Energy-Efficient Integrated O-RAN/PON Access Network

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***Abstract*—The adoption of Time Division Duplexing (TDD) in 5G not only facilitates efficient spectrum utilization but also paves the way for the implementation of innovative schemes that leverage the unique characteristics of the TDD patterns. For example, Cooperative Dynamic Bandwidth Allocation (CO DBA) exploits information about the TDD pattern to reduce latency in Time Division Multiplexing Passive Optical Networks (TDM-PON)-based fronthaul.**

In this paper, we harness the information about 5G TDD patterns alongside the programmability offered by Open Radio Access Network (O-RAN) and Software Defined Optical Access Networks (SDOANs) for a different purpose: enhancing x-haul energy efficiency. The scheme we propose seeks to minimize the energy consumption of PON-based x-haul networks by dynamically adjusting the operational states of selected subsystems within the Optical Network Terminal (ONT) in coordination 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

Several strategies have been already proposed for energy conservation in Time Division Multiplexed Passive Optical Networks (TDM-PONs). These strategies have been incorporated into industry standards with the dual goal of extending the operational lifespan of Optical Network Terminals (ONTs) during main power outages and reducing their average energy consumption. This is achieved without impacting the quality or availability of services [1], [2]. Additionally, TDM-PONs are considered for supporting fronthaul connections, particularly between Radio Units (RUs) and Distributed Units (DUs) [3].

In this context, the latency requirements imposed by certain 5G functional split options might be critical [4]. Specifically, when 5G Medium Access Control (MAC) functions are situated remotely from the RU, located in the DU or the Central Unit (CU), corresponding to split option 4 or higher — the fronthaul interface is subject to stringent latency requirements, typically in the order of hundreds of microseconds [3]. To address this, Coordinated Dynamic Bandwidth Allocation (CO DBA) methodologies have been proposed to minimize the latency in the upstream direction of PONs, thereby satisfying the fronthaul's latency specifications [5], [6].

CO DBA establishes an interface for the Optical Line Terminal (OLT), connected to the DU, enabling it to acquire insights into the wireless scheduling. As an example, such information might consist of the Time Division Duplexing (TDD) patterns employed in 5G for sharing the wireless medium for uplink and downlink transmissions [7]. These insights allow the OLT to anticipate the volume and timing of the fronthaul (FH) signal arriving at an ONT, thereby decreasing the latency in the uplink transmission.

The advent of software programmability and the open architecture of software-defined mobile networks, particularly O-RAN, facilitate a collaborative synergy between RAN and optical transport networks. This integration has been recognized for its potential to enhance network efficiency and reduce the total cost of ownership for network operators [8]. Concurrently, the emergence of Software Defined Optical Access Networks (SDOANs) introduces the capability to implement adaptable strategies for bandwidth allocation and energy efficiency, employing a dynamic and programmable approach [9].

From the energy saving perspective, PONs represent an interesting playground thanks to the possibility to dynamically switch ON and OFF specific network components (such as lasers, electronic circuitry, network interfaces) according to traffic conditions. Table I shows the power consumption levels for ONT active and idle states for different PON technologies [10]. Such flexibility can be exploited in conjunction with software defined programmability of PON and O-RAN to effectively achieve energy saving in PONs while adapting to mobile network traffic conditions.

This paper, building upon [11], details a cooperative strat-

TABLE I: ONT power consumption levels [10]

Technology	Idle State Consumption [W]	Active State Consumption [W]
GPON	2.7	2.9
1G-EPON	2.7	2.9
10/1G-EPON	2.8	3.8
10/10G-EPON	3.0	5.0
10/2.5 XG-PON1	2.8	4.5
10/2.5 NG-PON2	3.0	4.5
10/10 XGS-PON	3.0	4.8
10/10 NG-PON2	3.3	5.5

egy, akin to CO DBA, that harnesses the programmability features of O-RAN and SDOANs. Our proposed methodology exploits the TDD used in the 5G physical layer to reduce the fronthaul energy demands. This approach combines the cyclic sleep mode delineated in [3] with the PON's capability to synchronize with wireless scheduling. The proposed methodology involves deactivating selected receiver components of the ONT when 5G New Radio (5GNR) slots or symbols are allocated for uplink communication. Notably, the versatility of the proposed technique allows for its application across various x-haul interfaces (e.g., fronthaul, midhaul, backhaul), accommodating different configurations of next generation NodeB (gNB) splits, or even in the absence of splits.

