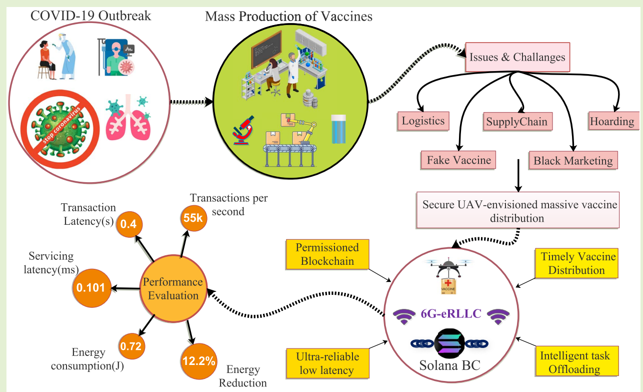
SanJeeVni: Secure UAV-Envisioned Massive Vaccine Distribution for COVID-19 Underlying 6G Network

Ashwin Verma, Pronaya Bhattacharya, Deepti Saraswat, Sudeep Tanwar, *Senior Member, IEEE*, Neeraj Kumar, *Senior Member, IEEE*, and Ravi Sharma

***Abstract*—Recently, unmanned aerial vehicles (UAVs) are deployed in Novel Coronavirus Disease-2019 (COVID-19) vaccine distribution process. To address issues of fake vaccine distribution, real-time massive UAV monitoring and control at nodal centers (NCs), the authors propose *SanJeeVni*, a blockchain (BC)-assisted UAV vaccine distribution at the backdrop of sixth-generation (6G) enhanced ultra-reliable low latency communication (6G-eRLLC) communication. The scheme considers user registration, vaccine request, and distribution through a public Solana BC setup, which assures a scalable transaction rate. Based on vaccine requests at production setups, UAV swarms are triggered with vaccine delivery to NCs. An intelligent edge offloading scheme is proposed to support UAV coordinates and routing path setups. The scheme is compared against fifth-generation (5G) uRLLC communication. In the simulation, we achieve and 86% improvement in service latency, 12.2% energy reduction of UAV with 76.25% more UAV coverage in 6G-eRLLC, and a significant improvement of ≈199.76% in storage cost against the Ethereum network, which indicates the scheme efficacy in practical setups.**



***Index Terms*—6G, blockchain, COVID-19, edge offloading, Solana chain, UAV swarms, ultra-reliable low latency communications, unmanned aerial vehicles.**

I. Introduction

WORLD health organization (WHO) emergency response programs are constantly working across Asia, Pacific, and European regions to support essential health services, early Novel Coronavirus Disease-2019 (COVID-19) detection, and advance pandemic preparedness [1]. COVID-19 has taken more than 1.5 million lives worldwide due to unavailability of required vaccine [2]. To gear up the vaccine distribution, WHO has started the initiative for efficacious deployments of COVID-19 vaccines global access (COVAX) in collaboration with epidemic preparedness innovations (CEPI) [3]. The clinical trial indicates ≈95% efficiency of Pfizer/BioNTech to prevent COVID-19 infection [4]. Thus, massive vaccine development and its distribution are required globally. A recent report by *Research & Markets* estimates that COVID-19 and generic immunity builds to tackle future pandemics is expected to reach over 5.8 billion USD by 2025 [5]. Thus, large scale massive vaccine generation and distribution schemes are required to target high vaccination coverage across the globe.

On the distribution side, the pharmaceutical supply chain plays a vital role in providing critical medical support in hospitals and aids emergency activities/operations, human missions, and other allied services. However, due to the worldwide lockdown, the supply chain was severely disrupted [6] which

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Ashwin Verma, Pronaya Bhattacharya, Deepti Saraswat, and Sudeep Tanwar are with the Department of Computer Science and Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat 382481, India (e-mail: ashwin.verma@nirmauni.ac.in; pronoya.bhattacharya@nirmauni.ac.in; deepti.saraswat@nirmauni.ac.in; sudeep.tanwar@nirmauni.ac.in).

Neeraj Kumar is with the Department of Computer Science Engineering, Thapar Institute of Engineering and Technology, Patiala 146004, India, also with the Department of Computer Science and Information Engineering, Asia University, Taichung 413, Taiwan, and also with the Department of Computer Science and Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia (e-mail: neeraj.kumar@thapar.edu).

Ravi Sharma is with the Centre for Inter-Disciplinary Research and Innovation, University of Petroleum and Energy Studies, Dehradun 248001, India (e-mail: ravisharmacidri@gmail.com).

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TABLE I
COMPARISON OF EXISTING UAV PROJECTS IN MEDICAL DELIVERY SCENARIOS

Drone	Year	Highlighted	Company	Application	Advantage
Wing Drone	2016	Medical aid to people in emergency	Google	Medical aid, medicine, baby food	20 km in range with live update of estimated arrival time
HQ-40 UAV	2017	Large distance transportation of blood with temperature monitoring in Arizona desert	Johns Hopkins University	Blood delivery	Resilient drone build to cover long distances
HiRo	2018	Specially designed to provide faster access to life-saving medical aid for critically injured people in dangerous and hostile environments	William Carey University	Integrated rescue operations	
Ehang AAV	2020	China-based company world-first autonomous UAV capable of transporting patients from one location to another	EHang Holdings	Transportation of donated organs to all over the places	Load-carrying capability excellent
Kite	2021	An advanced aircraft designed for a range of tasks, from delivering medical supplies and disaster responses	Swoop Aero	Delivery of medical supplies and supply chain management	Enhanced load carrying capacity, real-time tracking with digital twin technology. Speed of 200km/h across a range of more than 180 km flight
Wingcopter 198	2021	German-based company to provide commercial, medical services with 110km/hr speed an up to 100km range	Wingcopter	Transportation of blood samples, medicines, diagnostic kits	Heavy payload delivery, all-weather capability, compact size

affected production, distribution, and safety standards. Vaccine supply chains require secure and smooth operations among multiple suppliers, manufacturers, and distributors to deliver the vaccine to the end-user. The vaccine generation, maintenance, and production at vaccine manufacturing labs (VML) and production warehouses (PWs) requires effectiveness and stability, which is achieved through *cold-chain* process to maintain a standard temperature of -70° for dose administration. The vaccine containers, after packaging at PWs are shipped to nodal centers (NCs), that have the registered list of potential users eligible for vaccination. Due to high round trip times (RTTs) of logistics cargo shipments via land, water, and air, the container stability is heavily affected, and thus it jeopardizes the effectiveness of the *cold-chain* process. Moreover, different countries have their national and international boundary regulations on the movement of vaccine cargo, which hampers vaccine stability. The records of potential vaccination users are maintained through the national population register (NPR), and once the user is vaccinated, the record is maintained on either centralized or distributed servers [7].

Owing to the challenges, critical steps are required to address the timeliness in vaccine deliveries and reduce supply costs with minimal human interventions. Thus, unmanned aerial vehicles (UAVs) are considered a viable choice due to their lower round trip time (RTT) than traditional shipments, optimal cargo capacity management, lower cost, and travel to adverse climatic and habitat zones [8]. UAVs also act as Ground Controllers (GCs) to provide seamless connectivity in remote rural locations. Modern UAVs are equipped with global positioning system (GPS) transceivers coupled with localization techniques and routing protocols making it easier to navigate easily through an unknown area for delivery services [9], [10]. Benefits of UAVs include minimizing carbon footprints,human efforts, and improved flexibility and speed. Thus, UAVs make an agile choice for efficient delivery compared to traditional truck-based delivery. Potential UAV applications in healthcare are based to emergency response, improving the lab testing, delivery, and surveillance operation. To support the operations, Table I presents the existing healthcare drones deployed in practical use-case setups. The UAV type differs in weight, cargo, and in-flight operations for the specific application. The article focuses on the delivery aspect of UAVs, potentially to vaccine delivery. UAV assures $\approx$90% vaccine deliveries from VMLs to PWs before the *cold-chain* expiration [11].

In the UAV communication network (UAV-N), both human-to-machine (H2M), and machine-to-machine (M2M) links require fast response time, high-reliability, and very low end-to-end (EE) latency. Tactile internet (TI) provides haptic and sensory feedback, low RTT ($<$10 ms), and high availability (99.99999%). 5G-TI vision is to provide ultra-reliable low-latency communication (uRLLC) service and EE latency of $<$1 ms, with 99.99999% availability.

However, delivery-UAVs communicate in UAV-N at high mobility. To maintain the flight path set-up and trajectory information, a swarm controller module is set-up at GCs to precisely monitor the UAV-N movements. 5G-eRLLC spectrum communication has a transmission time interval of $0.125 - 1$ ms for control connection set-up, limiting the real-time EE latency for mission-critical applications. However, with the rise in massive and dense H2M and M2M connections, delivery-UAVs require effective resource orchestration from edge nodes at proximity range where the EE delay cannot exceed 1 ms, and packet loss probability should be less than 10^{-7}, with 99.9999999 % availability in the radio access network (RAN) core.

