Design and Evaluation of a Bidirectional Communication Channel for O-RAN Digital Twins

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***Abstract*—The Open RAN paradigm enables programmability and automation through openness and disaggregation, but introduces new challenges in terms of reliability, observability, and validation prior to field deployment. Digital Twins (DTs) can address these challenges by providing a controlled and synchronized representation of the real system, enabling planning, optimization, validation, and security-oriented analyses. However, this paradigm requires an efficient bidirectional communication channel, as the fidelity of the DT depends on continuous synchronization. In this paper, we design and implement a bidirectional communication channel for Real World-DT synchronization based on brokerless technologies and we provide an experimental assessment of Zenoh and ZeroMQ as enabling technologies. Using a reproducible pipeline, we assess the performance in terms of latency, jitter, round-trip time, throughput for different payload sizes ranging from 100 B to 1 MB and in both Real World-to-DT and DT-to-Real World directions. Results show sub-millisecond mean latency for payloads up to 10 KB and only a few milliseconds for larger messages. When placed in context with prior MQTT-based Real World–DT systems, the measured values suggest that brokerless communication is a promising alternative for reducing application-level synchronization delay.**

***Index Terms*—O-RAN, Digital twin, 5G, Zenoh, ZeroMQ**

I. INTRODUCTION

The 5th generation (5G) of cellular networks is designed to accommodate diverse service categories, each characterized by distinct requirements [1]. Managing and optimizing next-generation mobile networks requires solutions enabling virtualization and programmability of the Radio Access Network (RAN). In the past decade, research and standardization efforts have promoted Open RAN Intelligent Controller (RIC) as the paradigm for the future. O-RAN is based on disaggregated, virtualized, and software-driven components, connected via open, standardized interfaces, and designed for interoperability across vendors [2]. A key innovation introduced by O-RAN is the RIC, which enables programmability and closed-loop control in the network. However, RIC-based control is typically limited to timescales above 10 ms and does not provide direct access to fine-grained user-plane information. To address this limitation, dApps are introduced as software components that can operate in the Centralized Unit (CU) and Distributed Unit (DU), enabling sub-millisecond intelligence and access to low-level data that are not directly exposed to the RIC, such as I/Q samples, packet-level information, and other user plane data [3].

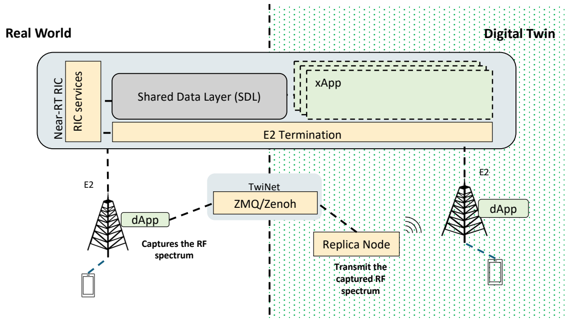

Fig. 1: Digital Twin architecture using O-RAN and dApps to exchange the spectral measurements

A Digital Twin (DT) is a virtual representation of a physical system that can reproduce realistic network conditions and behaviors in a controlled and repeatable environment, enabling the generation of representative datasets and the safe evaluation of AI/ML-based xApps, rApps, and dApps before deployment in the physical system. In addition, DT frameworks can support the definition of standardized benchmarking scenarios, thus improving the repeatability and comparability of experimental results [4], [5]. These capabilities are especially valuable in O-RAN, whose openness and disaggregation extend the attack surface and introduce new threats to the availability, integrity, and confidentiality of the infrastructure [2]. In telecommunications, interest in DTs has grown significantly in recent years, and they are widely regarded as a key enabler for future communication systems, especially in the evolution toward 6G [6]. A fundamental requirement of any DT architecture is the availability of a bidirectional communication mechanism between the digital and physical domains, so that the DT can remain synchronized with the state of the physical system [5]. Such synchronization is essential not

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only to maintain a good representation of the Real World, but also to enable closed-loop optimization based on AI and advanced analytics. In this context, the communication channel must support timely and reliable exchange of information in both directions, while preserving low latency and sufficient throughput under heterogeneous payload sizes.

