

# Performance Monitoring and Evaluation of FTTx Networks for 5G Backhauling

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**Abstract** One of the main challenges in today's access networks for 5G base stations (BSs) is the final links (or the last mile) of the network. The links that constitute the main backbone of the network are mostly based on Internet Protocol (IP) / Multi-protocol Label Switching (MPLS) networks with connection over fiber cables. However on the access network side, Mobile Network Operators (MNOs) may also benefit from existing copper lines in addition to fiber and microwave lines. Therefore, developing a 5G deployment strategy to connect BSs that are installed indoor and outdoor locations with these different connection types to the backhaul network, will be important to ensure cost-effective installations. Utilizing Fiber-to-the-x (FTTx) networks that are already installed for broadband connectivity will provide MNOs significant initial investment benefits. In this paper, we have analyzed 5G readiness of the backhaul links of a real infrastructure provider using the proposed evaluation methodology. Our large-scale experimental analysis identifies the problematic sites (where possible solutions and suggestions are also proposed) and determines the suitability of the copper circuits for services that can be provided over the next generation networks. At the end of the paper, we

also discuss the challenges and advantages of utilizing different 5G services when FTTx is used as a backhaul and propose an ordering of the measurable FTTx specific quality parameters according to next generation service deployment scenarios.

**Keywords** Quality of service, FTTx, performance, 5G, deployment, real-time testbed

## 1 Introduction

Mobile Network Operators (MNOs) aim to provide uninterrupted 5G services thanks to the dense deployments of a large number of 5G base stations such as small cell and femtocell devices. However,

TABLE 1  
SYMBOLS USED THROUGHOUT THE PAPER

Nomenclature	
Symbol	Meaning
$N$	Number of tones (subcarrier)
$P_{max},$ $P_{measured}$	Max. transmit power, Measured transmit power for VDSL2
$M_{max},$ $M_{measured}$	Noise margin maximum Measured noise margin
$\alpha_n,$ $\alpha_{max}$	Bit gain at n-th tone, Max. bits per tone
$\Upsilon$	Showtime (in sec.)
$\beta_{actual}$	Actual rate
$\beta_{att}$	Attainable rate
$\gamma_n$	bits carried over n-th tone
$\beta_{target}$	Target data rate
$N_{CO}$	# of analyzed CO
$N_{FTTC}$	# of analyzed FTTC
$N_{FTTB}$	# of analyzed FTTB
$N_{port}$	total # of analyzed ports
$N_{bands}$	# of bands
$N_{Subscribers}$	Total # of subscribers

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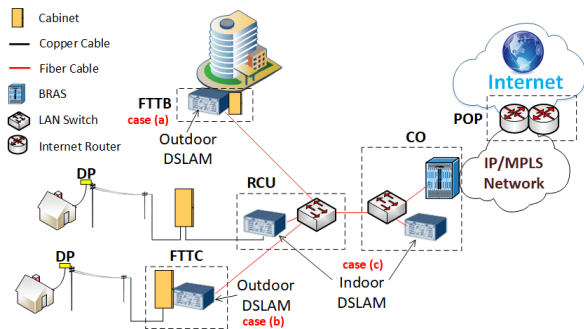


Fig. 1: High level architecture of FTTx deployment scenarios.

together with the spread of 5G services, MNOs are also expected to experience many installation problems. Unlike Long Term Evolution (LTE), 5G requires the installation of new 5G enabled small cell and femtocell devices to provide more robust coverage, especially for mission-critical services. One of the major problems that can be encountered here would be the high capacity backhaul requirement for such a high number of interconnected small cell devices [1]. For normal backhaul connection, the usage of both fiber and microwave are expected. However, for small cells that provide limited capacities and connections, it may seem inappropriate for MNOs to invest on a fiber/microwave backhaul for each small/femto cell locations due to additional capital expenditure (CapEx) and operating expenditure (OpEx) costs [2].

We are entering a new era of communications where cooperation of mobile networks with fixed networks will play a vital role in achieving the benefits of 5G networks and services. Fiber to the x (FTTx) lines that are currently available for broadband services can be an alternative solution for the prospective huge 5G installations [3]. Although copper-based backhaul was the main backhaul technology and initially designed for 2G and 3G networks, the densification of 5G deployment and new enhancements such as vectoring and G.fast [4] constitute a need for the re-usage of this technology. At the same time, there is also a need for robust FTTx lines that can provide very short latency from end-to-end perspective for the establishment of fault tolerant 5G networks. Another notable advantage that can be provided with the use of FTTx lines is that together with the FTTx lines, indoor areas (that are expected to be highly dense in terms of small cell and femtocell deployments) can also be covered thanks to extended coverage [5]. Broadband services that are carried over FTTx lines are not too sensitive to delay. Those networks that are non-problematic from a fixed broadband services perspective may seem inadequate when they are

deployed to provide backhauling to 5G services. Moreover, these FTTx networks were mostly installed a long time ago and may have been affected by many outside effects and may have quality problems. For this reason, it will be necessary to question the quality status of existing FTTx lines and how prepared the existing broadband networks are at the points where 5G services can be provided. In this paper, we study the answer to the question of how dense 5G deployment (that includes many small cells and femtocells) can be achieved using FTTx networks. However, to perform this deployment it is necessary to deduce the current conditions of the already existing network infrastructure. In order to address this issue, we have proposed a new FTTx backhaul evaluation methodology. The proposed methodology consists of four main steps: (i) Evaluation phase (to evaluate the actual required rate increase for each potential port), (ii) test phase, (iii) analysis (to determine Bit Error Rate (BER), Resync rate and line length) phase and (iv) optimization (to identify ports with physical problems) phases. The details of each phase are explained in Section 3.2.

Fig. 1 shows a high level architecture of the FTTx broadband network discussed in this article. As shown in the Fig. 1, the deployment of broadband networks can be made in three different methods. The case (a) of Fig. 1 shows the method called Fiber to the Block (FTTB). In FTTB method, an outdoor Digital Subscriber Line Access Multiplexer (DSLAM) and a cabinet that is providing distribution of copper Digital Subscriber Line (DSL) lines are placed inside the building. There is a fiber connection up to the outdoor DSLAM inside the building of FTTB. The case (b) of Fig. 1 shows the Fiber to the Curb (FTTC) method. The FTTC method includes an outdoor DSLAM just like the FTTB method. However with this method, this outdoor DSLAM is placed into a suitable location around a residential area or on the street in a sheltered location. Additionally, there is a cabinet that provides access of copper lines to the surrounding houses and users. Traffic from FTTB and FTTC is aggregated with a Local Area Network (LAN) switch in an Remote Concentrator Unit (RCU) point and then transmitted to Central Office (CO). RCUs are smaller locations/buildings than COs. RCUs and COs have indoor DSLAMs as shown in case (c) of Fig. 1. Copper cables from the cabinets in the RCU and FTTC are reaching to the Drop Points (DPs) through the posts. Through DPs that are connected to the cabinets, the access line cables reach to the users in the houses or buildings. CO points are equipped with Broadband Remote Access Server (BRAS) devices that provide

and distribute different user broadband services. Finally, internet access is provided through locations called Point of Presence (POP) with internet routers.