6G-eRLLC (enhanced uRLLC) service sets with guaranteed delay bounds of $<$0.1 ms, and over-the-air latency of $10 - 100\ \mu$ s, 1 Tbps user-experienced data rate, and would maximize Quality-of-Experience (QoE) to overcome the above bottleneck. With artificial intelligence (AI)-supported RAN core, 6G-eRLLC would support resource provisioning to UAV-N through edge nodes. 6G-RAN core collects network information as training samples and improves network reliability, EE delay bounds, trajectory set-up, path planning, collision avoidance, route optimization, and precise localization of UAVs in UAV-N utilizing deep neural network models.

As mentioned above, 6G-eRLLC furnishes end-to-end delivery and distribution of vaccines from VMLs to the registered user (based on the priority list, vaccine type, age, and service occupation) through NPR. The distribution is a complex task owing to the challenges of illegal drug counterfeiting, limited raw material for drugs, drug caching, and huge price variation between the manufacturer and supplier, which finally increases the cost of supply-chain [12]. Employing traditional database management for storing records results in heterogene-

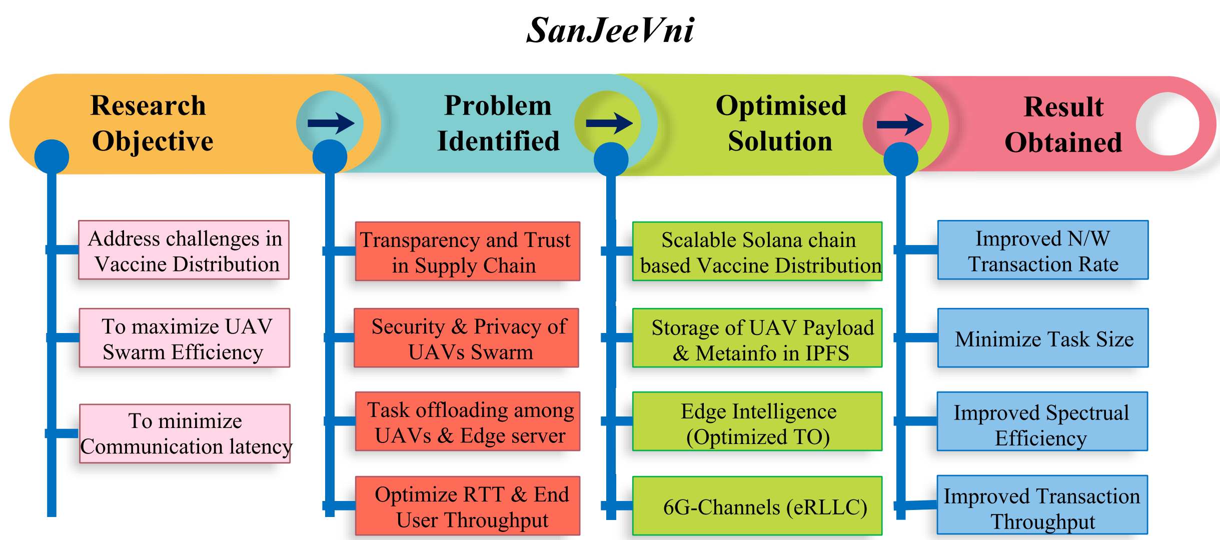


Fig. 1. Design goals for *SanJeeVni*.

ity in record maintenance, asynchronous data, and duplicity. Blockchain (BC) based vaccine registrations thus provide trust, provenance, chronology, and transparency in the entire supply chain with no duplication [13].

The above discussions highlight the need for a holistic scheme to address practical challenges in vaccine distribution, network management, and the improvement of UAV communication parameters. Thus, we present the design goals of our scheme, *SanJeeVni*, that integrates 6G and BC in UAV delivery scenarios. Figure 1 presents the design goals of the scheme. Via BC, the scheme assures transparency in the vaccine supply chain from VMLs to NC. BC also mitigates security attacks on UAV swarms and allows trusted vaccine registration among users. We design an intelligent task offloading scheme from edge servers in close proximity at the networking front. The scheme uses 6G-eRLLC scheme to propose embedded task intelligence, which optimizes the swarm management. Also, 6G-eRLLC has low EE latency, which ensures vaccine stability and expiration conditions are met during the delivery process. to address massive registration and distribution on BC network, we preferred a Solana chain over Ethereum owing to the high transaction rate and included interplanetary file systems (IPFS) to store the user information. IPFS allows content information to be fetched through the IPFS key, and only meta-information is maintained on the main BC ledger. This minimizes the transaction size on the main BC. The vaccine payloads and supplier information is registered in the Solana network. The scheme also forms an intelligent traffic offloading (TO) to optimize the swarm route and traffic condition, which orchestrates the swarm management during flights. As part of the experimental discussion, the proposed results indicate the scheme's effectiveness in terms of network rate, minimized task size, packet loss, and transaction throughput.

A. Research Contributions

Based on the design goals, we highlight the research contributions of the article as follows.

- A UAV swarm setup is proposed at the backdrop of 6G-eRLLC setup, which addresses the stringent EE latency of vaccine deliveries from SAs to NCs. This addresses our objective of optimizing RTT cycles, which allows a single UAV to have multiple in-flight operations in a day.
- To address the issues of task offloading, a 6G-eRLLC TO scheme is proposed. A swarm controller initiates high computing intensive tasks to nearby edge servers. To optimize the task processing, different training samples are collected from UAVs, and short term and long term predictors are generated that simplify the UAV traffic and network management.
- To address issues of transparency and throughput of BC, we propose a permissioned Solana BC between VMLs, PWs, and NCs for vaccine tracking and registration. User vaccine registration is done on BC through unique identification numbers (UIN). A permissioned Solana Chain *DApp* infrastructure is preferred that assures on-chain clock verification, global consensus through effective Proof-of-History (PoH) consensus, and directly forward of unconfirmed transactions to validators instead of storage into mempool.
- A case study of our proposed scheme with comparative analysis over 5G-uRLLC scheme is presented. The scheme performance is analyzed for metrics like BC transaction throughput, gas fees, energy consumption of UAV swarms, UAV covered range, spectral efficiency, and edge servicing latency. The obtained results indicate the scheme's efficacy in real-world setups.

B. Article Layout

The structure of the article is as follows. Section II presents a discussion on existing state-of-the-art scheme in vaccine and medical distribution via UAVs. A comparative analysis is also outlined with the proposed scheme. Section III presents the background information of key technical drivers. Section IV presents the entity description and the data flow model in the proposed scheme.Section V presents the key entities and operating process of *SanJeeVni* scheme. Section VI highlights the open issues and challenges in the proposed integration. Section VII presents a case study of the proposed scheme. Section VIII presents a discussion on the obtained results, the significant impacts, challenges, and future aspects of the study. Finally, section IX concludes the paper.

II. State-of-the-Art

A few recent studies focus on the deployment of UAVs in vaccine and healthcare deliveries. For example, Huang *et al.* [22] discussed UAV co-operative path-planning using ant colony and grey wolf optimizations. They considered the service capability of heterogeneous nodes at different demand points. The numerical results analyze the scalability for resource and area dimensions. However, the scheme complexity increased many folds. The authors present a simplified view in [23], where they proposed a self-sovereign identity framework that identifies and authorizes UAVs, with transactional ledger states in BC. The setup is considered on an edge-assisted delivery process. Gupta *et al.* [14] proposed a scheme *VaHaK*, which is based on an ethereum BC-based outdoor healthcare supply scheme that prioritizes healthcare supplies based on patient criticality. The scheme ensures smart contract (SC) execution through payment wallets over the backdrop of 5G-TI communication reliability. Zuhair *et al.* [16] proposed an improvement of the scheme over 6G communication channels. The scheme is named as *BloCoV6*, and it integrates 6G and BC in UAV communication for massive COVID-19 patient surveillance in dense regions. A contact-tracing ecosystem is designed on BC, where the collected patient thermal data are sent to GC through 6G channel. To address the scalability factor, authors in [24] studied BC-based COVID-19 vaccination that utilizes SCs to induce automation and handle impersonation attacks. The scheme proposed algorithms for beneficiary registration, vaccine tracking, handling rule-sets, and production condition over the entire vaccine supply-chain.

In vaccination delivery scenarios, to improve scalability and transaction rates, recent works have used permissioned setups. For example, Rathee *et al.* [25] proposed a permissioned BC-based vaccine distribution ecosystem, with a three-level distributed architecture for secure distribution of vaccines among different supply-chain points. Verma *et al.* [26] proposed *VaCoChain*, a scheme that integrates BC and 5G-TI based UAV services to support resilient vaccine distribution with reduced RTT delays from PW to NCs. However, the scheme fails to address compromised nodes in the supply chain. To address the issue, Cheema *et al.* [17] proposed a UAV based delivery system that utilizes BC for authentication of participating entities, medical centers, and UAV swarm nodes. The scheme is developed using ethereum based SC and a machine learning (ML) enabled intrusion detection system for robust communication performance. The authors in [18] propose an automated UAV based secured real-time traffic management scheme. The scheme utilizes BC, mobile edge computing (MEC), and deep learning (DL) algorithm for two-factor authentication and low latency communication in pair-wise UAVs. It achieves robust performance in terms of security, UAV training, end-to-end throughput, and energy consumption. The authors in [27] proposes a hybrid reinforcement learning based vaccine distribution scheme. The scheme develops an optimal trajectory for UAVs to deliver test kits to patients with a high probability of COVID-19 infection in a short time. Rani *et al.* [19] explored various UAV enabled societal applications and proposed a secured delivery system that utilizes a voice-based authentication system and provides various features such as image recognition, voice recognition, location-based tracking, and security. Table II presents a comparative analysis of the proposed scheme against the existing state-of-the-art.

