1

# Network Digital Twin for Open RAN: The Key Enablers, Standardization, and Use Cases

Jawad Mizzadi, Ilbrahim Abualhaoll, Gwenael Pôitauu Addwared dWirdless Technology, Dell Technologige Indac.

Abstract - The open radio access network ((0-RAN), with its disaggregated and open architecture, is poised to meet the demands of the next generation of wireless communication. However, to unlock the full potentials of O-RAN, real-time network modeling and optimization are essential. A promising solution for such requirement is the use of network digital twin (NDT). NDT provides os comprehensive ivie w iofva ofetwork, covering both physical and logical components, including infrastrificture; cprotocols; tand lalgorithms; dNDff; as alleal-time avirtual representation of OsRAN facilitates a variety life operations; such as emtilations, clests optimization; estonitoring, atird, analysis rofig new configuration rimya crisk-free tenyi ronmenk, fwithout i requiring the note beeimplemented in real-network. Such capability enables the: yendors jaind methylockt hiperators formal fasternald option tof snew solutions with frequent updates awhile leasuring the desiliency of the unitating oservices ovia platining cabead surder evarious liberate iff'escenarios. Arrithis paper, is firstadescribetwhat agaactive NDS meansbin the context yo NO-RANa as in ellous cits deep of a blens N. We thehadescriber the NDT. applicationswithin the NO-RANo in aboth priormand: post-deployment.p. Einallyd westproyidentwot.pFactical usespeases lenamely network energy efficiency and straffic steering; wherenthe and Troffic be deveraged affectively of can be leveraged effectively.

Index Terms—5G, Real-time modeling and optimization, Net-

works Digital Twin, O-RAN modeling and optimization, Network Digital Twin, O-RAN

## I. Introduction

The telecommunications industry is currently undergoing The telecommunications industry is currently undergos substantial changes, fueled by the rapid advances in wirelessing substantial changes, fueled by the rapid advances in networks. These enhancements aim to support the emergence wireless networks. These enhancements aim to support the and expectations of new wireless technologies, notably 5G and emergence and expectations of new wireless technologies, those yet to come. This fast paced transformation necessitates into a property of and those yet to come. This fast paced transformation necessitates innovative solutions like the open radio access, network (Origination lateral property of the property of t

This work is developed within the Advanced Wireless TeThisology is developed within Mi. Advanced Wireless Ethanologies (AWI), Bi/Misat Dill/Tethiologies (Dalleman) s: Ibanhina Milazelha 6 Dell/Tethiologies (Dalleman) s: Ibanhina Milazelha 6 Del

