Information technology sets formation and "TNTU Smart Campus" services network support

Oleksii Duda, Andrii Mykytyshyn, Mykola Mytnyk, Andrii Stanko

Ternopil Ivan Puluj National Technical University, 56 Ruska St, Ternopil, UA46001, Ukraine

Abstract

Large cities in the modern world are high-tech innovative socio-economic centers that generate complex population migration processes and increase their demand for resources. Those are complex systems where various entities interact and within which residents and visitors of the city interact with these systems every day. This interaction is accompanied by the city systems and processes continuous measurement state through a large number of sensors and devices integrated into extensive network technology platforms. The following document describes the features of cyber-physical systems and communication networks used in practical smart city projects. Based on the analysis of cyber-physical systems used in smart cities, their classification has been developed and presented in graphic form. A smart cities functional model has also been developed. It is based on cyber-physical systems that can measure and control the air environment parameters of smart buildings. The communication networks classification and features used in smart cities cyber-physical systems are studied. A developed method allows the information and technical set general structure creation for the services and applications formation based on smart cities cyber-physical systems. On the DaaS model basis, the NDN network structure has been developed which allows the network measurement and the air quality regulation in the "TNTU Smart Campus". For this is used a IoT devices mesh network operating under the LoRa 433 MHz protocol. Two ways of choosing paths between the "Producer" and "Consumer" of data are proposed: reactive and proactive.

Keywords

cyber-physical system, named data networking, network, platform, protocol, routing, smart service, software defined networking.

1. Introduction

Modern large cities are high-tech, innovative socio-economic centers that generate population migration processes and increase the need for resources. They are complex systems in which heterogeneous and diverse entities interact, with which residents and visitors interact on a daily basis. This interaction is accompanied by continuous measurement of the urban systems and processes state using a sensors and devices large number that are integrated into extensive networked information technology platforms. In general, any object in the city can perform the collecting functions, transmitting, and consuming information. For example, this may relate to energy consumption, resource supply, production processes, city residents and visitors mobility, as well as measurement of living and environmental characteristics.

"A smart city is a city that uses information and communication technologies to improve its resident's quality of life and the urban systems functioning" [1]. The smart city concept is a future cities prototype that combine functional, structural and innovative aspects. At the present stage, municipalities, institutions and organizations are actively implementing the smart city model to improve

Proceedings ITTAP'2023: 3rd International Workshop on Information Technologies: Theoretical and Applied Problems, November 22–24, 2023, Ternopil, Ukraine, Opole, Poland
EMAIL: oleksij.duda@gmail.com (A. 1); mikitishin@gmail.com (A. 2); mytnyk@networkacad.net (A. 3); stanko.andrjj@gmail.com (A. 4)
ORCID: 0000-0003-2007-1271 (A. 1); 0000-0002-2999-3232 (A. 2); 0000-0003-3743-6310 (A. 3); 0000-0002-5526-2599 (A. 4)

the citizens quality of life and optimize the urban resources use. The smart city projects implementation is often based on the information and communication technologies (ICT) wide range aimed at improving the modern cities functioning, ensuring their sustainable development, expanding the range and improving the quality of municipal services. At the same time, there is a growing interest in information technologies aimed at improving healthcare, education, and the overall quality of life of citizens.

Smart city services are being implemented using a advanced information and communication technologies variety, including cyber-physical systems (CPS), the Internet of Things (IoT), wireless sensor networks (WSNs), edge computing, fog computing, 5G, cloud computing, data lakes, and many others. These smart services and solutions use helps to optimize resource and financial resources.

The innovative technologies use, including the IoT, is creating a basic information infrastructure for the smart cities development. This infrastructure includes cyber-physical systems that allow the smart things integration into the urban environment physical objects. This creates the opportunity to develop innovative smart city services and applications that urban activity various aspects support at any time and from any urban location.

These smart things and devices are controlled by special software applications that promptly monitor decision-making processes and increase the city operation and management efficiency. At the same time, smart devices and things provide information about their status in real time, including information about the air conditioning filters operation and possible malfunctions, which helps to predict the need for maintenance and repair.

Wireless sensor networks are used for urban infrastructure and resource supply systems real-time measurement. Sensor devices powered by the Internet of Things collect information about the smart building’s physical environment, including air temperature parameters and warehouse conditions. Cyber-physical systems combine network and physical processes with computing paradigms of cloud, fog, and edge computing to observe and control the smart city physical environment [2]. They are effectively used to form and ensure a stable and reliable practical connection between the virtual digital and physical worlds.

Smart city services and applications actively use the cloud computing paradigm. This provides an accessible and scalable information technology platform for storing data from IoT devices and cyber-physical systems, analytical processing, and supporting decision-making processes [3]. Comprehensive integration of an extensive list of ICTs increases mobility and improves citizens’ awareness, increases the smart city services and applications efficiency and responsiveness in real time [4]. Therefore, the integrated design of a networked information technology platform for supporting cyber-physical system objects is an important area of modern research. Currently, the count of sensors integrated into the smart cities physical environment is growing exponentially, in particular, the smart buildings air pollution indicators monitoring. The process of large-scale analytical processing of accumulated data sets requires a complex information technology and computing infrastructure [5]. In order to improve smart urban services, it is necessary to formulate integrated approaches to measurement, transmission, storage, and multi-level analytical processing for optimal operational and long-term solutions.

2. Cyber-physical systems and information technology platforms of smart cities

CPS are steadily spreading in industrial and scientific circles. CPS are complex, heterogeneous, distributed systems that interact between cybernetic components, such as sensors, actuators, control centers, and physical processes, such as controlling the residential premises parameters, managing traffic, detecting emergencies or fires, etc. Reference [6] defines a cyber-physical system as "integrations of computation, networking, and physical processes". In the future, these systems will become the critical urban infrastructure basis, allowing to expand the list of innovative smart municipal services, and improve the urban environment and life quality.

The authors [7] provide definitions: " Information systems and information technology related fields (IS/IT) are an important and unique domain for the study of platforms because: (i) IT-platforms provide the foundations that enable a large family of applications and related business practices; and (ii) IT-platforms are shared by complementary goods that frequently interoperate with the core technology foundation to add there are a number of information technology platforms types that are classified according to various criteria". Currently, there are a number of information technology platforms types that are classified according to various criteria. One of the most popular criteria in scientific and industrial circles is the way users interact with the platform. According to this criterion, platforms are divided into individual and networked. Individual platforms are designed for a single user. This platform type includes project management tools, CRM and ERP systems. Networked information technology platforms are one of the most platforms common types today. They play an important role in the modern smart city projects formation and in modern society in general. According to [8], a networked information technology platform is a platform that allows users to interact with each other over a network. Since network platforms are a type of information and technology platforms, and in this paper the information and technology platform are formed on the network interaction basis, the terms "network information and technology platform" and "information and technology platform" will be considered synonymous hereinafter.