The aforementioned schemes of UAV-based vaccine distributions do not address the issues of stringent EE delay constraints, edge-based UAV resource provisioning, and the integration of BC at the backdrop of 6G-service sets. Thus, the proposed scheme integrates the mentioned technologies and provides a secured vaccine distribution network with improved transaction throughput and improved spectral efficiency compared to 5G counterparts, which ensures smooth coordination among vaccine administrative entities.

III. Background of Key Technical Drivers

The section discusses the key technical drivers of the proposed architecture.

A. 6G-eRLLC Enabled UAV

UAVs are primarily used for medical aid supplies to remote hospitals, such as first aid kits, pharmacies, blood transfusions, and sample collections in the healthcare sector. It is estimated that UAVs reduce the shipping costs by $\approx$25% in comparison to conventional logistics [28].

UAV-N experiences bottlenecks in battery consumption, energy management, routing paths, flying control, wing-torque, and control operations at GC with increased UAV density and high request load. 6G envisions 50 times higher peak achievable data rate (1 Tbps), $3-5$ times higher spectrum efficiency, $10-100$ times higher UAV connection density (due to increased usage of heterogeneous networks (HetNets)), 10 times higher energy efficiency (due to effective AI radio management), with an area traffic capacity of 1 GB/s/m^2 compared to 5G counterparts. 6G-eRLLC enabled communication supports high UAV mobility of 1000 km/h, which would induce shorter RTT delays during vaccination trips. Moreover, 6G-eRLLC UAV channels support open UAV-UAV (U2U) links, and UAV-to-ground (U2G) links to facilitate both H2M and M2M communication and provide high directivity slight path loss, less blockage, and scattering due to atmospheric absorption and channel fading.

To support intelligent offloading, 6G-eRLLC enabled UAVs would communicate with multiple egde nodes through AI-based intelligent UAV sensing and transmission mechanisms. It provides dynamic orchestration of networking, caching, and computing resources. 6G enables iterative UAV

TABLE II
COMPARATIVE ANALYSIS OF THE PROPOSED SCHEME WITH EXISTING STATE-OF-THE-ART

Author	Year	Objective	1	2	3	4	Pros	Cons
Gupta *et al.* [14]	2020	BC based medical supply scheme with priority queue to expedite delivery to critical patients	Y	N	Y	N	A criticality score assessment is proposed and smart contracts are embedded between healthcare stakeholders	Does not discuss the security issues in UAV communication
Das *et al.* [15]	2021	Proposes a BC, AI and IoMT enabled vaccine distribution scheme for COVID-19 disease in Internet-of-Medical-Things environment	N	N	Y	N	Utilizes BC for storing health assets of patients at cloud end through threat models and AI based analytic	Does not discusses computation offloading through edge based communication network
Zuhair *et al.* [16]	2021	Proposes a UAV-enabled, 6G-assisted contact tracing scheme for COVID-19 patient	Y	Y	Y	N	Explores usage of UAV for identifying potentially affected COVID-19 patients and storing their records on BC at the backdrop of 6G communication network	Does not explain the edge offloading phenomena for UAVs with high dynamics
Cheema *et al.* [17]	2022	Explores UAV based secured delivery of medical aids using BC	Y	N	Y	N	Proposes a BC based scheme for registering delivery agents and utilizes machine learning-based intrusion detection system for securing UAVs during in-flight operations	Does not explores communication network between UAVs and ground entities
Masuduzzaman *et al.* [18]	2022	Proposes an automated real-time surveillance scheme using UAV	Y	N	N	Y	Utilizes deep learning-based vehicle detection & two factor authentication for faster and secured verification	Does not discuss radio communication network between UAVs and server
Rani *et al.* [19]	2022	Discusses societal applications of UAV for secured and authentic delivery	Y	N	N	N	Discusses technologies like voice based authentication, GPS navigation tracking and visual detection	Does not discuss the end-to-end communication requirement with server and adversary attacks
Johannessen *et al.* [20]	2022	Discusses the assessment of time and cost saving for sample transport using UAVs	Y	N	N	N	Provides an analytical study on time savings of drone transport compared to ground, differing distance & route frequency, and elements to assess the UAV transportation cost	The proposed approach does not dictate assessments in heavy traffic and battery limitations of UAVs
Sham *et al.* [21]	2022	Examines the attitude of rural health care workers towards drone delivery	Y	N	N	N	Classifies the attitude of participants or healthcare workers based on different classes	Explores theoretical calculations based on limited factors.
Proposed	2022	Proposes a generic scheme to integrate UAV, 6G, and BC for secured vaccine distribution	Y	Y	Y	Y	Utilizes SC and 6G-enabled edge offloading technologies for handling high end UAV computations, provides very low latency compared to 5G counterpart	-

1-UAV, 2-6G, 3-BC, 4-Edge Offloading, Y-shows parameter is considered, N-shows parameter is not considered.

sensing, swarm mobility model (Manhattan model), and transfer of vaccine payload data to destination NCs based on routing control algorithms.

B. UAV-N Swarm Network

A UAV swarm network is formed by scaling multi UAV networks through ubiquitous 6G connectivity U2U and U2G links. The advantages of a UAV swarm network include maximization of the operational altitude, communication, coverage, and computing capabilities, wider coverage range, high probability of line-of-sight (LOS) links, directed fly path, and many others. Leader-based selection algorithms are used to elect swarm controllers in the coverage range of UAVs to form cooperative relays. After controller setup at GC, it communicates with UAV-N through the H2M link. The Manhattan grid mobility model (MGM) randomizes UAV mobility patterns to prevent malicious attacks. In MGM, random patterns are mapped to random numbers, so malicious eavesdroppers do not intercept UAV-N mobility patterns [29].

Once it is done, the swarm controller module sets up aerial maps and flight control parameters, UAV-N stabilization parameters, initial flying measurements (start and end map coordinates), horizontal and angular speed, and wing angular momentum. 6G-eRLLC service enables UAV swarm setup and oral propagation message delivery in 0.125 ms & 0.02 ms, respectively. The swarm network manages oral updates to maintain paths, avoid collisions, and connect to heterogeneous radio links. The computational task can be scheduled to close mobile edge devices while caching the required contents at their end.

C. 6G-Enabled Edge UAV Offloading

In 6G-eRLLC networks, UAV swarms require task offloading based on edge intelligence (EI), owing to a huge amount of ingested data. EI predicts UAV coordinates, the number of UAV task offload requests, the time of the request, UAV path precision, and the flying time of the UAV swarm. Once the task offloading request is received, EI encompasses the time-series data through various models, which measure the channel temporal characteristics to form the task offload grant to UAVs. Based on communicated messages over 6G-eRLLC links, the EI node predicts the potential hotspots of overloaded UAV routes and assists UAVs to make topology selection nodes and optimize battery management and route map planning with swarm nodes. EI also allows ubiquitous UAV connectivity at large scales and monitors the environment perception based on real-time classification.

D. Solana Chain, Vaccine Registrations and Prioritization

Solana is the native fastest BC. It is designed as an alternative to Ethereum *DApp* platform. Table III highlights the advantages of preferring the Solana Chain in terms of node

TABLE III
COMPARISONS OF DIFFERENT BC NETWORK

BC/Parameter	Solana	Ethereum	Smart chain	Polkadot	Cardano	Tron
Transaction per second	55,000	15	100	1000	270	1000
Avg. transaction fee	0.0015$	15$	0.01$	1$	0.25$	-
Transaction latency	0.4 sec	5 min	75 sec	2 min	10 min	3 sec
Number of validators	702	$\approx 11,000$	21	297	2376	27
Consensus mechanism	Proof-of-Stack	Proof-of-Work	Proof-of-Authority	Nominated PoS	Proof-of-Stack	Delegated PoS
Overall transactions	15 billion	1.07 billion	227 million	1.7 million	5.9 million	1.7 billion