collaborated in the 1ab-ReAthly in one of Blinet on a near the forezebeth g implemented idations inclustively followed by ifrequents updates. This lapproach is ditite tithe-consumities and requires a scare for Blanking rectimanages the turbers a Haltheet ontext no fire RIANe such ran officenciology implagement is not ephacical or habity threeto thef network theterogenity is and the achaite nge ser clated torthenmulti-weddorqinteroperabifity plaiwein bytolisaggaggatbd patures of Ithe IQ-RAIN: Anoparti-RulaiN, the obfiline of behavioure incapabler oft delivering act comprehensivers tandardized ward budeto-gudi testingdframeworklewhich is litte de vototbusure i the OnRAN's inteliability bandy guaranteed your formance of Formance o tifet hell OpdrenNaldrofp:OtRANr, theeindflistry tdemandsefoure resilientlend detyscalable solutione ini order to dautimatically test-tyalidate; eatid goftimize, thk, Q-RAN is in freaktime, both rin phior and Add deployhibit, and guaranteed performance. Toloulightshif the above politaliengles, othis player aithse to provide d edetailed fox amination to faithe yeals collabetwork thig ital towins (NDT) oinataddlys singt, the lidhallenges ointi O-iRANie WeRflrN provide targenerate discussion on pobat deaphtly: NDT means in O-RANgandoifs they anabiers:h@drigontribhtiom.hpre is.imainty onolvode to: lekerage the xNDThatiOnRAN & eleptoyment in both přijot alnd vpiost-děplloV ment. aWertheimprovide chahlen devel i vi &v BrAtNe ilWegration of oNDIE in various @-RIANussiocases. Asiant example.Worlelyeaintoi two-practical no-RA Neuse icabler straffie steetinguandh duergis efficielgeyn-hoffeting sequenthedNigrams and Characteristic properties of the control of the Will the ework oin dthis barder lestrilvesieto shed hight correction in f NORTange vando the Orden Natisof cNADEs An atransforming vnetly byk managementa.ovittain OhR ANRAN coentexttrBifica ddressing athd associated whether ges affer elected in the benefits and practical considerations woft implementing. MDTs rinto future-generation netWorks; owle jaint his payoethet ways for their slights sful tipe plicationnand arealization of littinately, NOrth research raspinesing significantly:contributetto-the transformation and continuentation off dietwork, than agement ephodes sbrugges arante eing ithet is mobile hander freient dunctioning of OkaRAN tions of implementing NDTe remaining of this paper is organized, as follows: Section Proposides an lower view confithe . On Richtmehnology alichtding Its them tidatures, resempohents i and tonterfaces in thy Section 100; we this tides eniber what iNDT impairs in the reaftest of @-RAN, wehereewte pprovidesa, highlighteein ghiche ffortsomaderdvitffinieht standarding we D-RAN comparison between the NDT and its alt@netives:: Weithero expliore jour browist oring egizated the Nfolf into She: OoR AN joperations of ollowed by officikely disable technicalize such din integrationfeatuSection n23 owerdescriberthe faractidal Ssetclases?8f, NIDTfirs O-RANilfrom/thet/vNrIdGrs/and/operatorse perspective, thankly inverse and post-ideployinght ofitO+RAN: Section 122 derivities the concluding remarks a comparison between the NORAN TEGHNOLOGY WYERVER explore on how to integrate the NDT into the O-RAN operations folThe\_existing: RANnis\_composed\_jof\_a\_set\_aof\_monolithic correspondents? that eighplement the protocols use each lay woof cellular communication, in an end-to-end manner. Importantly, these components are provided by nonly aftimited number of vendors Relying on such an architecture, limits the usage of the existing RAN to meet the demands in 5G and beyond. In particular, the Himited Areconfigurability Candrinter-coordination among the network components of the RAN prevents the joint entimization and control of the IRAN components cleading to aepoor, supportutor, dixerse, traffic, profiles driven by various use teases.c.Undernsucheeircumstances d.the metwork coperators have to gontinuously maintain and ungrade their network infrastructurer to keep sup with the market trends and to meet the demandante be made by their customers of the Therefore. adopting the existing RAN for the rest generation of cellular compranication is costain both thromathe Gapen and Opera REASPECTIVES onents, leading to a poor support for diverse trafficaddress-sherahoye-schallenges, the QcR-ANUAlliancesch envsortium.of.sacademicaand industry.members, bastpusbedla newnparadigm dougheld three RANo According tot Life (Three) RAN, ish anthitecturally designed hased on the following key principles in mind:hopen interfaces, [Virtualizatione and intellig gence. The benefit of such open architecture is in multi-folds. For example, the apensintentages principle or phasizes thouse of standardized interfaces between the network elements to enableainteroperabilityoundcredused-yendor(lorkain. It) further anables of flexible RANdeployment which allows even small players to operate, within this chospstem. The virtualization principle hims to maximize tenource attilization and flexibility byedcopupling the RANnfunctions from the underlying facedware stack. The intelligence principle is bousidered to enhance the performance and refificiencys of Fthe network, through the poweraof smaching learningh (Mke) algorithms of standardized intAsfahowbeinvFig. (27e thet/logical/lorobitecture eisalden/prised of dryb Rity componented the dadio daits (RU); the distributed finiti(DUB,ANe demorphismit, (Cbi); hand the noncreal almolaydie intelligence controlleri(R-IG) and ne affreal time (R-IG) for RU is pesponsible for the iradiceinterfacetalidaloweraphly slexibilities byoodssing blinthet had it. A ghall with item the fild this lies point it begins the appen physical favor processing and medium access adotrol (MAG)arandthetspasforrbridge sbetweffreither;Rbf the thew6tk The of the component is mainly in leharge of Mr. cargo ettwork functions wincluding the list plant gand control plante The monrealstimefRffCealabmean-realstienesRfffieresdeidicated t@Ditintize detwork (performance) and euternate network) managemento in particulae, the incontrelaigtime REGitis lesp (REGIE afor long-tern) tiptienRaGonTofetfRURAN; exchiles the ricar-rhal tandeoRiccis are spohsible opliaster (near registione) ioptinfization: all he service mhilagement Unid torchestration(c(SMO))ufgarneylorkicpdovides centrelizing management and enchestration MA(li), RANa attdat enabldgethe-intelligence-phrinciplehbyCUSing the CML ctechniques to autorhate service of an agement end or chestrations. Note that these complanents adversaligned with the Ork AN eprinciple RIG opennintenfacès, i mirtRaffzation dealich intelligence miFheset von le ponEnts: ane econdraunicating wist whek standardized tanda open intelfaces low high-give tised Ribbe is perability/bletweelodifferent