The cyber-physical systems proliferation is associated with the Internet of Things (IoT) emergence, a vast devices set with limited computing capabilities that transmit information and provide services via the Internet and the TCP/IP protocol stack. At the same time, cyber-physical systems are physical computing devices networks that interact with each other. The active cyber-physical systems development has covered various domains and led to the software and algorithmic applications creation in various economic sectors. At present, a large number of smart cities cyber-physical systems different types have been formed (see Fig. 1).

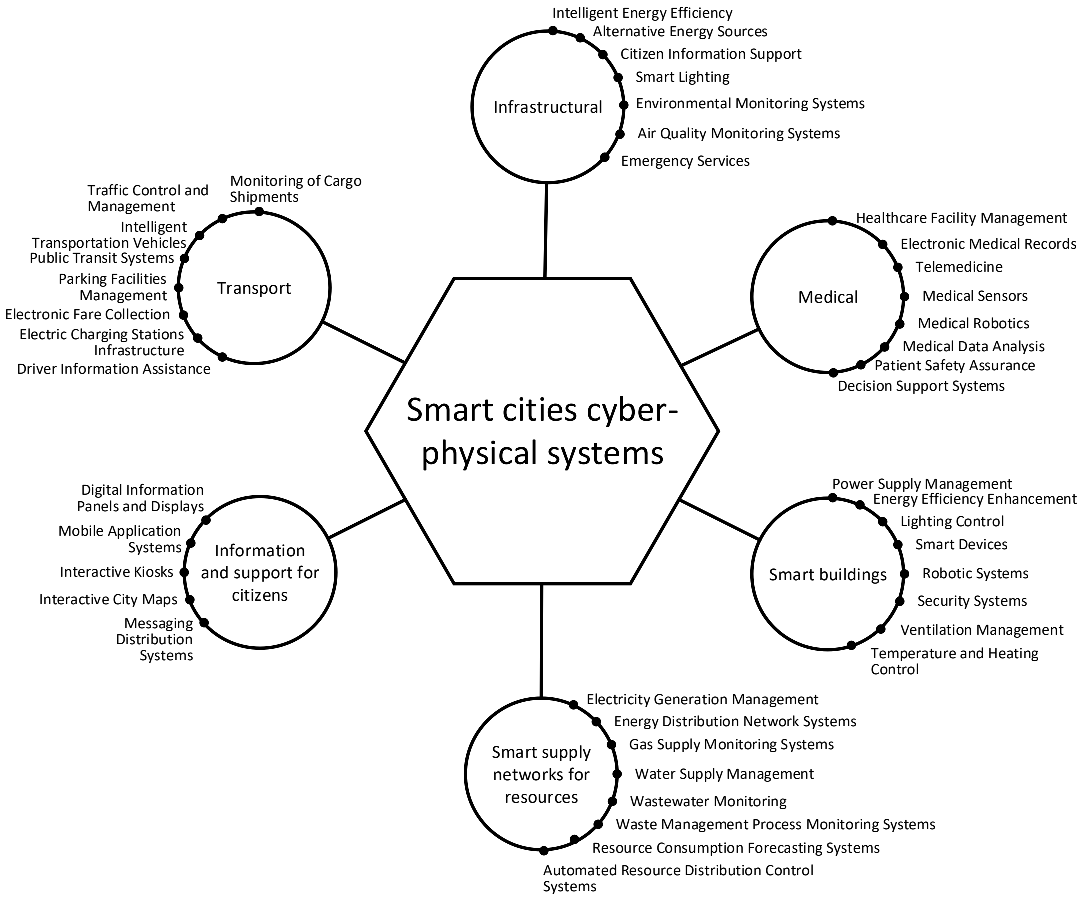


Figure 1: Smart cities cyber-physical systems

In smart cities, CPS are used for implement real-time data collection and exchange processes. This involves the complex integration of a devices different types large number, including sensors, actuators, microcontrollers, mobile communications, server hardware, network and cloud infrastructure.

In smart cities, CPS are used to:

- creating an interactive and adaptive smart urban environment;

- expanding the list and improving the quality of municipal services;
- improving the decision-making processes efficiency;
- creating a smart urban infrastructure;
- improving the digital, cyber and physical resource management processes characteristics;
- complex urban tasks and problems integrated solution;
- transportation management;
- improving energy efficiency;
- improving public health;
- reducing environmental pollution;
- introducing innovative tactile applications to improve the urban resident's quality of life;
- optimization of the communication innovative means implementation and use processes, in particular, 5G, etc.

Cyber-physical systems transmit data to central systems for processing, correlation, and decision-making to activate actuators or inform citizens, municipal institutions, and organizations. They typically operate alongside many other cyber-physical systems, such as smart HVAC systems, smart vehicles, smart production lines, smart buildings, smart infrastructure, etc. This complicates or even makes it impossible to create and implement unique information technology structures for managing cyber-physical systems on a large scale for a reasons number [9], including:

- No network protocol stack has been formed. Cyber-physical systems implemented at different times use information and communication technologies different stacks.
- Unified approaches lack to the extensive information technology architecture formation.
- The data volumes exponential growth and generally accepted approaches lack to the data storage and analytical processing development.
- Equipment and physical environments are owned by a specific group of private, municipal, or public owners, who are free to make their own choices based on various factors, including financial, legal, bureaucratic, and other constraints.
- Incompatibility with previously deployed information technologies.
- Increased requirements for security features and tools.

If necessary, cyber-physical systems can be used to quickly create and deploy new municipal services, set up procedures and algorithms for assessing the state of urban systems, and use software and algorithmic tools to support decision-making processes. The cyber-physical systems integration is a new area of modern scientific research that allows managing, coordinating, and organizing integrated cyber-physical systems, sensors, actuators, and resources to create high-quality smart city services [10]. In the fusion process, the involved domains must agree on the access and service levels used for cooperation. In [11], innovative approaches to the formation of the urban cyber-physical systems computing architecture are analysed, which allow to coordinate the data collection and transmission processes integration, computing infrastructure deployment, management and decision support processes support at abstraction different levels. However, most publications focus on only one cyber-physical systems particular aspect, and only a few studies are aimed at forming a unified architecture for a specific smart urban systems class. The new ICTs active development leads to the new tasks extensive list emergence, creates the need to develop unified information technology models and architectures for supporting the cyber-physical systems objects of smart cities.