Motivated by prior studies reporting favorable latency and throughput performance with respect to other messaging technologies, we consider Zenoh and ZeroMQ as promising candidates for the bidirectional communication link between the Real World and its DT. In particular Liang et al. [7] compare Zenoh against MQTT, Kafka, and DDS in terms of throughput and latency, showing that Zenoh achieves very competitive performance. Khatiwoda et al. [8] report lower latency for ZeroMQ than MQTT in 5G V2X communication. La Corte et al. [9] show that, among brokerless messaging libraries, ZeroMQ is particularly effective for throughput and large payloads. On this basis, we compare the two technologies under a common experimental methodology. The practical relevance of this communication link is further demonstrated through a proof-of-concept application in which uplink spectral observations produced by a real Next Generation Node B (gNB) are transferred to the DT and replayed for analysis.

The main contributions of this paper are:

- Design and implementation of a bidirectional communication channel between the Real World and the DT, based on brokerless technologies, enabling low-latency and synchronization under heterogeneous payload conditions.
- Systematic experimental evaluation of Zenoh and ZeroMQ for Real World–DT communication under a unified and reproducible methodology, measuring latency, Round-Trip Time (RTT), throughput, and jitter across payload sizes and directions, with implications for data freshness, temporal consistency, and feedback-oriented DT workflows.

The remainder of this paper is organized as follows. Section II reviews the most relevant literature on digital twins for networking and O-RAN, as well as on bidirectional communication between the physical and digital domains. Section III describes the proposed system architecture and the roles of the main software components, including a proof-of-concept application of the proposed channel. Section IV details the implementation of the bidirectional link based on Zenoh and ZeroMQ. Section V presents the experimental setup and the comparative performance evaluation under different payload sizes and traffic directions. Finally, Section VI concludes the paper and discusses future developments.

II. RELATED WORK

DTs have been increasingly explored across networking domains to improve automation, observability, and security. Wang et al. [10] propose a general framework for DT-enabled wireless systems and outline a layered threat model, highlighting the potential of DTs for proactive analytics and online control, while also pointing out open challenges related to cross-layer and mixed attacks. Jagannath et al. [11] discuss DTs for IoT and beyond-5G networks, emphasizing AI/ML-based modeling, live simulation, and bidirectional synchronization with the physical system to support online learning, predictive modeling and validation of control policies. In the O-RAN context, Mirzaei et al. [12] present the concept of a Network DT integrated with the RIC, enabling testing, optimization, and assurance across different deployment phases.

Among the works most closely related to this objective, Polese et al. [13] describe Colosseum as an Open RAN digital twin based on a high-fidelity RF channel emulator and end-to-end software-defined O-RAN and 5G-compliant protocol stacks. In their architecture, MQTT is used to support real-time communication between the physical and digital domains. Similarly, [14] introduce TwiNet, a system that uses MQTT to synchronize the real and digital worlds and demonstrate how the link can support applications such as safe adaptive data rate control and pilot jamming detection.

This paper differs from previous studies by focusing on the implementation and evaluation of the Real World-DT bidirectional channel rather than on the conceptual role or application potential of the DT. In contrast to Polese et al. [13] and TwiNet [14], which rely on MQTT-based synchronization between the real and digital domains, we investigate Zenoh and ZeroMQ as alternative technologies for this link. To the best of our knowledge, Zenoh and ZeroMQ have not been directly compared for this Real World–DT communication problem. Accordingly, we evaluate them through a uniform measurement pipeline with the goal of identifying the more suitable solution for low-latency bidirectional synchronization. When placed in context with the latency values reported for the MQTT-based approaches in [13], [14], our results suggest that brokerless communication technologies can achieve a lower application-level latency regime. These values are therefore used only as contextual references. Furthermore, rather than treating the communication channel only as a supporting mechanism, we show how it can enable the reproduction in the DT of a frequency-domain observation of the uplink spectral content seen by the real gNB. In this sense, our contribution is centered on the communication substrate itself as a fundamental building block for wireless network digital twins.

III. SYSTEM ARCHITECTURE

This section describes the experimental architecture adopted in this work. In line with the DT requirements defined in [14], which include a virtual model of the physical system, a near real-time bidirectional link, and large-scale experimentation capability, we build our architecture upon Colosseum, OpenShift, and OpenAirInterface.

Our system is composed of two coupled domains, as shown in Fig. 1. On the physical side, the Real World Over-The-Air (OTA) testbed is deployed on an OpenShift cluster. The underlying Kubernetes-based architecture provides orchestration, networking, and the low-latency execution support required by radio applications with strict timing constraints. On the digital side, Colosseum acts as the DT environment, providing a wireless experimentation platform for reproducible RF and network experiments, through hardware-in-the-loop network emulation [13]. This allows to reproduce RF and protocol-stack conditions, ensuring the alignment with the physical system.

