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Research Article

Bringing Context into IoT: Vision and Research Challenges

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Abstract:

The Internet of Things (IoT) has undergone a remarkable transformation, linking an extensive array of devices far beyond traditional computers and smartphones. This intricate network facilitates seamless communication and data interchange, leading to more astute devices and systems capable of revolutionizing myriad industries. Context-awareness with its synthesis with IoT can enable us to mobilize considerate areas of IoT that have to been explored yet. Context-Aware (CA) IoT systems possess the ability to adapt and respond to ever-changing environments, delivering personalized and anticipatory services. The evolution of IoT now encompasses everyday appliances, wearable technology, and industrial frameworks. This expansion augments connectivity and data interchange, fostering automation and valuable insights across diverse domains. Driven by advancements in sensors, wireless communication, cloud computing, and data analytics, IoT finds applications in various domains. Context-awareness is indispensable for personalized and efficient IoT services, attuning to user preferences and dynamic environmental factors. The focus of current research is on innovating CA systems with heightened responsiveness and inter-device collaboration. The vision is to craft intelligent ecosystems with proactive behavior, enriching user experiences, and optimizing Resource Utilization (RU). Moreover, CA IoT significantly contributes to energy efficiency and environmental conservation. Embracing context-awareness in IoT heralds a more interconnected, efficient, and intelligent global landscape.

1. Introduction

1.1 Main Significance of IoT

Over the past few years, a variety of devices other than widely used computers and smartphones are being connected to the Internet, which has paved the way for this revolutionary concept of IoT. The ability of physical devices to interact and communicate over the internet makes them smart.

The growth of IoT has been driven by advancements in sensor technology, wireless communication, cloud computing, and data analytics. This convergence of technologies has paved the way for the proliferation of smart devices and the integration of intelligence into everyday objects [1]. Cohesive connectivity and data exchange between the things is one of the significant applications of IoT. As there is more inter-domain collaboration, it has resulted in the advent of distributed information processing system technologies to be integrated with every domain, enabling immense information sharing [2]. All of this has contributed to bringing IoT into our daily lives, and different industries and enterprises. We connect everything to the internet, like home and kitchen appliances; wearables like smart eyewear, linked fabrics; industrial infrastructure; grids; vehicles, and much more [3]. This also facilitates automation in various other domains. A list of the application areas of IoT is provided in Table 1.

According to [4], the global IoT connections have grown from by 18% in 2022, and the number is estimated to grow more 16% and amount to approximately 17 billion active devices. Table 2 lists some interesting numbers about IoT [5].

Figure 1 shows a comparative analysis between the growth of IoT and non-IoT devices over the years, where it is evident that the usability of non-IoT devices has remained steady but that of IoT devices has raised exponentially.

The significance of IoT stems from its potential to bring unprecedented levels of efficiency, convenience, and innovation by acquisition and analysis of huge volumes of data, to both individuals and industries.[6]. For individuals, IoT offers personalized and CA services, improving everyday life experiences. Furthermore, IoT plays a crucial role in shaping the future of industries, enabling predictive maintenance in manufacturing, optimizing energy usage in smart grids, and revolutionizing healthcare through remote monitoring and telemedicine. The interconnectedness and intelligence brought about by IoT have the potential to drive economic growth, foster sustainability, and improve overall quality of life [7-12].

However, with the growing adoption of IoT, there come challenges related to data privacy, security, interoperability, and scalability [13]. Addressing these challenges is essential to fully unlock the potential of IoT and ensure its responsible and widespread implementation. Overall, the significance of IoT lie in its transformative power to connect the physical and digital worlds, paving the way for a more connected, efficient, and intelligent future. Understanding and harnessing the potential of IoT will be critical for leveraging its benefits and addressing its challenges to create a sustainable and innovative ecosystem.

As IoT is becoming an integral part of our lives, it has become imperative for IoT frameworks to consider the contextual data along with the data that is being fed to the intelligent processing systems. An IoT device is considered to be context aware if the device is able to adapt and respond in real-time according to the changing conditions of the surroundings. These changing situations are what constitute dynamic contextual data. [14]. Contextual data can have varied forms, like location, user preference, time, and device characteristics [15]. The integration of context into IoT will result in intelligent frameworks with enhanced responsiveness. The developed framework is Context-Driven (CD) and a homogenization of varied devices, and data [16]. In our research we aspire to traverse the implication of context awareness in the various application domains of IoT, and investigate the associated research challenges. By leveraging context-awareness, IoT applications can provide personalized and proactive services, optimizing resource usage and improving overall efficiency [17].