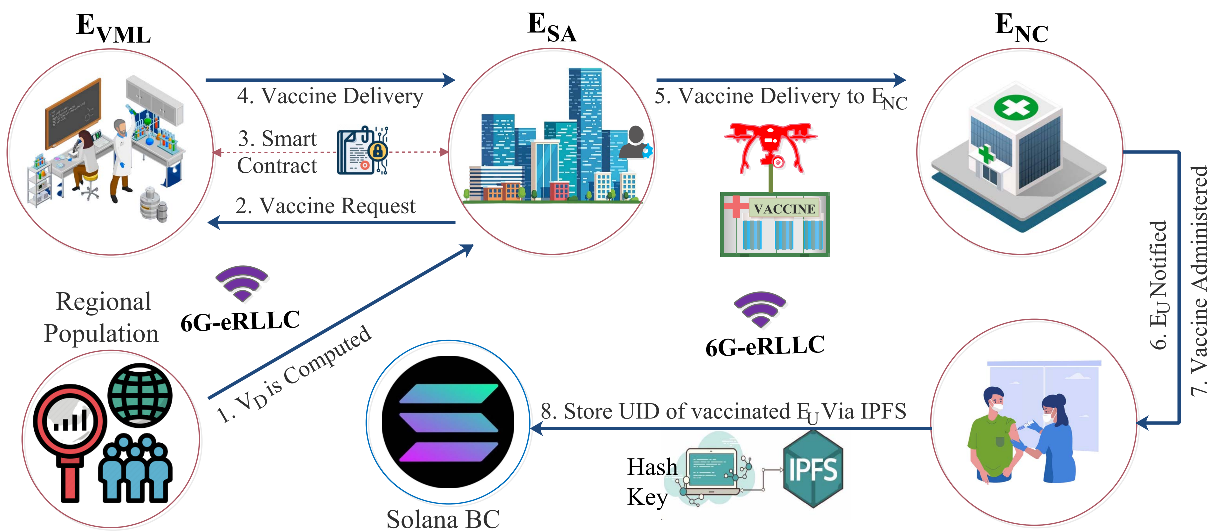


Fig. 2. *SanJeeVni*: The data flow among entities.

parameters over other similar chains. Solana uses Proof-of-History (PoH) in contrast to Ethereum's Proof-of-Stake (PoS), which allows a verified sequence of computation between two events in time which is verified cryptographically through hashes to generate the consensus output.

Solana has a single-state chain with no shards; it offers decentralization, very low transaction cost (around 0.0001 US dollars), and a high transaction rate (65000 transactions/s (TPS)) which solves scalability issues of BC. Solana uses *Turbine* and *Gulf Stream*, a block propagation protocol and forwarding protocol, respectively, which do not refer to the mempool.

In comparison, Ethereum uses a Proof-of-Stake (PoS) consensus that selects validators in proportion to the stake (or quantity) of cryptocurrency they hold. PoS suffers from a nothing-at-stake issue, where malicious validators present alternate copies of the chain and allow issues like double-spending on the forged chain. Ethereum 2.0 uses PoS consensus and sharding to create sidechains that link to the main Ethereum chain to increase the transaction speed. Ethereum 2.0 has a transaction rate of 100 transactions/s (TPS). Owing to the above advantages, we utilize a permissioned and public version of Solana Chain to handle fast transaction requests between VMLs, PWs, & NCs, ensure complete fairness and transparency in vaccine registration at NCs and maintain scalability. Moreover, U2U and U2G transactions meta-information is also stored in Solana. Before registration, we consider a priority queue Q, which signifies the priority of vaccination assignment. Thus, once a user registers through public *DApp* via U_{ID}, the age, and the profession is fetched from government NPRs. Based on this, a priority score P is assigned to every user, and Q is initiated.

IV. *SanJeeVni*: ENTITIES AND THE DATA FLOW MODEL

In this section, we outline the entities and the communication and data flow among them. Figure 2 presents the introduction to the entities in the scheme and the data flow among the entities.

The complete scheme is divided into three working layers-namely the Vaccine infrastructure layer, UAV & communication layer, and Distribution layer. We consider an entity set $E = \{E_H, E_{VRC}, E_{SA}, E_{VML}, E_{PW}, E_{NC}\}$, that represents the hospitals, vaccine research centers, state administration, VMLs, PWs, and NCs, respectively. E_{VRC} is responsible for developing vaccines with better efficacy and based on National Population Register (NPR) data. The data flow among the entities is formulated as follows.

1) E_{SA} computes the number of vaccine doses V_D required to meet the supply demands for vaccine users in a region, which is calculated from the NPR.
2) Based on the computed V_D quantity, a request is placed to E_{VML}, which represents the amount of V_D, that summarizes the need of each E_{NC} which comes under E_{SA}.
3) Each entity is registered in consortium Solana BC, based on the vaccine request a SC between E_{VML} and E_{SA} is executed to initiate the vaccine delivery.
4) Based on V_D, vaccine supplies is transported to E_{SA} by E_{VML}, based on the shared coordinates mentioned in the SC.

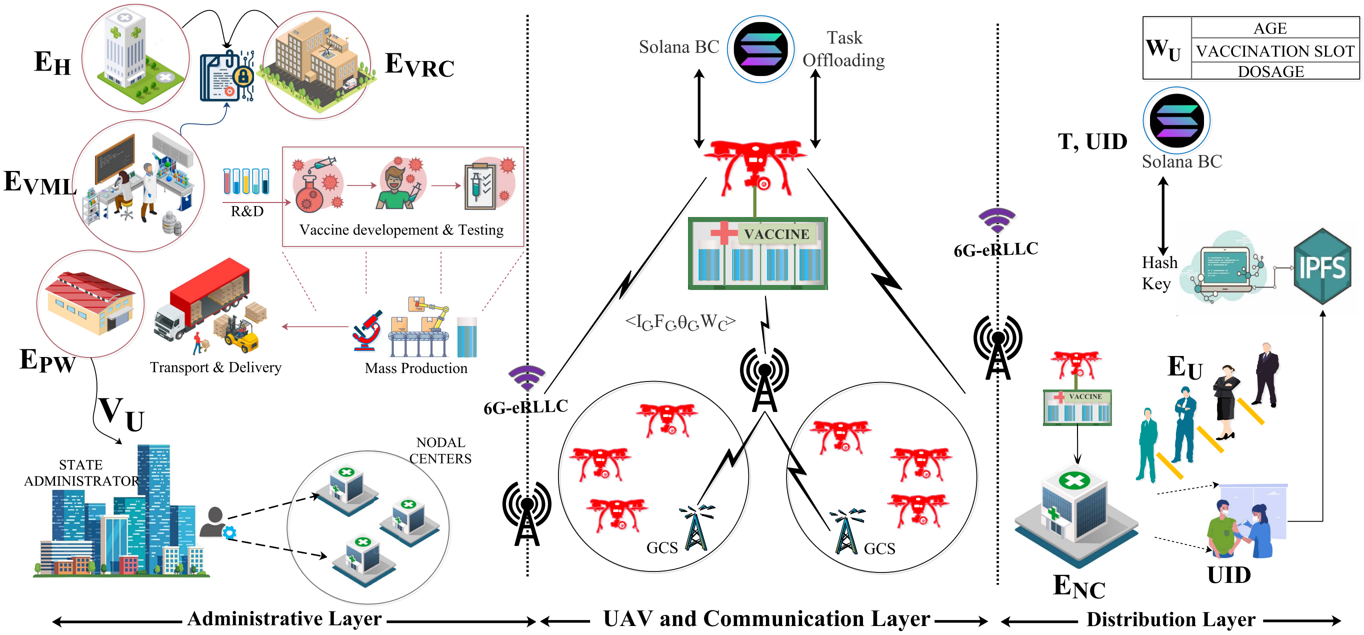


Fig. 3. *SanJeeVni*: The proposed architecture to handle massive vaccine distributions.

5) Once V_D reaches to S_A, depending on quantity and UAV payload, UAV swarms are initialized with vaccine payload and location coordinates to target E_{NC}.
6) Once the computed vaccine doses V_D reaches to E_{NC}, a notification is sent to all beneficiaries E_U about the vaccination slot and time.
7) UID is verified at E_{NC}, and vaccine is administered to E_U.
8) Post the vaccine dosage, the E_U UID along with dosage meta-information about the beneficiary is added in the IPFS, and the content reference from IPFS is stored in Solana BC ledgers.

V. *SanJeeVni*: The Proposed Scheme

As outlined in section IV, Figure 3 presents the proposed three-layered scheme, *SanJeeVni*, that integrates BC and 6G-eRLLC to handle massive vaccine distributions for COVID-19, and future pandemics. The details are presented as follows.

A. Vaccine Infrastructure Layer

At this layer, we consider the vaccine infrastructure and basic entities that are involved in the manufacturing, design, and packaging of the vaccines based on *cold-chain* operating conditions. Initially, E_{SA} builds the list of possible demographics (locations), to decide on requirements of E_{NC} at each location. Normally, based on fetched information from E_U UIDs, which are denoted as U_{ID}s, we compute the number of NCs required to meet the vaccine coverage requirements.