In both environments, the 5G NR/O-RAN stack is implemented through OpenAirInterface (OAI), an open-source software platform providing a reference implementation of 3GPP cellular protocol stacks [15]. Using OAI in both the Real World and DT domains ensures protocol-stack consistency across the two sides of the system. OAI supports the implementation of key RAN functions and interfaces, including CU/DU components and the related 3GPP and O-RAN interfaces. This design supports a DT architecture in which the digital and physical domains remain aligned not only at the application level, but also at the radio and protocol-stack levels, supporting continuous synchronization through the bidirectional information exchange between Real World and DT.

Within this architecture, the potential of our proposed bidirectional communication mechanism can be illustrated through a proof-of-concept in which the DT reproduces uplink spectral observations acquired by the real gNB. This use case imposes low-latency communication requirements, since the frequency-domain sensing data generated on the Real World side must reach the DT with limited delay in order to remain representative of the current uplink spectral conditions. In this deployment, frequency-domain sensing data exported by the physical layer of the real gNB are acquired through the E3 interface by a dApp, presented in [3], and forwarded to the DT. Through E3, the dApp can interact in real time with DU and CU for data collection and control exchange. On the digital side, a replica node running on Colosseum receives the data in real time and processes them in GNU Radio, an open-source framework for signal processing and software-defined radio, to reconstruct the corresponding uplink spectral view. This enables spectrum-sensing-oriented analyses, including interference monitoring and PRB occupancy evaluation, under controlled and repeatable conditions.

IV. PROPOSED BIDIRECTIONAL COMMUNICATION ARCHITECTURE

In this section, we present the proposed bidirectional communication architecture enabling information exchange between the Real World and the DT. The design supports continuous synchronization under low-latency requirements while accommodating heterogeneous payload sizes. To this end, we consider Zenoh and ZeroMQ as communication technologies in a common framework to enable comparisons under the same system conditions.

A. Communication Technologies

The design of the proposed communication channel is guided by three main requirements: i) support for bidirectional communication between the Real World and the DT, ii) low-latency delivery to sustain near-real-time synchronization, and iii) flexibility in handling heterogeneous traffic and payload conditions. These requirements motivated the selection of brokerless communication solutions, which avoid the additional indirection and overhead typically associated with broker-based architectures.

Among the candidate technologies, Zenoh and ZeroMQ were selected. Zenoh unifies data in motion, data at rest, and distributed computations. It is transport-agnostic, can operate over multiple transport protocols such as TCP and UDP, and supports peer-to-peer communication without requiring a central broker [16]. This approach improves flexibility and scalability, simplifying the development of distributed applications while reducing infrastructure complexity. Zenoh establishes bidirectional connections among nodes and supports both best-effort and reliable communication modes, while also optimizing link utilization through automatic batching and fragmentation. The reliable channel guarantees ordered, lossless delivery and is appropriate when integrity and reliability are essential. It defines three main types of network entities: publishers, subscribers, and queryables. ZeroMQ is a high-performance asynchronous messaging library for distributed systems [17]. Like Zenoh, it adopts a brokerless design, enabling direct communication between nodes and reducing deployment complexity and runtime overhead. Its socket-based API and built-in messaging patterns make it a flexible solution for implementing lightweight and efficient communication channels. It improves performance through techniques such as message batching and zero-copy transfer, thereby reducing CPU and memory costs during communication. In addition, its messaging patterns can be used to support reliable propagation of updates, commands, and data streams across nodes.

