Energy-Efficient Integrated O-RAN/PON Access Network

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***Abstract*—The utilisation of Time Division Duplexing (TDD) in 5G enables the implementation of schemes exploiting the opportunities provided by the TDD pattern. For example, Cooperative Dynamic Bandwidth Allocation (CO DBA) was proposed for reducing the fronthaul latency contribution in Time Division Multiplexing Passive Optical Networks (TDM-PON).**

This paper exploits 5G TDD and programmability of Open Radio Access Network (O-RAN) and Software Defined Optical Access Networks (SDOANs) for a different purpose: x-haul energy efficiency. The proposed scheme aims at reducing the energy consumption of an PON-based x-haul by turning ON and OFF selected subsystems of the ONT (and, in some cases, of the OLT) in a cooperative fashion with the TDD patterns.

Preliminary simulation results show that up to 80% energy savings can be achieved with the proposed cooperative technique.

***Index Terms*—Next Generation Access Network, Energy Savings, O-RAN, SDN, PON**

I. INTRODUCTION

Energy efficient Time Division Multiplexing Passive Optical Network (TDM-PON) schemes were proposed in the recent past and adopted in the standards to extend the lifetime of an Optical Network Terminal (ONT) during main power failures, as a primary target, and to reduce average power consumption at all times, as a secondary target, while not sacrificing service quality or availability [1], [2]. In addition, TDM-PONs have been considered for supporting fronthaul interfaces between Radio Unit (RU) and Distributed Unit (DU) [3].

In the latter case, an important requirement is represented by the latency constraints of some considered 5G functional split options [4]. Indeed, if 5G Medium Access Control (MAC) functions are positioned far from the RU, that is either in the DU or in the Central Unit (CU) (i.e., split option 4 and above), latency constraints for the fronthaul interface are around hundreds of μs [3]. Thus, solutions based on Coordinated DBA (CO DBA) have been proposed for reducing the PON latency in upstream and meeting the fronthaul latency requirements [5], [6].

CO DBA exploits the Time Division Duplexing (TDD) utilized in 5G for sharing the wireless medium between uplink and downlink transmissions [7]. CO DBA defines an interface for an Optical Line Terminal (OLT), to which the DU is connected, to receive wireless scheduling, and can estimate the amount and arrival timing of the fronthaul (FH) signal to an ONT in advance, thus reducing the uplink latency.

The software programmability and openness of software defined mobile networks and, in particular, O-RAN paves the way towards the cooperation between RAN and optical transport network infrastructures, which has been shown to offer advantages in terms of network efficiency and savings in cost of ownership for operators [8]. Parallelly, the introduction of Software Defined Optical Access Networks (SDOANs) allow to implement flexible strategies for bandwidth allocation and energy efficiency in a dynamic and programmable way [9].

This paper proposes a collaborative approach, similar to CO DBA, which leverages the programmability of O-RAN and SDOANs. The proposed technique exploits the TDD utilized in the 5G physical layer for reducing the fronthaul energy consumption. The method combines cyclic sleep mode defined in [3] with the possibility for the PON to receive wireless scheduling. In this study, selected ONT receiver components are turned OFF when 5G New Radio (NR) slot or symbols are dedicated to uplink transmission. The method is so general that can be applied to different x-haul interfaces (i.e., fronthaul, midhaul, backhaul) with different next generation NodeB (gNB) splits or none.

Preliminary simulation results show that up to 80% energy savings can be achieved in TDD patterns where the upstream traffic is prevalent.

II. SYSTEM MODEL

We consider the reference architecture as shown in Fig. 1 where a gNB (or alternately a RU or RU+DU) is connected to the core network (or DU+CU/CU, and core network) through a PON. TDD is adopted as duplexing mechanism at the wireless side. The gNB/RU/RU+DU is equipped with an ONT while DU/DU+CU is deployed at the OLT side. The PON can be configured according to the adopted mobile configuration. When a RU is deployed at the ONT side, the PON acts as fronthaul infrastructure and ad-hoc resource allocation strategies are implemented to offer very low latency to fulfil fronthaul latency requirements. When RU+DU or gNB are deployed at ONT side, the PON acts as mid-haul or backhaul infrastructure adopting and dynamic bandwidth allocation strategies are adopted based on specific end-to-end services' requirements.