The cyber-physical systems complex (see Fig. 2) is a smart cities new stage in the development, which can be expanded to larger or smaller territorial and sectoral formations. For example, it can represent a "smart community", "smart city", "smart sociopolis", "smart region" or "smart country", etc.

Complex smart cities cyber-physical systems are formed from smaller systems set belonging to different administrative or territorial domains, for example, different private owners or a private and public owners conglomeration based on a federated cooperative approach [12]. The federated interaction between cyber-physical systems provides a advantages number, in particular:

- allows to expand and increase data sets for generalization and analytical processing;
- provides computing resources sharing between cyber-physical systems;
- creates a computing infrastructure using edge, fog, and cloud computing without increasing financial costs for cyber-physical systems owners.

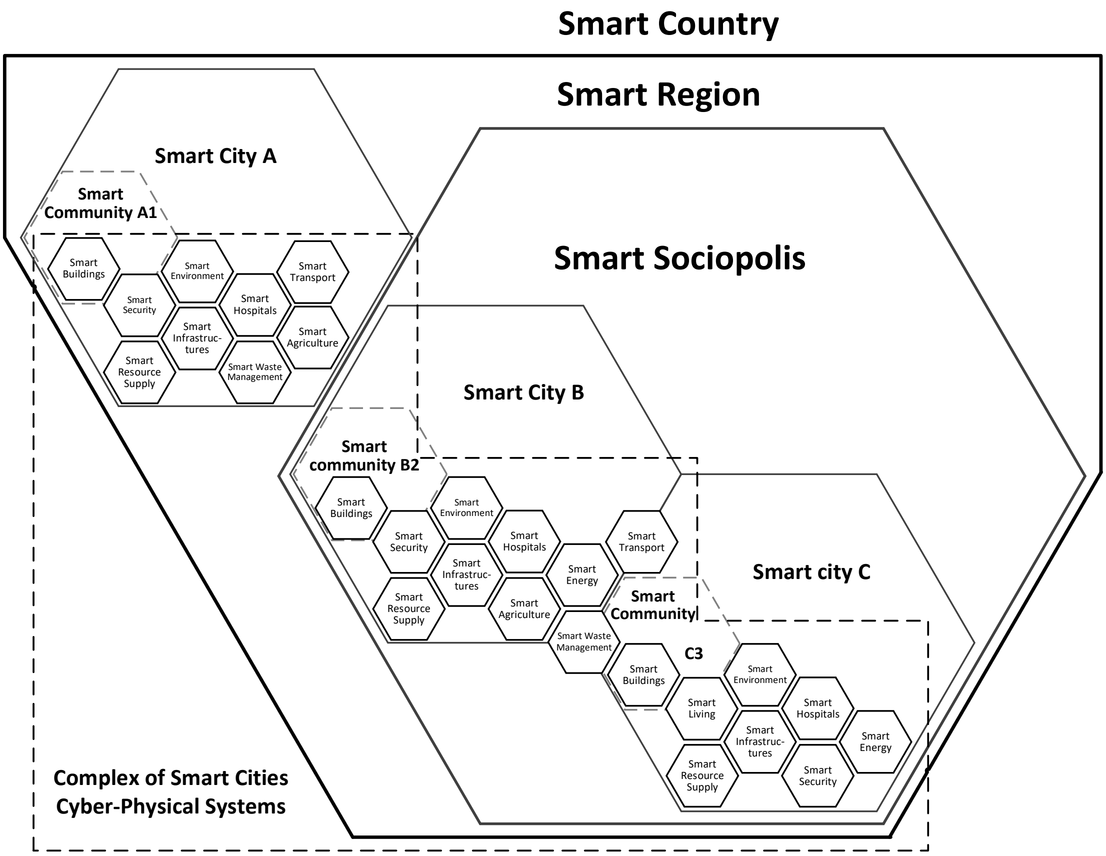


Figure 2: Complex of cyber-physical systems of smart cities

Based on the one published in [13], we will form a smart city cyber-physical systems functional model (see Fig. 3).

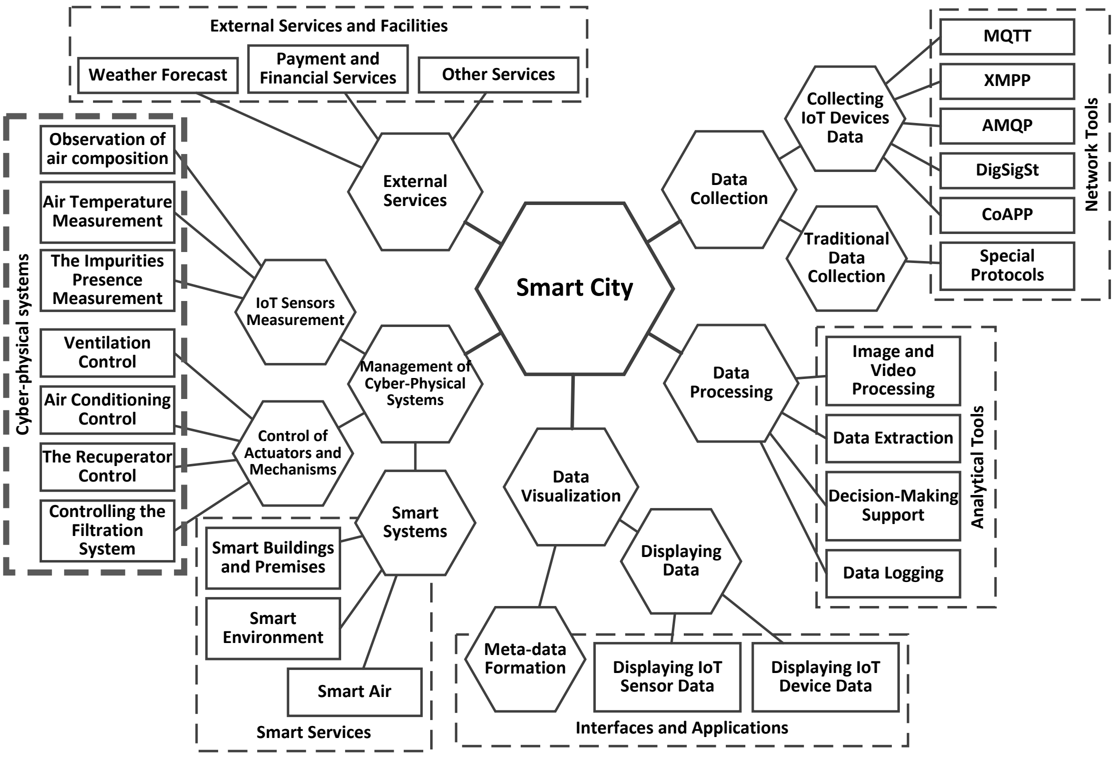


Figure 3: Smart cities functional model based on cyber-physical systems

The cooperation between smart cities cyber-physical systems benefits creates innovative opportunities for the networked information technology platforms and applications implementation that improve the citizens living conditions. This has created the need to design the network platform information technology architecture for supporting objects in complex cyber-physical systems of smart cities based on a variety of modern ICTs

