Indonesian Journal of Electrical Engineering and Computer Science
Vol. 41, No. 2, February 2026, pp. 764~772
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v41.i2.pp764-772

Driving connectivity: a thorough review of networking protocols in electric mobility

Ramandeep Sandhu[1], Harpreet Kaur Channi[2], Nimay Chandra Giri[3], Pulkit Kumar[4], Mohamed A. Elaskily[5], Mohamed A. Hebaishy[5]
[1]School of Computer Science and Engineering, Lovely Professional University, Phagwara, India
[2]Department of Electrical Engineering, Guru Nanak Dev Engineering College, Ludhiana, India
[3]Department of Electronics and Communication Engineering, Centurion University of Technology and Management, R. Sitapur, India
[4]Department of Electrical Engineering, Chandigarh University, Chandigarh, India
[5]Department of Informatics, Electronics Research Institute (ERI), Cairo, Egypt

Article Info

Article history:

Received Apr 23, 2025
Revised Dec 30, 2025
Accepted Jan 11, 2026

Keywords:

Electric mobility
Electric vehicle
Ethernet communication in EVs
FlexRay protocol
Networking protocols
Time-sensitive networking

ABSTRACT

The rapid advancement of technology has transformed the automotive sector through intelligent systems for safety, control, and infotainment. This study reviews key networking protocols controller area network (CAN), local interconnect network (LIN), FlexRay, MOST, Ethernet, and Master-Slave used in electric vehicles (EVs) in India and worldwide, providing insights into their application trends across different regions. CAN provides reliable low-latency communication for safety-critical functions (1 Mbps), while CAN FD extends support up to 12 Mbps. LIN and Master-Slave topologies enable cost-effective low-speed operations (2–20 kbps). FlexRay ensures real-time communication (10–100 Mbps), and MOST supports 150 Mbps for multimedia applications. Ethernet offers superior bandwidth up to 10 Gbps for advanced driver assistance and autonomous systems, but it involves higher complexity and cost. The review identifies key challenges in interoperability, scalability, and cybersecurity and evaluates protocol suitability for next-generation EV architectures. It also integrates Industry 5.0 principles and SDGs 7, 9, and 13, emphasizing human-centric, sustainable, and resilient mobility.

Corresponding Author:

Mohamed A. Hebaishy
Department of Informatics, Electronics Research Institute (ERI)
Cairo, Egypt
Email: hebaishy@eri.sci.eg

1. INTRODUCTION

The adoption of electric vehicles (EVs) is accelerating globally, including in India, driven by technological innovation and sustainability goals. According to the international energy agency (IEA, 2024), global EV adoption surpassed 14 million units, reflecting rapid advances in connected mobility technologies [1]. However, disparities in infrastructure, communication standards, and regulations continue to influence the development of EV networks. High-speed in-vehicle networking is essential for implementing advanced protocols in Industry 5.0, resulting in sustainable development goals (SDGs) for the country [2], [3]. Wang *et al.* [4] proposed the block alliance consensus (BAC) approach to overcome these difficulties. Lin *et al.* [5] Introduced semi-Markov decision process–medium access control (SMDP-MAC), a time division multiple access (TDMA) protocol with adaptive slot management and dynamic parameters. Once the network is stable, vehicle time slots will be dynamically allocated based on each vehicle's position. This study replicates the SMDP-MAC protocol performance on a roadway. To assess its efficacy, it compares SMDP-MAC to vehicular medium access control (VeMAC), binary message authentication (BMA), and adaptive slotted medium access control (ASMAC). As software problems and vulnerabilities increase, electric and electronic vehicle architectures need over-the-air (OTA) software updates to reduce recalls. Shoker *et al.* [6] published ScalOTA, a comprehensive and scalable OTA software update system and secure protocol for modern cars. EVs are replacing gasoline-powered cars due to their increased availability. The expansion of electric vehicles charging station (EVCS) has increased its cybersecurity vulnerabilities in [6]. Hamdare *et al.* [7] analyzed EVCS network cybersecurity risk. Modern cars have mechanical parts, complex electronics, and network connectivity. After reviewing and comparing protocols in modern car-embedded networks. Douss *et al.* [8] showed how new autos' increased communication capabilities can benefit attackers. Wireless network integration into time-sensitive networking (TSN) is necessary due to industrial mobility and wireless network use [8]. Zanbouri *et al.* [9] examined the structure and several wireless technologies and protocols used in wireless TSN networks. Recent studies demonstrate rapid advancements in automotive Ethernet, vehicle-to-everything (V2X) communication, and artificial intelligence (AI)-driven network optimization for autonomous EV architectures, highlighting the need for unified communication frameworks capable of supporting heterogeneous sensor networks [10], [11]. Although significant progress has been made in electric powertrains and battery technologies, the communication backbone of EVs. The major research gaps identified to carry this work are based on individual EV protocols, where a unified comparison across performance, determinism, cybersecurity, and Industry 5.0 alignment.

