# Reinforcement Learning-Assisted Transmit Signal Power Savings in Variable Bit-rate Fronthaul

Mohsan Niaz Chughtai, Philippos Assimakopoulos, Nathan J. Gomes

***Abstract*—The increasing bit-rate demands placed on the fronthaul from higher user rates and multiple antenna technologies will make the consideration of its power consumption an important issue. In this study, it is assumed that the fronthaul bit-rate can be reduced from the maximum required rate through prediction of the fronthaul traffic using deep reinforcement learning (DRL). Using such predictions, and benchmarked simulations of a discrete multitone (DMT) modulation electro-absorption modulator (EAM)-based optical fiber-link, as an example of a fronthaul transmission system, it is shown that the power reduction from reducing the transmitter signal power alongside the reduction in modulation level can be between 22.3% and 34.6% within a fixed bandwidth of 34 GHz and 18 GHz respectively. Such a transmitter could be built as a bandwidth variable transponder in a Flexible Ethernet fronthaul.**

***Index Terms*—Mobile fronthaul, beyond-5G, discrete multitone modulation, power conservation.**

## I. Introduction

Fronthaul networks are beneficial for the energy efficiency of the network in terms of reducing wireless distances. For functional splits other than option-8, the fronthaul will transport very high and varying bit-rates from changing numbers of antenna flows and numbers of allocated radio resource blocks [1]. Therefore, the power consumption in the fronthaul segment of a mobile network warrants a meaningful investigation.

In fronthaul links, EAMs and Mach-Zehnder modulators (MZM) may be used to modulate the optical carrier for data transmission, requiring drive signal amplification via a drive amplifier. The modulator module's power consumption, including the drive amplifier, constitutes a significant portion of the overall transmitter power in a fiber optic transmission link [2],[3]. By reducing drive signal powers, the power consumption of MZM, EAM, and drive amplifiers can be minimized, based on the power consumption models in [3] and [4]. The drive signal powers can be reduced via a reduction in fronthaul bit-rates, as it will require lower quadrature amplitude modulation (QAM) levels and receiver signal-to-noise ratios (SNRs). Although power-consuming components in an optical link, such as digital signal processing (DSP) functions, laser source, optical amplifier, photodiode and analog-to-digital/digital-to-analog converters (ADC/DAC), warrant a complete investigation, due to the dependence of modulator power consumption on the transmit signal power, this letter focuses on reducing transmit signal power through bit-rate reduction in a variable bit-rate fronthaul.

The bit-rate reductions may be achieved using bandwidth variable transponders (BVTs) in fronthaul nodes, where a BVT can change the link rate by varying the bandwidth used or by varying the modulation level within a given bandwidth (varying spectral efficiency) [5]. Studies in [5] and [6] have examined varying bit-rates between standard optical transport networks (OTN) or Ethernet physical layer (PHY) rates (e.g. multiples of 100 Gbps), but this research considers a finer granularity of bit-rate variation. A 5 Gbps granularity was chosen because it is supported by the Flexible Ethernet (FlexE) calendar mechanism (the FlexE shim).

In the studies in [7] and [8], the PHY layer bit-rates are reduced from the fixed maximum bit-rate, in increments of 5 Gbps, following the input traffic bit-rates predicted by using auto-regressive moving average (ARIMA) and DRL. The results presented in [8] for traffic predictions via DRL and subsequent 5 Gbps slot allocations, are used to indicate the reduction in the bit-rate of a fronthaul link that is enabled by DMT-type transmission of 5 Gbps slots. Using these reductions in fronthaul bit-rate, it is shown that savings in the transmit DMT signal power, required to drive the EAMs, are possible.

## II. Fronthaul network and simulation model

The architecture of a beyond 5G network with fronthaul based on studies in [8] is shown in Fig. 1. The aggregation in the fronthaul comprises three stages: first, Ethernet switches aggregate the traffic from remote units (RUs), and then FlexE nodes aggregate traffic from the first stage Ethernet switches. The traffic from these second-stage FlexE nodes is then aggregated by a third-stage FlexE node linked to a combined central unit/distributed unit (CU/DU).