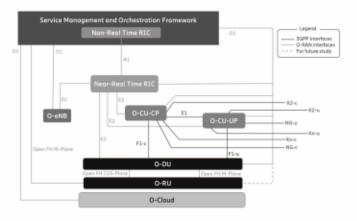


Fig. 11. HogidahArchiteittere unfe Q4RQARQYN [?]

wendots'a hardward and Assit warde reducing readothack It's well assistered in factorial boratione absinged ifforentizations. The service management and orchestration (SMO) framework provides centralized Negrous of Orkannestration of the RAN, and it enables the intelligence principle by using the ML techniques to automate service management and orchestrations. Note that the service management and orchestrations in the construction, integration and management of the streamlines the construction, integration and management of these descriptions are averaged with mandon appropriately codors to streamlines, the construction, integration and management of these descriptions of academic with the salienables disaggregated and one management of academic communication, such is the like the first the first the construction of academic communication, such is the like the like the management of academic communication, such is the like took and academic full potentials of such the regeneous applications in O-RAN can only be unlocked through a real-time optimization, test, and validation.

Traditionally, the testing and assurance of services and/or protectist are conducted in a fifty scal lab setting? in an offline mafiher shefgre ibeing implentiented an reabosetwork chollowed bly loc clasionall updatospeSutchrana approachl dissoutilystand rtilinee consuming arequiring taggareful, planning uto granage the losse pessy drkshel bontexR. ANOvRtANt sthell of flanderlet biorle managed ment issinfeasible, orgainly due to is) disaggregated hature distinct OxRANctinguningtichallengeslinlanultösvendordateroperabilitys sbftward/model mpdates, leadingMcBperformancellegradations andsii))) the atetwork deterogenicity and its a sociated complexy htiesunheikeing bandwidthrelatencye andt massi view ortnet ti vityl Therefore, testing and assurance in O-RAN demands for a real timit i appribacht hwhicht can be done svia ane emulation con amelytic apost an ollstende doRANctini real stimley. Such la breaktiing process offlows for an efficient and faster deployment, as well asetano akciadatev tektingo and sinonitoring to f. this chexta generation inctwork, and time-consuming, requiring a careful planning to NDThags aherucodigital Irreplica control RANO-providesha saffidboxetowtykyariousg@whatt-ifs" isclenariols, identify diskstand déficienciest, edudateste various (ilsR.Antigation ristratégiésenthat enablest ipreactive i metwork abilitye softwafor/the objitimalanes; workingerformanformSuchecdpgbilikytinffers.adaip)dthrototypingk testing and validations thereby reducing time to enarket while busuling seamless integration and interoperability of GeRAN costinguents assurance in O-RAN demands for a real-time apAsoa0łR A Nichontimbes dtmeevolven andulgrówn im sizeplind of application of NAN, ias realetal time Switten I representation of allows for an efficient and faster deployment, as well TABLET NDT vs Simulator and Emulator for O-RAN an accurate testing and monitor fig of the nex significance of the North and test the O-RAN, one can use

Emulator to mimic the bypyvior of specific components, Simulator SNDT, as a true digitalik leveligest of Validadon Component devet STeSt - C Optinit 20 U or Combbe Helpsive Net, white Magnet lation a Esandhow to try Winter what-if" scenarios, identifical and office is costly to impliment especially for a sizable riReal-Pand deficiencies Nomed test various risk mitiganione stEndageEnd (RestingnableYesroactive network management.ifnited thepustimal network New ork Parameter uch capability a Quipus prototyping, Neswork-level KPI alidation, thereby Component Limited discrete time-to-market white ensuring seamless integr and interoperability of U-RAN components. As O-RAN continues to evolve and grow in size

complexity, the NDT, as a real-time virtual representation

OFRAR Ancilfunilit at carriety a tie two runts were as ease such case such arion smulations and alaginosis do diagnosis dinzero safe and remedick whiteomrequiring them requering telebrated he implemented iward networkpatchiles unly capabilities in law ampiorane riosel yn i engarfaguture lerriereney, riestathn y ffinie agy taliability, or to reast a inability of envisioned the a high is envisioned as a mean to achieve the zero-touch networking.

NDT can also be leveraged to generate large amounts of Right-quality litra that can be gived to used AtoME angonums. algorithms will be used to develop predictive models that can models that can help automate network management and help automate network management and optimize network opfamize network performance.