### 1.1 Related Work

In the literature, there are some studies that focus especially on the compatibility and possible architectures of FTTx network for 5G backhaul deployments. The increasing role of the FTTx footprint is to connect more residential and enterprise customers and its support for more mobile broadband traffic that eliminates the need to create parallel and dedicated networks for 5G backhaul as detailed in [6]. In the article [7], the infrastructure costs for very fast networks in rural areas for 5G and FTTC are simulated. The article in [8] proposes a novel mobile-over-FTTx network architecture where an FTTx network is enhanced as an integrated rather than a simple backhauling component of a new mobile network delivering low-cost and powerful small cell solutions. The possible technologies and architectural solutions for 5G indoor communications including FTTx networks is explored in [9]. Other studies in [10] and [11] discuss the Fixed-Mobile Convergence (FMC) from the perspective of the operator in which the broadband copper networks are evaluated as the solution for hybrid access. Additionally in [12], the authors adopt a system view of the hybrid DSL and LTE access network and present a framework to perform cooperative downstream resource allocation. The backhaul network capacity and the backhaul energy efficiency of ultra-dense cellular networks are investigated to find the amount of densification for 5G ultra-dense cellular networks in [13]. In other words, considering that 5G installations will be intensive, these aforementioned studies show that FTTx solutions will be a suitable alternative. Therefore, it is important to examine the current performance status of FTTx lines in real MNO networks and analyze their current situations for 5G installations, as discussed in this paper. Although many studies suggest that the use of FTTx would be an alternative to 5G backhaul, there is insufficient information about the current availability of these FTTx networks.

There are also various academic studies that investigate the challenges of using FTTx in 5G backhaul networks. In [14], the authors described a Multiple Input Multiple Output (MIMO) system on copper wires that fills in the missing link between outdoor and indoor wireless stations for 5G wireless cellular systems. The letter in [15] presented a solution by defining an enhanced remote

radio unit architecture for transparent cross-talk mitigation in LTE-over-copper systems which is transparent to baseband processing. The patent in [16] proposes a solution for 5G that converts a radio frequency signal received from a user equipment or indoor radio station to transmit over copper wire pairs so that 5G coverage can be extended for indoor locations. Another patent in [17] is proposing a solution to replace layer-2 switching to provide ultra-high speed in backhaul networks based on different types of connection methods. A backhaul model is demonstrated in [18] using 37 picocells to provide enough bandwidth for cellular in an urban and suburban environment and shows that the fiber and Data Over Cable Service Interface Specification (DOCSIS) are the two most optimal solutions for backhaul in all environments. In the cases where there are different types of backhaul networks such as optical, cable, wireless, etc., an algorithm is presented in [19] that finds the most suitable way for data delivery between the mobile user equipment (UE) and the cells performing computation for this particular UE. In our previous study in [20], we proposed a method and criterion for the migration of the FTTx access lines that will serve better for the value-added services in broadband networks. Ethernet and copper based fronthaul challenges are presented in [21] while focusing on delay and jitters requirements in their experiments and simulation. The article in [22] investigates the downlink of the analog MIMO architecture, in which the overall channel from the baseband unit (BBU) to the end users is made by the cascade of a MIMO cable and a MIMO radio channels. The article in [23] presents the possible swap opportunity between fixed and mobile access and concludes the fixed lines will continue to serve in future as in the focus of this study. The challenges of heterogeneous networks (HetNets) in 5G including FTTx backhaul scenarios and possible solutions are investigated in the survey [24]. Similarly after examining the status of FTTx lines, we also present some recommendations on how MNOs should take precautions in real life scenarios for the enhanced deployment of their 5G networks in this paper.

### 1.2 Main Contributions

While 5G backhauling has been covered extensively in the literature, no prior works exist regarding the methodology and corresponding experiments on determining the status of the existing network infrastructure. Moreover, these studies lack results using real network measurements of fixed and mobile network operators using their telecommunica-

tion infrastructure. However, in many telecommunication companies that are both mobile and fixed operators, it is cost-effective to try to benefit from FMC paradigm. For such operators, the efficient usage of copper circuits is also important for reliable 5G services. Our main contributions in this paper can be summarized as follows:

- We analyze the existing copper circuits of a major fixed operator to determine whether they are suitable for 5G backhauling in terms of service quality and network stability.
- Experimental tests are made on fixed network sites to identify the problematic sites (where possible solutions and mitigation techniques are also proposed) and to determine the suitability of the copper circuits for services provided over the next generation networks.
- An FMC architecture is suggested as an implementation level design that can provide an approach to service operators. The system integration structure and the communication between the Operations Support Systems (OSS) Business Support Systems (BSS) and core networks of both the mobile and fixed networks are also presented.
- An importance ranking of the measured parameters as well as the challenges and advantages of utilizing different 5G services using FTTx as backhaul are also proposed.

In addition to above contributions, the key points of the paper that can be highlighted from our experimental study outcomes are itemized as follows:

- The large-scale experimental results performed in Turkey show that indoor based FTTx equipment (CO DSLAMs) cannot be used to provide all complementary 5G services. They must be swapped with outdoor based equipment to shorten the line length to provide higher bandwidth.
- The results also revealed that only 5G Machine-Type of Communications (MTC) service can be provided nearly in all FTTx locations with the existing infrastructure.
- Measurement result analysis concludes that with only simple changes to be made on the user side (such as on modem and splitter), nearly %30 of the access lines can be repaired to work properly. Hence, end user equipment focused investments will be less costly than repairing the whole lines or making outdoor investments for telecommunication infrastructure providers.

Table 1 provides a list of symbols and their description used throughout the paper. The rest of the paper is organized as follows. Section 2 is

presenting system design and architecture of 5G with FTTx networks. Section 3 is describing the quality parameters used for FTTx and evaluation method for our analysis. Section 4 provides the experimental results. Section 5 presents a discussion on the experimental outcomes and the benefits, limitations and importance ranking of measurable parameters of using FTTx networks as backhaul architectures. Finally, Section 6 gives the conclusions.

## 2 System Model, Concepts & Architecture

### 2.1 Pre-5G Mobile Backhaul Topology & Technologies: Historical Perspective

Since Global System for Mobile (GSM) and Universal Mobile Telecommunications Service (UMTS) both utilize the spectrum in Frequency Division Duplex (FDD) mode hence in backhauling, they required the frequency synchronization signaling to be delivered via High-density bipolar 3 code (HDB3) encoding technique on standard E1 frame [25]. GSM backhaul technology depended mostly on microwave links in star and chain topologies. The usage of fiber started to emerge in UMTS and migration to fibre dominated via High Speed Packet Access (HSPA). LTE and Long Term Evolution Advanced (LTE-A) technologies attracted major investments to fibre, and paved the way to the development of 1GE (10 GE in some cases) fibre connectivity. LTE frequency synchronization in backhaul is achieved by using Institute of Electrical and Electronics Engineers (IEEE) 1588 and Synchronous Ethernet Clocks (SyncE).

5G is also expected to have a major impact on macro-cell backhaul. 5G networks are now starting to be alive in many countries of the world initially supporting Enhanced Mobile Broadband (eMBB) services. As 5G technology usage increases daily, fiber connectivity also needs to be upgraded. Moreover, alternative connectivity options that can also be integrated with fiber connectivity is also of interest. For example during initial 5G deployments, products that can provide fiber connectivity with upgraded access to Dense wavelength division multiplexing (DWDM) via 10GE backhaul are also available [26].