Preliminary simulation results indicate that energy savings of up to 80% can be realized in TDD configurations where upstream traffic predominates.

II. System Model

We consider the reference architecture illustrated in Fig. 1, in which a gNB (or alternatively, a RU or RU+DU) is connected through a PON to the core network (or to a DU+CU/CU, and then to the core network). The wireless side employs TDD as the duplexing mechanism. At the network's edge, the gNB/RU/RU+DU is equipped with an ONT, while the DU/DU+CU is positioned at the OLT side. The PON can be configured according to the adopted mobile configuration. In scenarios where an RU is situated at the ONT side, the PON serves as a fronthaul infrastructure, implementing ad hoc resource allocation strategies to achieve the low latency required by fronthaul operations. Conversely, when the RU+DU or gNB configurations are located at the ONT side, the PON takes on the role of mid-haul or backhaul infrastructure, respectively. In these cases, dynamic bandwidth allocation strategies are employed, tailored to meet the demands of specific end-to-end services.

The PON is managed by an Optical Access Controller (OAC), that communicates with an agent situated at the OLT via the NETCONF protocol. The primary role of the OAC is to enforce policies related to the management of quality of services, bandwidth allocation strategies, and energy efficiency. Furthermore, it provides northbound Application Programming Interfaces (APIs), enabling operators or third parties to implement their desired software-defined control mechanisms.

The management of the Radio Access Network (RAN) is governed by a so-called Radio Intelligent Controller (RIC), as defined by the O-RAN alliance. The RIC is tasked with decision-making across two temporal scales. The Near Real Time (Near-RT) RIC is charged with implementing decisions and conducting monitoring activities on a millisecond time scale, facilitated through the standardized E2 interface. This Near-RT RIC engages in interactions with a Non-RT RIC, which is responsible for setting policies on a time scale of $\geq$ 1s. Atop the Near-RT layer, specialized applications known as xApps are deployed to execute the control logic specified by the network operator. These applications leverage APIs provided by the Near-RT RIC to implement their functionalities.

On top of the network controllers two applications are realized to facilitate energy savings within the PON x-hauling infrastructure. Specifically, a *TDD Pattern Monitor* xApp is dedicated to monitoring the TDD pattern at the cell level, monitoring the communication between the User Equipments (UEs) and the RU/gNB. This *TDD Pattern Monitor* xApp works in synergy with an *Access Energy Manager* application. The latter is crafted using the OAC APIs and is tasked with