3. Smart cities communication networks

A smart city formed by cyber-physical systems means contains a different objects wide range that are connected through networks and communication systems various types. At the same time, a powerful network infrastructure is used to identify, authorize, track the location and transmit data of IoT devices integrated into the urban environment. Communication networks of smart cities are characterized by [14]:

1. Abnormal traffic patterns.
2. High density.
3. Unorganized network topology.
4. Heterogeneity.
5. Specific security and privacy requirements.
6. Coexistence of heterogeneous technologies.
7. Security and confidentiality.
8. Flexibility and versatility.
9. Accessibility and provision.
10. Delay.
11. Scalability and size.
12. Reliability and consistency.
13. Bandwidth of communication channels.
14. Ensuring the data flows speed.

Currently, a wired and wireless network protocols wide range are commonly used in smart cities cyber-physical systems based on IoT devices. They are used for city networks and smart applications different classes (see Fig. 4).

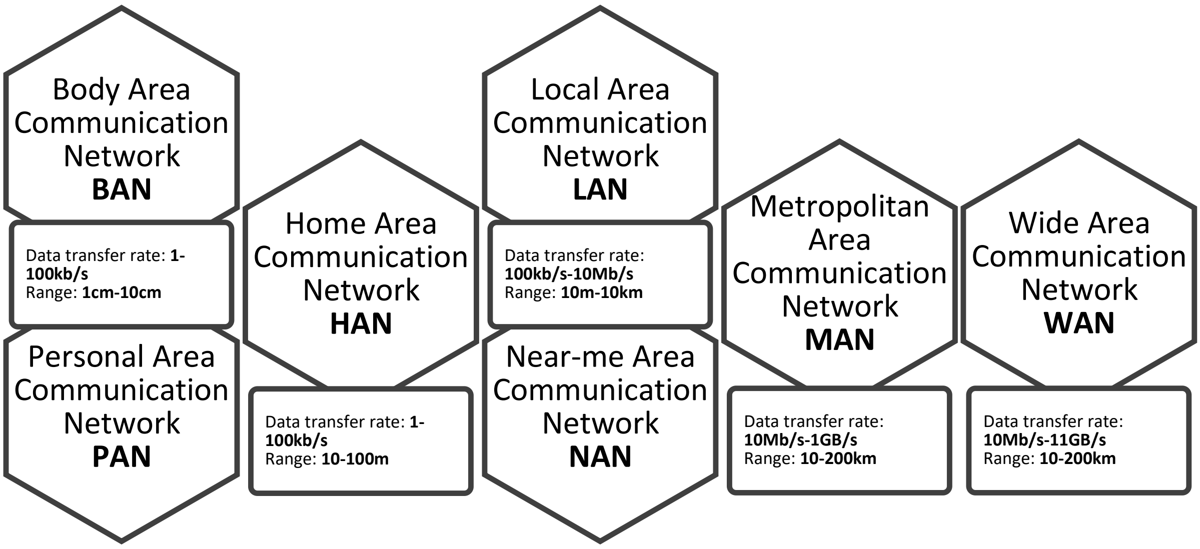


Figure 4: Communication networks classification and characteristics for smart cities cyber-physical systems (based on [15])

Body Area Networks, or BANs, use cyber-physical systems to integrate wearable RFID tags, sensors, and IoT devices, and connect to smart services and urban surveillance and control systems through communication technologies such as NFC, Bluetooth/BLE, and others. BANs are also connected to personal area networks, or PANs, which are used to connect the human body to information technology platforms and smart systems using technologies ZigBee, WiFi, Z-wave, etc. [16].

A Home Area Network (HAN) includes RFID sensors, actuators, actuators, video cameras, scanners, etc. that are connected to smart devices such as fans, air conditioners, heaters, meters, etc. HANs are connected to higher-level networks and the Internet and use short-range communication protocols ZigBee, Z-Wave, WiFi, MQTT, HTTP, XMPP, CoAP, etc.

The commonly known local area network (LAN) is mostly a short- or medium-range network within a small area. LANs use communication technologies similar to global networks and are the user part of various IoT interactions in smart cities cyber-physical systems.

The Neighborhood Area Network (NAN) is formed for smart buildings and premises, network stations, smart campuses, city institutions and organizations. Medium-range communication protocols are used to connect cyber-physical systems objects to the Internet. Power-Line Communication (PLC), Digital Subscriber Line (DSL), LoRaWAN, Sigfox, LTE and 5G mobile communications, Nuel, WiFi, etc. are used for smart NAN communication.

A Metropolitan Area Network (MAN) is a network type that operates on the large smart metropolis territory. MANs have appeared relatively recently. They are characterized by fairly large distances between nodes and high-quality communication lines with high data transmission speeds. When building a MAN, existing communication lines are not used, but are laid anew. MANs occupy an intermediate position between LANs and WANs and combine them.

Smart cities connected via Wide Area Networks (WAN) are long-range networks used to connect cyber-physical systems, objects, devices over long distances and with high data transfer speed, low latency, high security and efficiency

4. Forming information technology sets method for digital services and applications

An information technology set is a set of tools, methods, technologies and processes used to create, store, process and disseminate information [17]. We have proposed a generalized model of the structure of the information technology set for the services and applications formation based on smart cities cyber-physical systems (see Fig. 5), which contains four levels: cyber-physical (L^{CPS}), network (L^{Net}), cloud-based (L^{Cld}) and service (L^{Srv}).

The L^{CPS} used to collect data from sensors (S) by IoT devices. The primary information and resource filling process of the smart city information system functional architecture is being implemented. The direct impact on the physical environment is carried out using actuators ($Acttrs$). Special drivers (Drv) and interfaces ($Intrfs$) are used to interact with devices integrated into the physical environment, recuperators, air conditioners, humidifiers. Network technologies LoRa, Bluetooth, Zigbee, RFID, etc. are usually used to transmit the selected data.