At every NC, we compute the received vaccine requests, which is denoted by a mapping $M : E_{NC} \rightarrow R(E_U, U_{ID})$ i.e. each E_U with their U_{ID} is eligible for immunization program. Based on requests, the vaccine dose requirements are calculated as $V_D = N \times P \times A_c \times W$, where N is the required number of vaccine doses to be administered to each E_U in multiple phases, P is the overall target population at NC to be vaccinated, T_c represents the formulated target coverage, and W is the expired vaccines during the cold-chain process. As per WHO guidelines, 2 vaccine dosage is required to be administered to each E_U, with a preferred time gap of T, depending on vaccine type. To demonstrate the formulation, we consider the sample space of 1000 users, with considered value of W to 1.21, and we would like to coverage of 85% target population then T_c would be 0.85, and based on the formula the estimated V_D required is 2057.

Based on V_D estimation, the request is forwarded by E_{SA} to E_{VML} for required vaccines. V_Ds are sent in packed containers via road logistics. We consider permissioned SCs deployed at every point in the Solana supply chain to automate the system. Once V_D reaches E_{VML}, it is forwarded with *cold-chain* packed containers, and forwarded via UAVs to E_{PW}. At E_{PW}, we maintain the *cold-chain* conditions, and through E_{SA}, we forward the vaccines to E_{NC} via UAV setups.

B. 6G-UAV Communication Layer

In our proposed approach, we deploy the UAVs to collect vaccine payloads from E_{SA} to E_{NC}, with transactional entries recorded in permissioned Solana Chains. At each supply point, we estimate the required number of UAVs based on V_U requests at E_{NC}. The UAVs are selected based on UAV type UAV_t, payload size UAV_{ps}, and destination route UAV_{rt} to E_{NC}. In a particular coverage drone-cell range, denoted as D_c, we initiate the UAV swarm selection.

The UAV swarm selection algorithm initiates inside a coverage range C_S. We consider a service-controller mechanism at GCs, denoted as $T(C)$, that initiates the parameters for swarm controller S_{con}. For all C_S and S_{con}, the service-parameter setup is $\{I_C, F_C, \theta_c, W_c\}$, where I_c denotes the initial flying coordinates, F_c denotes the final destination coordinates, θ_c denotes the flying Euler angle of UAVs, and W_c denotes

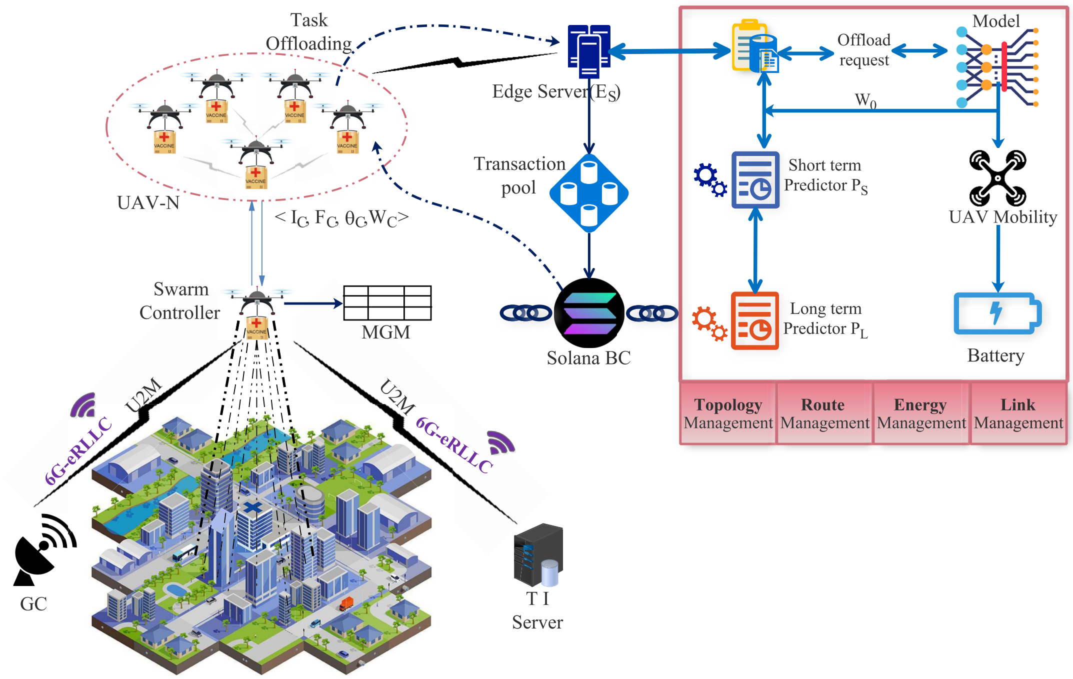


Fig. 4. The intelligent tO process by UAV_k at edge servers E_s.

the amount of computational work involved in the process. Any k^{th} UAV-N, S_{con} identify the swarm leader S_l through leader selection algorithms [30]. S_l manages cooperative paths and route planning through optimization.

During the in-transit phase, the UAV flocks follow the MGM mobility model, where we position all UAVs in a $q \times q$ grid. We assume that the position of any k^{th} UAV be (x_k, y_k). The next move can be at any of the four-possible quadrants, namely, $\{(x_{k-1}, y_k),\ (x_k, y_{k-1}),\ (x_{k-1},\ y_{k-1}), (x_{k+1}, y_{k+1})$. The selection of the particular grid depends on the computed joint probability P of all UAVs in C_S.

The UAVs are encapsulated with V_D and packet header P_H. 6G-eRLLC allows 10 times higher mobility than 5G-uRLLC U2U links. To support the computational requirements, the UAV swarms can initiate an intelligent task offloading process, as depicted in Figure 4. UAV_k offloads high-compute intensive tasks to nearby edge-node E_s if required. The task, denoted as T_k, is depicted as $\{T_k, I_k, L_k^{max}\}$, where T_k denotes the task size (in bytes), I_k denotes the edge-CPU instruction cycles, and L_k^{max} denotes the maximum permissible latency. To optimize the task processing, training samples TS, collected from different UAV swarms and fed to a learning model M. The generated output by M is W_0, which contains two sets of predictions, a short term predictor sequence P_S, and a long term predictor, denoted as P_L for UAV_k.

Based on TS, P_S focuses on relationships among task offload requests T_k, and patterns of task context for any i^{th} time slot, denoted as T^i. For example, UAV distributions in C_S, vaccine load L, channel state $S(C)$, and UAV event information to predict the number of task offload requests for the next slot, T^{i+1}. This approach is termed optimal task offloading (TO), as it measures the micro-estimations of requests over a time window W. In P_S, E_s learns about task request patterns that are slow parameters, with less drift rate over a specific period. The model M estimates the UAV locations through map regions and input data distribution to predict the max peak and off periods. P_L signifies the macro-estimation models. The model also communicates the prediction results to improve the topology, route, energy dissipation, and link-state management. The offload request-response is managed over 6G-eRLLC up-link and down-link channels. We assume that UAV_k offloads B_k bits to E_s through up-link, and $\gamma_k B_k$ bits are sent as a response from E_s to UAV_k, with constraint $\gamma > 1$. The controller node is assumed stationary to assist in offloading.

C. Vaccination Layer

In this layer, based on E_{SA} regulations, the vaccines V_D are delivered at E_{NC}. Beneficiary E_U, registers to Solana BC. We consider a *DApp* that registers E_U. The registration is processed through the NCs wallet identifier E_W. The vaccine requirements V_D are recorded into a permissioned version of Solana Chain, at every supply point of the delivery, i.e. between $\{E_{VRC}, E_{SA}, E_{VML}, E_{PW}, E_{NC}\}$. This eliminates the fake and illegal vaccination generation and dissemination by intermediaries. Once V_D is registered in the chain, the vaccine availability and slot information are displayed to E_U through the *DApp* via a push notification. At this point, we consider a priority-based scenario of vaccination, where a priority queue P_Q is formed by the assignment of the priority score of each user. The scores are recorded in the permissioned chain and depends on age, and occupation type i.e. senior citizens, healthcare workers, front line workers, and administrative task force.

Once user E_U is vaccinated with the first dose, the meta-records are reflected in the permissioned Solana chain, to estimate the time interval of the next dosage. The transaction is represented as $Trx = (U_{ID}, D_t, E_{NC_k}, D_n, T_t)$ where U_{ID} is the unique identity of the citizen, D_t is the date, E_{NC_k} is the identity of the NC, D_n is the dose number and T_t is the vaccination time-stamp. As Solana Chain has a high transaction rate, it can process the transaction meta-information easily, which handles the scalability issue of BC. Moreover, the information overhead can be further reduced by publishing the transaction to IPFS, which acts as a distributed storage handle. IPFS returns a hash key to access that record R that is then recorded in the public chain.