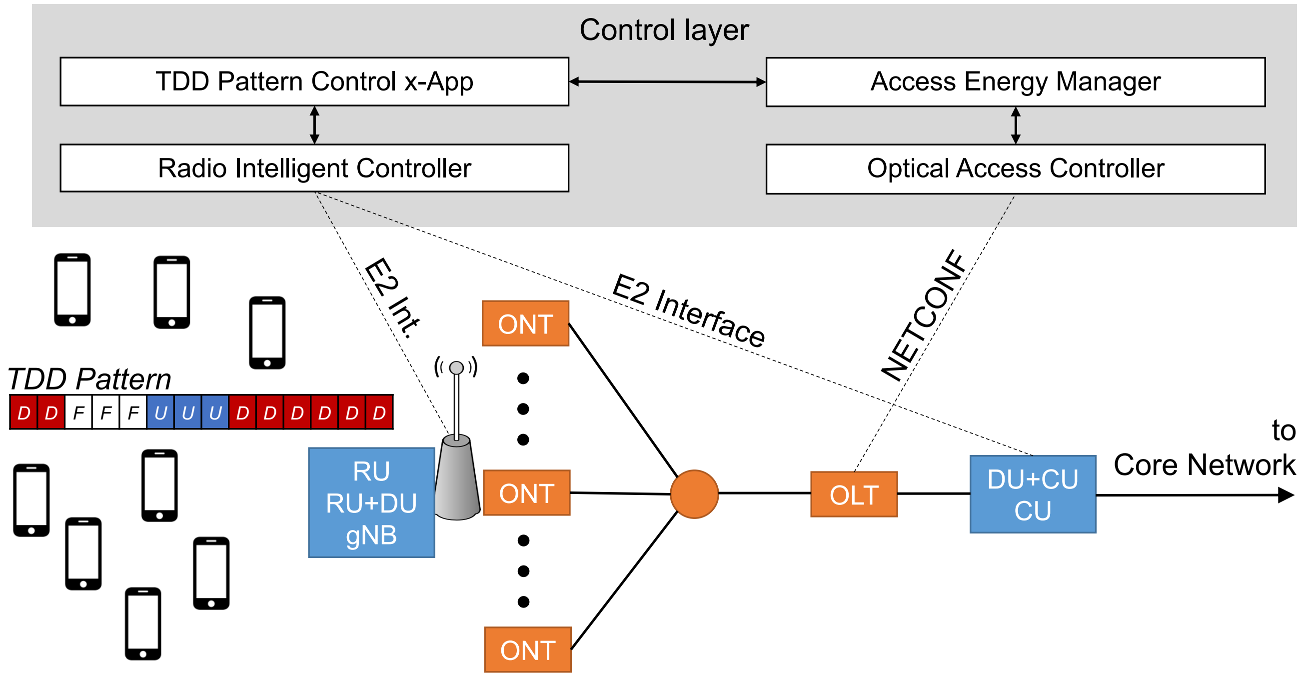


Fig. 1: System Model

The PON is managed by an Optical Access Controller (OAC) which interacts with an agent placed at the OLT using NETCONF protocol. The OAC is responsible to enforce policies at the OLT for the management of quality of services, bandwidth allocation strategies, and energy efficiency. Moreover, it exposes northbound Application Programming Interfaces (APIs) to allow operators or any other third party to implement desired software defined control.

The Radio Access Network (RAN) is managed by a so-called Radio Intelligent Controller (RIC) according to O-RAN alliance definition. The RIC is responsible to take decisions with two time-scale levels. Near Real Time (Near-RT) RIC is responsible to apply decisions and perform monitoring on a millisecond time scale via the standardized E2 interface. The Near-RT RIC interacts with a Non-RT RIC which provides policies with a time scale $\geq$ 1s. On top of the near-RT controller, custom-built applications called xApps implement the control logic desired by the network operator via APIs exposed by the near-RT RIC. On top of the network controllers two applications are realized to achieve energy savings in the PON x-hauling. In particular, a *TDD Pattern Monitor* x-App keeps track of the adopted TDD pattern at the cell-level for the communication between the User Equipments (UEs) and the RU/gNB. The TDD Pattern Monitor x-App interacts with a *Access Energy Manager* application developed utilizing OAC APIs which is responsible to plan optimized energy efficiency operations in the PON as described more in detail in the following section.