B. Bidirectional communication channel design

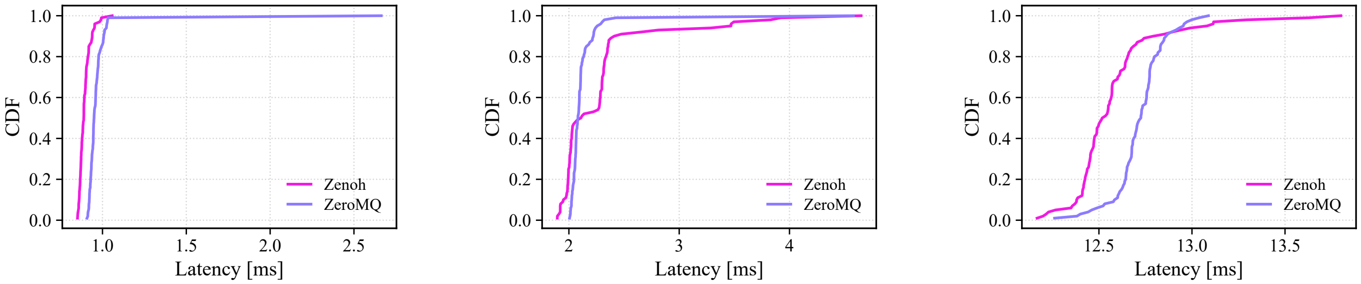
In our system, bidirectional communication is realized using Zenoh in peer mode and ZeroMQ through the PUB/SUB pattern. Static endpoints are adopted in both cases in order to ensure deterministic behavior during the experiments and to simplify integration with testbed network policies. Communication is organized into two logical flows, identified by the names traffic/mgen and ack/mgen. The former is used to carry MGEN application data, whereas the latter carries the corresponding application-level acknowledgments. In addition, each application payload includes a header carrying a timestamp and a sequence number, which enables the end-to-end computation of metrics. In the Zenoh-based implementation, a session is established by explicitly configuring the peer mode and the local and remote endpoints. A subscriber is declared on the `traffic/mgen` resource to receive application data, while acknowledgments are sent on the `ack/mgen` resource. This design provides a clear separation between Real World and feedback paths while leveraging Zenoh's native transport-level mechanisms for batching, fragmentation, and queue management.

In the ZeroMQ-based implementation, communication is realized by instantiating a local messaging context and creating a subscriber socket for incoming data and a publisher socket for

(a) Average latency (Real World→DT).

(b) Average latency (DT→Real World).

Fig. 2: Contextual comparison between the end-to-end latency measured in this work for Zenoh and ZeroMQ and the latency values reported by prior MQTT-based Real World–DT systems [13], [14].

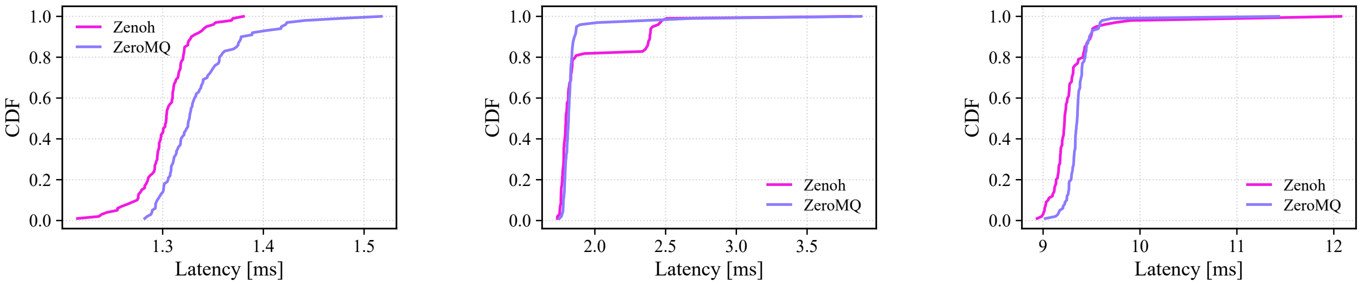


(a) Latency CDF for 10 KB payloads

(b) Latency CDF for 100 KB payloads

(c) Latency CDF for 1 MB payloads

Fig. 3: End-to-end latency CDFs for the Real World→DT direction for payload sizes of 10 KB, 100 KB, and 1 MB. The CDFs capture the full latency distribution, thus highlighting both typical and tail behavior.



(a) Latency CDF for 10 KB payloads

(b) Latency CDF for 100 KB payloads

(c) Latency CDF for 1 MB payloads

Fig. 4: End-to-end latency CDFs for the DT→Real World direction for payload sizes of 10 KB, 100 KB, and 1 MB. The CDFs capture the full latency distribution, thus highlighting both typical and tail behavior.

outgoing data. Topic filtering is explicitly applied so that only messages associated with the desired topic are delivered to the receiver. Message exchange follows a topic-plus-payload framing, consistent with the logical separation adopted in the Zenoh-based design.

A relevant implementation difference emerged under bursty traffic conditions. Zenoh already provides built-in transport-level queue management and configurable congestion-control mechanisms. By contrast, in the ZeroMQ-based implementation, preserving low latency under traffic bursts required explicit tuning of the receiver-side high-water mark and of the operating-system receive buffer. This tuning increased the effective socket buffering capacity and reduced backpressure during short traffic peaks.