Data from sensors (S) is transmitted using the local NET^{Mesh} and processed by communication nodes that communicate with local data processing devices. Smart building integration tools are responsible for collecting information that is used to generate smart services. Local data processing devices use CP^{EDGE}, elements, as this shifts part of the computing load to the edge nodes instead of concentrating it in centralized cloud facilities.

L^{Net} supports a network access technologies variety. This functional layer provides the wireless technologies implementation. Smart building integration tools define communication technologies, use appropriate access points and interfaces to receive and transmit data. At this level, CP^{Fog} is implemented, which allows you to transfer part of the computing load to network nodes and equipment, in turn unloading centralized cloud facilities.

On L^{Cld} the functions execution is provided:

- storing information in DL;
- creating queries for searching, filtering, and selecting data;
- formation data hypercubes (HC);
- analytical data processing tools use;
- decision support systems implementation.

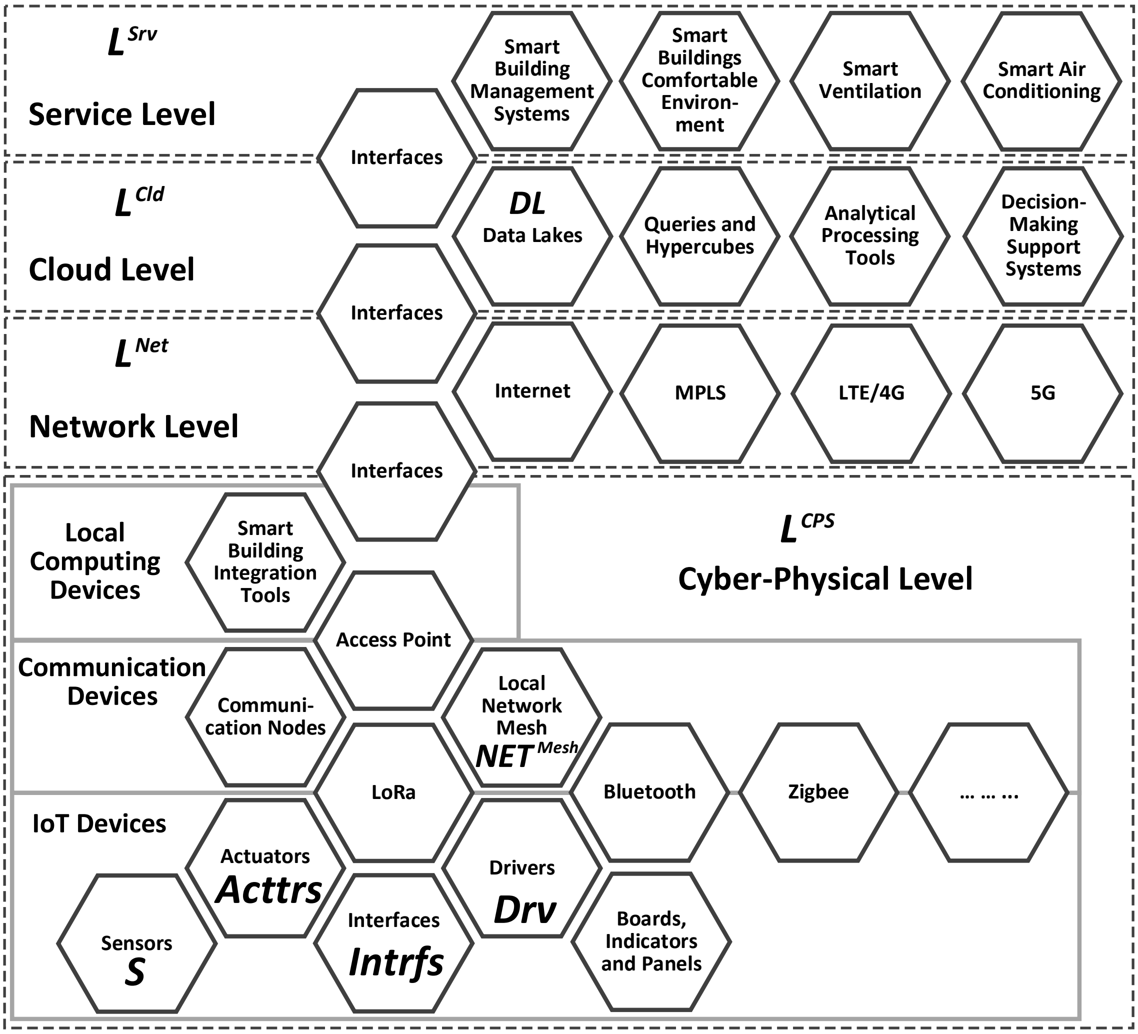


Figure 5: Generalized structure of the information technology set for the services and applications formation based on the smart cities cyber-physical systems

In the services set formation context in smart cities, each of them can be integrated in different applications. A smart city significant part applications requires $INFR^{Cloud}$ to function properly. However, some services can be realized using lower-level computing and communication tools. In particular, this is inherent in the implementation of smart ventilation or smart air conditioning systems.

L^{Srv} contains a vast array of various smart services, including smart building management systems, smart building environments, smart ventilation and smart air conditioning systems, etc. The such services classification may be based on a wide range of criteria and parameters. In services each class provided, applications different types can be developed and implemented, focused on solving single individual or systemic complex tasks.

5. Network support for measurement and regulation of air quality indicators in "TNTU Smart Campus"

The DaaS service delivery model allows users to access data as a service. NDN (Named Data Networking) is an L^{Net} architecture that provides an efficient way to exchange data between network devices. Thus, NDN is a technology that is effectively used to deliver smart services based on the DaaS model. A NET^{Mesh} – is a $INFR^{Net}$, in which devices are connected to a other devices set. This enables data transmission processes between devices in different directions, improving network reliability and performance. Currently, some researchers [18] use NDN in NET^{Mesh}, as it allows devices to exchange data directly, without the need to search for each other.

The NDN network for measurement and regulating air quality indicators at "TNTU Smart Campus" is formed in the form of a software-configurable network (Software-Defined Networking, SDN). Its software and algorithmic and network tools are aimed at flexible and adaptive NDN operation in the conditions of IoT devices unstable interaction of "TNTU Smart Campus" CPS via the LoRa protocol. The NDN network main functions are to support the air quality indicators measurement and regulating processes at "TNTU Smart Campus":

- the wireless NET^{Mesh} centralized monitoring;
- dynamic decision-making to select the best path and configuration of the NDN according to the selected routes.
- A network information system consists of functional components:
- SDN controller - the central network management unit;
- network nodes that provide NDN communication via wireless NET^{Mesh}.