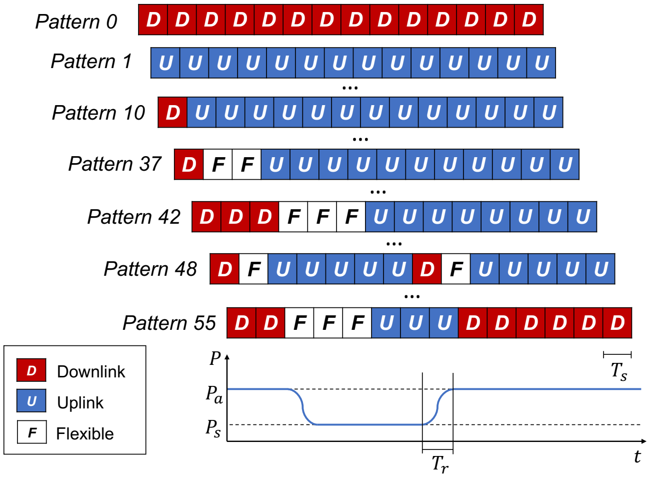


Fig. 2: CDR activation and deactivation

III. PROPOSED COOPERATIVE SLEEP TECHNIQUE

While in LTE TDD, if a subframe (equivalent to a slot in NR) is configured for DL or UL, all of the symbols within the subframe should be used as DL or UL, in 5G New Radio (NR), as specified in [7], the symbols within a slot can be configured in various ways as follows: uplink (U), downlink (D) or flexible (F). Slot configuration is achieved through the exchange between gNB and UE of the *tdd-UL-DL-ConfigurationCommon* message, through which the UE sets the slot format per slot over a number of slots. The UE can be provided also with another configuration message, namely the *tdd-UL-DL-ConfigurationDedicated*, that overrides

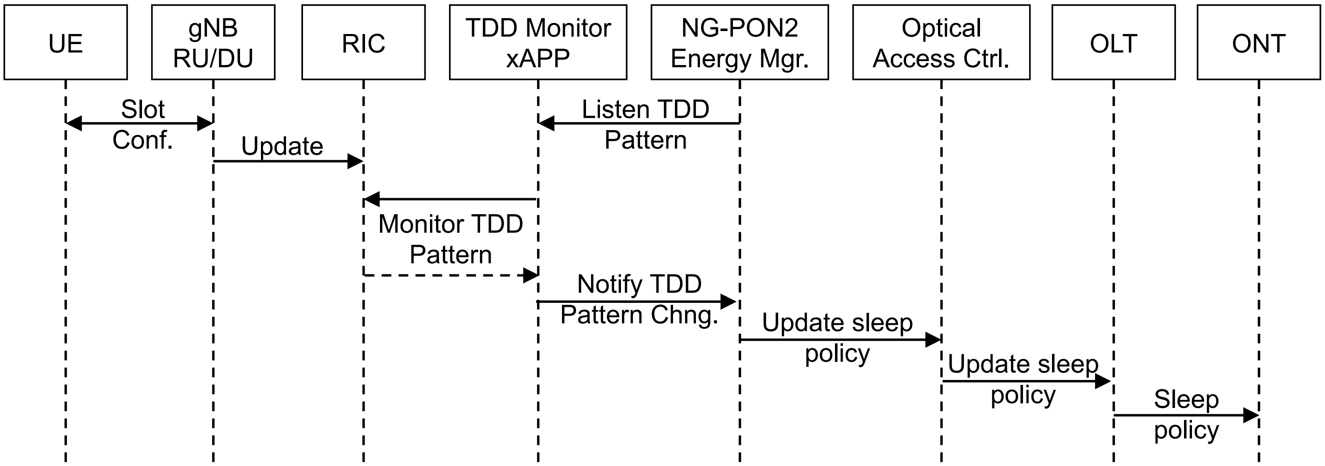


Fig. 3: Workflow

only flexible symbols per slot over the number of slots as provided by the *tdd-UL-DL-ConfigurationCommon*.

For the sake of simplicity, in this paper the *tdd-UL-DL-ConfigurationCommon* is considered only. The *tdd-UL-DL-ConfigurationCommon* provides a slot configuration period (i.e., Transmission Periodicity) of P ms by the *dl-UL-TransmissionPeriodicity* field, a number of slots d_{slots} with only downlink symbols by *nrofDownlinkSlots*, a number of downlink symbols d_{sym} by *nrofDownlinkSymbols*, a number of slots u_{slots} with only uplink symbols by *nrofUplinkSlots*, a number of uplink symbols u_{sym} by *nrofUplinkSymbols*. As reported in [7] a Transmission Periodicity of up to $10ms$ is valid but for a selected set of reference subcarrier spacings (i.e., $\mu_{ref} = 0, 1, 2, 3, 5$ only. For what concerns symbol pattern in a slot, some sample patterns are provided in Fig. 2. In [7] 56 slot formats for normal cyclic prefix are defined and indexed from 0 to 55.