In this paper, we provide a comprehensive overview of the current research on CA IoT systems. We review the state-of-the-art techniques and technologies for capturing and processing contextual information. In the upcoming sections we focus on the key research challenges we face during the development of context aware-IoT Systems. Our focus remains on the domains scalability, interoperability, security and privacy. Furthermore, in the subsequent sections we deliberate about the potential applications and benefits of CA IoT systems in the existing application areas of IoT. We emphasize the opportunities for innovation and improved user experiences that arise from leveraging context in IoT deployments. By understanding the implications and possibilities of CA systems, we can pave the way for a more intelligent and responsive IoT ecosystem. 1.2 The Need for CA Systems in IoT

As the IoT burgeons and infuses myriad facets of our existence, the need for CA systems within this framework becomes paramount. Conventional IoT apparatus often exhibit a deficiency in their capability to discern and react intelligently to fluctuating environmental conditions and user preferences. This constraint impedes their comprehensive efficacy in furnishing personalized and proficient services [18].

If we want to define context awareness in relation to IoT we can refer to it as the proficiency of devices to apprehend and adjust to their milieu by assimilating pertinent and relevant contextual data [19]. This encompasses factors, such as location, temporal aspects, user behaviour, environmental parameters, and device characteristics [20]. Through the amalgamation of context-awareness, IoT systems can render more significant and meaningful interactions, thereby augmenting user experiences and optimizing resource deployment. A primary impetus for CA systems in IoT is the burgeoning intricacy and heterogeneity of devices and the data they engender. As the proliferation of IoT devices and sensors escalates, the magnitude of data they generate becomes overwhelming. Context-awareness empowers IoT systems to sieve and prioritize data predicated on its pertinence to specific contexts, mitigating information deluge and enhancing decision-making. CA systems further enable IoT devices to exhibit greater proactivity in addressing user requisites. By discerning the user's context and preferences, IoT devices can preempt needs and operate autonomously, obviating the necessity for explicit user directives and crafting a more fluid and intuitive user experience.