Algorithm 1: V_D Request and Delivery

Input: $P, N, W, A_c, E_{VML}, E_{SA}, E_{NC}$
Output: $D_{Status}\{1 : Success, 0 : Failure\}$

1 **Procedure** *VACCINE_REQUEST/DELIVERY*$(P, N, W, A_c, E_{VML}, E_{SA})$
2 $V_D = P \times N \times W \times A_c$
3 **if** $(Vaccine\_Stock > V_D)$ **then**
4 $Execute\_SC(E_{VML}, E_{PW}, E_{SA})$
5 $Pending\_Order(E_{SA}) = FALSE$
6 $Vaccine\_Stock \leftarrow Vaccine\_Stock - (V_D)$
7 $Delivery(E_{SA}) \leftarrow INITIATE$
8 $D_{Status} \leftarrow SUCCESS$
9 **else**
10 $D_{Status} \leftarrow FAILURE$
11 **if** V_D *reached at* E_{SA} **then**
12 $Add\_Payload(UAV_k, V_D)$
13 $Initiate(UAV_k) \leftarrow (I_C, F_C, \theta_C, W_C)$
14 $Status(UAV_k)$ = IN_TRANSIT
15 **if** $Location(UAV_k) == F_C$ **then**
16 $Status(UAV_k) = DELIVERED$
17 $Send\_Notification(E_U)$
18 **for** $\forall\ E_U \in E_{NC}\ Notified$ **do**
19 **if** *Verify(*E_U*_Notification) == TRUE)* **then**
20 $Administer(E_U, V_{D_u})$
21 $Hash_{key} \leftarrow IPFS(E_U, V_{D_u}, U_{ID}, E_{NC}, D_t, D_n, T_t)$
22 $List_{Trx} = (Hash_{key}, T_t, Mr)$
23 $Block \leftarrow Append(List_{Trx})$

To summarize the process, algorithm 1 presents the schematics of vaccine request and delivery. Lines 2-10 formulate the V_D estimation. We check if vaccine stock is available to deliver, a SC will execute between E_{VML}, E_{PW}, and E_{SA}, and deduct the stock count by V_D units. We initiate the delivery at E_{SA}, and record the delivery status.

Once V_D reaches E_{SA}, we initiate the UAV swarm initial parameters to deliver vaccines to E_{NC}. Any k^{th} UAV is loaded with data $\{I_C, F_C, \theta_C, W_C\}$, and the status of the UAV_k changes to *IN_TRANSIT*, the same is represented with Line 11-14. Lines 15-17 depict the condition, If the UAV reaches the final coordinates F_C, then the status of the UAV_k is changed to *DELIVERED*, and the notification is sent to each E_U. Line 18-23 depicts, For every E_U that belongs to E_{NC}, the notification is verified before administrating vaccine dose V_{D_u}. Once the vaccine is administered to beneficiary E_U, details of the same is stored in the IPFS server, and a hashed content reference key $Hash(key)$ is returned that is added to the transaction list $List_{Trx}$. Finally, $List_{Trx}$ will be appended in the block of transactions along with timestamp T_t and merkle root M_r. Due to the inclusion of 6G-eRLLC and Solana BC, a large number of E_U are registered in the network, and the swarm network is supported by S_l, which communicates with intelligent E_s. This leverages a massive distribution framework support that maximizes the vaccine coverage at E_{NC}.

VI. Open Issues and Challenges

In this section, we discuss the potential issues and challenges in the deployment of the proposed scheme. The details are presented as follows.

A. Congestion and Scalability Issues in Large-Scale Networks

In 6G networks, owing to the intelligent protocol stack, optimization algorithms perform well for small-scale networks. However, in the proposed scenario of mass vaccine distributions, we require a large number of networked UAV swarms to effectively orchestrate the logistics. With more UAVs, the networks tend to become dense, and thus they force the developers to add more optimization variables and constraints to the scenario to maintain similar efficiency. Thus, the complexity and scalability increase many folds and become a challenging issue. A possible solution is to explore simpler optimization algorithms that can operate with fewer variables and fewer iterations to improve the overall complexity.

B. Variations in Successive Control Packet Arrivals at UAVs

UAVs have to maintain stringent latency requirements over large distances. Thus, stability and control operations supplied by GC and TI controllers are crucial for maintaining UAV swarm stability. However, this requires high arrival rates, and in some cases, the time to process the control information of the packet at the network layer is more than successive packet arrivals. Due to this, the instruction control by the TI controller would be different for different routers, which is a race condition in networks, and it results in unpredicted behaviour of UAV swarms. The behavior also gives rise to induced jitter, which increases the overall propagation delay over large distances and might create bottlenecks in the network. Thus, software-defined UAV flow mechanisms is a preferred approach, where packets would follow a defined control designated by the flow switch and not the underlying network.

C. Pre-Offloading Scenarios

The proposed vaccination scheme considers the backdrop of 6G communication networks, where UAV mobility is crucial. As UAV mobility is relatively high, the resource offloading to a stationary edge is affected. Thus, a challenging aspect is to send a request for pre-offloading to those edge nodes that fall in the selective paths of MGM. This would increase the computing capability when the UAVs move to the grid coordinates where the edge node is present, as handshaking between

UAV-Edge is completed prior. However, distributing the MGM grids to map edge nodes prior to the UAV movements is an open issue and requires investigation. A possible direction is to map all proximity edge nodes as MGM and map the two MGMs to decide the edge coordinates.

D. Task Offloading Split for UAV Swarms

Owing to the high mobility of UAV swarms, a cooperative task model among all UAV sets is generally preferred, which is communicated to the edge node by the swarm leader. However, the challenge is to split the results of the coherent tasks obtained from the edge into smaller-sized subtasks, which can be communicated back to the individual UAVs. To determine the split, we need to administer the UAV location at all times, which is challenging owing to high mobility. Moreover, this induces an additional overhead on the swarm leader to locate and coordinate the results back to all UAVs, which consumes a lot of power.

E. UAV Swarm Coordination

In UAV swarms, the UAVs are directed to complete the vaccine delivery task to the scheduled NCs. However, in cases of poor network communication, the aerial 3D road layouts become unclear, owing to the collective fading in the wireless channels, which increases the signal dropouts. In such scenarios, the UAV swarm coordination is affected as UAV radio communication among U2U links is affected. Thus, selective mechanisms to handle the link dropouts to monitor the UAV swarm control is a challenge. Given this, accurate channel modeling and signal distribution model are required to handle the channel issues in order to maintain consistent bandwidth for swarm communication.

F. Solana Consensus: The BC Trilemma

Solana project is designed to handle the BC trilemma, i.e. trade-offs between security, scalability, and decentralization. However, to manage the high TPS rate, Solana compromises with its consensus approach and the validator requirements. Owing to the high TPS rate, validators in Solana are powerful machines and thus require a high cost to build and maintain such machine sets. Thus, in Solana Chains, selective nodes are elected as validators, which tend to centralize networks. In case validators are not powerful, the Solana network experiences instability, and thus fair and optimized PoH consensus should be designed to manage the trade-off of scalability, and decentralization, at desired security levels.

VII. Performance Evaluation: A Case Study

In this section, we consider the vaccine distribution ecosystem at the backdrop of 5G-assisted UAV communications. Currently, vaccine registrations are managed as distributed database systems, that manages V_D requirements from E_{NC}. We have considered 5G-uRLLC U2U and U2M links, with peak rates of 20 Gbps, and RTT latency of <10 ms. The details of the simulation parameters are presented in Table IV. We considered the Solana *v1.7.12*, with prebuilt binaries in Linux.

TABLE IV
Simulation Parameters

Parameters	Values
Communication Standard	6G-eRLLC and 5G-uRLLC
Link setups	U2U and U2M
Channel Multiplexing	5G-OFDM
No. of GC	2
UAV Coverage area	1000×1000 m
UAV Swarms	4
UAV Placement	Random
GC range	1 km of UAV swarms
Transmission Power	32 mW, 197 mW
TS	[200 kB, 1 MB]
CPU-cycles	9×10^{10} instructions
UAV Payload	10 kg
Validators	10
Network Switch	10 GbE
Mining setup	NVDIA RTX 1650 graphics
RAM	8 GB
Processor	Intel®Core™$i7-960X$
Operating frequency	3.2 GHz
UAV flying altitude	120 kms
UAV air drag resistance	20 m/s

For traditional UAV vaccine delivery ecosystems, we have considered the architecture proposed by Verma *et al.* [26]. The paper proposes an Ethereum-based vaccine registration ecosystem, at the backdrop of 5G-TI communication, with uRLLC channel RTT latency of <1 ms. The authors considered 5G-uRLLC multiplexed channels via OFDM that operates at 20 Gbps. Figure 5 presents the details.

A. Effectiveness of SanJeeVni in the Case-Study

In this section, we discuss the advantages of the deployment of our proposed scheme in the traditional setup. We discuss the effectiveness in terms of three key parameters, namely, the scalability of vaccine registrations, benefits of 6G-eRLLC assisted UAVs, and impact of EI to support optimal TO. The details are presented as follows.

1) Impact of BC in Maintaining Vaccine Record: In the proposed ecosystem, we have considered Solana Chain for E_U vaccine registration and dose administration. Figure 6a presents the details of transaction throughput in comparison to other legacy networks. As indicated, for 55, 000 transactions, Solana Chain takes ≈1000 ms, or 1 s, compared to 15 transactions in ethereum, 100 in Smart Chain, 1000 in Polkadot, and 270 in Cardano. Moreover, the average transaction fee of Solana is 0.0015 USD, with a low transactional latency of 0.4 secs.