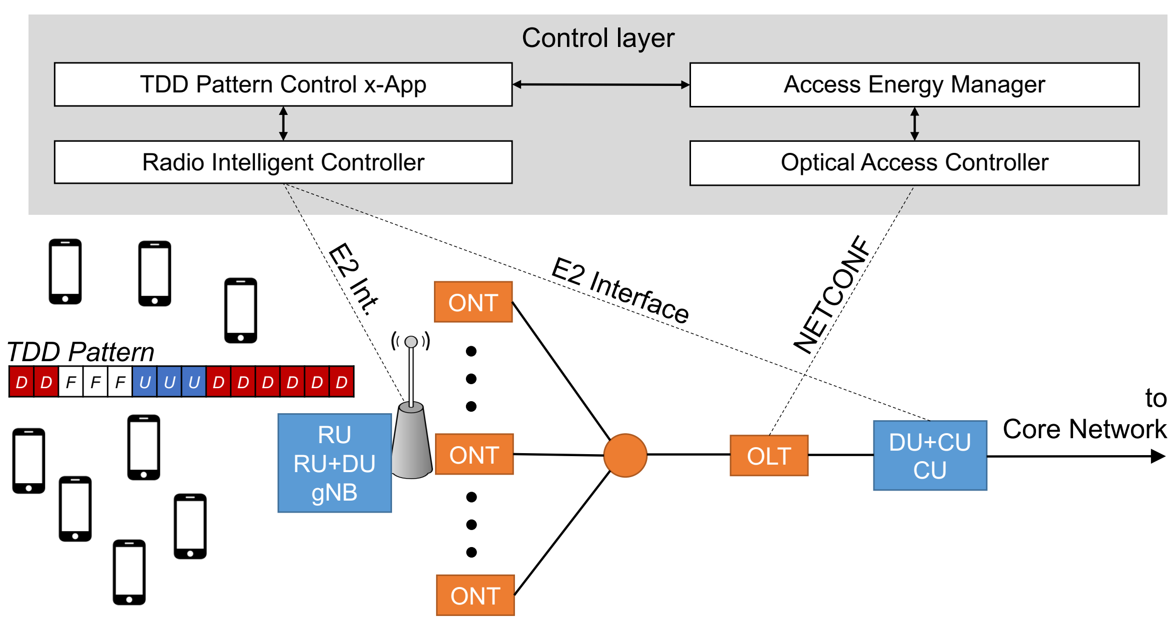


Fig. 1: System Model

orchestrating optimized energy efficiency operations within the PON, a process that will be elucidated further in the subsequent section.

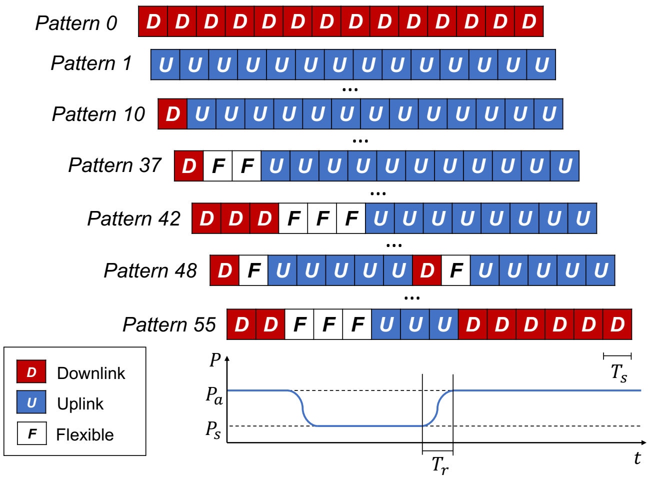


Fig. 2: CDR activation and deactivation

III. Proposed Cooperative Sleep Technique

In LTE TDD, a $1ms$ subframe, within the $10ms$ frame, is configured for either downlink (DL) or uplink (UL) transmission. 5G New Radio (NR) introduces a more versatile approach. As specified in [7], 5G NR allows that the slots within a subframe and even the symbols within a slot can be configured as uplink (U), downlink (D), or flexible (F). As reported in [12] each subframe contains slots of 14 OFDM symbols. The number of slots within a subframe varies and it depends on OFDM symbol duration that, in turn, depends on the specified numerology/subcarrier spacing.

This flexibility in slot/symbol configuration is enabled by the exchange of the *tdd-UL-DL-ConfigurationCommon* message between the gNB and UE, enabling the UE to determine the slot/symbol format on a per-slot/per-symbol basis across a sequence of slots/symbols. Additionally, the UE may receive a *tdd-UL-DL-ConfigurationDedicated* message, which provides the ability to override only the flexible symbols per slot, according to the framework established by the *tdd-UL-DL-ConfigurationCommon*.

For the purposes of clarity and simplicity within this paper, only the *tdd-UL-DL-ConfigurationCommon* message is taken into consideration. This message establishes a slot configuration period, or Transmission Periodicity, of $P\ ms$, as indicated by the *dl-UL-TransmissionPeriodicity* field. It specifies a number of slots d_{slots} dedicated exclusively to downlink slots, as defined by *nrofDownlinkSlots*, and a corresponding number of downlink symbols d_{sym}, as detailed by *nrofDownlinkSymbols*. Similarly, it designates a number of slots u_{slots} for uplink symbols exclusively, as defined by *nrofUplinkSlots*, and a number of uplink symbols u_{sym}, as defined by *nrofUplinkSymbols*. As documented in [7], the Transmission Periodicity can extend up to $10ms$, although this is valid exclusively for a selected set of reference subcarrier spacings, specifically $\mu_{ref} = 0, 1, 2, 3, 5$. Regarding the symbol pattern within a slot, Figure 2 provides examples of some pattern configurations. In the standard [7], a total of 56 slot formats for the normal cyclic prefix are identified 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 [13].