V. PERFORMANCE EVALUATION OF THE COMMUNICATION ARCHITECTURE

This section evaluates the performance of the bidirectional channel between the Real World and the DT. In particular, Zenoh and ZeroMQ are compared under the same hardware and software conditions. To generate and monitor network traffic, we use MGEN (Multi-Generator Network Test Tool) [18], an open-source tool developed by the NRL PROTEAN group. MGEN supports both TCP and UDP flows and allows the

TABLE I: Measured latency, RTT, and throughput for Zenoh and ZeroMQ in the Real World→DT and DT→Real World directions under the same hardware and software conditions. For each payload size, the table reports the average value over 100 consecutive packets together with the corresponding 95% confidence interval (CI95).

Direction	Payload	Zenoh			ZeroMQ		
		Latency [ms]	RTT [ms]	Throughput [MB/s]	Latency [ms]	RTT [ms]	Throughput [MB/s]
Real World→DT	100 B	0.89 ± 0.111	2.00 ± 0.011	0.12 ± 0.002	0.87 ± 0.009	2.02 ± 0.010	0.12 ± 0.001
	1 KB	0.84 ± 0.006	2.03 ± 0.010	1.22 ± 0.008	0.89 ± 0.008	2.04 ± 0.012	1.15 ± 0.010
	10 KB	0.89 ± 0.007	2.08 ± 0.042	11.47 ± 0.082	0.97 ± 0.034	2.11 ± 0.008	10.65 ± 0.150
	100 KB	2.26 ± 0.090	3.35 ± 0.187	46.58 ± 1.273	2.12 ± 0.051	3.23 ± 0.041	48.59 ± 0.611
	1 MB	12.57 ± 0.049	13.75 ± 0.114	83.42 ± 0.311	12.72 ± 0.026	13.81 ± 0.029	82.44 ± 0.168
DT→Real World	100 B	1.23 ± 0.021	1.98 ± 0.017	0.08 ± 0.001	1.21 ± 0.012	1.97 ± 0.012	0.08 ± 0.001
	1 KB	1.26 ± 0.010	2.04 ± 0.020	0.81 ± 0.005	1.24 ± 0.008	2.00 ± 0.007	0.83 ± 0.005
	10 KB	1.30 ± 0.005	1.98 ± 0.025	7.86 ± 0.032	1.34 ± 0.008	1.94 ± 0.031	7.67 ± 0.044
	100 KB	1.92 ± 0.059	3.19 ± 0.780	54.33 ± 1.226	1.85 ± 0.046	2.94 ± 0.786	55.83 ± 0.761
	1 MB	9.30 ± 0.072	10.02 ± 0.132	112.92 ± 0.734	9.38 ± 0.046	10.33 ± 0.237	111.88 ± 0.468

definition of real-time traffic patterns through scripts, thereby enabling reproducible experiments. For each test configuration and for both communication directions, indicated throughout the paper with "Real World→DT" and "DT→Real World", 100 consecutive packets are transmitted for each payload size, namely 100 B, 1 KB, 10 KB, 100 KB, and 1 MB.

As a primary performance metric, we use the end-to-end latency, which is defined as the time interval between the timestamp assigned by the sender application and the complete reception of the payload at the receiver. This definition captures the delivery time of the full message and reflects practical effects such as fragmentation, batching, queuing, and flow control. For each protocol, direction, and payload size, latency is analyzed through summary statistics. To ensure time consistency, the hosts are synchronized via Network Time Protocol (NTP). We first characterize latency as a function of payload size. As shown in Fig. 2a and Fig. 2b, both Zenoh and ZeroMQ achieve low latency in both communication directions. When considered against the latency values reported in prior MQTT-based Real World–DT systems [14], [13], the measurements obtained in this work show lower end-to-end latency across the considered payload sizes, especially for small and medium messages. However, since the MQTT-based values were obtained in different experimental environments, this comparison should be interpreted as contextual positioning rather than as a controlled head-to-head benchmark. These results suggest that brokerless communication technologies are promising candidates for reducing application-level synchronization delay in Real World–DT channels, in line with the lower overhead expected from avoiding broker-based message indirection.