The SDN controller is a key component of the NDN network for measurement and regulating air quality indicators at "TNTU Smart Campus", which provides NDN integration with dynamic software and algorithmic tools of the wireless routing protocol [19]. For the NDN paths operational configuration, wireless IoT nodes centralized monitoring is carried out. The SDN controller main functions (see Fig. 6) of the NDN network are to support the air quality indicators measurement and regulating processes:

- information collection about the network status in real time and network changes prompt detection;
- determining the best route for each request between the NDN consumer and the NDN data source;
- laying NDN routes with the definition of NET^{Mesh} boundaries and the routing table formation (Forwarding Information Base, FIB).

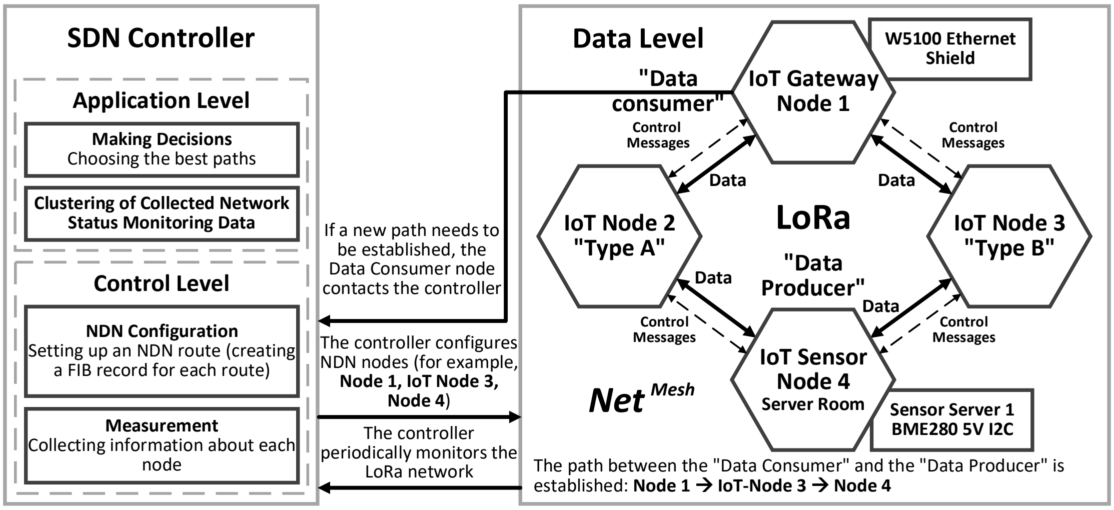


Figure 6: The "TNTU Smart Campus" NDN network structure for measurement and regulating air quality indicators

In the process of monitoring the state of NET^{Mesh} data is collected centrally from IoT nodes distributed across the "TNTU Smart Campus". At the same time, the each IoT node neighbors and the routes between them are detected. The routing between channels cost is based on the BATMAN routing protocol quality metrics for IoT networks [20]. The controller is also located in the NET^{Mesh} and interacts with the network nodes through the LoRa protocol. It manages data requests for measurement and regulating the "TNTU Smart Campus" air quality indicators using a reactive operation by performing:

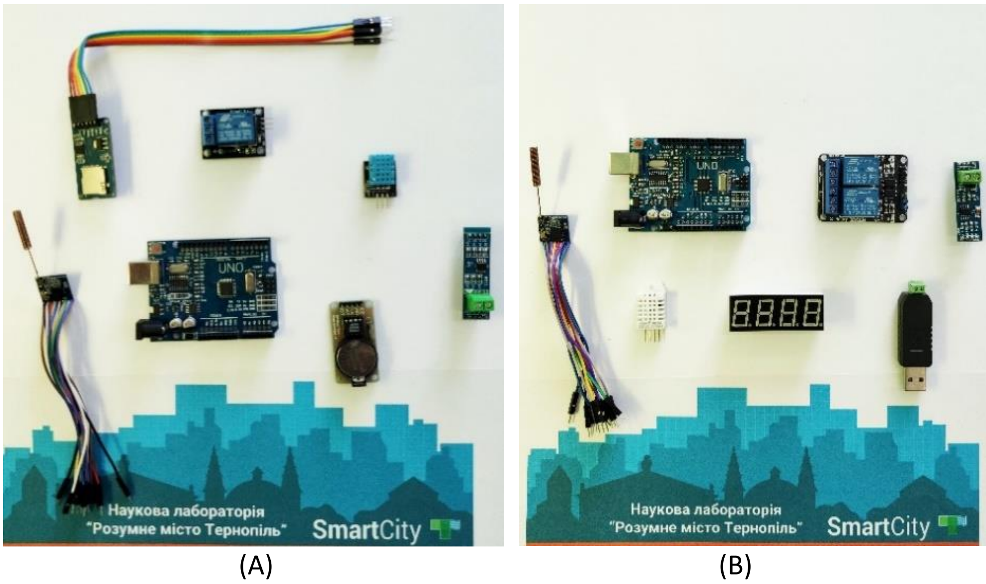
- updating information about the "Data Consumer" for each a new package of interests;
- determining the best wireless routing path between the "Consumer" and the "Producer" of data;
- forming the selected NDN route;
- initialization of sending a specific interest package to the «Consumer».

The information system stores metadata (MTD) on the processes of the NDN network functioning and the measurement and regulating processes the "TNTU Smart Campus" air quality indicators. In particular, the SDN controller associates the data prefix with the corresponding MTD for the NDN routes used and the data freshness information to determine whether the data is cached. The controller is located in a wireless mesh IoT network and communicates with IoT nodes. The $INFR^{Net}$ NET^{Mesh} consists of interconnected wireless nodes "Type A" and "Type B" (see Table 1) that communicate via wireless channels using the LoRa protocol. The NDN and NET^{Mesh} functions are independent and integrated with the SDN controller.

Table 1
$\boldsymbol{NET^{Mesh}}$ nodes characteristics list

Components	IoT nodes "Type A"	IoT nodes "Type B"
Microcontroller	Arduino UNO R3 (CH340)	Arduino UNO R3 (CH340)
Sensor	DHT11	DHT22
Actuators	Relay module 5V 10A	2-channel relay module 12V 10A
Additional components	MicroSD card module and real-time module DS1302, W5100 ethernet shield	7-segment LED indicator 0.56", 4 digits, common anode and/or RS-485 to USB converter (CH340)

Both nodes types (see Fig. 7) are implemented on the Arduino UNO R3 (CH340). Sensors "DHT22" or "DHT11" were connected to individual IoT nodes to monitor the classrooms air quality in accordance with the "TNTU Smart Campus" concept. If local storage of the collected data was required, these nodes ("Type A") were equipped with a microSD card module and a "DS1302" real-time module. Some "Type B" nodes were equipped with a 7-segment LED indicator to directly display the air quality indicators in a particular room where they are installed. The "Type A" and "Type B" nodes are equipped with a 433 MHz "LoRa" modem on an "SX1278" chip, as well as a "MAX485" and "UART-RS485" interface module.