This paper aims to analyze and compare key in-vehicle networking protocols to support efficient data management in electric mobility systems. The main contributions of the study are:
- To thoroughly examine how well standard networking protocols work for electric vehicles.
- To find new trends and future directions that could affect how networking architectures change in intelligent EV systems.
- To improve interoperability, connectivity, and cybersecurity in EV systems by protocols such as TSN, BAC, and SMDP-MAC.

This sustainable and resilient electric mobility is in line with Industry 5.0 and SDGs 7, 9, and 13.

2. PROCEDURE OF ELECTRIC VEHICLES NETWORKING

EV networking shapes intelligent transportation systems, as shown in Figure 1. As the car industry moves towards sustainable and electrified transportation, current networking technologies are essential for improving vehicle performance, safety, and efficiency. Their external connections include charging infrastructure, smart grids, and other linked vehicles. Remote vehicle monitoring, OTA upgrades, and intelligent charge management are enabled by external connectivity. EV networking follows networked and self-driving transportation trends. Future improvements will likely prioritize cybersecurity protocols, latency difficulties, and communication network complexity to construct safer, more efficient, and more intelligent electric transportation systems. EV networking is essential for a sustainable and interconnected road future as the automotive industry adopts electrification and smart technologies [12].

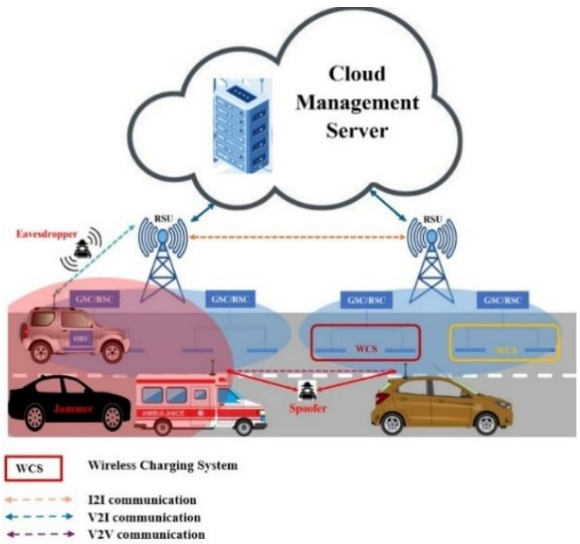

Figure 1. Networking in electric vehicles (CC by 4.0) [10]

3. METHOD

This paper covers FlexRay, Ethernet, controller area network (CAN), local interconnect network (LIN), master and slave configurations, frames, and MOST, the leading networking protocols used in EVs. Ethernet enables scalable, high-bandwidth connections for advanced driver assistance systems (ADAS) and infotainment, while FlexRay delivers high-speed, deterministic data transmission for vital safety applications. Due to its robustness and real-time capabilities, CAN is used for engine control and other crucial activities. LIN is cost-effective for climate management and other simple applications. Finally, MOST is optimized for multimedia data transport, guaranteeing high-quality car audio and video streaming. Our article analyzes these protocols to understand their roles and interoperability in the EV ecosystem, paving the path for car networking advancements.

3.1. Controller area network

The CAN bus standard enables communication between electronic control units (ECUs) in vehicles without a host computer, as shown in Figure 2. It uses CAN-L and CAN-H wires to transmit data up to 1 Mb/s, enhancing noise immunity through differential voltage signals. The system prioritizes messages using arbitration IDs, granting bus access to high-priority signals while lower-priority nodes wait. The average terminal resistance is 120 ohms, preventing data echoing as shown in Figure 3. Each node receives broadcast frames and either accepts or rejects them based on their ID. If multiple nodes transmit simultaneously, the node with the highest priority wins. This setup ensures deterministic, reliable, and efficient communication, making CAN ideal for real-time applications in vehicles [13].