#### B. The Standard Perspective for NDT

B. Franshindard Persperspersive of ival There is limited effort on establishing a standardized NDT for O-RAN. The existing effFromathenstandardo perspective)-BherN isesfinsitedifeffortoren Establishingle, stelldardized NDTa fort OdRXN.sprediexisting efforts:staregntainty: focuseft out O+RAN (test) specifications. (For example e3GPsprovides a set of 5Gespecifications footosting Hias Loversa functional imperformative, gandriconformative tests based architespecificGARA protogalanEEStpones worknitent finderwhek géneric-sautomatid networknardhitecturen (@ANA) progranks piropostisng demeral gfraithemorlo don testing lättativalidating[]thesAhintegratedonetworkd, including data ealgogithin, And thodbly adidation, tax well-fasmonis unctional and Abtegration testings The Whirk shelrfoods of other cefforts es if mainly out Ale enabled/systems/networks/theygdo not provide spealfics/about Hit Sietwork requirements; management tasks; rort Altimodelsl ETELemphasizes on the need for Alesystem testing and defines alige@edicApyoceski.thotweverlit\_isantitealigned doith that OpRoAfyi hrehiteotutestImparticulary it ldoes) notAspesifychow intestaand vlerify Ahpp()-RAAN specRffCinterfacts, thetwApps/rAppinsRfO; and NicAletwork functions of RANGAlliance works group (IWG) Affin to existed deliver that a Carlotta extends the BGPP netander decard definese tests cased, paramèters; and protingutes for itésting ithe conformance and pefformance bit the CUDE O CRIAnd O Rid (7-IR The A)-IRANe Allianged Test cand tintegration of focus of 6th (FG) if is petitifies other, spopls, goal sprand sprodesses i for dato end! treendr ketwork greating; where the AO-RANessy stories and lert the testrisatrehted asblablabloboSuSuqhrprocess isusferfering from aecentainl deficiencies www.blchldemands.fooraan.NDT-based O-RAN anchitécture that amebles les real-timé i optimization, tost, and validation dation.

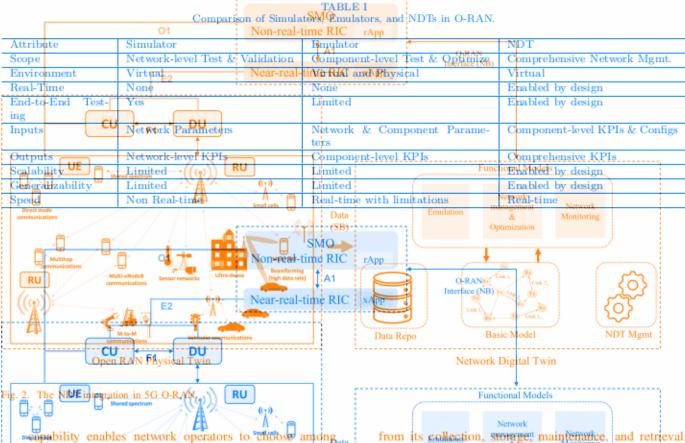
idation. Alternatively, simulators baffesign at a virtualized oNetwork & Component Parameters the Component-level KPIs & Configs or a ent-level KPIs

process. However, the simulators do not rully represent the real-world O-RAN mainly die to modeling deficiencies. Real-time with finitations employing the simulators are both timely and computationally expensive to be used for O-RAN use cases. In contrast, an NDT, leveraging the state-of-the-Ct MDT tec Simulator pand Emulator for Or RANensive model of the entire network in real-time, one king it easier to be used in Qo PANia poliberation of specific components, such as b-cuy orburer of reing to be the Roman and its control is count great like at he O-RIAN or a sizable O-RAN, and poses cominumication an Thiri is the main varidations. Afternatively, NDT atord cits close a virtuatives environment un latore and behalviors of a licenthen simulator occess. However, whe simular tors a on of third represencine hearen on a local contract to the deling deficiencies with the may sign laying the simulators are result that the distant of any expensive to be sized life. OPRIAN Use Tables. In convider, an comprehensive comparision the wremthe chinques, provides a move comprehensive model of the entire network in real-time, making it easier to be used In OFRA Nitapplications NDT in O-RAN