The cooperative sleep technique we propose leverages the directional nature of the TDD pattern: during periods when the UE is engaged in uplink (U) transmission, the downstream communication from the OLT to the ONT within the PON is either non-existent or minimal. Conversely, when the gNB is handling downlink (D) transmission, upstream communication is similarly absent or minimal. Accordingly, in the former scenario, selected receiver subsystems of the ONT may be temporarily deactivated, while in the latter, it is the selected transmitter subsystems of the ONT that can be temporarily switched off. This scheme is not exclusively applicable to x-haul transport over Time Division Multiplexing Passive Optical Networks (TDM-PONs) but can also be extended to point-to-point connections, such as those in Wavelength Division Multiplexing PONs (WDM PONs). In the context of point-to-point connections, the scheme is applied directly to the transceivers, akin to the principles of energy-efficient Ethernet [13].

As highlighted in [1], the Clock Data Recovery (CDR) circuitry within the ONT is identified as the most power-hungry component of the receiver front-end, accounting for approximately 43% of its power usage in Gigabit-capable Passive Optical Networks (GPONs). Given that the CDR's primary function is to facilitate the reception of downstream traffic, the energy-efficient technique introduced in this paper aims to transition the CDR into sleep mode during periods when downlink traffic is absent/minimal in the air interface (i.e., during U slots/symbols), thereby minimizing downstream traffic towards the ONT. Moreover, for further energy conservation, the possibility of deactivating the entire receiver front-end is considered, especially in integrated systems. This approach is substantiated by findings that the complete receiver front-end contributes to around 20% of the total power consumption of an ONT in a GPON, as reported in [1].

The workflow of the proposed scheme is illustrated in Fig. 3, with the involved functional elements depicted in Fig. 1 and illustrated in section II. Following the exchange of slot/symbol configuration messages between the gNB (or RU,

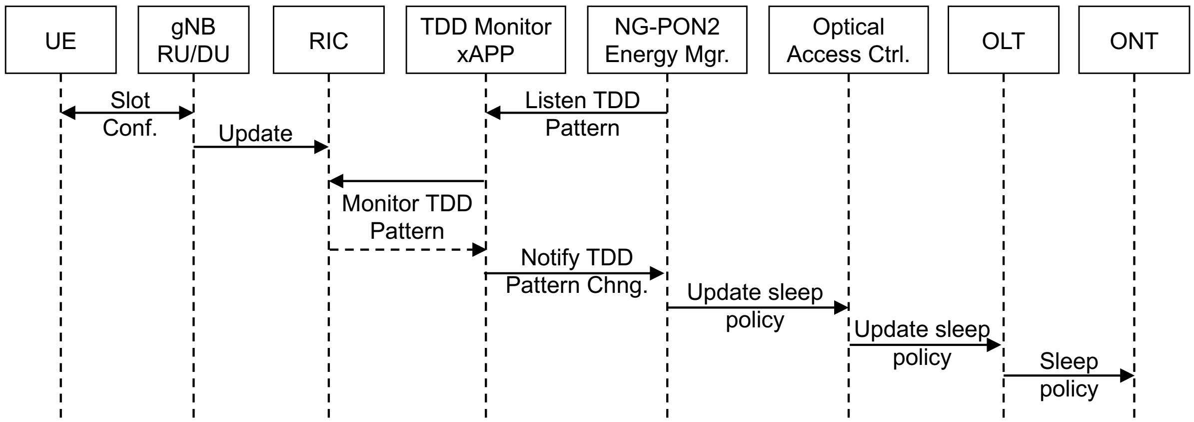


Fig. 3: Workflow

RU/DU) and the UE, the TDD Pattern Control xApp forwards this configuration to the Access Energy Manager (in figure referred to as NG-PON2 Energy Mgr.). The Access Energy Manager then collaborates with the Optical Access Controller, which determines an appropriate sleep duration for the ONT. This sleep time is subsequently communicated to the ONT, employing a methodology akin to previously established cyclic sleep mechanisms [1].

