attenuation is not significant (A_{atm} = 0.36 dB/km used). If the FM of the radio link (with selected antenna pair and distance) exceeds these losses, the link operates for more than (100-*p*) % of the time. The availability of the radio link with these antenna size, length, modulation mode parameters is found iteratively, where FM becomes equal to calculated losses.
3. To simulate the switchback to the subsequent simpler modulation mode (if not already at BPSK ¼), the calculation continues using the *p*% value from Step 2. Step 2 is repeated by applying the same iterative method with simpler modulation mode to determine its availability.
4. Repeating this iterative method yields a throughput-availability series for an antenna pair at a specific radio link length. (e.g., the yellow dot series for a 65 cm antenna pair in Figures 1–3). Repeating the above steps for all applicable antenna pairs produces Figures 1–3.

Nokia *E*-band Wavence radio outdoor units feature fiber-optical ports. With single polarization and a single RF channel, these units support baseband throughputs up to 10 Gbps (see Figure 7) [18]. Throughputs exceeding 10 Gbps are achievable by doubling the radio transceivers behind the antenna enabling cross-polarization or RF channel aggregation.

Figure 7. Antenna and *E*-band transceiver with Gbps optical ports.

The experimental verification is based on long-term radio hop measurements. A high fading margin is unnecessary during sunny days. Automatic transmit power control reduces the output power dynamically to avoid unwanted interference in other links and to save energy. When intensive rainfall reduces the Received Signal Level (RSL), ATPC increases the transmitter output power. For instance, during intensive rainfall (Figure 8a), ATPC increased transmitter power from 0 to +5 dBm on April 24th and from 0 to +9 dBm on May 15th. Even with increased output power, the RSL decreased with approximately 1 dB on both rainy days (Figure 8b). Despite the power increase, throughput briefly dropped to

6.14 Gbps and 6.2 Gbps on these days (Figure 8c) [52]. Figure 8d shows systematic rainfall intensity data recorded by a meteorological station 1.8 km away from the transceiver [53,54].



(**a**) (**b**) (**c**) (**d**)

Figure 8. (**a**) Transmit power with automatic transmit power control in [dBm]; (**b**) received signal level in [dBm]; (**c**) measured throughput of an experimental 6 Gbps *E*-band link; (**d**) Rain intensity measured at 'Budapest-Lágymányos' meteorological station.

7. Conclusions

The algorithm guarantees finding a single radio link solution for FWA. The algorithm can also be extended to handle solutions with multiple radio links. This extension is straightforward when different services use separate radio links. Future network design considerations include:

- consider dual polarization, dual RF channel or dual frequency band links to further increase the possible throughput of the wireless radio hop,
- include free space optics (FSO) links or hybrid radio/FSO links [24,25],
- allow potential targets *pCT*s can be either exclusive or inclusive "OR" (e.g., the client (PL) may connect its factory traffic to multiple data centers, e.g., the low latency robotics traffic to one industrial ultra-reliable low-latency communication server and the office workers' traffic to a less reliable communication server at another *pCT* location. Other options are also possible),
- consider the impact of adding multiple PLs simultaneously,

- extend the algorithm to find cost optimal solution,
- support CSP in executing trade-off analysis of cost versus technical requirements (availability, throughput, latency). This is done by allowing the definition of input parameter ranges instead of single values and performing the feasibility check for all input parameter combinations. The topic involves several interacting factors: (i) diverse service traffic, (ii) variable network load, (iii) differing fiber-optical and wireless link characteristics, and (iv) cost-performance trade-offs. The proposed algorithm provides support and an important first step in solving this complex problem.

For large networks the calculations may become computationally intensive. Since these calculations are performed offline during the design phase, the necessary computing resources are available both time- and CPU power-wise. It is also possible to run draft calculations by reducing the granularity (i.e., calculations with longer timeslots). The above improvements are the subject of further research to extend the feasibility check algorithm into a powerful planning tool.

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Abbreviations

The following abbreviations are used in this manuscript:

5G	fifth-generation mobile network (also known as new radio)
6G	sixth-generation mobile network
$A_{\max}$	the highest availability
ATPC	automatic transmit power control
BPSK	binary phase shift keying
BW	bandwidth (radio)
BWA	broadband wireless access
CSP	communication service provider
CP	connection points
CT	connection target
dBm	decibel milliWatt
DL	downlink
e2e	end-to-end
FiWi	fiber-wireless
FSO	free space optics
FTTH	fiber-to-the-home
FWA	fixed wireless access

Gbps	Gigabit per second
GBR	guaranteed bitrate
ITU	International Telecommunication Union
ITU-R	ITU-Radio (sector)
km	kilometer
LoS	line-of-sight
LT	link throughput
LT_{est}	link throughput estimation
m	meter
MBR	maximum bitrate
Mbps	Megabit per second
NR	new radio
PL	planned location
PON	passive optical network
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RF	radio-frequency
RSL	received signal level
SDN	software defined network
SNR	signal-to-noise ratio
TP	throughput (bandwidth in networks, measured in multiples of bit per second)
TP_{max}	the maximum throughput
UL	uplink
WOBAN	wireless-optical broadband access network

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