### 2.2 5G Deployment with FTTx Backhaul

A traditional telecommunication architecture includes network nodes, Network Management Server (NMS), OSS (that tracks network inventory) and

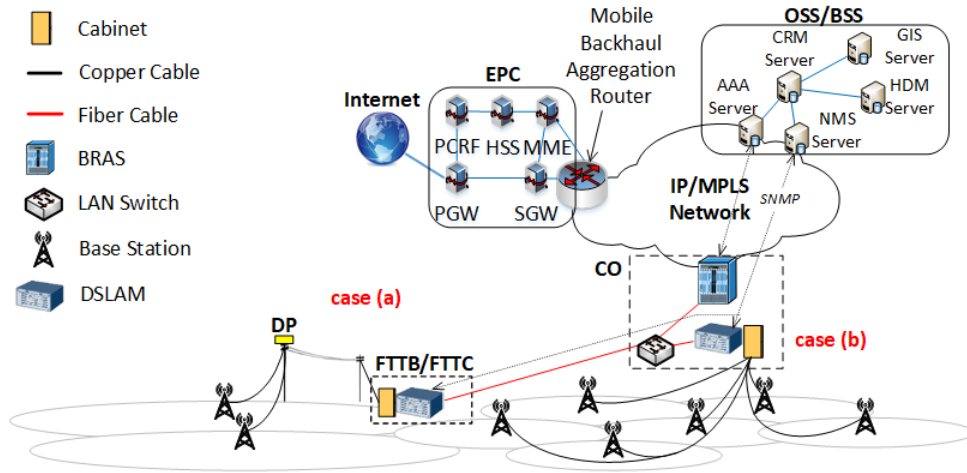


Fig. 2: FMC architecture illustrating FTTx backhaul for dense 5G deployment case (a) Outdoor DSLAM case (b) Indoor DSLAM.

BSS (that deals with customer relationship management (CRM) aspects (taking orders, billing processes, etc)). However, modern architectures are moving towards FMC architecture [11]. We have extended and detailed how the FTTx architecture can be combined with the radio network and core network of the mobile networks, which is different in our proposed architecture. Fig. 2 shows the dense 5G deployment scenario with FTTx backhaul in a FMC architecture with two different deployment scenarios. In the case (a) of Fig. 2, FTTB or FTTC is connected to the base station over DPs with a copper access cable. Note that separate connections on the same physical path are required for each base station and FTTB/FTTC systems are outdoor DSLAMs. The feature of these outdoor devices is that they have relatively less capacity than indoor ones and are more resistant to outdoor conditions. In case (b) of Fig. 2, a separate copper cable is accessed to each base station with an indoor DSLAM located inside the CO building. DSLAMs to which base stations are connected, are aggregated on a BRAS to access the mobile core network. Through authentication and routing operations of the FTTx line over BRAS, they are connected to an Mobile Backhaul Aggregation Router (MBAR) located before the mobile core over the Internet Protocol (IP)/Multiprotocol Label Switching (MPLS) network. There can be layer-2 based tunnelling such as Ethernet pseudo-wire or layer-3 based connection such as Border Gateway Protocol (BGP) or MPLS Virtual Private Network (VPN) between the MBAR and the BRAS.

Different from the fixed broadband network of Fig. 1, this time access to the internet is provided through the mobile core network as shown in Fig.

2. In this deployment, the base stations connected to DSLAMs may need a DSL connection capability (e.g. with a modem or an embedded feature on them) if they are not compatible with the DSL type communication. Although this extra capability brings extra cost for MNO, the generated expense can be negligible besides the profit of using the existing FTTx based backhaul connection which is cheaper than fiber access. Note that the technology type over copper can be Asymmetric digital subscriber line (ADSL), very high speed digital subscriber line (VDSL), G.fast, etc. An important point to be noted in Fig. 2 is that the base station, MBAR and core network equipment belong to an MNO, while LAN switch, BRAS, DSLAM, cabinet and copper lines belong to an Fixed Network Operator (FNO). In the telecommunication operators who have applied FMC, all equipment are expected to belong to that operator. The most important point affecting the service quality in this architecture is actually access FTTx lines that provide communication between DSLAMs and base stations.

In Fig. 2, the communication interfaces between the network elements and the systems used for network and subscriber management are also shown on the upper right hand side. All interactions between the designated servers are done via web services. In this figure, CRM servers (at the top) are generally part of BSS and track billing, subscription application and cancellation processes, status of the subscriber tariffs, etc. The CRM servers are also interacting with NMS servers. During this interaction when the subscriber order is placed, service configuration can be applied to the DSLAM port automatically. After the subscriber application is initialized, the new subscriber configuration

process is transmitted to the NMS server by the CRM server. The NMS server performs the new subscriber definition on a Simple network management protocol (SNMP)-based device. In this way, manual configuration is not performed by FNO and the configurable removal processes are triggered by the CRM server and then deleted from DSLAM. During this time, the CRM server is also interacting with an Authentication, Authorization and Accounting (AAA) server. Subscriber's upstream and downstream quota limits are also configured on DSLAM via NMS based on their tariff information. This profile information is also set on the Broadband Network Gateway (BNG) via AAA. In this way, even if the data rate limitation on the DSLAM is removed by a mistake or a misconfiguration, the subscriber will not obtain a higher data rate than it is configured on the BNG.

The modem configuration information of the subscriber is sent from the CRM server to Home Device Manager (HDM) and configuration information is processed by the Customer-Provided Equipment (CPE) via HDM. Hence, new subscribers and subscribers having an ongoing reboot processing on modem will automatically obtain configuration information. HDM also periodically collects the stored Key Parameter Indicators (KPIs) on the modem. The purpose of the interaction between the CRM server and Geographic Information System (GIS) is to determine the DSL type (ADSL or VDSL) to be given to the subscribers based on the distance when they have new purchase or upgrade demand. This distance value between subscriber building and the nearby FTTx node can be extracted from GIS server in case it is required.

### 3 Quality Parameters and Evaluation Methods

#### 3.1 Quality Parameters

To start data transfer for modems, a control synchronization must first be established between the modem and DSLAM. This synchronization needs to be reestablished due to the occurring problems. These problems can be caused by different factors such as the quality and status of the copper line, DSLAM failure, modem problem, etc. Hence, evaluation of port stability and line rates should be monitored in real time and the port conditions should be gathered and reported constantly. Resynchronization actually means that data transfer is interrupted in each resynch attempt. Therefore, resynch is a parameter that shows the service quality. Mean Time Between Resynch (MTBR) is defined as the mean time between two resynchs and

giving the value of how often the service is interrupted. It can be formulated as

$$MTBR = \frac{\Upsilon}{Resynch}. \quad (1)$$

Note that MTBR value can be measured either from DSLAMs (where KPIs can be extracted per DSL) or directly from the DSL modems themselves. In our experiments, the measurement values are obtained directly from DSLAMs to investigate the performance of the lines using the proposed methodology.

Mean Time Between Errors (MTBE) metric is used to calculate the mean time (in sec.) between two bit errors. The formula between MTBE and BER is defined as below

$$BER = \frac{\Upsilon}{MTBE}. \quad (2)$$

MTBE is generally calculated daily (up to  $60 \times 60 \times 24 = 86400$  seconds). However, there may also be situations when burst errors occur. As an example, let's assume that showtime value  $\Upsilon$  is 86,400 seconds that is a day and burst error occurred in just a few minutes in one day. In this case, the line's MTBE value will appear high. However, this can be misleading. To fix this problem, we can calculate MTBE more frequently by lowering the  $\Upsilon$  values down to 12 or 6 hours. On the other hand, this will increase the computation complexity, network traffic and storage needs which indicates a trade-off between performance improvements and complexity.

ADSL and VDSL are still currently the most widely used technologies. Although they provide services with acceptable rates for end-users, their actual data rates decrease with increased distance between CPE and DSLAMs. The theoretical performance comparisons of the actual rates (Mbps) versus the increasing distance are given in Fig. 3.