O-RAN, and poses limitat to be a design ine test and val-

It tish worth, recutioning that in the is NDT pandrits aphysical counterparti(i.e., the iQ-RAM) require to have a real-time gommunication, This is the main difference between the NDT and itstelose alternatives such as simulator and emulator Unlike the simulator, and emulator where they have no interaction over the real physical environments, the tNDT egomests with the physical assets and tries to represent it with little-to no assumption and/or simplification Lift b Table 27 provides a coms prehensjye comparision between the NDT and its alternatives. sub-components, and iii) The real-time data flow between the Thir Integration of MD Counter Bar (i.e., the southbound (SIA))then thigh elever, this out of with Figure 2 to NEW Tender to the Condition of the Co RAN architecture Gs Trased honverteb for flowing tentricel spiritaris. To The PRysical Tewin at PTS; withick by the RIAN, physical detwork includings the RU, DU, and CU. The PT is the source of data, Si\u00e4nThe d\u00e4DT, Whielfais-saimed \u00bcprepresent The replica of itstaphysical-feountemart-in-oreal-timeur. The hND lifter the host of nyarious components such as the basic and functional models n(which awill when described datervin this heetien) frehe data definitiony vandable. NDT: managetment esub-leampenents; and iii) The real-time data-flow between the RT and its digital counterpart; (i.e. ortho; southbound; (SB)); and the northbound (NB) communication obstweens the NDT and RJC 1 To as hiere the full potentials of NDT in O.B.A.N. there are heveralthey enablers what we itemize as follows ward, without requiring

 Significalited lategrades and Rebicooks afflict standard Bntedfaced and optobols rensures that different components ofivisconetwork QaR Anveroperate and a communicatio with each other eview lettley are from different we never seek



the best solutions for their network operations, withouts relying on a single vendor. Additionally, as the network scales up, the inflegration of new components with the existing network becomes straightforward, without requiring significant changes to the network architecture.

Besides, due to the heterogeneity of services and devices envisioned in FRAN, the mobular construction of NDT is inevitable. This not only allows for an efficient scaling of the NDT but also, facilitates the multi-vendor NDT development. However, the key enabler of such modular design pattern remains in standard and vendor-agnostic interfaces between the modules.

Data Strategy: Developing a high-fidelity NDT requires
a comprehensive vertrof data gollegted from the physical
network while maintaining a halance between the quality
and the quantity of she date. This demands a careful
assessment on the type of data collection to avoid the

• maccostary egglundancies in and sayen and conjunity of a parties at and patentagive sources. The data collection mechanism has to be raligned with the existing Orach standardized interfaces asuch has a Elanthar congruentases different asayine models under the ELS Mal thandy ELA if the profession file as interfaces to sollect the required data from the RANata collection mechanism has to be also critical to recognize the significance of a reliable data management at organizating the longs term attability and indeptability in a NDT for 28 RAN. Such Ex Arame, work, should rever a complete life-cycle of data, starting

from its collection, storage, maintenance, and retrieval. To achieve an optimal data management, highly desirable, along with other essential features such as security, accurate record-keeping, traceability, and data integrity. These features ensure the proper handling of sensitive network data, while maintaining the accuracy, completeness and consistency of data.

Modeling: The models are used as a proxy to represent different entities of the PTC-which enable Various tasks, including analyzing, diagnosing, and emulation in its digital counterpart. The models are generally categorized as basic models and functional models. The basic models are mainly used to replicate the O-RAN components, such as the UEs, gNBs, eNBs, channels, topology and network slices, while the afunctional models are used to enable various network level functional ities such as emulations, prediction, network management, and smonitoring. It is worth noting, than the fidelity of NDT is thighly, related to albeit accuracy of such in podels for captorer the instance complexities. That is other Metalphiques can be deveraged in developing such models, storage, maintenance, and Daplayment, Depending on the intended use acases in O-

Performent: Depending on the intended use cases in Ot,
RAN MET can be deployed wither at the edge cloud
or sheir combination. The shoice of the deployment is de
halance between the delay requirement and the laxal able
computation power. Egge example, the edge hase deploye
ment, is an acceptable by lower computational power and
lower storage capability and it is mainly used in delayconstitution.

Musitive URL-Complications of ush as organization and fault detection. On

tasks, including analyzing, diagnosing, and emulation in its digital counterpart. The models are generally locategorized as basic models and functional models. The basic models are mainly used to replicate the O-RAN components such as the UEs, gNBs, eNBs, channels, topology and network slices, while the locational models are used to enable various network-representationalities such as emulations, prediction, network management, and monitoring that the representations worth noting that the representations. That is not located to the accuracy of such models to capture the network complexities. That is not located models.