The internal structure of the FlexE aggregation nodes is shown in the lower part of Fig. 1. Each FlexE node comprises a FlexE shim which offers 5 Gbps slots in a time division multiplexing (TDM)-based manner to different ingress traffic sources. A DRL agent in the FlexE node predicts the bit-rate of the aggregated traffic at the ingress ports of the FlexE node. Based on the predictions, a varying number of 5 Gbps slots of the FlexE shim are allocated. The BVTs within the

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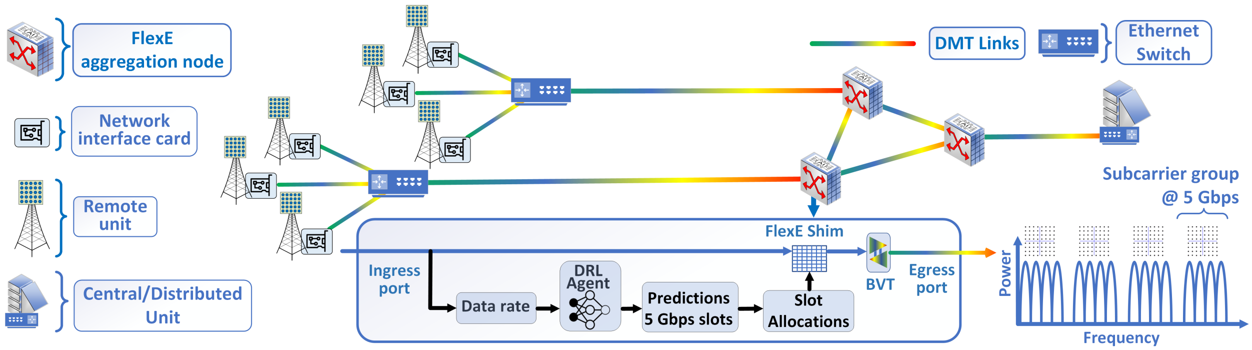


Fig. 1. Beyond-5G network with DRL-aided FlexE aggregation.

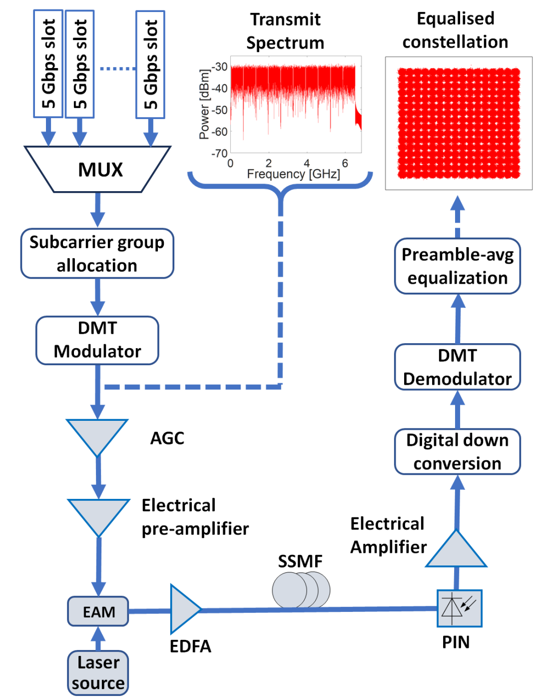


Fig. 2. Simulation setup in of a DMT link in Fig. 1.

FlexE nodes transport the allocated 5 Gbps slots over different subcarrier groups of the DMT signal, as shown in the lower right-hand side of Fig. 1. The subcarrier groups are modulated using QAM.

To assess the transmit DMT signal power, within the BVTs in Fig. 1, required for the transmission of different bit-rates, a single DMT link in Fig. 1 was modelled and simulated in VPI Transmission Maker® v11.2 and shown in Fig. 2. The non-shaded blocks were implemented in MATLAB® whereas the shaded blocks in VPI Transmission Maker ® v11.2.

The power consumption of the link was evaluated, at first, at five distinct fronthaul bit-rates of 5, 10, 50, 100, 150, and 200 Gbps, employing the same QAM modulation levels (4, 16, 64, and 256 QAM) and the same subcarrier spacing, across all subcarrier groups of the DMT signal. The transmission of the 5 Gbps slots was modelled using independent pseudo-random bit sequences, multiplexed in a round-robin fashion for subsequent allocation to the subcarrier groups, each comprising 3800 subcarriers, while a 24 MHz guard band was used between groups. The sampling frequency for the simulations was adjusted for different total bit-rates with a subcarrier spacing of 220 kHz for 64 QAM modulation as a reference.