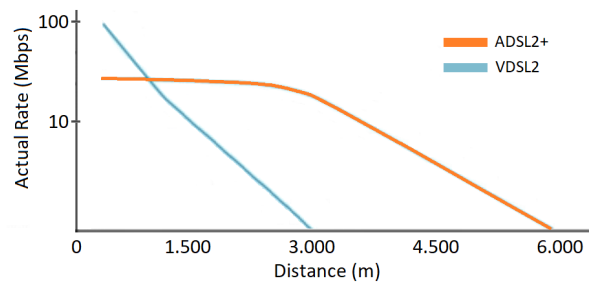


Fig. 3: Comparison of the theoretic performances of VDSL2 and ADSL2+ changing with distance [27].



Note that, as the distance increases more, the number of bits that can be supported on each tone decreases. In Fig. 3, the VDSL signal is getting weaker quickly, while the ADSL signal cannot reach to further distances [27].

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**Algorithm 1:** Calculate attainable line rate.

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**Input:**  $P_{max}$ ,  $P_{measured}$ ,  $M_{measured}$ ,  $M_{target}$ ,  $\beta_{target}$  (target rate),  $\beta_{actual}$  (actual rate)

**Output:**  $\beta_{att}$  (attainable rate)

```

1 foreach  $tone-n$  do
2   // Calculate bitgain  $\alpha_n$  for n-th tone.
   Compute:  $\alpha_n = ((P_{max} - P_{measured}) + (M_{measured} - M_{target})) / N_{bands}$ 
   // Calculate bits  $\gamma_n$  carried over each tone.
3   if  $(\gamma_n + \alpha_n > \alpha_{max})$  then
4      $\gamma_n = \alpha_{max}$ 
5   else
6      $\gamma_n = (\gamma_n + \alpha_n)$ 
   // Calculate attainable line rate  $\beta_{att}$ 
7 if  $(N \times \sum_{i=1}^N \gamma_n > \beta_{actual})$  then
8    $\beta_{att} = N \times \sum_{i=1}^N \gamma_n$ 
9 else
10   $\beta_{att} = \beta_{actual}$ 
   // Compare  $\beta_{att}$  and  $\beta_{target}$ 
11 if  $(\beta_{att} > \beta_{target})$  then
12    $\beta_{att} = \beta_{att}$ 
13 else
14    $\beta_{att} = \beta_{target}$ 
15 return  $\beta_{att}$ ;

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### 3.2 FTTx Backhaul Evaluation Methodology

To evaluate the status of network lines, we have followed the following four steps: Evaluation phase (to evaluate the actual required rate increase for each potential port), test phase, analysis phase (to determine BER, Resync rate and line length), and optimization phase (to identify ports with physical problems).

**Line Evaluations:** In this phase, the actual rate potentials of the ports are evaluated. The outcome of this phase provides an insight on how much the rate of line/port can be increased. This can be used on determining the feasible services that can be accommodated using this line. AAA server in the OSS/BSS system is used at this stage to distinguish which line is running and which subscriber is active. Only one subscriber can be activated on each line. The information about each subscribers' active line (or port) will later be matched with the information received on the HDM server.

Algorithm 1 summarizes the attainable line rate calculation methodology used in the evaluation phase.

TABLE 2  
LINK CONDITION ANALYSIS BASED ON BIT  
ERROR RATIO (USING MTBE) AND  
RESYNCHRONIZATION RATE (USING MTBR).

Link Condition	MTBE (sec)	MTBR (hours)
Stable (Green)	> 1800	>6
Risky (Orange)	600~1800	3~6
Unstable (Red)	< 600	< 3

In steps 1-6 of the algorithm, bit-loading is applied to determine the amount of bits to be transmitted on each tone based on Signal to Noise Ratio (SNR) values. In steps 7-10, attainable line rate is obtained based on the summation of bit gains over all tones and compared with the theoretical actual rate values obtained based on Fig. 3. In this step, the theoretical line length values are collected from GIS server in Fig. 2. In steps 11-14, attainable and target rates are compared and final attainable rate values are returned by the algorithm.

**Line Test:** During this phase, Single-Ended Loop Testing (SELT) or dual-ended loop testing (DELT) testing [28] are performed to test DSL loop either from CO (in SELT case) or at CPE site (in DELT case). SELT test yields information on subscriber lines such as Upstream (US) and Downstream (DS) attainable rates, line length, device IP, name, version etc whereas Double-Ended Line Testing (DELT) test is used to obtain line values during active port period such as line attenuation, transmit power, signal attenuation, noise margin, etc in both US and DS.

**Line Analysis:** In this phase, various analysis such as BER, resync rate and line length are conducted. For the line length analysis, the distance between DSLAM and CPE of the subscriber is calculated using the empirical value. Table 2 shows the link condition criteria values obtained based on the measured MTBE and MTBR values for BER and Resync rate analysis respectively. MTBE and MTBR values are quality KPIs that are observed independent of each other. According to Table 2 if two conditions are satisfied together, then the link condition holds true. Therefore, both MTBE and MTBR conditions should meet simultaneously to define the condition of the link. For example, if MTBE value is greater than 1800 sec. and MTBR value is measured to be greater than 6 hours, the link is considered to be stable. On the other hand, if the MTBE value decreases below 600 seconds and MTBR value is below 3 hours, the link is considered to be unstable and necessary appropriate actions should be taken by the service provider.

**Line Optimization:** This phase is used to identify ports that are unhealthy based on collected

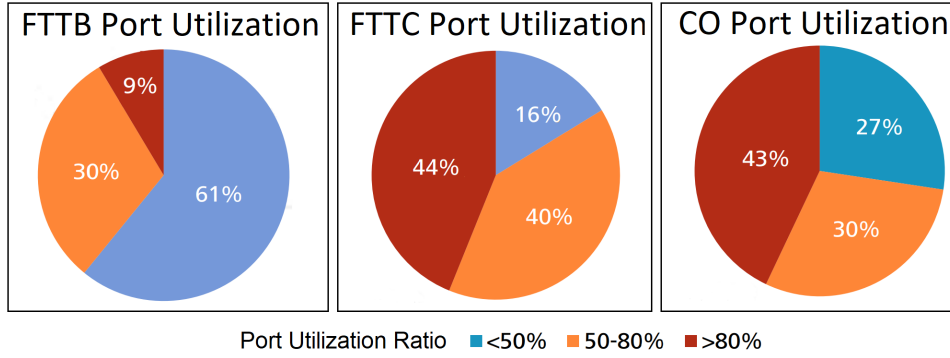


Fig. 4: Percentage of port utilization ratios according to different deployment scenarios over  $N_{port} \approx 4.3$  million.

data statistics and line analysis results. After data collection, optimization is done so that unhealthy and risky lines of subscribers can be stable again after application of appropriate profiles to CPEs by OSS/BSS system of Fig. 2. One of the biggest problems in access lines is the impulse noise that comes from the outer side that can provide very high instant noise instantly. Since the impulse can be very strong at an instant, it can significantly damage the quality of the line. One way of protection is to determine the magnitude of the impulse noise, which can occur by continuously pulling data from the line. Some data types that can be collected from single access line to protect the line are power/ Power Spectral Density (PSD), attenuation, SNR margin, rate/bit loading, delay, bit error or Impulse Noise Protection (INP) (a parameter to measure the length of noise bursts). For example, a line with a 30 dB SNR actually means it is 30 dB impulse resistant to noise. The optimization steps also check whether the pre-defined targets on MTBR, MTBE, rate or latency are met. Other problems that may occur during evaluation of type of noise and density phase may be Radio