(A) (B)

Figure 7: The "TNTU Smart Campus" IoT network components for measurement indoor air quality. (A) - the IoT node "Type A" components set. (B) - the IoT node "Type B" components set

The NET^{Mesh} was formed using LoRa modems on the "SX1278" chip. LoRa modems with a transmission frequency of 433 MHz were chosen because they provide a longer signal transmission range and better penetration through obstacles, including the server rooms walls. However, additional difficulties may arise in high-loaded areas due to the limited bandwidth at this frequency.

At the same time, the controller monitors the NET^{Mesh} operation to set up the NDN. In an NDN network, consumers send an interest packet to the network to receive the corresponding data packet containing the requested content and MTD.

For the interaction of the formed NET^{Mesh} for monitoring air quality indicators with the higher levels of the network information technology platform multilayer architecture for supporting the smart cities cyber-physical systems objects, IoT gateways and the server room IoT sensors are used (Table 2).

Table 2
List of $\boldsymbol{NET^{Mesh}}$ characteristics gateways and server room sensors

Components	IoT nodes "Type A"	IoT nodes "Type B"
Microcontroller	Arduino Leonardo (ATmega32u4)	Arduino UNO R3 (CH340)
Modem	LoRa 433 MHz on SX1278 chip	LoRa 433 MHz on SX1278 chip
Sensor	none	BME280 5B I2C
Interface module	MAX485 UART-RS485	MAX485 UART-RS485
Actuators	no	Relay module 12V 10A, or 4-channel relay module 12V 10A
Additional components	W5100 ethernet shield	W5100 ethernet shield; MicroSD card module; Real-time module DS1302

The IoT sensor shown in Fig. 8 was developed on the Arduino Leonardo (ATmega32u4) with an expansion board "Wiznet W5100" Ethernet controller.

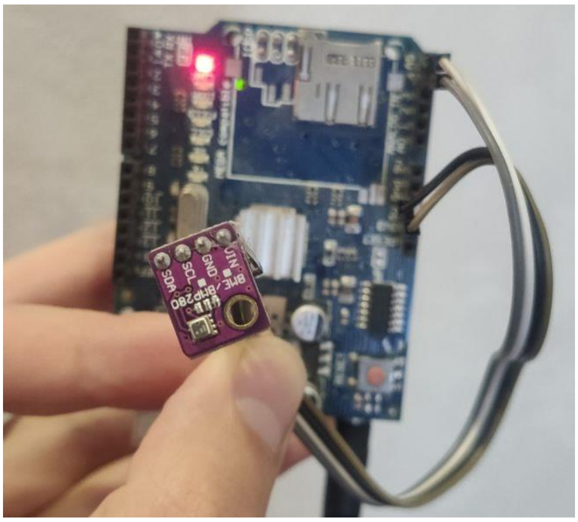


Figure 2: IoT device with "BME280" sensor

Each IoT node uses three information components: a content repository, a Pending Interest Table (PIT), and a FIB. To ensure the NDN network effective operation for "TNTU Smart Campus" air quality indicators measurement and regulating, reactive and proactive tactics for choosing paths between the "Producer" and "Consumer" of data are proposed.

With the reactive tactic of selecting an NDN path, it is coordinated with the stored NET^{Mesh} routing data. In this case, each IoT node selects the best route for each destination from its neighbors set, which is sent by the SDN controller during the NET^{Mesh} dynamic configuration. For example (see Fig. 6), the "Data Consumer" (IoT Gateway, Node 1) intends to receive data with the MTD- prefix "Sensor Server

1". It sends a request to the SDN controller asking it to inform it about the specific data. If the data is not cached in the NET^{Mesh}, then the SDN controller finds the best path to the "Data Producer" (IoT sensor, Node 4). For example, "Node 1 → IoT-Node 3 → Node 4" and establishes NDN routes. At the next stage, the SDN controller initiates the "Data Consumer" to transmit the packet of interest along the formed path.