IV. Results

An initial assessment of the proposed scheme has been conducted through simulation, with the numerical analysis carried out within the MATLAB environment. The scenario under consideration involves a single gNB interconnected via a TDM-PON. It is assumed that the gNB employs a cell-specific TDD slot format configuration, based on the *dd-UL-DL-ConfigurationCommon* information [7]. Consequently, a single TDD pattern is applied concurrently across all the Physical Resource Blocks (PRBs) allocated to the UEs.

The primary metric for performance evaluation in this study is energy saving. We quantify the energy saving S, achieved via the proposed cooperative approach, as follows:

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

where E_{BL} represents the baseline energy consumption, that is, the energy consumed when CDR circuitry remains in an *active* state on the ONT side always, and E_C denotes the energy consumption achieved utilizing our proposed cooperative technique.

We denote P_a as the power consumption of the CDR circuitry in its *active* state, and P_s as the power consumed during the *sleep* state. T_s represents the symbol time in the mobile network, which depends on the 5G numerology/subcarrier spacing employed in the wireless interface. According to [14], T_s can range between 4.17μs and 66.66μs. For the purposes of this study, we operate under the assumption that a singular numerology is in use, resulting in uniform symbol lengths.

During a period T_P, defined by the Transmission Periodicity P:

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

E_C represents instead the energy consumption when the proposed cooperative energy-saving scheme is in effect. This consumption is calculated over the period T_P as:

$$\begin{aligned} E_C = & T_s \left[P_s(u_{sym} + nu_{sym}u_{slot}) + P_a(d_{sym} + nd_{sym}d_{slot})\right] + \\ & + (P_a - P_s)T_r \end{aligned} \tag{3}$$

where nu_{sym} and nd_{sym} are the number of symbols per uplink slot and downlink slots, u_{slot} and d_{slot} are the number of uplink and downlink slots (i.e., the slots where all the symbols are either uplink or downlink symbols), and u_{sym} and d_{sym} are the number of uplink and downlink symbols in a slot with both uplink and downlink symbols, T_s is the symbol time, and T_r is the recovery time required by the CDR circuit to transition from the sleep to the active state (that is the time for which the CDR must be on during the uplink symbols to recover synchronisation).