Frequency Interference (RFI) or cross talk. Generally, a line is operated with INP or G.INP [29] profiles to be protected from impulse noise. In these two profiles, a buffer area is provided to the line with some extra coding, that makes the line much more noise resistant. Unfortunately, this creates a delay, but this delay does not cause problems for eMBB and Massive Machine Type Communications (mMTC) services. However, it may cause problems for Ultra-reliable Low-latency Communication (URLLC) type services.

The OSS/BSS systems that are inevitably important in the mobile backhaul management, are used during the optimization step. The HDM server in Fig. 2 simply receives data directly from the CPE that is connected at the end of the access line. Thanks to the HDM server, information about the health of the CPE is obtained. The NMS server on the other hand, receives the same data with the HDM server from the CPE, however this data is now from the other end of the line i.e. from DSLAM. NMS server collects network related values for each line separately. In this way, the data from the NMS and HDM servers can be compared to verify their integrity. Hence, the data is received from both ends of the access lines. DSLAM model types and installation types (FTTB, FTTC, CO) are also available on the NMS server. CRM server collects all access line related data and ensures the execution of the line optimization. The GIS server is used to check the previously analyzed line length value for the optimization step. As can be seen in Fig. 2, CRM server is in communication with all other servers and holds all the data that belong to each of the lines. Consequently, it is reasonable to run the scripts for the optimization process, in CRM server. Thus, the information is kept synchronous and up-to-date for all other servers.

TABLE 3  
EXPERIMENTAL PARAMETERS AND THEIR  
CORRESPONDING VALUES PER LINE

Parameter	Value
$N$	4096
$\alpha_{max}$	15
$P_{max}$	14.5dB
$M_{target}$	6dB
$\Upsilon$	86400 sec.
$Resynch$ (min.)	3 (hours)
tone BW (kHz)	4.3125
$N_{Subscribers}$ (million)	$\sim 0.96$
$N_{port}$ (million)	$\sim 4.3$
$N_{CO}$ (thousand)	$\sim 1.8$
$N_{FTTC}$ (thousand)	$\sim 7.6$
$N_{FTTB}$ (thousand)	$\sim 22$
$N_{bands}$	3
$\beta_{target}$ (Mbps)	16, 24, 35, 50 or 100



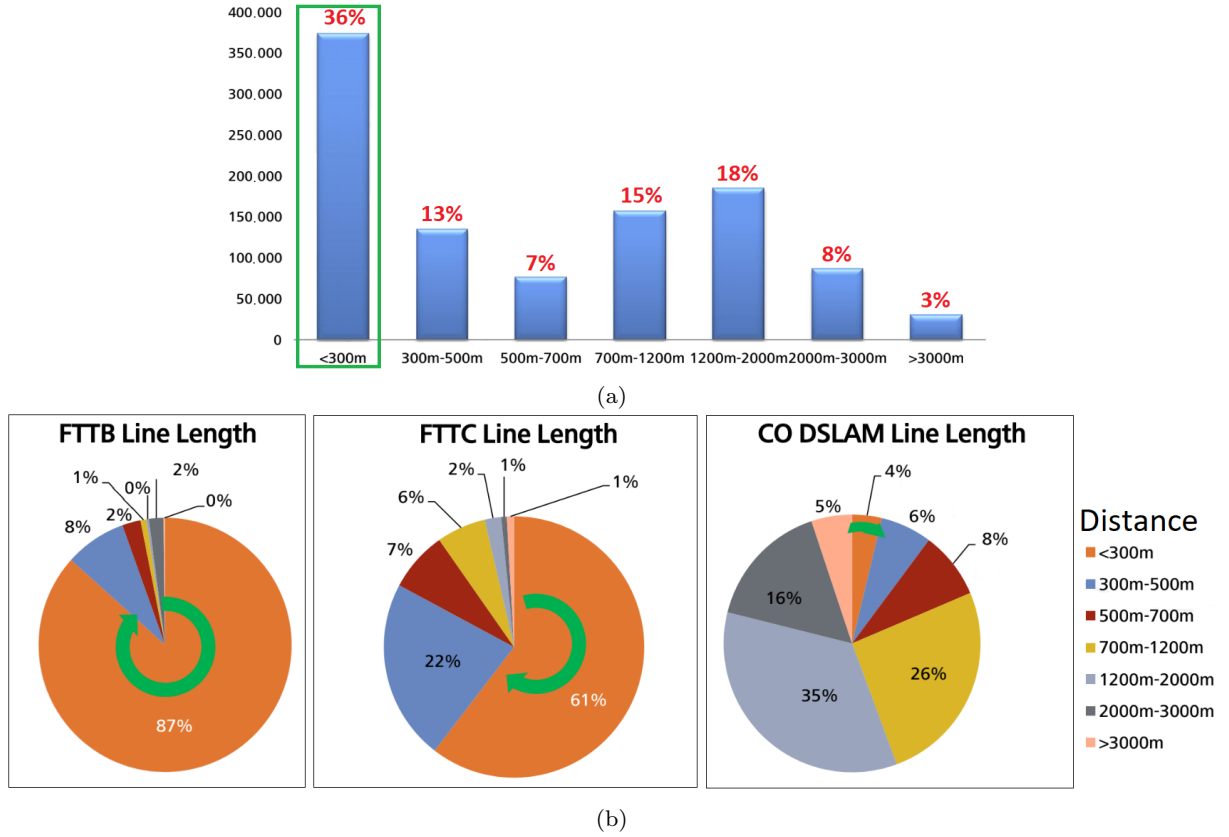


Fig. 5: Line length distribution analysis of subscriber lines according to different deployment scenarios (a) bar chart plot (b) pie chart plot according to different deployment scenarios.

## 4 Network Evaluation Outcomes

### 4.1 Line Length Evaluations

During evaluation of the service quality and network stability, we have utilized one week of large-scale measurement campaign. Table 3 provides the utilized experimental parameters and their corresponding values. Port utilization values of the different deployment scenarios are shown in Fig. 4. Overall used port number is  $N_{Subscribers} = 0.96$  million of all the  $N_{ports} = 4.3$  million ports, hence the overall port utilization percentage is 22%. Majority of all port utilization percentages is under 50% for FTTB and over 80% for both FTTC and CO respectively. These results indicate that port utilization of FTTB has some room to be increased if careful planning is accomplished by the telecommunication provider.

Fig 5(a) shows the FTTx access line length values of subscriber lines measured by the method specified in Section 2. These lengths are the distances between DSLAM and the end user modem. They can be either DSLAM outdoor or indoor. Line attenuation is assumed to be 10db/km during calculations. It is observed that 36% of the line is less than 300 meters. On the other hand, the num-

ber of lines over 3,000 meters is 3%. The important thing in this analysis is selecting those subscribers that are below 700 meters (which corresponds to 56% of all subscriber lines) that have the potential to obtain higher speeds. Those lines with low line distances belong to FTTB lines as well as lines between FTTC and CO's. It is also observed that 29% of copper lines has distance greater than 1,200 meters which can practically diminish the performance of VDSL as can be observed from theoretical curves in Fig. 3 as well.

Fig. 5(b) shows the sub-diffraction of all line lengths for different FTTx deployment scenarios. When the line distances for FTTB are examined on the left side of Fig. 5(b), it is seen that the distance of the line is 87% and the line length is below 300 meters. The same ratio is 61% for FTTC shown in the middle of Fig. 5(b) and 4% for CO shown in the right side of Fig. 5(b). Therefore, FTTB is observed to be better than FTTC and CO DSLAMs. As can be concluded from these observations, CO DSLAMs serve subscribers in a wide geographic area. Hence, it is not always feasible to invest in FTTB and FTTC in locations that have distance over 3,000 meters. In these distances, these points are mostly accessed over CO. While the access line percentage of FTTC that are more than 3,000 me-

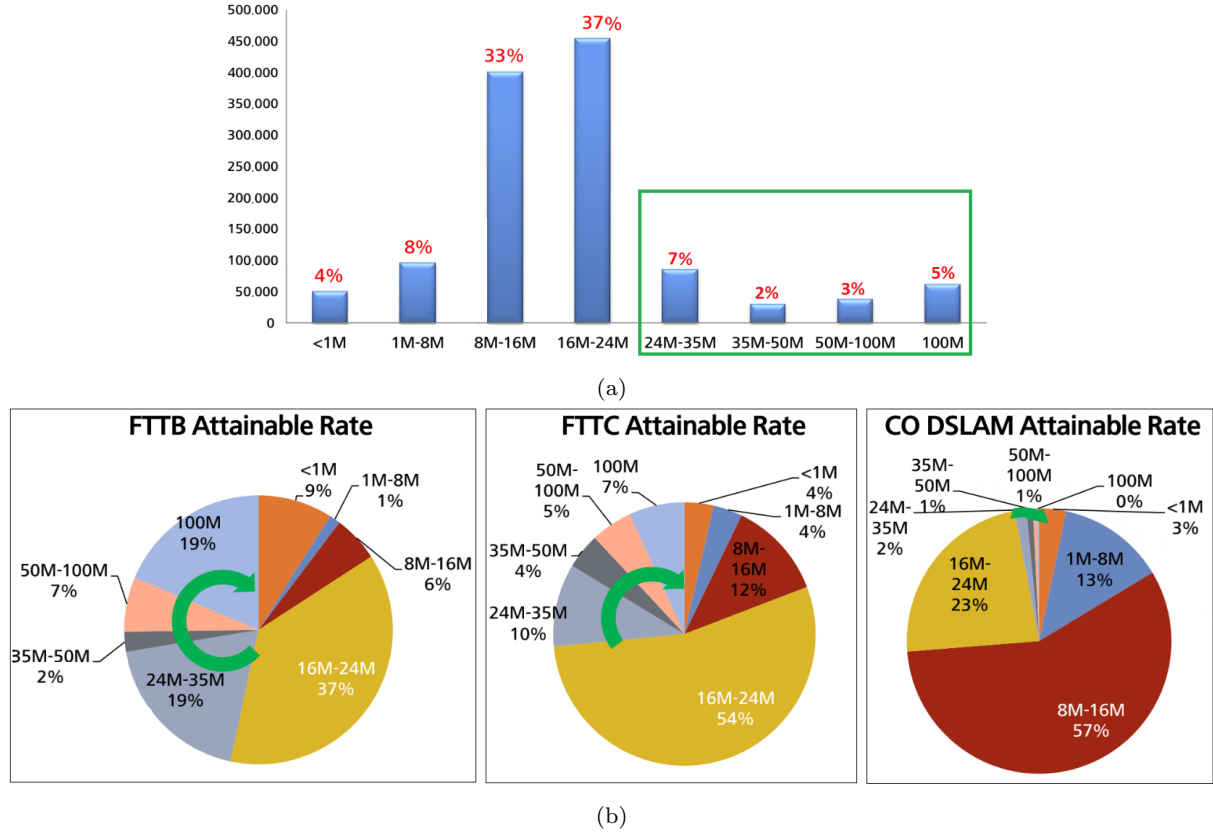


Fig. 6: Distribution of the attainable rates of the FTTx subscriber access lines using the proposed evaluation methodology (a) bar chart plot (b) pie chart plot according to different deployment scenarios.

ters is around 1%, this is not the case with FTTB lines. In fact for the FTTB installation type there is no line length above 700 meters, which is to be expected.