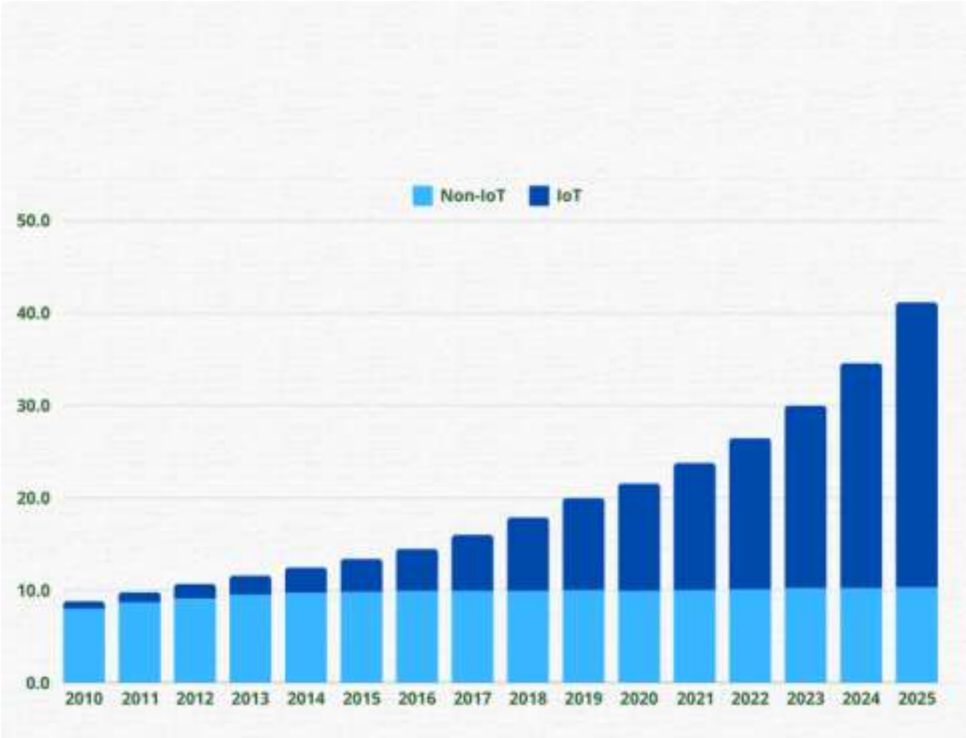

Figure 1. *Growth in the number of IoT vs non-IoT devices (in billions)*

Table 1. *Applications of IoT*

Domain	**Applications**
Healthcare	Remote Care and Monitoring, Hospital Management
Urban Development	Food Traceability, Smart Agriculture and Breeding, Smart Safety, Smart Transportation, Smart Grid, Smart Home, Smart Tourism
Industry	Production Monitoring, Logistics, Supply Chain Tracking, Energy Saving and Pollution Control, Safety in Manufacturing
Agriculture and Breeding	Agriculture Resource Utilisation, Safety of Agriculture Produce, Environmental Monitoring of Production and Cultivation
Logistics	Inventory Control, Smart e-commerce, Distribution Management
Transportation	Traffic Alert System, Intelligent Traffic Control, Vehicle Positioning, Remote Vehicle Monitoring, Smart Public Transport System
Grid	Smart Substation Management, Smart Power Scheduling
Environmental Management	Remote Pollution Source Monitoring, Water Quality Management, Air Quality Management, Endangered Species Protection, Weather Monitoring
Safety	Social Security Monitoring, Food Safety Monitoring, Emergency Response
Home Application	Home Security, Smart Applications, Energy Management
Independent Living	Ambient Assisted Living
Education	Library Services, Smart Classrooms
Tourism	Smart Navigation

Table 2. *Some interesting numbers about IoT*

Interesting Numbers	**Details**
3.5 billion **[2]**	Expected cellular IoT connections (2024)
646 million **[6]**	IoT devices used in hospitals, clinics, and medical offices (2020)
$805.7 **[1]**	Annual spending on IoT security measures (2020)
300% increase **[8]**	Cyberattacks on IoT devices
Estimated 152,200 **[9]**	IoT devices connecting to the internet every minute (2025)
70 billion **[9]**	IoT devices connected by 2025
$15 trillion **[4]**	IoT investment between 2017 and 2025
73.1ZB **[5]**	Estimated volume of data generated by IoT devices by 2025
5 minutes **[7]**	New IoT devices attacked within

Moreover, context-awareness fortifies the interoperability of diverse IoT devices and platforms. Devices can interchange contextual data, fostering collaboration and engendering more sophisticated and coordinated functionalities. This interoperability is indispensable in actualizing the full potential of IoT's interconnected ecosystem.

In the realm of healthcare, CA IoT systems can metamorphose patient care by providing real-time health monitoring and bespoke treatment recommendations. In the ambit of smart cities, context-awareness enables IoT devices to optimize energy utilization, traffic flow, and public services in consonance with real-time conditions and user exigencies. In industrial automation, CA systems amplify efficiency by prognosticating machine failures and optimizing production timetables.

In summation, the exigency for CA systems in IoT emanates from the aspiration to render IoT devices more sagacious, responsive, and user-centric. By incorporating contextual data into IoT systems, we can harness the full potential of IoT's intricate web of devices, crafting a future where technology seamlessly adapts to human needs and elevates quotidian life experiences.

2. Integrating Context Into IoT Frameworks

2.1 Role of Context-Awareness

Context-awareness is a pivotal aspect of IoT applications that enhances their effectiveness and relevance in various domains. Understanding the importance of context-awareness is vital for harnessing the full potential of IoT in delivering personalized and intelligent services.

Personalization and User Experience. Context-awareness enables IoT applications to tailor their services and interactions based on individual user preferences, behavior, and situational context. This personalization enhances user experience by providing relevant and timely information, recommendations, and automation [21].

Real-Time Decision Making. By considering real-time contextual information, IoT devices and applications can make informed and adaptive decisions. This capability is particularly valuable in time-sensitive scenarios such as emergency response, where quick and accurate decisions can save lives [22].

Resource Optimization (RO). CA IoT applications optimize the use of resources by tailoring actions based on available context. E.g., smart energy management systems can adjust power consumption based on occupancy patterns and environmental conditions, leading to energy efficiency and cost savings [23].