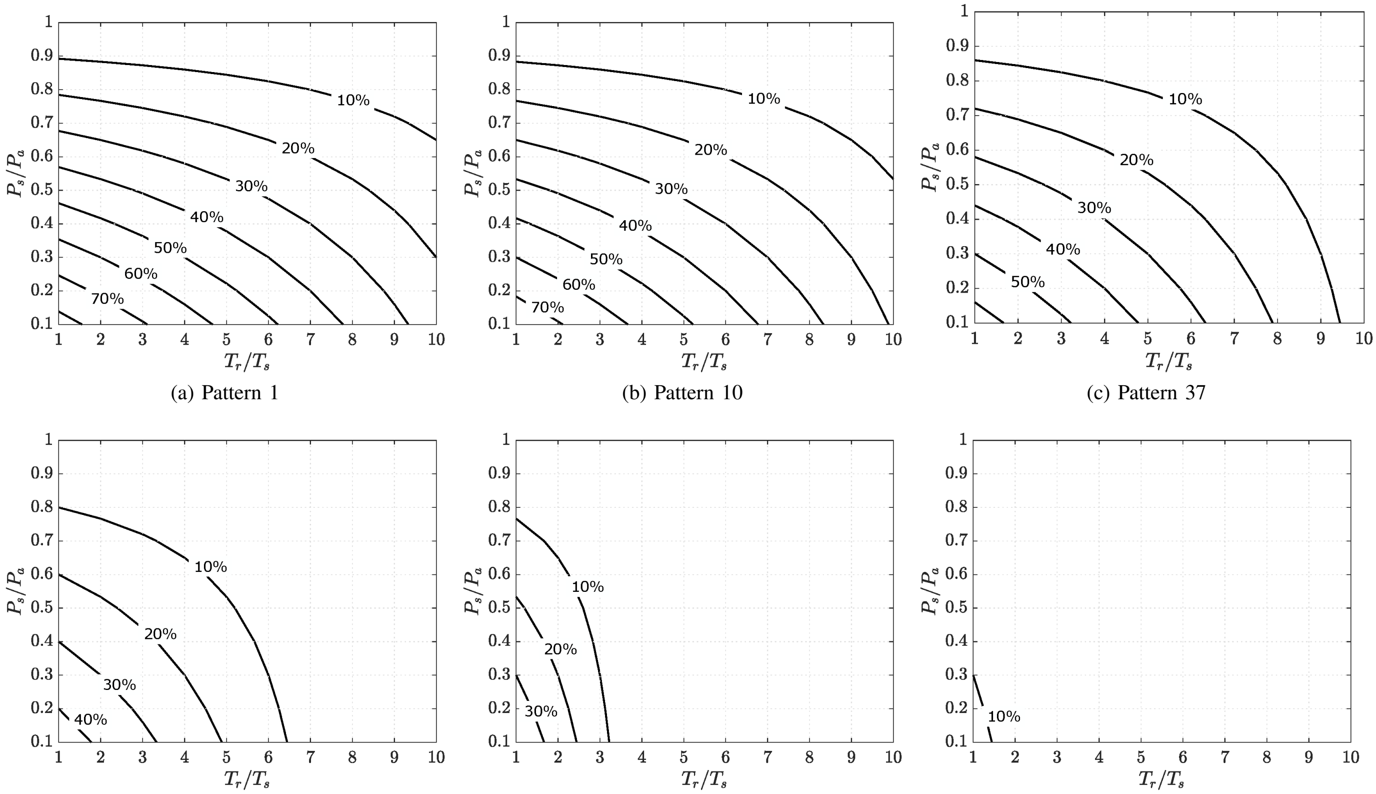
E_{BL} can be rewritten as:

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

Then, the energy efficiency S can be written as:

$$\begin{aligned} S = & \\ & 1 - \frac{T_s\left[P_s(u_{sym} + nu_{sym}u_{slot}) + P_a(d_{sym} + nd_{sym}d_{slot})\right]}{P_a T_P} + \\ & - \frac{(P_a - P_s)T_r}{P_a T_P}. \end{aligned} \tag{5}$$

For the proposed cooperative technique, the efficiency in energy saving is significantly impacted by T_r required for the CDR circuit to transition from the *sleep* to the *active* state. As depicted in Fig. 2, this recovery time may encompass the duration of one or several symbols, each lasting T_s. Consequently, the energy savings are assessed by examining variations in the ratio T_r/T_s. A higher recovery time diminishes the duration



(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

the CDR spends in *sleep* mode, thereby reducing potential energy savings. Additionally, the ratio P_s/P_a emerges as a critical factor; a lower power consumption in the *sleep* state correlates with greater energy savings.

While this evaluation focuses on the symbol pattern within a single slot, analogous considerations apply to the repetition of this pattern across slots within a Transmission Periodicity.

In this paper, the evaluation focuses on the symbol pattern within a single slot, thus when $T_P = 14T_s$ Fig. 4 presents the energy savings achieved as a function of the ratios P_s/P_a and T_r/T_s, across different TDD patterns within a slot among the ones reported in [7]. The comparative analysis of these patterns reveals that more significant energy savings are attainable with patterns featuring a higher number of uplink symbols (U). Specifically, Pattern 1, characterized exclusively by uplink symbols, facilitates energy savings of up to 80%. Conversely, Pattern 0, which dedicates all symbols to downlink transmission (D), does not afford any energy savings, as there are no intervals during which the CDR can be transitioned to the *sleep* state. It is important to highlight that, for the sake of adopting a conservative approach, we assume that all flexible symbols (F) are designated for downlink transmission in our analysis.

