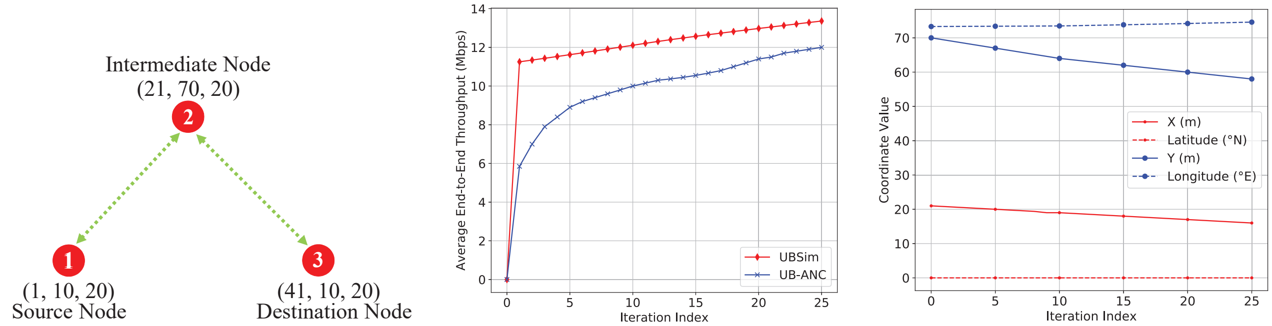
This paper has been accepted for publication on IEEE Workshop on Wireless Communications and Networking in Extreme Environments, LA, California, June 2022



(a) (b) (c)

Fig. 4: (a) Topology of simulated network ; (b) End-to-End throughput; and (c) Distance between nodes.

Notation	Attribute Name	Data Type
T	Total Simulation Time	Integer
N	Total Number of Nodes	Integer
K	Total Number of Packets	Integer
R_n	Data Rate for Node n, $n = 0, 1, 2, \cdots, N$	Float
P_n	Transmission Power for Node n	Float
S	Packet Size	Double
x_n	Initial x-coordinate for Node n	Double
y_n	Initial y-coordinate for Node n	Double
z_n	Initial z-coordinate for Node n	Double

TABLE I: Network setup attributes.

network parameters are sent back to UB-ANC via *network optimization and specification interface* (denoted as ③ in Fig. 2) for next-round simulation.

D. SimSocket in Action

We briefly describe *SimSocket* in action to help readers understand better how the signals are exchanged between UBSim and UB-ANC. Table I summarizes the involved network attributes.

As illustrated in Fig. 2, in Step ① UBSim sends the simulation configuration parameters to UB-ANC. These include the simulation time T, the number of nodes N, the number of packets K. Additionally, for each node n in the network, UBSim sends the data rate R_n, transmission power P_n, and the coordinates of the node x_n, y_n and z_n. These attributes are sent as a comma-separated message for easy decoding at UB-ANC (refer to *packet encoder/decoder* in Fig. 2). For example, the first message will be of form $[T, N, K]$ and the second message will be sent for individual node n which will be in the form of $[R_n, P_n, x_n, y_n, z_n]$. After all the messages are sent, UBSim listens for the response from UB-ANC (refer to *transmitting/receiving UDP socket* in Fig. 2). In the meantime, UBSim will load the corresponding optimization algorithms to solve the network control problem and send the optimized network parameters to UB-ANC periodically during the simulation.

Once UB-ANC receives the necessary information from UBSim through *transmitting/receiving UDP socket*, it decodes the message using *packet encoder/decoder* and performs coordinate conversion using *coordinate system converter*. The decoded messages are then used to update the simulator and node attributes of the NS-3 protocol stack. Then, the network simulation module of UB-ANC conducts simulations and updates the network performance attributes. Example network performance attributes include link capacity, link delay, end-to-end delay, among others. After the current round of simulation, UB-ANC exchanges the simulation results with UBSim, as shown with ② in Fig. 2. The same as in Step ①, the reply messages will also follow the comma-separated format. The network performance results received from UB-ANC is decoded and the values are updated in the optimization algorithm loaded earlier in Step ①. After solving the optimization problem, the *network optimization agent* replies to UB-ANC in Step ③ with the optimized results.

IV. Demonstration and Discussions

In this section we showcase multi-fidelity simulation based on SimSocket, considering ad hoc flying network with IEEE 802.11n as the radio access technique for UB-ANC and the wireless channels experiencing Friis propagation loss in UBSim [1].