To further characterize latency behavior, we analyze the latency Cumulative Distribution Function (CDF), which captures the full distribution of delays and highlights both typical and tail behavior. As shown in Fig. 3 and Fig. 4, the relative performance of the two protocols depends on the payload size. For 10 KB messages, Zenoh exhibits more favorable behavior in both directions, with a more left-shifted CDF and a shorter tail (Figs. 4a and 3a). For 100 KB messages, ZeroMQ outperforms. Specifically, in the DT→Real World direction, it shows a steeper rise and a more compact latency distribution (Fig. 4b). In the Real World→DT direction, its advantage becomes more evident, with a more left-shifted CDF and better tail containment (Fig. 3b). For 1 MB messages, both protocols remain stable for most samples, and the main differences emerge in the tail. In the DT→Real World direction, Zenoh is slightly more favorable at lower latencies, whereas ZeroMQ provides better containment of rare delay spikes (Fig. 4c). In the Real World→DT direction, Zenoh reaches the lower quantiles earlier, while ZeroMQ exhibits a steeper rise in the intermediate region and a shorter tail (Fig. 3c).

A complete quantitative analysis of some key parameters are reported in Table I. Concerning the latency, the table confirms the trends observed in the previous figures, with comparable average latency for the two protocols across all payload sizes and directions. To complement the analysis, we also consider the application-level RTT, defined as the time elapsed between sending a message and receiving the corresponding acknowledgment at the sender. As reported in Table I, the average RTT is very similar for Zenoh and ZeroMQ across all payload sizes and in both communication directions. We also evaluate throughput, whose average values are likewise summarized in Table I. Also in this case, the two protocols exhibit closely comparable performance, with throughput increasing monotonically with payload size, thereby confirming similar transfer capacity under the considered conditions.

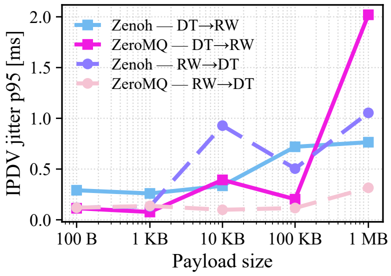


Fig. 5: 95th-percentile IPDV jitter versus payload size for the two directions of the Real World–DT bidirectional channel.

To evaluate flow regularity, we use an IPDV-based jitter metric, defined as the absolute difference between the RTTs of consecutive packets. Its 95th percentile is reported to capture the largest delay fluctuations. RTT is preferred to one-way delay because it is more robust in practice and does not require perfect clock synchronization between hosts. As shown in Fig. 5, in the DT→Real World direction Zenoh becomes noticeably more irregular than ZeroMQ starting from 10 KB, with IPDV p95 increasing significantly with message size. In the Real World→DT direction (Fig. 5), ZeroMQ is more consistent than Zenoh for 100 B, 1 KB, and 100 KB, whereas Zenoh becomes more favorable at 10 KB and 1 MB, where ZeroMQ exhibits higher IPDV p95 peaks. From the perspective of a Real World–DT communication channel, the evaluated metrics quantify the freshness, responsiveness, and temporal consistency of the DT representation. Low one-way latency reduces the age of the observations delivered to the DT, while RTT captures the responsiveness of feedback-oriented workflows in which the DT may return decisions, commands, or configuration updates to the Real World. Throughput determines the ability to sustain larger transfers, such as spectral observations, I/Q-related information, or aggregated monitoring data. Finally, jitter affects the regularity of the update stream and the temporal alignment between Real World measurements and DT-side processing, replay, or AI/ML pipelines. Under the considered experimental conditions, ZeroMQ emerges as the more suitable solution for the DT bidirectional channel, as it achieves latency values comparable to those of Zenoh while exhibiting consistent delay behavior in most of the evaluated cases.

VI. CONCLUSION

This paper presented the design and evaluation of a low-latency bidirectional communication channel for O-RAN DTs. By integrating OAI, OpenShift, Colosseum, and brokerless communication technologies, the proposed architecture provides a practical substrate for transferring telemetry and sensing data between the physical and digital domains. Such a channel is essential to keep the DT aligned with observations collected from the Real World and to make it a practical tool for analysis, experimentation, and validation, rather than a purely offline replica. The evaluated metrics, namely latency, RTT, throughput, and jitter, are relevant to the freshness, temporal consistency, and usability of DT-side observations for monitoring, replay, and AI/ML-assisted decision making. Although OAI, OpenShift, and Colosseum provide a realistic and reproducible environment, the evaluation does not capture all the variability of operational 5G deployments, including mobility, background traffic, congestion, packet loss, and failures of intermediate components. Moreover, the current study considers a single Real World–DT communication pair, whereas commercial-scale deployments may involve multiple RAN nodes, distributed DT instances, and concurrent data streams. Future work will extend the analysis toward multi-node DT deployments, robustness under less controlled network conditions, and DT-assisted optimization workflows for testing, validating, and training AI/ML-based functions before deployment in the real network.

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