The influence of the CDR circuit's recovery time on energy savings is clearly demonstrated in Fig. 4e. This figure elucidates the case of Pattern 48, which allocates 10 out of 14 symbols to uplink transmission (U). Despite this allocation favoring energy savings, the necessity for the CDR to exit the *sleep* state at the 8-th symbol, because the 10 uplink sybmols are grouped into two non-consecutive groups of 5 symbols each, significantly curtails the benefits afforded by the proposed technique. Nevertheless, a 30% energy saving is still achievable. Consistent with expectations, an extended recovery time T_r inversely affects the duration for which the CDR can remain in the *sleep* state, thereby diminishing the potential for energy conservation.

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.

A critical factor impacting the efficacy of policy updates in our proposed scheme is the communication delay between the control layer and the OLT, particularly concerning the transmission and enactment of policies via the NETCONF protocol. This delay is a crucial consideration in the design of practical systems due to its significant impact on the timeliness of policy

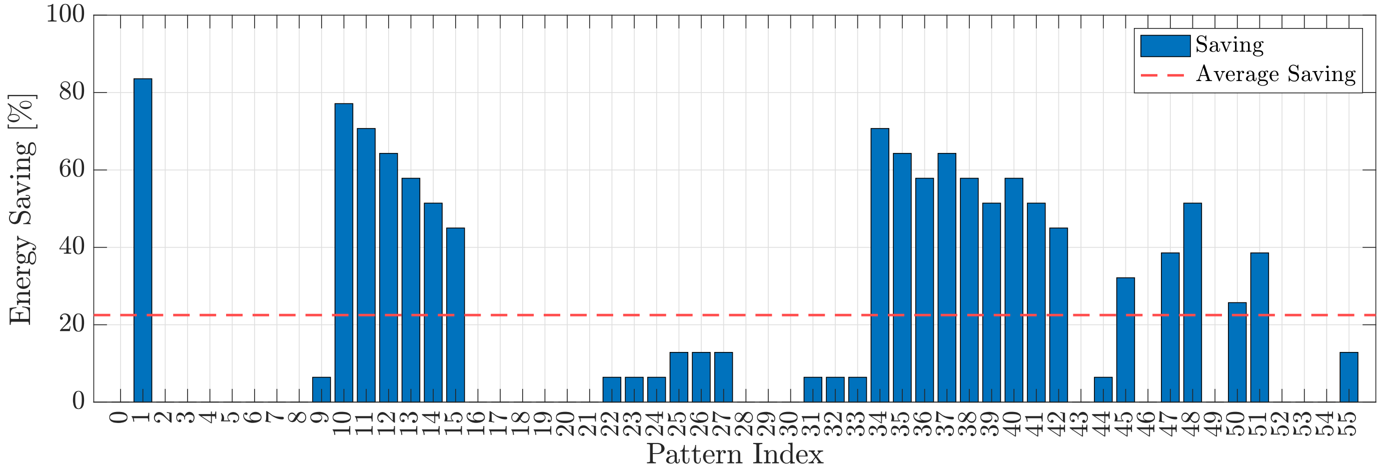


Fig. 5: Saving per pattern and average saving.

application. Through experimental measurements conducted on the commercially available Calix Axos E7-2 NG-PON2 system, we observed that the delay associated with applying general scheduling policies—quantified by the variable length of the transmitted XML lines via NETCONF—ranges between 100ms and 200ms. To mitigate the potential adverse effects of this delay on system responsiveness and efficiency, Machine Learning (ML)-based forecasting techniques can be leveraged. Such techniques are capable of predicting future Time Division Duplexing (TDD) patterns, thereby facilitating the proactive and timely deployment of optimized policies to the ONT through NETCONF.

V. Conclusion

This paper detailed a novel approach that leverages the TDD capabilities of 5G, along with the programmability afforded by O-RAN and SDOANs, to enhance energy efficiency across x-haul networks. The core strategy involves deactivating portions of the ONT receiver during periods when the air interface TDD pattern presents upstream slots/symbols.

Preliminary analyses indicate that, particularly for TDD patterns characterized by extended uplink transmissions, the potential for energy savings is substantial, reaching up to 80%. Nonetheless, the realization of such energy efficiency is contingent upon the recovery time from the sleep mode and the reconfiguration latency of the PON in response to dynamic traffic patterns.

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