Fig. 3. Call flow between the NDT data collectors and E2 Node in O-RAN.

Data Collector Subscription to E2 Node
(Periodic or Triggered-based action: Report)

the other hand, the cloud-based deployment is mainly

asset of a network-wide planning, slicing, optimization,

and droubleshooting.

E2 Node detects event
triggeritimer expires

Environment features

NDT indication Message (E2 Report)

IV. PRACTICAL USE CASES OF NDT IN O-RAN

From the vendors and operators? perspectives, development and operation of O-RAN is a significant challenge mainly due to its virtualized, disaggregated, and multi-vendor design. To address such challenges, NDT can be everaged in both prior and post-deployment of O-RAN. In the former stage, NDT allows for extensive testing and validation, while in the fater stage, the NDT facilitates the deal time optimization and operation across different domains (access, transport, and core) Diploy following sections we will eliberate on the sease cases in further details T can be deployed either at the edge, cloud, or their combination. The choice of A. NDT for perior are time above easy ween the delay re-

A this stage, the NDT provides a true replica of the network example, the edge-based deployment is characterized environment to plan, test, and validate the design of new applications and services in O-RAN [7]. In particular, the NDT can assess the operations of different components, applications and services in O-RAN [7]. In particular, the NDT can assess the operations of different components, applications, and/or services against a variety of what-if scenarios (e.g., performance optimization, and fault detection. On traffic loads) that have never been expenenced before. Doing so, the vendors ensure the integrity and robustness of their used for network-wide planning, slicing, optimization, intended services to meet the demands of a hypothetical situation before they are deployed on a live network. This provides a risk-free process to seamlessly onboard different services in O-RAN.

Thenintégration of ML desperiques in O-RANi is extensively covered in the distributor of (?), R2LNT he authoristica [?] qualidege detailed introduction voit disfreent climagenegated, O-RANi until then bighlights how these components will graph NTE integration of ML its choriques is acide postor point robust of integration of the Metteshi question of the integration of the integral o

seeming (RL)vithelalgorithmois thained sua castrial and ether mechanism by constantly interacting with an environment. Indeed, the algorithm needs to explore various choices in the agrion space to Jean the hest policy that optimizes the NITT for Prior deployment of CPRANIAL optimizes the objective function in a long run. Such a continuous trial and At this stage, the NDI provides a true replica of error process in not affordable in real physical network. The the network environment to plan test, and validate the NDI provides a safe and realistic-like environment to trial design of new applications and services in O-RAN [7]. In such models and enable laster integration of RL techniques in particular, the NDI can assess the operations of different production. The authors of [7] proposed a detailed framework components, applications and/or services against a variety to leverage, the NDI to train an RL algorithm for capacity of "what it" scenarios (e.g., traffic loads) that have never sharing use case. sharing use case, been experienced before. Doing so, the vendors ensure the integrity and robustness of their intended services to BeNDTeforepostate prometro in their intended services to BeeNDTeforepostate prometro in Carly ituation before they are deployed on a live network. This provides a risk-free in a five O-RAN, multiple vendors generate agile individual process to seamlessly on board different services in O-RAN, network functions that require to push updates frequently. The integration of ML techniques in O-RAN is extendanced in the literature of the provides of the provide a defailed introduction of different components which is costly to setup and provides no guarantee on the integration of ML techniques as a closed-the relevancy of the outcome importantly, in order to ensure will enable the integration of ML techniques as a closed-the relevancy of the feets in a multi-vendor setting, each loop control mechanisms in RIC. However, the successful vendor has to track the compatibility of their service with adoption of the ML techniques is tied to an accurate others, which is not feasible. With the O-RAN roll-out, it training of ML models prior to deployment. This is where then becomes necessary to ensure an automatic and contain operational assessment that validates interoperability, for example, in the case of reinforcement learning. RL1, standard conformance among other performance certificates the algorithm is trained via a trial-and-error mechanism by ror any changes made by the vendors. This requires the algorithm needs to explore various choices in the action continuous-development (ClCD) pipeline. The ND1, as a true objective the continuous development of the live of NAN, provides an algorithm needs to explore various choices in the action continuous-development (ClCD) pipeline. The ND1, as a true and performance of the function updates. It also facilitates to provide a safe and real-time digital replica of the live O-RAN, provides and provides a safe and real-time and performance of the function update the integrity process in not affordable in, real physical network. The and performance of the function is possible to the li Brew Drefole postude of contemposting in Alexitation before they or to predict any service disruptions before they even happen. Phe Magration of Maple Continues in this Context will further enliance lithe OnPaA-Nmentdripspouserd(MSTER) er lit e Tabile: ??. we isluminarize the fapplication of NDTirfotoprior hand doeses deployment of OsRAN. RU, DU, and CUs. Traditionally, evětyis v worltbr rloting othat, tlhere glreavárioù sgOpRANsstesting andulatidation:platforms[delectoped:[byteitherpuniversities]] or industryalabsewithtdifferent levelsfoftmaturitynHolweyer,taottayl these dranteworks fully supportative testing and splanning rofiltie OnRAN sint though prior and dpost-deptoyment. He particular, If the existing solutions withbased on erhidations and/ersibhula/fotis which-limitheid-capabilities for a comprehensive yautomated; anda(rteara), tiealatime otestranda y alidationo ofala asizable (0-RtAN). In laddition in the openist bright solutions lead only osenverce partially deployee OrRAN; which catays be sufficient gloratal appropria of nrbsearch hand edevice opthent. OHB we've to vendors teoperators; and obthe'r ecosystem players who are on volved sing the business oCb@fillingpipreliperaffilgeONDAIN as a service anebdreal-focus fligitudreedeeplyfoth@bimpOndRtA.Nystem-ldvelatestingrossswell as the toross-ivenidor tinster operability lates essments togrity deared realizenaanefficietheO+RANodepjolaneat.Hmbortantl\(\)jtaNe3Tis