#### 4.2 Attainable Rate Evaluations

A fundamental quality parameter is the maximum rates that lines can yield named as attainable rates of the access line. In our analysis, VDSL lines are evaluated. In Fig. 6(a), the distribution of attainable rate ratios including FTTB, FTTC and CO deployment models are indicated all together as bar chart after using the proposed evaluation methodology in Algorithm 1. We can observe from Fig. 6(a) that only 17% of all lines can provide rates above 24 Mbps (as illustrated with green box) whereas most of the lines can provide rates between 8-16 Mbps with 33% and 16-24 Mbps with %37 ratio respectively.

Fig. 6(b) shows the attainable line rates based on each FTTx deployment scenario. On the left side of Fig. 6(b), analyzes are made for the FTTB installation type. Only 47% of the lines in FTTB installation type can get speed over 24 Mbps (as

illustrated with green colored arrow). Here, the number of lines receiving speeds below 1 Mbps is 9%, due to the shortening of the copper distance with the DSLAM device placed inside the building. The main reason for the high number of lines that can receive speeds lower than 24 Mbps is mostly related to the inadequate cabling in old buildings or the houses in urban sites. In the middle of Fig. 6(b), the rates that can be obtained for the FTTC installation type are shown. Here, it can be seen that the number of subscribers who can get speed over 24 Mbps has reached 26% (as illustrated with green colored arrow). This may seem quite consistent considering that the copper distance is extended. In Fig. 6(b), when the attainable speeds for CO deployment type are analyzed on the right side, the number of lines that can receive speed over 24 Mbps has dramatically decreased to 24%. Therefore, FTTB's attainable rate values are observed to be better than FTTC and CO DSLAM.

#### 4.3 BER, Resync & Faulty Line Evaluations

MTBE and MTBR are defined at Layer 1 level. So when MTBE occurs, if the layer protocols (application level protocol) are Transmission Control Pro-

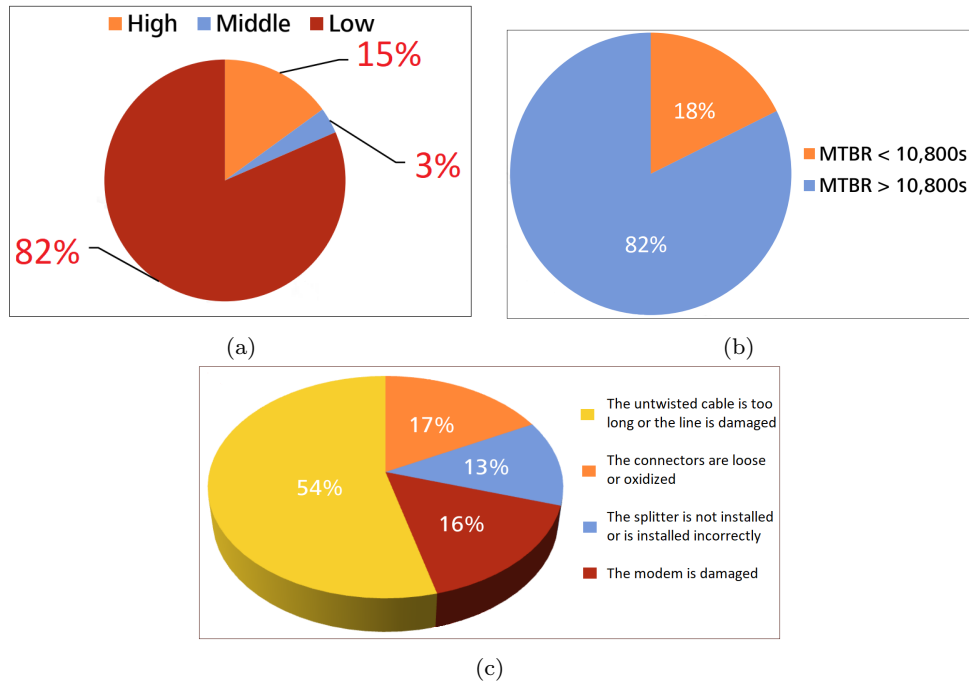


Fig. 7: (a) Bit error rate distribution analysis of access lines. (b) Resync analysis distribution analysis of access lines. (c) Faulty line analysis for possible reasons and solutions for the fault lines.

protocol (TCP) based, a delay for the upper layer application can be created. TCP by its nature, deals with the re-transmission for the upper layer application protocol and this is the reason for the delay. However, since User Datagram Protocol (UDP) does not have connection control, MTBE is reflected as a packet loss ratio for UDP-based applications.

Fig. 7a plots the BER ratios of all lines (or ports) calculated using (2). BER is generally caused by the quality of the copper loop as some bits are lost during transmission. Out of all ports, 15% of them are having high BER while 82% are having low BER. Moderate MTBE is observed in 3% of all ports. The port is healthier when the BER value is low and MTBE value is high. From this figure, we can conclude that an optimization is required in 15% of the lines due to high BER or low MTBE.

Resynch attempts constitute a complete connection loss. In case it occurs, rather than a decrease in the level of quality, the communication is completely broken and the communication cannot be achieved until synchronization occurs. Fig. 7b shows the resync analysis and the distribution of MTBR values above and below 10,800 sec (3 hours). The ratio of the circuits with high MTBR value (that we can call as healthier) is 82%. The remaining 18% circuit needs a line optimization phase due to low MTBR. These results indicate that service interruptions in existing copper lines are relatively low. However for URLLC services that require stringent reliability requirements, those

access lines exhibiting low MTBR values need to be upgraded further.

Fig. 7c describes fault line analysis results and some solution methods that can be applied to classified access lines according to measured MTBE, MTBR, line length and attainable rate values. For lines designated as “too long line or the line is damaged”, the calculated attainable rate is lower than the calculated rate that can be achieved when the noise level is low (around -130 dbm/Hz) i.e. in ideal environments. Here, the percentage of lines that need optimization due to modem damage is 16% and the percentage of lines that need optimization due to splitter installments problems is 13%. While cable damage and cable length were 54% of all line problems, 17% of problems occurred due to oxidation and loosening of the connection points.

**In summary:** The following observations are obtained by using the utilized evaluation methodology in Section 3, after one week of duration large-scale measurement campaign. First, the attainable rate is observed to be weak where only 17% of all ports have line rates larger than 24 Mbps. Second, 18% of all ports are observed to exhibit high resync ratio, 3% of all ports have high BER problems. Finally, 29% of line length of subscriber lines are observed to be greater than 1,200 meters which diminishes the performance of VDSL lines.

TABLE 4  
COMPARISONS FOR THE DEPLOYMENT OF DIFFERENT 5G SERVICES USING FTTX BACKHAUL

5G Service	Parameter Importance	Challenges	Advantages
eMBB	<ol style="list-style-type: none"> <li>1. Attainable Rate</li> <li>2. MTBR</li> <li>3. MTBE</li> <li>4. Line Length</li> </ol>	<ul style="list-style-type: none"> <li>— Needs too much bandwidth.</li> <li>— Line length must be shortened.</li> <li>— Need more FTTB investment for shorter access lines.</li> <li>— Require bonding or G.fast to increase bandwidth that brings extra cost.</li> </ul>	<ul style="list-style-type: none"> <li>— Does not get affected much with packet loss.</li> <li>— Provides ideal backhaul with FTTC and FTTB.</li> <li>— Allows high bandwidth usage in mid-distances (12 bonded pairs provide 150 Mbps over 1.5 km [3])</li> </ul>