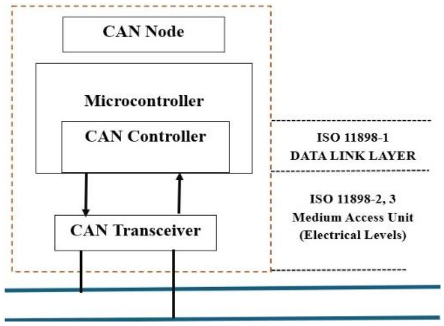

Figure 2. The architecture of CAN network

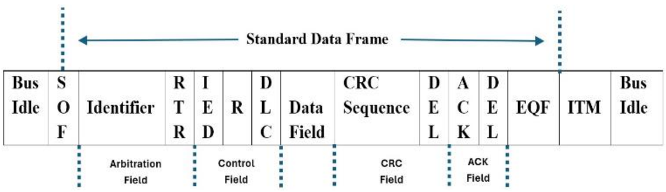

Figure 3. CAN bus data frame

3.2. Local interconnect network

LIN is a cheap automotive multiplex network supplement. A hierarchical vehicle network with LIN will improve car quality and save money. Standardization will minimize low-end multiplex alternatives and auto electronics manufacturing, development, servicing, and logistics costs. The LIN standard covers data transport, software programming interfaces, and development tool interfaces. Hardware and software network node compatibility and predictable EMC are promoted by LIN. LIN 2.0 standardizes slave node descriptions. This simplifies node buying and automates cluster creation. An authentic mobile cluster can factor and play. Below is the recommended workflow: connections form LIN clusters [14]. Slaves serve masters. System-defining tool builds LIN (LDF) description files from node capability files. System generator builds LDF-based master and Slave3 LIN functions. LIN bus analyzers/emulators debug clusters with LDF. Since the method builds the LIN cluster interface module, the developer merely needs to offer the program a node's logic function [15].

3.3. Master and slave

A LIN cluster consists of a master task and multiple slave tasks. In this configuration, the master task and at least one slave task are typically located on the master node (Node 1). All other nodes in the network exclusively contain slave tasks. The model presented below illustrates a LIN network with one master node and two slave hubs. A node within the network can belong to multiple clusters, and if a node has multiple LIN bus interfaces, the term "node" refers to the specific interfaces on that node. In this architecture, the master task is responsible for determining which frame will be transmitted on the bus and when. The data carried by each frame is provided by the respective slave tasks. The frame handler is composed of both the master task and the slave tasks, with each task coordinating the transmission and reception of frames within the network [16].

3.4. Frames

A frame is made consists of a header and a reply. A break-and-sync pattern appears in the header, which is followed by an identification. The function of the frame is specifically defined by the identification. Frames containing two reserved IDs are used to convey diagnostic messages [17].

3.5. Flexray

The FlexRay consortium, which collapsed in 2009, created the FlexRay automobile networking standard. Figure 4 illustrates the FlexRay communication structure, developed through the FlexRay consortium that included general motors, Volkswagen, BMW, and Daimler. Flex Ray's flexibility, a 10 Mbps maximum data throughput, and time-triggered deterministic TDMA behavior are its key advantages over CAN. However, FlexRay nodes cost more than CAN nodes, making them unattractive for big-scale manufacturing. Through clock synchronization, it offers constant jitter and latency. Due to its strict timing and latency properties, it is frequently employed in "drive-by-wire" applications where deterministic performance is essential. TTP is a related standard [18].

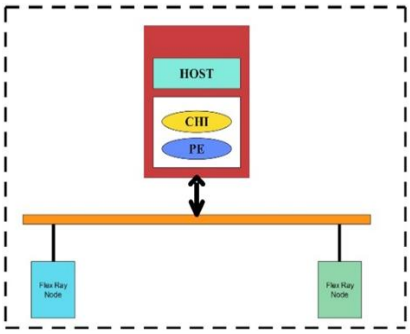

Figure 4. Structure of FlexRay

3.6. MOST

The main reason to support the communication of multimedia data, MOST was developed. The 150 Mb/s throughput of the MOST150 standard makes it much more suitable for multimedia traffic transport than CAN. Although the MOST Corporation released the MOST standard, it is missing particular information about the OSI Layer 2 data link layer, making it exclusively accessible in exchange for payment [19], [20]. Table 1 provides the case studies available in various articles regarding the networking protocol applications.