TABLE III

NND For Princand President of O-RAN. Use Cases are from [?].

Deployment	Use Cases =	NDT Application			
Stage		Planing	Operation	AM/MIL	Menitoring
	O-RAN-based Industrial IoT	✓			ing
	QoEAANdber PhJandneig in IkAN	€		✓	
	Apprelateleser-Pesitioning in RAN	€		<b>√</b>	
	Massive Man/O Beimforming Optimization	€	✓	<b>√</b>	
Prior Prior	MINIO SUNIU MEMO OPERMINE GPTIMIZATION	<b>€</b>	<b>√</b>	¥	
	OUR OPTIMIZED OP	€	¥	€	
	Poergo Critic Resource Optimization	<b>√</b>	¥	<b>*</b>	✓
	Network Efferigncy	✓	✓	<b>√</b>	✓
	Yrame Steelinging		¥	<b>*</b>	¥
	Byndinie Specinum Sharing (DSS)		¥	<b></b> ✓	¥
	Dynamic Caversano Reserves AlloSation		¥	<b>*</b>	¥
	Bruapaiging Afor Rachoefficenesses Allocation		<b>√</b>	<b>√</b>	¥
	BBU-Booling Own RAM of lasticity	✓	V	<b>√</b>	¥
	Contex Pranai Derains Praintever	✓	V	V	¥
	Syntage-Rayed Dring mic Handover		<b>√</b>	<b>V</b>	V
	Shanamic RAN Sharing		V	<b>√</b>	¥
	SharredtiOn/Services Validation	✓	V	V	¥
	Applicable Model training itesting & Validation	€	✓	<b>√</b>	✓
	pApp/pApp Model Training, Testing & Valida-	€		<b>√</b>	
Post	tion Calibration		1	1	
Post	RAN Slice SLA Assurance	✓	7	ý	/
	Calibration		Ý	ý	/
	RAN Slice SLA Assurance KPIs report: Resources Utilization, Throughput		Ý	ý	Ý
	Security Threads Assessment Process & Visualize the Network Performance		Ý	¥	Ý
	RAN Slice SLA Assurance KPIs report: Resources Utilization, Throughput Security, Threads Assessment Frocess & Visualize the Network Performance KPIs report: Resources Utilization, Throughput Congestion Prediction & Management		Ý	<b>√</b>	ý
	Process & Visualize the Network Performance Anomaly Detection		ý	,	ý
	Congestion Prediction & Management		<del></del>	<del></del>	<del></del>
	Anomaly Detection		✓	✓	✓