The proposed cooperative sleep technique is based on the directionality of the TDD pattern: when the UE is transmitting uplink (U), downstream transmission from the OLT to the ONT is absent (or minimal) in the PON; when the gNB is transmitting downlink (D), upstream transmission is absent (or minimal). Thus in the former case selected receiver subsystems of the ONT can be turned temporarily OFF and in the latter case selected transmitter subsystems of the ONT can be turned temporarily OFF. The proposed scheme can be applied not only when the x-haul is transported by a TDM-PON but also when a point-to-point connection, such as in WDM PONs, is utilized. In this latter case the scheme is applied to the transceivers, as in, for example, energy efficient Ethernet [10].

As shown in [1] the Clock Data Recovery (CDR) circuitry at the ONT represents the most power consuming element in the receiver front-end, consuming about 43% of the receiver front-end power in GPON. Because the CDR is used for the reception of the downstream traffic, the objective of the energy efficient technique proposed in this paper is to put the CDR in sleep mode when no traffic is transmitted downlink in the air interface (i.e., U slots/symbols), thus no (or minimal) traffic is directed downstream towards the ONT. However, especially if integrated, the whole receiver front-end could be turned-off for further energy savings. Indeed, the whole receiver front-end accounts for about 20% of the whole ONU power consumption in a GPON as reported in [1].

The proposed scheme workflow, shown in Fig. 3 is as follows. The functional elements involved in it are depicted in Fig. 1 and described in the previous section. Once the gNB (or RU, RU/DU) has exchanged the slot/symbol configuration messages with the UE, the TDD Pattern Control x-App sends the configuration to the Access Energy Manager. The Access Energy Manager interacts with the Optical Access Controller that, in turn, selects a sleep time for the ONT. Such sleep time is communicated to the ONT as in formerly devised cyclic sleep schemes [1].

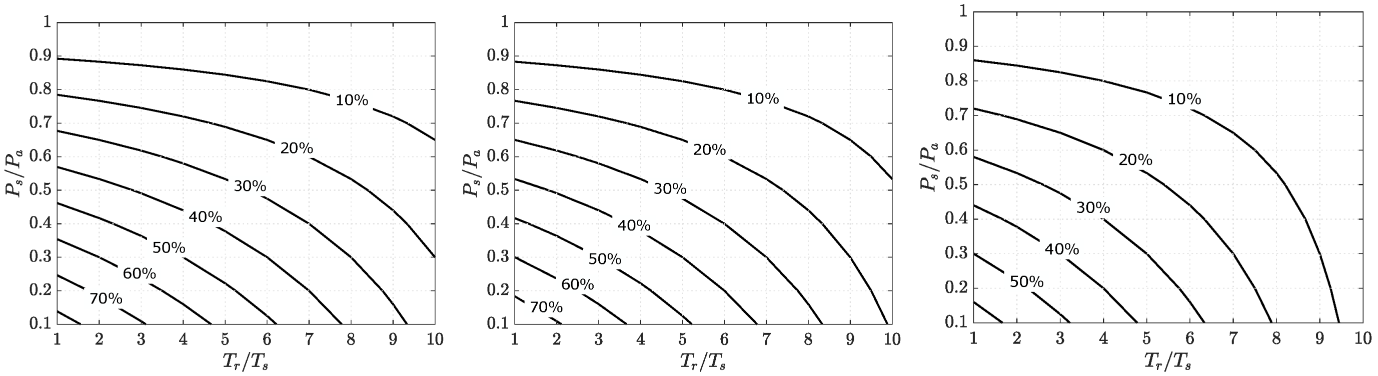
IV. RESULTS

An initial evaluation of the proposed scheme is performed through simulation. Numerical evaluation is performed using MATLAB environment. The considered scenario is represented by a single gNB connected using a PON. The gNB is assumed to adopt a cell-specific TDD slot format configuration (*dd-UL-DL-ConfigurationCommon* in [7]), thus the same TDD pattern is adopted at the same time for all the Physical Resource Blocks (PRBs) assigned to all the UEs.