The power of the transmit DMT signal, to drive an EAM, was controlled by varying the gain of the electrical pre-amplifier shown in Fig. 2, with a power spectral density (PSD) of 8.62x$10^{-12}$ (A/$\sqrt{\text{Hz}}$). The EAM shown in Fig. 2 had a transmission polynomial given as follows,

$$T_{dB}\,(V) = 0 - 2.75\ V - 6.3V^2 + 1.5V^3, \qquad (1)$$

where $T_{dB}$ is the optical transmission in dB. The frequency response was assumed not to cause a limitation for the signal frequencies used of up to 34 GHz. The bias voltage was set at 0.4 V to avoid crossing the zero-voltage threshold. The drive amplifier was assumed to operate in the linear gain regime. The laser source in the link in Fig. 2 had an average power of 8.5 dBm, an emission frequency of 193.1 THz, relative intensity noise (RIN) of -150 dB/Hz, a linewidth of 1 kHz, similar to an external cavity laser (ECL) in an experimental setup for benchmarking of simulations [10]. Note that the analysis of the link in Fig. 2, in Sections III and IV, focuses on demonstrating relative power reductions rather than absolute performance, and is applicable for a laser source with higher linewidth.

The erbium-doped fiber amplifier (EDFA) in Fig. 2 had a noise figure (NF) of 3dB and fixed output power of 19 dBm, to maintain the error vector magnitude (EVM) of 3.5% for an aggregate bit-rate of 200 Gbps and 256-QAM modulation. The length of standard single-mode fiber (SSMF) was 10 km. At the receiver, the signal was detected using a positive-intrinsic-negative (PIN) photodiode, with the load resistor thermal noise set at 0.33x$10^{-10}$ (A/$\sqrt{\text{Hz}}$). The received signal was amplified by an electrical amplifier having a gain of 19 dB and a noise spectral density of 19x$10^{-10}$ (A/$\sqrt{\text{Hz}}$). In MATLAB®, the received DMT signal was digitally down-converted via Nyquist zone de-mapping [10], where each Nyquist zone comprised a single subcarrier group. In MATLAB® the subcarrier groups were equalized by averaging the channel estimates from 50 preamble symbols (preamble-avg block in Fig. 2).

## III. DMT LINK CAPACITY AND POWER SAVINGS

Using the formulation for the output power of an EAM in [9], with the transmit DMT signal power as an input

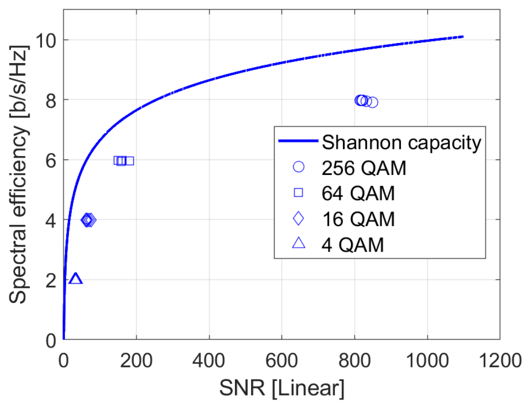


Fig. 3. Spectral efficiencies for the estimated SNRs of the link in Fig. 2.

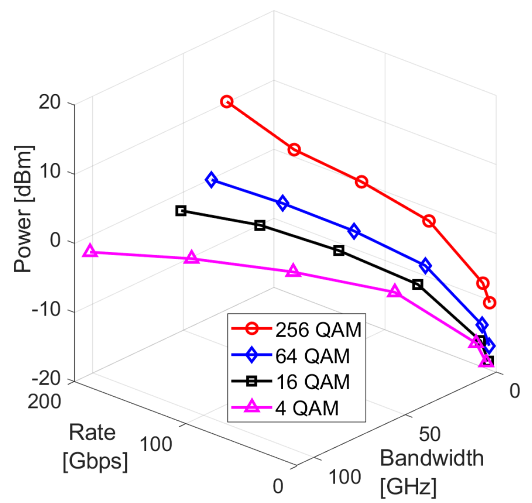


Fig. 4. DMT signal powers for different fronthaul bit-rates and DMT multiplex bandwidths for the link in Fig. 2.