holistic view effectively addresses use cases across multiple domains, such as access, transport, core, and application, in person en identificathair eartish refinitions calors a dation and atheorement and distributed the appropriate and a state of the contraction and a state of undateris pushed to the live network. For example, NDTs can be leveraged in network monitoring and real-time anomaly detection when the network deviates from its normal operations or to predict any service disruptions beforthishsection weappoide two important use cases in Q: RANewhere the NDTE gan be leveraged. For each use rease. the common process between the NDT and its physical counterparta(i.e., the NERAN) is depicted in Fig. 2? This process involves the following key components: the O-RAN Physical Twin, the Data Layer, the Models Layer, the Management Lalters and then Neitwork a Operator a Tehradetailed - description in of each datadyperfor the feample level cased any prity ided in Table The or industry labs with different levels of maturity. HobjeNADT fort Traffict Steering mi Frafficks Steeling sispanuse case that involves plynamically directing that fich in the network itd optimize performance and inahage the twoist iloads al Within the OaRANuthenploposed aND To architectureneaw be lievering edictor coffect libereabitime data from the network and dreated digital model-thatecanssimulate adifferent traffic sizenarios)-RheNVDT swilli hielp, nietworki stipegatorki tóomake in fortyest-dee isi onsrábólyt

optimizing traffic flow and managing network loads in order to satisfy the required QoS/QoE. Additionally, the NDT can depletized to leave various network configurations that numerity of central stand developmental power in the reducer operators, and other properties and developmental power in the control of the AN, and other properties and optimize energy usage within the network. This can be accomplished by imposite thin the network. This can be accomplished by imposite thin the network. This can be accomplished by imposite thin the network. This can be accomplished by imposite thin the network. This can be accomplished by imposite thin the network of the properties of the properties of the properties of the network of the networ

### C. Use Cases

#### V. CONCLUSION

In this section, we provide two important use cases in NDRsAbave/theepotentNDf6 transformethe aglecommunical tions: industrye byopmoviding real-stime woodelting. Midfoptindizas tions: industrye byopmoviding real-stime woodelting. Midfoptindizas tions: industrye byopmoviding real-stime woodelting. Midfoptindizas tions: industrye byopmoviding real-stime woodelting. Nitroptindizas tions: industrye and provided the stime of the state of the state

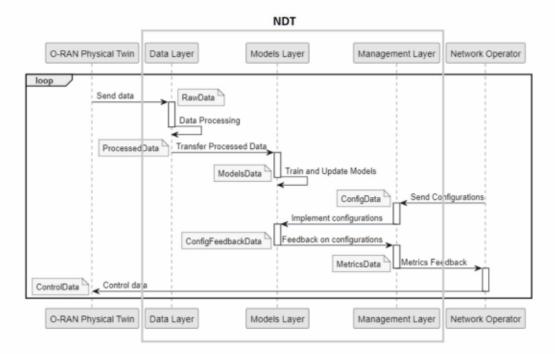


Fig. 41. Dittat Flow between the O-R O-Rph Night wind Milift, and Differential operators for various fire various for the Co-RAN.

Layer, the Management In and the Network Operator. The detailed description of the Network Operator.

2) NDT forsteinings Entirency: Handher Torgreet of O-RAN, energy efficiency aims to optimize energy usage within the network. This can be accomplished by undernations "what if usernation in a risk circumitronment without requiring them to be implemented in the real right of the trial right of the trial right of the trial right of the real results of the real results of the real right of the real results of th

NDTs have the potential to transform the telecommunications industry by providing real-time modeling, and optimization of the next-generation of wireless networks. As a digital replica of the O-RAN, NDT enables vendors

TABLE III
Use case specific data type description.

Data Toma	Use Case			
Data Type	Energy Efficiency	Traffic Steering		
RawData	Energy Consumption	Traffic Load		
ItawData	Traffic Load/Type	User Mobility Pat-		
		tern		
Processed Data	Energy Usage	Traffic Demand		
1 Tocesseur/aca	Traffic Demand	User Mobility		
ModelsData	Energy Consumption	Traffic Demands		
(Predictions)	Traffic Abnormality	Routing Decisions		
ConfigData	Energy Saving Config.	Traffic Steering		
ComigData		Rules		
	Power Allocation	Load-Balancing		
		Param.		
ConfigFeedback Date	Compliance Configuration			
MetricsData	Energy Usage	Throughput, Delay		
Metricapata	Energy Saving	Traffic Distribution		
	Power Control	Traffic Re-Routing		
ControlData	Carrier/Cell Switch	Load Balancing		
	On/Off			
	Sleep Modes Config.	Handover Trigger		

and network operators to emulate, test, and optimize their intended services under various "what-if" scenarios in a risk-free environment, without requiring them to be implemented in real network.

Throughout this paper, we provided an overview on how NDT can be leveraged in the context of O-RAN. We described the architecture of NDT within the O-RAN operation, and the key enablers of such integration. We also provided a comprehensive discussion on the practical application of NDT in various O-RAN use cases, including the both prior and post-deployment. Furthermore, network energy efficiency and traffic steering are provided