Once the E_U vaccinated with its dose, the U_{ID} and meta information such as will be forwarded to IPFS server such as D_t, D_n, NC and T_t. The server will generate one fixed length unique content reference, that will be added as a part of the transaction in the BC. To store one transaction in Ethereum network in odd hrs is 2.51$ on Etherscan, whereas Solana network in peak hrs is 0.0015$. Figure 6b represents the cost of storing U_{ID} in after vaccination in Solana chain and the cost of storing the medical aid details on Ethereum chain [14]. There is a significant improvement of ≈199.76 % in storage cost 0.15$ and 250$ for storing the 100 vaccinated E_U.

2) Potential of 6G-eRLLC UAV Management: Next, we present the analysis of spectral efficiency of 6G-eRLLC channels over 5G counterpart. Figure 6c presents the details.

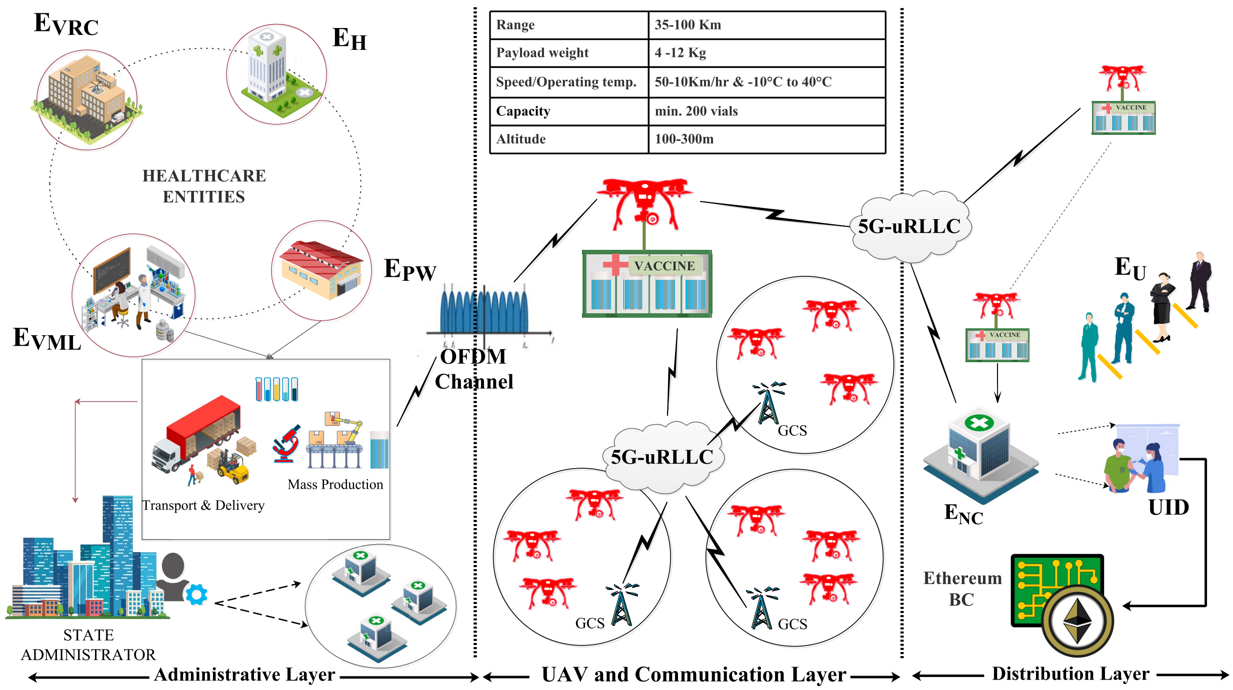


Fig. 5. *Case Study*: Permissioned 5G-UAV assisted traditional vaccine delivery [26].

6G-eRLLC envisions a low RTT latency of <0.1 ms. If we fix the UAV delivery in the 15 sq. km range, the servicing latency of 5G-uRLLC channels is ≈0.5076 ms. However, the value is ≈0.1018 ms in the case of 6G-eRLLC U2U swarm setups. 6G channels have higher spectral efficiency than 5G channels, where the spectral coefficient β is defined as $\beta = \frac{T_D}{\omega} \times C_S$, where T_D represents the total data traffic by UAV swarms, and ω denotes the U2U channel bandwidth. As depicted, at $C_A = 20$ sq.km, the value of β for 6G-U2U link is 52.112 earlangs/MHz, compared to 170.4 Earlangs/MHz in 5G-uRLLC. Thus, 6G servicing antennas have a higher lifetime and can communicate over distanced UAV-N to support real-time operations and control.

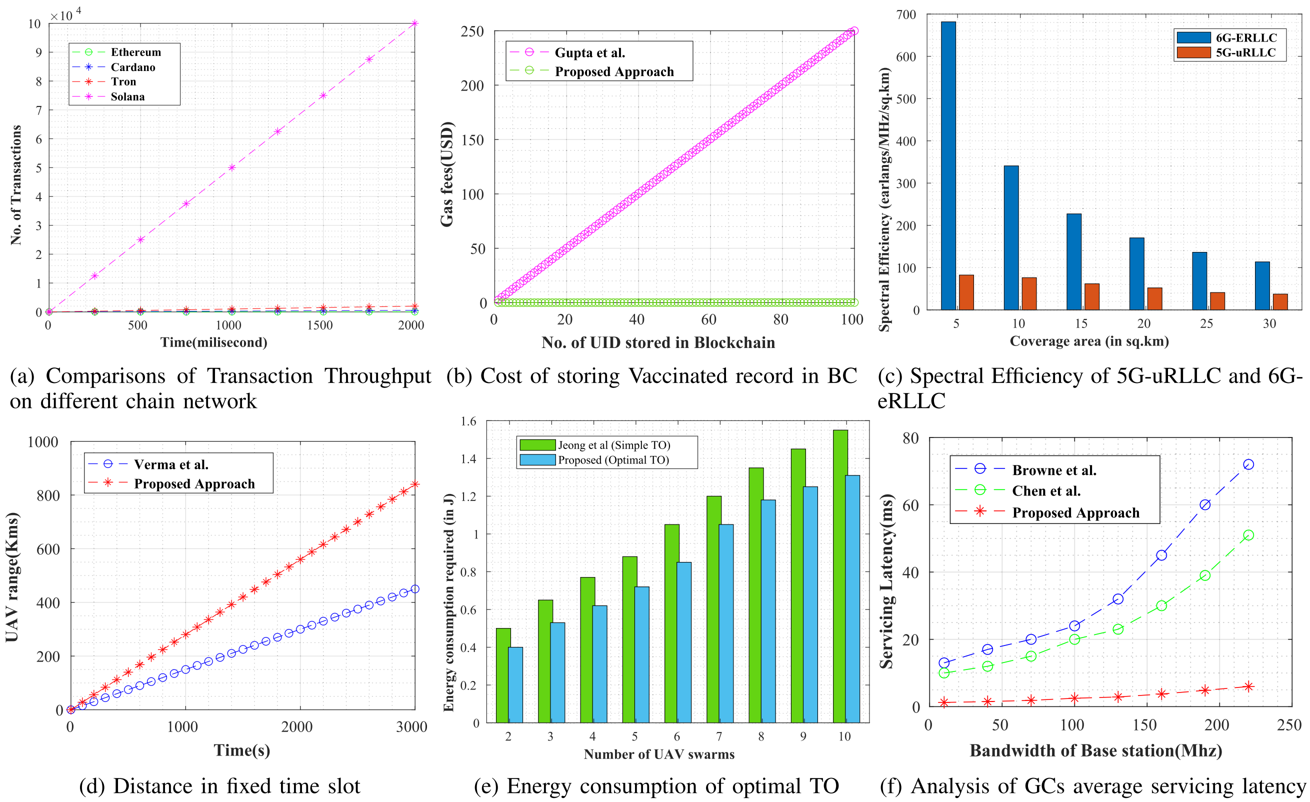
The main problem with 5G-eRLLC is less spectral efficiency as compared to 6G-eRLLC, and that divides the overall coverage of UAV in a fixed amount of time. Figure 6d presents the covered distance by UAV in given time slots. In 1000 seconds, Verma *et al.* [26] covers ≈160Km whereas the proposed scheme covers ≈282Km, that shows an improvement of ≈76.25% in UAV coverage. This shows that 6G-eRLLC enabled UAVs are capable of more vaccine round trips from E_{SA} to E_{NC}, which shortens the time duration of vaccination dosage to eligible E_U.