variable, the transmitted optical signal power in the link in Fig. 2 was calculated. The detected DMT signal power in the PIN diode was calculated using the estimated received optical power. The overall noise in the link was computed by combining noise from electrical amplifiers, signal-spontaneous, shot, thermal, and RIN noise terms calculated from noise PSDs values given in Section II. Using the overall noise, the SNRs were calculated for different bit-rates and modulation levels. The corresponding spectral efficiencies of the link were compared with Shannon's channel capacity, plotted in Fig. 3. The SNRs were estimated such that the link maintains the $3^{\text{th}}$rd generation partnership project (3GPP) 5G standard EVMs. The spectral efficiencies for various modulation formats in Fig. 3 suggest that the DMT transmission system operates at approximately 1 b/s/Hz below the Shannon capacity indicating a margin for further improvement.

Studies in [2] and [3] have shown that the drive amplifier of the modulator unit is responsible for the majority of power consumption in fiber optic transmitters. The models presented in [3] suggest that dynamic consumption can be reduced by lowering the signal's power driving an EAM. For a variable bit-rate fronthaul link, the bit-rate reduction will require less

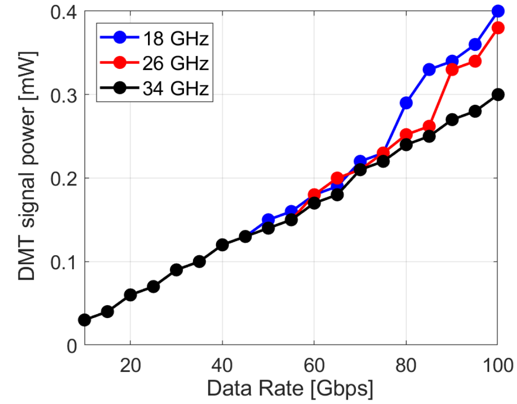


Fig. 5. Estimated DMT signal powers for different fronthaul bit-rates and fixed DMT multiplex bandwidths for the link in Fig. 2.

overall bandwidth and/or lower QAM levels and consequently, less transmit DMT signal power for the required receiver SNR. Lower transmit DMT signal powers will lead to the reduction of power consumption of drive amplifiers. In this letter, power savings in the transmit DMT signal power at the input of EAM, are analysed through varying the bit-rates on the DMT transmission link of Fig. 2. The analysis did not include the power consumption of the digital electronic circuits in the transmitter and receiver, ADC/DAC, laser, EDFA, and photodiode.

For the simulation of the link in Fig. 2 at a given fronthaul bit-rate, the total number of DMT subcarriers was fixed albeit with the same allocation of different QAM levels in all subcarrier groups, resulting in varying overall bandwidth. The results are shown in Fig. 4 with the required powers of the transmit DMT signal at the input of the EAM driver, dependent on fronthaul bit-rates and DMT multiplex bandwidths. The employed DMT input signal power ensures that after equalization, the receiver EVM is below the limit defined in the relevant 3GPP 5G standard. Decreasing the bit-rate from 200 Gbps to 5 Gbps leads to reduced DMT input power: 20.26 dB for 256 QAM, 16.24 dB for 64 QAM, 16.21 dB for 16 QAM, 16.02 dB for 4 QAM, and a reduction of 12.46 dB for 200 Gbps when using 4 QAM instead of 256 QAM.

The performance of the link in Fig. 2 was also benchmarked for a fixed DMT multiplex bandwidth. To transmit different fronthaul bit-rates within a fixed DMT multiplex bandwidth, combinations of 5 Gbps subcarrier groups with different modulation levels were chosen. In this case, the total DMT signal powers were estimated with the assumption that the total power is the sum of individual powers of 5 Gbps subcarrier groups, plotted in Fig. 4. The estimated DMT input signal powers for fixed DMT multiplex bandwidths of 18 GHz, 26 GHz and 34 GHz are shown in Fig. 5. Reducing the fixed bandwidth from 34 GHz to 18 GHz increases the required DMT signal power to meet the minimum EVM, due to the selection of more 5 Gbps subcarrier groups with higher modulation levels. Fig. 5 shows that reducing the bit-rate from 100 Gbps to 40 Gbps yields approximately 70%, 68%, and 60% total DMT signal power savings for fixed bandwidths of 18 GHz, 26 GHz, and 34 GHz, respectively.