Table 1. Case studies for network protocol applications available in electric vehicles

Vehicle type	Network protocols	Applications	Performance matrices	Future enhancement
Electric sedan	CAN, Ethernet	ADAS	Latency, reliability, throughput	Integration with TSN for deterministic control
Electric SUV	FlexRay, LIN	Battery management system (BMS)	Real-time capabilities, scalability	Enhanced fault tolerance with redundancy
Electric city car	MOST, Ethernet	Infotainment system	Bandwidth, latency, user experience	Migration to Ethernet AVB for multimedia synchronization
Electric delivery van	Master-Slave, CAN	Telematics and fleet management	Integration complexity, data accuracy	Cloud-linked diagnostics and OTA updates
Electric autonomous shuttle	Ethernet, FlexRay	autonomous driving system	Latency, redundancy, reliability	TSN-based low-latency backbone for AI-driven control

3.7. Ethernet

Ethernet, a high-speed and low-cost communication bus, now dominates in-vehicle networks due to its scalability and flexibility. Legacy systems such as CAN and MOST were sufficient for early low-bandwidth control, but cannot meet modern data demands. Ethernet enables rapid diagnostics and software flashing reloading 81 MB of firmware takes 10 hours via CAN but only 20 minutes via 1 Gb Ethernet [21], [22]. Advanced driver-assistance systems rely on multiple high-bandwidth sensors, including infrared cameras and high-GHz radar, efficiently supported by Ethernet's superior data capacity [23].

4. RESULTS AND DISCUSSIONS

The study presents a comparative analysis of various networking protocols used in EV systems, including CAN, LIN, Master-Slave, frames, FlexRay, MOST, and Ethernet. For high-bandwidth applications such as ADAS, Ethernet proves most suitable due to its exceptional data rates, reaching up to 10 Gbps. MOST also supports high data transfer speeds (up to 150 Mbps) but is limited by greater complexity and cost. In contrast, the low latency of CAN and FlexRay makes them ideal for real-time and safety-critical communication, although FlexRay's superior performance comes with higher implementation complexity. For large-scale or less demanding operations, the simplicity and low cost of LIN and Master-Slave topologies are advantageous.

The development of EV communication protocols depends primarily on data rate, latency, reliability, complexity, and cost-effectiveness. LIN is inexpensive and ideal for low-speed applications (2–20 kbps) but unsuitable for large data volumes as shown in Figure 5. MOST offers high bandwidth (150 Mbps) for information systems, but it is costly and complex. CAN (1 Mbps) and CAN FD (10–12 Mbps) provide reliable and robust communication with moderate speed, while FlexRay (10–100 Mbps) excels in deterministic, real-time safety operations but at a higher cost, as shown in Figure 6. Ethernet, with speeds up to 10 Gbps, supports ADAS and autonomous driving but requires careful network management. Master-Slave systems remain simple and affordable but have limited scalability. Comparing these protocols helps determine the most appropriate solution based on specific application requirements, as illustrated in Figure 7. Table 2 summarizes protocol data ranges for several communication technologies. This table is a great resource for understanding how different communication protocols convey data across technological domains.

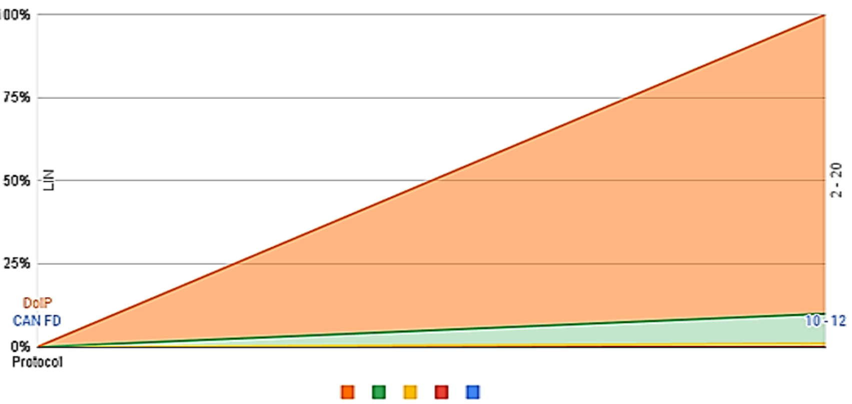

Figure 5. Data rate plotting of the protocol

Table 2. Protocol data range [23]

Protocol	Data rate (kbps-Mbps)
LIN	2-20
MOST	Up to 150
CAN	1
CAN FD	10-12
FlexRay	10-100
Ethernet (10BASE-T)	10
Ethernet (100BASE-TX)	100
Ethernet (1000BASE-T)	1K
Ethernet (10GBASE-T)	10K
DoIP	Varies (depends on the underlying network)