3) Impact of 6G-eRLLC Enabled Edge Intelligence: We consider that any k^{th} UAV offload its task T_k to edge node E_S in C_A. In simple TO, as presented by Jeong *et al.* [31], the authors assumed that tasks are collected in UAV-N, and are sent to closest E_S from leader S_l. The drawback of a simple TO scheme is that the processor capability is not considered, whereas in the proposed scheme, we consider intelligent TO supported by EI in 6G networks. Figure 6e presents the results. Each E_S runs two local predictor models, P_S, and P_L, that depend on the relationship among T_k, and other patterns of similar tasks in that i^{th} slot unit. For 5 UAV swarm networks, the proposed energy consumption of simple TO, as presented in Guo *et al.* is ≈0.88 Joules (J), compared to 0.72 in the proposed scheme. Overall, we observe a significant improvement in the energy reduction of UAVs and E_S, with an average drop of 12.2 % over the U2M uplink and downlink channels.

Figure 6f represents the analysis of impact of bandwidth on GC against the latency in-service performance of Browne *et al.* [32], and Chen *et al.* [33]. We assume that the request generated from each UAV per time slot is in the form of Poisson Distribution, and the computing capability of the edge server is clocked at 12.70 Mhz. In the figure, we observe that less time is required to offload data, which improves the servicing latency. The service latency in Browne *et al.* [32] decreases from 72 ms to 11 ms when we increase frequency from 10 to 220 MHz, while in Chen *et al.* [33], the servicing latency drops to 9 ms from 51 ms at the same conditions. In the proposed approach, the servicing latency only drops from 5.98 to 1.25 ms when we increase the bandwidth from 10 to 220 Mhz. An improvement of 88% is observed against Browne *et al.* [32], and 86% improvement against Chen *et al.* [33] respectively.

VIII. Discussion and Future Aspects

As discussed in Section VII, and the obtained results, some key technical improvements are discussed in the section. As the scheme uses a scalable and permissioned Solana BC for vaccine registration and distribution, the cost of transaction storage of vaccinated records improves drastically. Moreover, 6G-eRLLC based UAV setups greatly orchestrate the covered



(a) Comparisons of Transaction Throughput on different chain network (b) Cost of storing Vaccinated record in BC (c) Spectral Efficiency of 5G-uRLLC and 6G-eRLLC

(d) Distance in fixed time slot (e) Energy consumption of optimal TO (f) Analysis of GCs average servicing latency

Fig. 6. Case study: Deployment of *SanJeeVni* scheme in vaccine distributions against future pandemics.

distance, spectral efficiency, and servicing latency, that justifies its effectiveness in real setups.

However, in practical healthcare scenarios, the deployment of *SanJeeVni* is challenged by a large number of users worldwide. First, a shift is required from a permissioned approach to a public BC, to make vaccination records fully transparent to end-users. In current public BC setups, Ethereum networks are mostly used. Owing to a large number of transaction networks, it is not a feasible option. Solana BC has a high TPS rate, which is suitable for public networks. Secondly, vaccine distribution is facilitated by 6G channels to minimize the communication latency. However, 6G practical deployments are still in their infancy. Although a large volume of literature is proposed on 6G, but there are critical challenges in the commercial adoption of 6G, due to lack of uniform standards.

6G envisions a low latency of 10 μ s at the PHY layer, but as the majority of the core communication follows legacy networks, the compatibility and flow control between devices is a challenge. Also, effective AI provisioning to envision a real-time EI is a complex task, owing to the heterogeneity in link formations. Thus, the effective realization of THz bandwidth is far-fetched in reality [34]. More stability in semiconductor design and open standards at PHY and MAC layers might envision the 6G service design to operate at desired frequencies in the near future. Finally, UAV flight operations are restricted into non-flying zones or personnel airspace, which restricts the scheme's utility in case of long flights. Moreover, UAV acceptance over human presence is still not acceptable by healthcare stakeholders. Thus, the openness toward UAVs in the general public is still in the early phases.

IX. Conclusion

COVID-19 vaccine distribution and registration requires a timely, supportive framework to manage transparency in massive supply chains. Thus, the article proposed a scheme, *SanJeeVni*, that fuses BC and 6G in vaccine setups to assure trusted logistics while meeting the requirements of stringent EE delay. The scheme proposes a UAV swarm network where path setup and swarm mobility is managed via intelligent edge. With 6G-eRLLC, UAV trip times are bounded, which assures timely vaccine coverage to users. For scalability, we integrate a permissioned Solana network for high transaction throughput, with simplified registrations and dosage maintenance at NCs. Extensive experiments were performed on UAV swarm and GC controller setup, and a significant improvement in storage cost and UAV coverage is obtained. Conclusively, the proposed scheme simplifies the UAV flight operations, owing to 6G-eRLLC setup, and supports an intelligent TO to reduce energy requirements for longer flight duration. As part of the future scope, an extension to the scheme would be investigated for security in UAV swarm communication. An anonymous and secured quantum key distribution channel would be set up, which allows perfect secrecy and privacy of user communication for massive dense networks.

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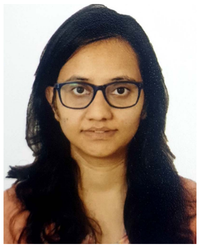
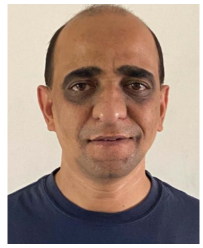
Ashwin Verma received the M.Tech. degree in CSE from NIT, Jaipur, India. He is currently pursuing the Ph.D. degree in the healthcare domain. He is employed as an Assistant Professor with the Computer Science and Engineering Department, Institute of Technology, Nirma University. He has seven years of teaching and academic experience and has authored and coauthored more than six articles in leading SCI journals and IEEE conferences. Some of his top findings are published in the IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS, *Journal of Information Security and Applications* (Elsevier), and IEEE-ICIEM-2021. His research interests lie in healthcare 4.0, federated learning, blockchain technology, and 5G and beyond communications.

Pronaya Bhattacharya received the Ph.D. degree in optical switching networks. He has over eight years of teaching experience. He is employed as an Assistant Professor with the Computer Science and Engineering Department, Institute of Technology, Nirma University, Ahmedabad, India. He has authored or coauthored more than 60 research papers in leading SCI journals and top core IEEE COMSOC A* conferences. Some of his top-notch findings are published in reputed SCI journals like IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE INTERNET OF THINGS JOURNAL, IEEE TRANSACTIONS ON NETWORK SCIENCE AND ENGINEERING, IEEE ACCESS, *ETT* (Wiley), *Expert Systems* (Wiley), *FGCS* (Elsevier), *OQEL* (Springer), *WPC* (Springer), ACM-MOBICOM, IEEE-INFOCOM, IEEE-ICC, IEEE-CITS, IEEE-ICIEM, IEEE-CCCI, and IEEE-ECAI. His research interests include healthcare analytics, optical switching and networking, federated learning, blockchain, and the IoT. He is a Reviewer of 17 reputed SCI journals like IEEE INTERNET OF THINGS JOURNAL, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE ACCESS, *IEEE Network*, *ETT* (Wiley), *IJCS* (Wiley), *MTAP* (Springer), *OSN* (Elsevier), and *WPC* (Springer).



Deepti Saraswat is pursuing the Ph.D. degree with the Dhirubhai Ambani Institute of Information and Communication Technology (DA-IICT), Gandhinagar, India. She is employed as an Assistant Professor with the Computer Science and Engineering Department, Institute of Technology, Nirma University, Ahmedabad, India. She had more than five years of industrial experience at the Samsung Research and Development Research Institute, Bengaluru, India, where she had worked on implementation of web browsers and the Internet of Things (IoT). Her research interests include data security and privacy, blockchain technology, optimization techniques, and the IoT.

Sudeep Tanwar (Senior Member, IEEE) received the Ph.D. degree in computer science and engineering from Mewar University, India. He is working as a Professor with Nirma University, India; and was a Visiting Professor with Jan Wyzykowski University, Polkowice, Poland, and the University of Piteşti, Piteşti, Romania. He has authored/coauthored more than 270 research papers in leading journals and conferences of repute and has edited/authored 20 books published in leading publication houses like IET and Springer. His research interests include WSN, blockchain technology, fog computing, and smart grid. He is an Associate Editor of *IJCS*, *Security and Privacy* journal (Wiley), and *Computer Communications* (Elsevier).



Neeraj Kumar (Senior Member, IEEE) received the Ph.D. degree in CSE from SMVD University, India. He was a Postdoctoral Research Fellow with Coventry University, U.K. He is working as a Professor with the Thapar Institute of Engineering and Technology, India. He has more than 300 research papers in leading journals and conferences of repute. He is an Associate Editor/Technical Editor of *IEEE Communications Magazine*, *IEEE Network magazine*, *IJCS* (Wiley), *JNCA* (Elsevier), *Computer Communications* (Elsevier), *Security and Privacy* (Wiley), IEEE SYSTEMS JOURNAL, and *ACM Computing Surveys*.

Ravi Sharma is working as a Professor with the Centre for Inter-Disciplinary Research and Innovation, University of Petroleum and Energy Studies, Dehradun, India. Dr. Sharma is passionate in the field of business analytics and worked in various MNC's as a Leader of various software development groups. He has contributed various articles in the area of business analytics, prototype building for a startup, and artificial intelligence. He is leading academic institutions as a Consultant to uplift research activities in interdisciplinary domains.