In the first demonstration, we consider a three-node network as shown in Fig. 4(a). The intermediate node (node 2) is initially placed far away from source node 1 and destination node 3. The data rates for the nodes are controlled by the *network optimization agent* in UBSim while the actual data transmission is conducted in UB-ANC. From Figs. 4(b) and 4(c), it can be seen that node 2 moves closer to the source and destination nodes in the network and the achievable throughput increases accordingly. It is worth mentioning that Fig. 4(b) plots the average end-to-end throughput for both UBSim and UB-ANC. It can be seen that UB-ANC achieves slightly lower throughput because it takes into account the lost and corrupted packets whereas UBSim assumes capacity-approaching transmissions. This indicates that, although UBSim and UB-ANC have different levels of simulation fidelity, the transmission decisions obtained by one can still be effective for the other. This will allow us to evaluate policy learning algorithms by training them in one domain (e.g., UBSim) and testing in the other (e.g., UB-ANC), and further study the generalizability of the learning algorithms across different domains. Figure 4(c) shows the corresponding trajectories of node 2 in the Cartesian coordinate system in UBSim and in the ECEF coordinate system in UB-ANC.

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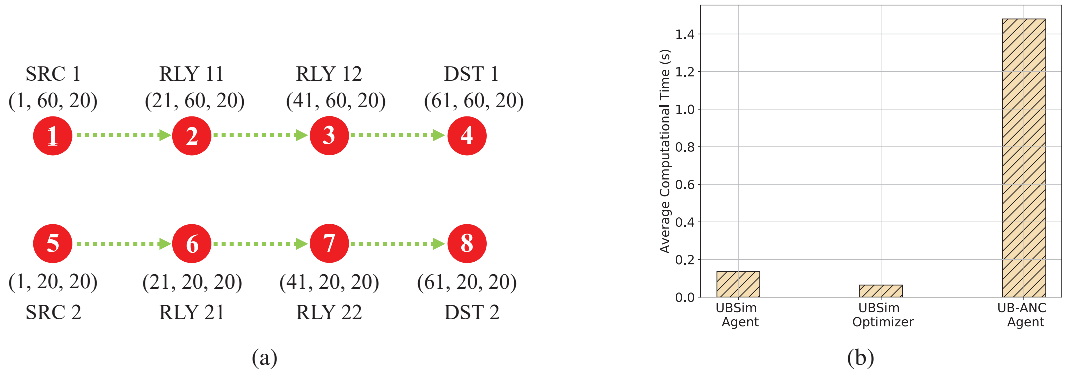

Fig. 5: (a) Example topology for a multi-session, multi-hop network and (b) comparison of the network optimization and simulation time.

In the second experiment, we analyze the computational time of the three main subcomponents of the multi-fidelity simulator, i.e., UBSim Agent, UBSim Optimizer and UB-ANC Agent. We consider a multi-session multi-hop network with four nodes per session. As shown in Fig. 5(a), node 1 (and 5) and node 4 (and 8) are respectively the source (SRC) and destination nodes (DST) for Session 1 (and Session 2). Similarly, node 2 (node 6) and node 3 (node 7) are the relay (RLY) nodes for Session 1 (and Session 2). Figure 5(b) reports the simulation time experienced by each of the three modules in each simulation round. It can be seen that UB-ANC simulator takes 1.48 s per iteration while UBSim simulator and UBSim optimizer take 0.136 s and 0.064 s, respectively. This is not surprising because UB-ANC simulates the network with higher fidelity based on NS-3 and hence higher computational complexity. This will allow us to test policy learning algorithms at different time scales in different domains.

V. Enabled New Research

The proposed multi-fidelity simulator can enable a wide set of new experiments. Examples include adaptive self-configuration, accelerated policy generation, and event prediction and off-policy learning for digital twin-enabled wireless networks.

Domain adaptation. The multi-fidelity simulator can provide a novel framework for testing domain adaptation techniques, leveraging the unique domain dynamics inherent to both UB-ANC and UBSim. Since these simulators provide different levels of fidelity, we can leverage the different observable dynamics between domains, as well as the behavioral differences between simulation and hardware, to evaluate the source-to-target gap of novel domain adaptation methods.

Learning acceleration. The multi-fidelity simulator can be used to accelerate policy convergence by using the UBSim optimizer for transfer learning. First, the training of deep neural networks can be conducted quickly on a high-level implementation of a given network control problem in the UBSim virtual environment. Then, keeping the lower neural network layers unchanged by "freezing" them, the trained model can be passed through SimSocket to re-train the upper network layers in the high-fidelity UB-ANC simulator to improve the accuracy of the learned policy, hence reducing the overall training time of the neural network.

Event prediction and off-policy learning. While performing high-fidelity simulations in UB-ANC, researchers are allowed to use the parallel lower-fidelity simulation instances in UBSim for event prediction and synthetic trajectory generation. This will further allow flexible implementation of both on-policy learning in UB-ANC as well as off-policy learning in UBSim.

VI. Conclusions

In this work we have developed a new multi-fidelity simulator for wireless UAV networks by interfacing UBSim with UB-ANC. We designed a middleware called *SimSocket* for signaling exchanges between the two simulators. We showcased the multi-fidelity simulation capability of the integrated simulator considering flying ad hoc networks. The new research topics that can be enabled by the integrated simulator have also been discussed.

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