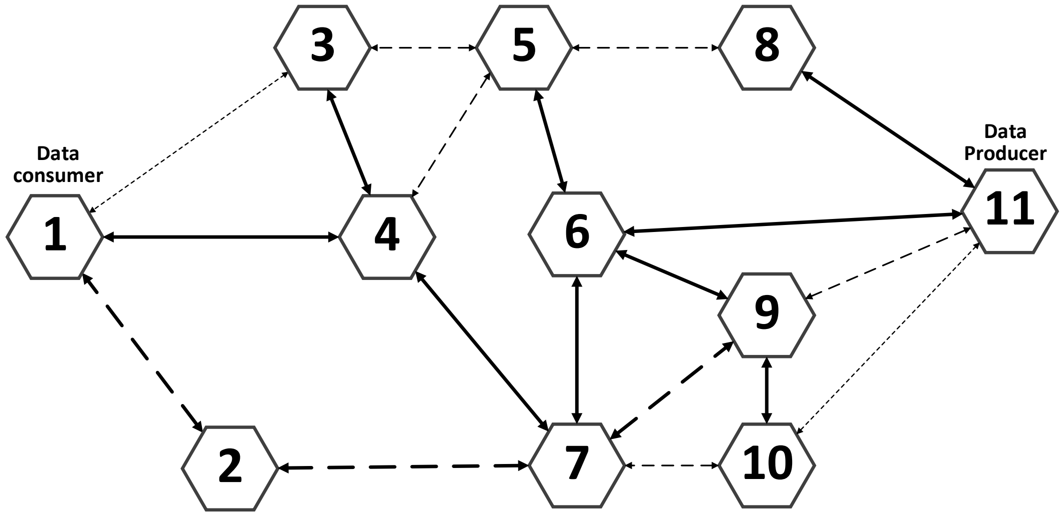


Figure 3: Choosing an NDN path using proactive tactics

The proactive tactic of choosing NDN paths is based on the information collected by the nodes. In this case, each IoT node in the network periodically collects information about its neighbours, including the received signal strength (RSSI) and delay time. The collected LoRa network monitoring data is transmitted to the SDN controller via the control channel. The SDN controller clusters the collected data (see Fig. 9) and selects the best paths, setting up the NDN network NET^{Mesh} accordingly. Compared to the reactive tactic, the SDN controller redirects all data requests to the selected path until the next best path is evaluated. Therefore, we consider this tactic to be proactive, as it is based on partial clustering and distance measurement based on the data collected similarity by IoT nodes. Fig. 9 illustrates the process of selecting an NDN path based on the clustering results. Consider four IoT nodes clusters sorted from best to worst based on the average value within the cluster. The thickness and length of the line indicates the cluster to which each connection belongs, i.e., the thinnest lines indicate the clusters with the worst performance, and the solid lines indicate the cluster with the best performance, respectively. Each path is characterized by the worst link, i.e., the worst path contains at least one link belonging to the worst cluster. For example, in Fig. 9, the best path runs through the nodes 1-4-7-6-11, since its links are clustered as the best, i.e., marked with solid lines. The clustering process is based on the similarity between time series according assessment to the Dynamic Time Warping (DTW) algorithm [21]. This will improve the clustering efficiency by providing a more reliable and less sensitive to local shifts in time series similarity assessment due to the nonlinear and time-independent nature of DTW, compared to typical measures, such as Euclidean distance.

6. Conclusion

This paper presents the cyber-physical systems and communication networks characteristics used for the innovative smart city projects practical implementation. Based on the smart cities using cyber-physical systems peculiarities analysis, their classification is presented in graphical form. The smart cities functional model based on cyber-physical systems, expanded by the ability to observe and control the smart buildings air environment parameters, is formed in graphical form. The communication networks classes features of smart cities cyber-physical systems are analysed. A method is proposed that allows developing a generalized structure of an information technology set for the services and applications formation based on smart cities cyber-physical systems. On the DaaS model basis, the NDN network structure has been developed, which makes it possible to provide network support for the air quality indicators measurement and regulating processes in the "TNTU Smart Campus" based on a IoT devices mesh network using the LoRa 433 MHz protocol. Reactive and proactive tactics for choosing paths between the "Producer" and "Consumer" of data are proposed.

7. References

[1] Gracias, J. S., Parnell, G. S., Specking, E., Pohl, E. A., & Buchanan, R. Smart Cities—A Structured Literature Review. Smart Cities, 6(4), pp. 1719-1743. (2023).

[2] Duda, O., Mykytyshyn, A., Mytnyk, M., Stanko, A. The network platform cyber- physical systems application for smart buildings air pollution indicators monitoring. Časopis Manažérska Informatika, Univerzita Komenského v Bratislave, Slovakia, vol 1 2023, no 1. (2023)

[3] Alam, T. Cloud-based IoT applications and their roles in smart cities. Smart Cities, 4(3), pp. 1196-1219. (2021).

[4] Abdali, T. A. N., Hassan, R., Aman, A. H. M., & Nguyen, Q. N. Fog computing advancement: Concept, architecture, applications, advantages, and open issues. IEEE Access, 9, pp. 75961-75980. (2021).

[5] Mohamed, N., Al-Jaroodi, J., Lazarova-Molnar, S., & Jawhar, I. Applications of integrated iot-fog-cloud systems to smart cities: A survey. Electronics, 10(23), p. 2918. (2021).

[6] Cyber Physical Systems Conceptual Map, Berkeley. URL: http://CyberPhysicalSystems.org.

[7] Sun, R., Gregor, S., & Keating, B. Information technology platforms: Conceptualisation and a review of emerging research in IS research. In Australasian Conference on Information Systems (ACIS) 2015 Proceedings. Association for Information Systems. pp. 1-17. (2015).

[8] Bhambri, P., Rani, S., Gupta, G., & Khang, A. Cloud and fog computing platforms for internet of things. CRC Press. (2022).

[9] Ahmad, M. O., Ahad, M. A., Alam, M. A., Siddiqui, F., & Casalino, G. Cyber-physical systems and smart cities in India: Opportunities, issues, and challenges. Sensors, 21(22), p. 7714. (2021).

[10] Puliafito, A., Tricomi, G., Zafeiropoulos, A., & Papavassiliou, S. Smart cities of the future as cyber physical systems: Challenges and enabling technologies. Sensors, 21(10), p. 3349. (2021).

[11] Ouchani, S. Ensuring the functional correctness of IoT through formal modeling and verification. In Model and Data Engineering: 8th International Conference, MEDI 2018, Marrakesh, Morocco, October 24–26, 2018, Proceedings 8. Springer International Publishing. pp. 401-417. (2018).

[12] Tricomi, G., Merlino, G., Longo, F., Salvatore, D., & Puliafito, A. Software-defined city infrastructure: A control plane for rewireable smart cities. In 2019 IEEE International Conference on Smart Computing (SMARTCOMP). pp. 180-185. (2019).

[13] Tekinerdogan, B., Köksal, Ö., & Çelik, T. System Architecture Design of IoT-Based Smart Cities. Applied Sciences, 13(7), p. 4173. (2023).

[14] Abadía, J. J. P., Walther, C., Osman, A., & Smarsly, K. A systematic survey of Internet of Things frameworks for smart city applications. Sustainable Cities and Society, 83, p. 103949. (2022).

[15] Rafiq, I., Mahmood, A., Razzaq, S., Jafri, S. H. M., & Aziz, I. IoT applications and challenges in smart cities and services. The Journal of Engineering, 2023(4), p. 12262. (2023).

[16] Salman, T., & Jain, R. A survey of protocols and standards for internet of things. arXiv preprint arXiv:1903.11549. (2019).

[17] Debbarma, J., Choi, Y., Yang, F., & Lee, H. Exports as a new paradigm to connect business and information technology for sustainable development. Journal of Innovation & Knowledge, 7(4), p. 100233. (2022).

[18] Kalafatidis, S., Skaperas, S., Demiroglou, V., Mamatas, L., & Tsaoussidis, V. Logically-Centralized SDN-Based NDN Strategies for Wireless Mesh Smart-City Networks. Future Internet, 15(1), p. 19. (2022).

[19] BATMAN Concept—Open-Mesh—Open Mesh. URL: https://www.open-mesh.org/projects/open-mesh/wiki/ BATMANConcept (accessed on November 2022).

[20] Gehreke, L., Kientopf, K., & Güneş, M. BATMAN in the IoT. In NOMS 2022-2022 IEEE/IFIP Network Operations and Management Symposium. pp. 1-6. (2022).

[21] Stübinger, J., & Walter, D. Using multi-dimensional dynamic time warping to identify time-varying lead-lag relationships. Sensors, 22(18), p. 6884. (2022).