URLLC	<ol style="list-style-type: none"> <li>1. MTBR</li> <li>2. Line Length</li> <li>3. MTBE</li> <li>4. Attainable Rate</li> </ol>	<ul style="list-style-type: none"> <li>— Require a very stable and flat FTTx connection.</li> <li>— Require highly qualified end terminal (DSL router or modem).</li> </ul>	<ul style="list-style-type: none"> <li>— Allows all FTTB locations to provide URLLC service. (e.g. buildings, houses, indoor, etc.)</li> <li>— Quality of FTTB access lines are dependent to indoor cabling not outdoor conditions.</li> </ul>
MTC	<ol style="list-style-type: none"> <li>1. MTBE</li> <li>2. MTBR</li> <li>3. Line Length</li> <li>4. Attainable Rate</li> </ol>	<ul style="list-style-type: none"> <li>— High error lead re-transmission that consumes battery.</li> <li>— Periodic transmission will be impacted hugely in frequent re-synchronization cases.</li> </ul>	<ul style="list-style-type: none"> <li>— Can run with minimum bandwidth requirements (e.g.1 Mbps).</li> <li>— Can be deployed to all FTTx locations (FTTB, FTTC, CO).</li> <li>— Can run with low-cost end terminals.</li> </ul>

## 5 Discussions on Evaluation Results

eMBB is a service that uses a lot of data and needs a lot of bandwidth. In this case, the most needed quality parameter before MTBR and MTBE will be the bandwidth capacity for the eMBB service. The most important point in URLLC service is that the data can be transmitted to the other requesting entity almost instantly. In this respect, a resynch process that will occur on the FTTx line and the time it takes for the line to synchronize again have an extremely negative effect for URLLC. Since all mission critical services will not require high bandwidth, bandwidth capacity will not be a very important quality parameter for URLLC. Considering MTC service, battery restrictions should be taken into account. It can be said that the devices using MTC service do not send data very frequently. In this case, an error that may occur during the data transmission and the data loss will have a great impact as most of the Internet of Things (IoT) protocols are not re-transmission capable. MTBR is less critical for MTC services than MTBE. The reason for this is that the devices do not start to send data without connection. Table 4 gives the important FTTx quality parameters as well as the challenges and advantages of FTTx backhaul based 5G deployment. Table 4 is classi-

fied according to various 5G services and taking into account the experimental test activities.

According to Fig. 7c results, a total of 71% of failures are actually due to line related problems. In this case, a physical repair on the line needs to be executed. Physical work may involve replacing the lines with new ones since they are old. On the other hand, if the defective locations are caused by DSLAMs connected to FTTC or CO, the copper circuit distance can be reduced by investing on FTTB as an alternative solution. However in this case, fiber extraction process up to FTTB and the installation of FTTB devices will be additional cost. Although changing the circuits physically with new ones provides a solution, this will not actually reduce the copper circuit distance compared to new FTTB installations. In this case, additional cost to rely only on cables replacements may in fact be insufficient.

From the experimental results, it is observed that the MTC service can be provided with FTTB, FTTC and CO installation types, which is related to bandwidth needs when the results are examined. FTTCs and FTTBs can be used in the eMBB services based on the dependency between MTBR and MTBE quality parameters. The most appropriate installation type for URLLC seems to be FTTBs due to the reduced line length, hence the expected

reduced delay. When the suggested faulty line analysis results in Fig. 7c are examined, the FTTx line length as well as the loose or oxidized connections at the DP are the main reasons for the majority of the quality problems. When evaluated in this respect, especially FTTB installations eliminate the need for DP, so that it can provide healthier and reliable FTTx transmission.

**In summary**, the following observations can be derived from the experiment outcomes: (i) Indoor based FTTx equipment (CO DSLAMs) cannot be used to provide all complementary 5G services. They must be swapped with outdoor based equipment to shorten the line length to provide higher bandwidth. (ii) Only 5G MTC service can be provided nearly in all FTTx locations with the existing infrastructure. (iii) With only simple changes to be made on the user side (such as on modem and splitter), nearly %30 of the access lines can be repaired to work properly. Therefore, these end user equipment focused investments will be less costly than repairing the lines or making outdoor investments for telecommunication infrastructure providers.

## 6 Conclusion & Future Works

Many case studies in the literature state that the deployment of 5G will be intensive and will benefit from many different backhaul technologies. In this article, we studied how the existing FTTx network, one of the backhaul technologies proposed, is ready for future 5G deployment using the proposed FTTx backhaul evaluation methodology. For this purpose, we analyzed large-scale FTTx network of a major fixed operator using different quality parameters in the real network environment in Turkey. The analysis results are done to assess the suitability of 5G backhauling in terms of service quality and network stability aspects. At the end of the paper, we have also proposed an ordering for the measured-parameters importance as well as the challenges and advantages of utilizing different 5G services using FTTx as backhaul. Our results have revealed some of the problems of using FTTx networks for backhaul purposes in the next generation mobile networks. It has been also observed that FTTx network technologies need to evolve towards the direction to provide better 5G backhauling in terms of decreasing error rates and robust access line synchronization.