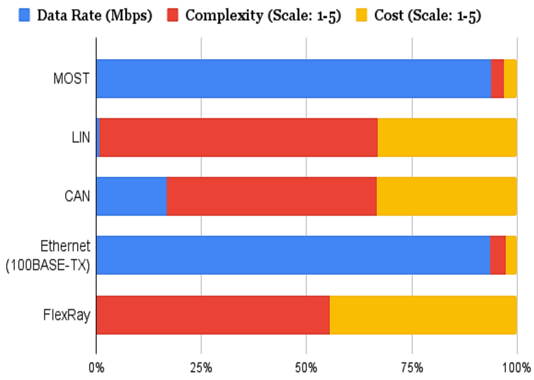

Figure 6. Data rate plotting of protocols

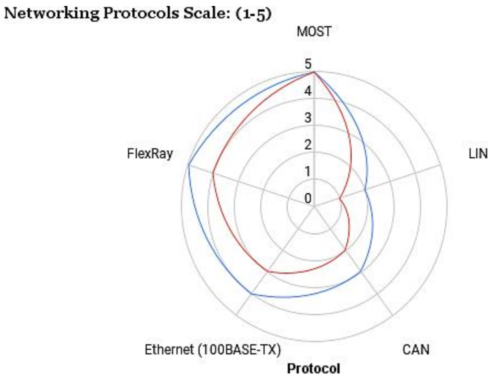

Figure 7. Spider chart for the cost of various networking protocols

4.1. Integration with 5G, V2X, and cybersecurity

5G-enabled V2X technologies provide ultra-low-latency and high-reliability communication between vehicles, charging stations, and cloud platforms, supporting autonomous driving and high-bandwidth sensor data. Cybersecurity remains essential as OTA updates, EVCS networks, and in-vehicle systems face increasing threats. Encryption, intrusion detection, and secure gateways are crucial to protect CAN, Ethernet, and V2X interfaces from spoofing, replay, and denial of service (DoS) attacks. These mechanisms will strengthen the resilience and safety of future EV communication architectures. The comparative analysis (Table 3) reveals that protocol selection in EVs is influenced by data rate, latency, reliability, cost, and scalability [24], [25].

Table 3. Quantitative comparison of EV networking protocols [24], [25]

Category	Representative protocols	Speed range	Latency	Reliability	Key uses
Body control networks	LIN	2–20 kbps	Medium	Medium	Comfort systems
Powertrain & safety	CAN, CAN FD, FlexRay	1–100 Mbps	Low–very low	High–very high	BMS, braking, drive-by-wire
Infotainment	MOST	up to 150 Mbps	Medium	High	Multimedia
High-bandwidth networks	Ethernet (10–10,000 Mbps)	10 Mbps–10 Gbps	Low–very low	High	Sensors, ADAS
Diagnostics/updates	DoIP	100–1000 Mbps	Low	High	OTA, service tools

This study provides a unified comparison of networking protocols used in EVs in India and worldwide, integrating performance, sustainability, resilience perspectives, and communication systems aligned with Industry 5.0 and the SDGs 7, 9, and 13. The findings contribute to cleaner, smarter, and more inclusive mobility solutions that will benefit society and advance sustainable transportation at both national and global levels.

5. CONCLUSION AND FUTURE SCOPE

This study provides a comparative evaluation of major networking protocols used in EVs in India and worldwide, including CAN, LIN, FlexRay, MOST, Ethernet, and Master-Slave architectures. The analysis shows that CAN and FlexRay deliver high reliability and real-time performance for safety-critical functions, while LIN and Master-Slave are cost-effective for low-speed operations (2–20 kbps). MOST supports high-speed multimedia communication (up to 150 Mbps), and Ethernet provides superior bandwidth (up to 10 Gbps) for advanced driver assistance and autonomous systems, though with higher complexity and cost. The results confirm that hybrid integration of these protocols enhances scalability, reduces latency, and improves communication efficiency, aligning with Industry 5.0 objectives for intelligent and sustainable mobility. The limitation is that the implementation of MOST is costly for small vehicles. Future research should focus on standardized, secure frameworks, enhanced cybersecurity, and 5G-based V2X systems. Incorporating AI, digital twins, and energy-aware networking will foster smarter, safer, and more sustainable EV ecosystems for societal and environmental benefit.