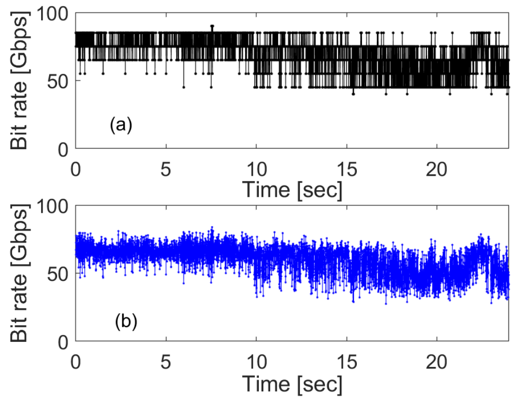


Fig. 6. Fronthaul bit-rate predictions from DRL agent (a), input traffic bit-rate from the WIDE project [8] (b).

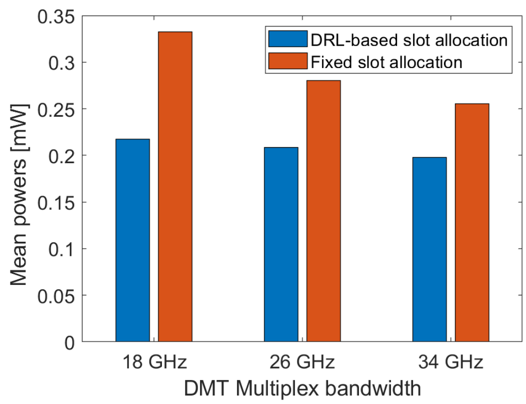


Fig. 7. Mean DMT signal powers for fixed and DRL-based slot allocations.

## IV. DRL-assisted DMT signal power savings

The aim of the DRL agent in the FlexE aggregation node in Fig. 1 is to carry out predictions of the bit-rate of the incoming aggregated traffic, with a granularity of 5 Gbps, and aid subsequent slot allocations in the FlexE shim [8]. Utilizing the results in [8] for the training of a DRL agent for the prediction of the input traffic pattern from the widely integrated distributed environment (WIDE) project [7], the power required for the transmission of 5 Gbps slots was calculated for different bandwidth limits. Note that the observation space, action space, Deep-Q network training parameters, and the reward functions for the training of the DRL agent are described in detail in [8]. The traffic pattern predictions, with a granularity of 5 Gbps, from [8], after the deployment of the trained DRL agent, are shown in Fig. 6(a). These show that the DRL agent attempts to follow the input pattern, reducing fronthaul bit-rate, and contributing to reducing transmit DMT signal power.

The transmit DMT signal powers required for transmitting the fronthaul bit-rates in Fig. 6(a) were computed based on the power values presented in Fig. 5 for the three different DMT multiplex bandwidths: 18 GHz, 26 GHz, and 34 GHz. Subsequently, the mean DMT signal power was determined for each bandwidth over a 24-second interval in Fig. 6(a) and shown in Fig. 7. The mean powers are also compared to the case where the number of 5 Gbps slots is fixed over the 24-second simulation time interval, to indicate the impact of a static bit-rate, equal to the maximum input traffic of 85 Gbps in Fig. 6(a). In Fig. 7, DMT signal powers decrease when using DRL-based slot allocation compared to fixed allocation, with a maximum reduction of 34.6% for an 18 GHz bandwidth and the lowest reduction of 22.3% for a 34 GHz bandwidth. In practical systems, higher DMT signal powers may be needed to achieve similar bit-rates due to, for example, higher linewidth in low-cost laser sources, but relative power savings will still be achievable.

## V. Conclusions

It has been shown that using DRL for traffic prediction and allocating bandwidth in gradations of 5 Gbps, corresponding to slot allocations, significant transmit signal power savings can be made for an EAM-based fronthaul link using DMT modulation. Power savings in the DMT signal driving the EAM of up to 34.6% were possible assuming a fixed 18 GHz bandwidth for the optoelectronic and radio frequency (RF) amplifier components, by adapting the QAM level for different groups of subcarriers.

The analysis in the paper focused on savings of the transmit DMT signal power since most of the power consumption in the transmitter is from the modulator unit including the drive amplifier. Power savings might also be increased via adjustments of laser source power and EDFA gain for different fronthaul bit-rates. In the future, the analysis in this letter can be extended to include other power-consuming components in the fiber optic fronthaul link.

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