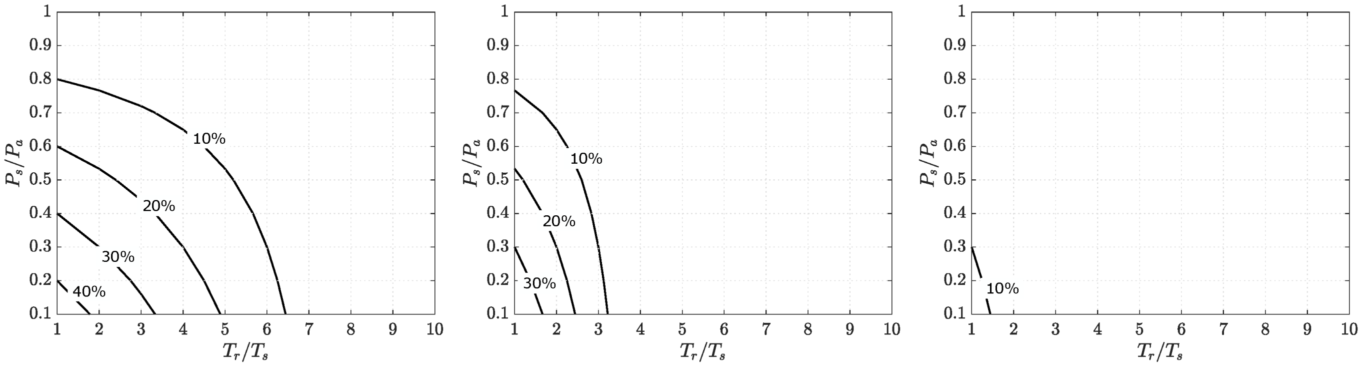
The considered performance evaluation parameter is energy saving. We define the energy saving S, obtained through the proposed cooperative approach, as:

$$S = \frac{E_{BL} - E_C}{E_{BL}} \tag{1}$$

where E_{BL} is the baseline energy consumption, i.e., the energy consumption obtained when the CDR circuitry is always in *active* state on the ONT side, and E_C is the



(a) Pattern 1 (b) Pattern 10 (c) Pattern 37



(d) Pattern 42 (e) Pattern 48 (f) Pattern 55

Fig. 4: Energy savings for different TDD patterns as a function of T_r/T_s and P_s/P_a

energy consumption obtained with our proposed cooperative technique.

We define P_a as the power consumed by the CDR in *active* state and P_s as the power consumed during the *sleep* state in a time window of duration T_s where T_s is the symbol time in the mobile network. It is worth to mention that T_s depends on the 5G numerology adopted at the wireless side and it can vary between 4.17μs and 66.66μs [11]. However, in this study we assume that a single numerology is utilised, symbols have the same length, thus power savings are equivalent to energy savings.

During a period defined by the periodicity P:

$$E_{BL} = P_a P. \tag{2}$$

E_C is, instead, the energy consumption when the proposed cooperative energy saving is implemented. During a period defined by the periodicity P:

$$E_C = P_s T_s (u_{sym} + nu_{sym} u_{slot}) + P_a T_r, \tag{3}$$

where nu_{sym} is the number of uplink symbols per slot.

E_{BL} can be rewritten as:

$$E_{BL} = P_a T_s (u_{sym} + n_{sym} u_{slot}) + P_a T_s (d_{sym} + nd_{sym} d_{slot}), \tag{4}$$

where nd_{sym} is the number of downlink symbols per slot.

The energy efficiency S can be written as:

$$S = 1 - \frac{E_C}{E_{BL}} = \frac{P_s T_s (u_{sym} + n_{sym} u_{slot}) + P_a T_r}{P_a P} \tag{5}$$

For the proposed cooperative technique, the number of symbols spent in the *sleep* state is impacted by the *recovery time* (T_r) needed by the CDR circuit to pass from the *sleep* to the *active* state. As shown in Fig. 2, such time can span over one or more symbols of duration T_s. For this reason we evaluate the achieved energy saving by varying the ratio T_r/T_s since the higher is the time required for the recovery, the lower is the amount of time spent by the CDR in the *sleep* state and consequently the lower the energy saving. Furthermore, the ratio P_s/P_a is expected to represent another relevant parameter as the lower is the power consumed in the *sleep*, the higher is the amount of energy saved. Although the evaluation is performed for the symbol pattern in a slot, similar considerations can be made when the same pattern is considered for the slots in a Transmission Periodicity.