ACKNOWLEDGMENTS

The authors thank Lovely Professional University, India, for its support in carrying out the research work.

FUNDING INFORMATION

The authors received no external funding to carry out this research work.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the contributor roles taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ramandeep Sandhu	✓	✓		✓					✓					
Harpreet Kaur Channi			✓			✓		✓		✓				
Nimay Chandra Giri					✓	✓				✓	✓			
Pulkit Kumar	✓	✓								✓			✓	
Mohamed A. Elaskily					✓					✓		✓		✓
Mohamed A. Hebaishy					✓					✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [FS] on request.

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BIOGRAPHIES OF AUTHORS

Ramandeep Sandhu works as an Associate Professor at the School of Computer Science and Engineering, Lovely Professional University, Punjab, India. She received a B.Tech, M.Tech in computer science engineering from GNE College Ludhiana, Punjab, India, and Ph.D. in computer science engineering from Lovely Professional University, Punjab, India. She has 14 years of teaching experience of reputed institutes. Her general research areas are cloud computing, AI/ML, and opinion mining/sentiment analysis. She can be contacted at email: ramandeepsandhu887@gmail.com.

Harpreet Kaur Channi works as Assistant Professor at the Department of Electrical Engineering, Guru Nanak Dev Engineering college, Ludhiana Punjab. She received a B.Tech in electrical engineering from BCET, Ludhiana, and M.Tech. in electrical engineering from GNE College Ludhiana, Punjab, India and a Ph.D. from Chandigarh University Mohali, Punjab. She is the author of more than 26 books. Editorial board member of various national and international bodies. More than 140 papers were indexed in Scopus, WoS, UGC care journals. She has 17 years of rich experience in teaching and research. She can be contacted at email: harpreetchanni@yahoo.in.

Nimay Chandra Giri received B.Tech. in electronics and communication engineering (ECE) from BPUT, Odisha, India, in 2010 and M.Tech. in communication systems engineering from CUTM, Odisha, India in 2014. He received a Ph.D. specializing in agrivoltaic systems (AVS) from C.U.T.M. Odisha, India, with the best 'Thesis Award' in 2023. He is an Assistant Professor at the Department of ECE and the Centre for Renewable Energy and Environment at CUTM, Odisha, India. He has 15 years of teaching, training, and skill experience. His research and skill areas include solar PV systems, energy conversion, protected cultivation, agrivoltaic system, and aquavoltaic system. He has published 50+ articles (20+ numbers of Q1) and 40 patents. He can be contacted at email: girinimay1@gmail.com.

Pulkit Kumar is currently working as a Research Scholar in the Department of Electrical Engineering at Chandigarh University, Mohali, Punjab, India. He has completed his B.Tech in electrical engineering from Kurukshetra University and currently pursuing his Post Graduation in electrical engineering with a specialization in electrical vehicles. His research skill includes solar photovoltaic technology, sustainable transportation, smart grids, renewable energy, and electric vehicles. He can be contacted at email: pulkitkumar90170@gmail.com.

Mohamed A. Elaskily received the B.Sc. (Hons.), M.Sc., and Ph.D. degrees in computer science and engineering from Faculty of Electronic Engineering (FEE), Menoufia University, Menouf, Egypt, in 2008, 2013, and 2019, respectively. He is currently assistant professor with the Department of Informatics, Electronics Research Institute (ERI), Cairo-Egypt. Mohamed got the CCNA and CCNP certifications from CISCO. In September 2009, he was worked in the Egyptian Universities Network. Since 2014, he has been a Ph.D. researcher in the Department of Informatics, ERI. The major fields of research interests are computer networks, information security, ad-hoc security, digital image and video forensics. He can be contacted at email: mohamed_elaskily@eri.sci.eg.

Mohamed A. Hebaishy received the B.Sc., M.Sc., and Ph.D. degrees in computer science and engineering from Faculty of Electronic Engineering (FEE), Menoufia University, Menouf, Egypt, in 1991, Faculty of Engineering, Cairo University 1997, and Faculty of Informatics Vladimir State University, Russia 2004, respectively. He is currently associate professor with the Department of Informatics, Electronics Research Institute (ERI), Cairo-Egypt. Since 2004, he has been a Ph.D. researcher in the Department of Informatics, ERI. His research interests are computer networks, information security, image processing, and remote sensing satellite. He can be contacted at email: hebaishy@eri.sci.eg.