From 6G perspective, terahertz communication is predicted to be a main actor for the backhaul by providing higher bandwidth speeds [30], [31]. In this case, using copper-based FTTx solutions for

the backhaul as main transport carrier technology does not seem very realistic. As future studies, it can be a research area to work on the conjunction and bundled operation of copper-based systems with terahertz systems, but only as backups of terahertz systems in the infrastructure. In the backup structure, FTTx systems can also only be used to protect control signaling messages of communication protocols when terahertz communication is interrupted. Moreover, voice communication that uses less bandwidth than data usage, can be provided from FTTx access lines when there is a terahertz communication failure. Consequently, providing data and broadband services over FTTx needs to be enhanced in terms of 6G.

## Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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## References

1. M. Jaber et al. 5G backhaul challenges and emerging research directions: A survey. *IEEE Access*, 4:1743–1766, 2016.
2. J. O. Edward and F. Zoraida. The cost, coverage and rollout implications of 5g infrastructure in britain. *Elsevier Telecommunications Policy*, 42(8):636–652, 2018.
3. GSMA Future Networks. Mobile Backhaul: An Overview. <https://www.gsma.com/futurenetworks/wiki/mobile-backhaul-an-overview/>, 2019. [Online; accessed 16-Jan-2020].
4. Recommendation ITU-T G.9701. Fast access to subscriber terminals (G.fast) – physical layer specification. *Telecommunication Standardization Sector of ITU*, 2014.
5. N. Wang, E. Hossain, and V. K. Bhargava. Backhauling 5G small cells: A radio resource management perspective. *IEEE Wireless Communications*, 22(5):41–49, 2015.
6. Filip de Greve. Nokia Blog: Fixed operators’ crucial role in mobile backhaul. <https://www.nokia.com/blog/fixed-operators-crucial-role-mobile-backhaul/>, 2016. [Online; accessed 08-August-2019].
7. M. Araujo, L. Ekenberg, and J. Confraria. Rural networks cost comparison between 5G (mobile) and ftx (fixed) scenarios. In *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 259–264. IEEE, 2018.

8. J. A. Zhang et al. Evolving small-cell communications towards mobile-over-fttx networks. *IEEE Communications Magazine*, 51(12):92–101, 2013.
9. K. Chandra, R. V. Prasad, and I. Niemegeers. An architectural framework for 5G indoor communications,. In *2015 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 1144–1149. IEEE, 2015.
10. E. Weis C. Behrens, S. Krauß and D. Breuer. Technologies for convergence of fixed and mobile access: An operator’s perspective. *IEEE/OSA Journal of Optical Communications and Networking*, 10(1):37–42, 2018.
11. Y. Turk and E. Zeydan. An experimental measurement analysis of congestion over converged fixed and mobile networks. *Wireless Networks*, pages 1–16, 2018.
12. T. C. Chuah and Y. L. Lee. Qos-aware cross-layer optimization of hybrid DSL-LTE access networks. *IEEE Systems Journal*, 2019.
13. X. Ge et al. 5G ultra-dense cellular networks. *IEEE Wireless Communications*, 23(1):72–79, 2016.
14. A. H. Fazlollahi and J. Che. Copper makes 5G wireless access to indoor possible. In *IEEE Global Communications Conference (GLOBECOM)*, pages 1–5. IEEE, 2015.
15. E. Medeiros et al. Crosstalk mitigation for lte-over-copper in downlink direction. *IEEE Communications Letters*, 20(7):1425–1428, 2016.
16. Amir H. Fazlollahi and Jiangnan Jason Chen. Copper-assisted fifth generation (5G) wireless access to indoor, 2016. [Online; accessed 15-Jan-2020].
17. Hans-Jochen Morper and Maximilian Riegel. Ultra high-speed mobile network based on layer-2-switching, 2019. [Online; accessed 16-Jan-2020].
18. A. Mian and D. Reed. Tomorrow’s backhaul: Comparative analysis of backhaul cost for policy decisions. In *IEEE 5G World Forum (5GWF)*, pages 123–128. IEEE, 2018.
19. Jan Plachy, Zdenek Becvar, and Pavel Mach. Path selection enabling user mobility and efficient distribution of data for computation at the edge of mobile network. *Computer Networks*, 108(1):357–370, 2016.
20. Y. Turk and E. Zeydan. Evaluation of fttx access network migration for IPTV services. In *10th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, pages 1–5. IEEE, 2019.
21. D. Chitimalla et al. 5G fronthaul-latency and jitter studies of cpri over ethernet. *IEEE/OSA Journal of Optical Communications and Networking*, 9(2):172–182, 2017.
22. A. Matera and U. Spagnolini. Analog MIMO Radio-Over-Copper Downlink With Space-Frequency to Space-Frequency Multiplexing for Multi-User 5G Indoor Deployments. *IEEE Transactions on Wireless Communications*, 18(5):2813–2827, 2019.
23. L. Grzybowski and F. Verboven. Substitution between fixed-line and mobile access: the role of complementarities. *Journal of Regulatory Economics*, 49(2):113–151, 2016.
24. Ali, M. et al. Smart heterogeneous networks: a 5G paradigm. *Telecommunication Systems*, 66(2):311–330, 2017.
25. A Sutton et al. *Mobile network design: Orange UK 2G to 3G mobile backhaul evolution*. PhD thesis, University of Salford, 2017.
26. OE Solutions. OE Solutions Announces 10G and 25G DWDM Optical Transceivers for 5G Wireless Fronthaul. <https://bit.ly/3aZsfI0>, 2019. [Online; accessed 31-January-2020].
27. R. Zhao et al. White paper: Broadband access technologies. <https://bit.ly/2WljT9Q>, 2013. [Online; accessed 21-May-2019].
28. Broadband Forum. DQS: DSL Quality Management Techniques and Nomenclature. *TR-197: Issue 2*, 2014.
29. ITU-T G.998.4 Recommendation. Improved impulse noise protection for digital subscriber line (DSL) transceivers. *Telecommunication Standardization Sector of ITU*, 2018.
30. P. E. Mogensen H. Viswanathan. Communications in the 6g era. *IEEE Access*, 8(1):57063–57074, 2020.
31. T. S. Rappaport et al. Wireless communications and applications above 100 ghz: Opportunities and challenges for 6g and beyond. *IEEE Access*, 7(1):78729–78757, 2019.