Fig. 4 shows the obtained energy saving as a function of P_s/P_a and T_r/T_s for different TDD patterns. Comparing different patterns, shows that higher energy saving can be achieved with patterns where the number of uplink symbols (U) is higher. In particular for Pattern 1, where only uplink

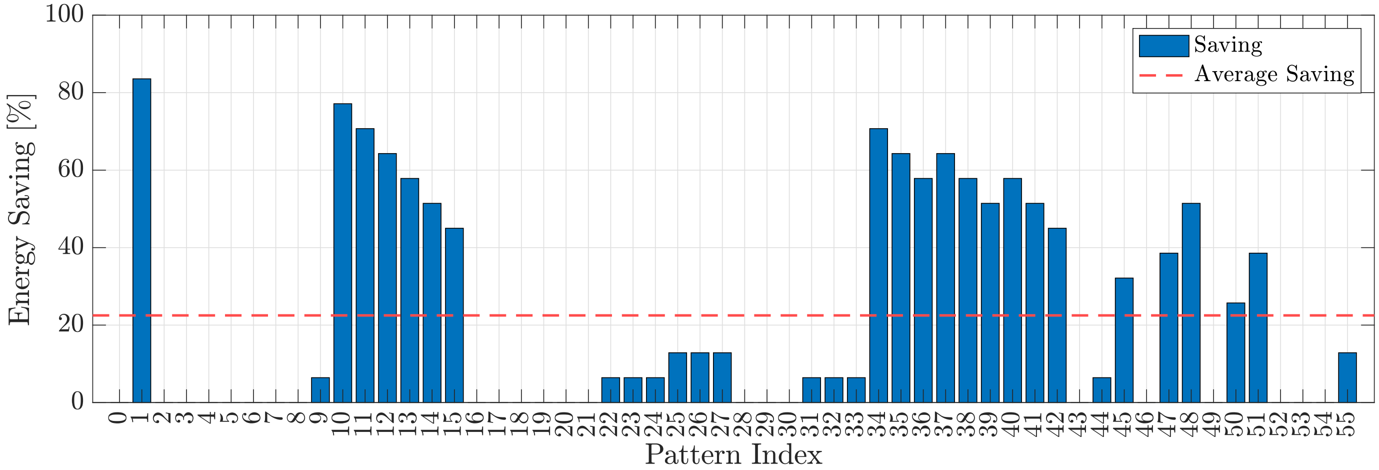


Fig. 5: Saving per pattern and average saving.

symbols are allocated, we can obtain up to 80% saving. In contrast, in Pattern 0, where all the symbols are allotted for the downlink transmission (D) no energy saving can be obtained since there are no opportunities to put the CDR in *sleep* state. Please note that, in order to consider worst case conditions, we assume all the flexible symbols (F) to be allotted for downlink transmission.

The amount of time required for the CDR recovery strongly impacts the energy saving. This appears evident by observing Fig. 4e. In fact, Pattern 48 presents 10 symbols over 14 allotted for the uplink transmission (U). However, the need to recover from the *sleep* state at the 8-th symbol strongly limits the advantages achievable by the proposed technique, which is anyway able to obtain 30% saving. As expected the longer is the recovery time T_r the lower is the amount of time spent in the *sleep* state and the energy saving.

In Fig. 5 we show the attainable energy saving for all the 55 TDD patterns defined by 3GPP. Here, we assume $T_r/T_s = 1$ and $P_s/P_a = 0.1$. As expected, patterns with higher number of uplink slots achieve higher energy saving. By assuming uniform probability distribution among the different patterns, we compute the average attainable saving which is equal to 22.5% and it is reported in Fig. 5 with a dashed line. Note that the implementation of the scheduling of the different patterns is left to the vendor, however it is expected that it will follow network traffic dynamics.

Finally, another relevant aspect is represented by the time required for the communication in between the control layer and the OLT, and the application of the policies transmitted via NETCONF protocol. This delay significantly affects the effectiveness of policy updates and must be taken into account in the design of real systems. We experimentally measure such time by utilizing the commercially available Calix Axos E7-2 NG-PON2. The delay measured for the application of general scheduling policies of variable length (i.e. number of XML lines) transmitted via NETCONF varies between 100ms and 200ms. ML-based forecasting techniques can be employed to predict future TDD patterns, thus enabling the timely deployment of appropriate policies to the ONT via NETCONF.

V. CONCLUSION

This paper proposed a method exploiting 5G TDD and programmability of Open Radio Access Network (O-RAN) and Software Defined Optical Access Networks (SDOANs) for x-haul energy efficiency.

The proposed method consists in turning OFF part of the ONT receiver when the air interface TDD pattern features upstream slots/symbols.

Preliminary results show that for patterns featuring long uplink transmission energy savings potentials are very high, up to 80%. However, the energy efficiency depends on the time to recover from sleep mode and on the time to reconfigure the PON when the traffic pattern changes.

ACKNOWLEDGMENT

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