Proactive Services. Includes taking proactive decisions based on user-requirement. E.g., a CA health monitoring system can detect early signs of health issues and prompt users to seek medical attention, preventing potential health complications [24].

Adaptability to Changing Environments. The dynamic nature of IoT environments requires adaptability. CA systems can adjust their behavior based on changing contexts, such as shifting weather conditions, user movements, or the presence of other devices [25-27].

2.2 State-of-the-Art Techniques for Capturing and Processing Context]

Sensor Fusion. These techniques integrate the data coming from heterogeneous sensors and generate a comprehensive interpretation of the surroundings. [28,29].

Machine Learning (ML). It enables IoT devices to learn from past experiences and make data-driven decisions. AI-powered CA systems can recognize patterns, predict user behavior, and adapt their actions accordingly [30,31].

Context Representation and Modeling. Efficient context representation and modeling are crucial for processing and interpreting contextual information. Various approaches, such as ontologies and knowledge graphs, facilitate the structured representation of context [32]**.**

Edge Computing (EC). EC features data processing closer to the source (at the edge of the network), reducing latency and enhancing real-time responsiveness. CA IoT applications can benefit from edge computing for faster decision-making and reduced network traffic [33,34].

CA Networking. CA networking protocols and architectures [35] enable IoT devices to communicate and share context effectively [36]. These networking solutions optimize data transmission and resource allocation based on contextual factors [37,38]. In summary, context-awareness is a key enabler for unlocking the true potential of IoT applications. By embracing state-of-the-art techniques for capturing and processing contextual information, IoT systems can offer personalized, adaptive, and efficient services across diverse domains, leading to enhanced user experiences and optimized RU.

3. Research Challenges in CA IoT Systems

These challenges span various dimensions, from data acquisition to security and interoperability, and require innovative solutions for seamless integration and efficient functioning of CA IoT.

3.1 Scalability Challenges.

Handling Big Data. CA IoT systems generate massive amounts of data from diverse sources, leading to data overload and processing bottlenecks. Efficient methods for data storage, retrieval, and analysis are needed to manage big data effectively [39,40].
Network Congestion. As the number of connected IoT devices grows, CA applications put immense strain on communication networks. In order to meet the growing needs for data transmission of high volume data scalable networking solutions are essential to accommodate the increasing volume of data transmissions [41].

3.2 Interoperability Challenges.

Device Diversity. There is a need to develop standards and protocols that facilitate uninterrupted communication and data exchange across heterogeneous nodes in a network [42].
Context Representation Standardization. Creating a common context representation framework is essential to enable interoperability between different CA systems. A standardized approach allows devices to understand and interpret context consistently [25, 43].

3.3 Security Challenges.

Privacy Concerns. Contextual information often includes sensitive user data, raising privacy concerns. Robust privacy-preserving techniques are needed to ensure that CA IoT systems can function without compromising user privacy [44,45].
Context Integrity. Ensuring the integrity of contextual information is critical, as inaccurate or manipulated context can lead to erroneous decisions. CA IoT systems must implement secure measures to prevent data tampering and unauthorized access [46].

3.4 Privacy Challenges.

Context Aggregation and Inference. Aggregating and inferring context from various sources may lead to unintentional disclosure of private information. CA systems need to strike a balance between context aggregation for improved services and preserving user privacy [47,48].
User Consent and Control. IoT applications must respect user consent and enable the users to manage contextual information. Implementing user-friendly consent mechanisms and transparent data-sharing policies are crucial for building user trust [49].
To address these challenges CA IoT systems must be designed with scalability, privacy, and interoperability in mind, while providing seamless and secure experiences for users.
Overcoming these challenges opens up exciting avenues for innovation and research, paving the way for the widespread adoption of CA IoT systems in diverse applications such as smart cities, healthcare, and industrial automation. Solving these challenges will ultimately lead to the creation of more intelligent, efficient, and user-centric IoT ecosystems.

4. Opportunities for Developing CA IoT Systems

Context-awareness presents numerous opportunities for the development of innovative and intelligent IoT systems. Embracing these opportunities will enable IoT applications to reach their full potential in delivering personalized and efficient services. The key opportunities for developing CA IoT systems include:

4.1 Context Acquisition and Sensing
Advanced Sensor Technologies.

Leveraging advancements in sensor technologies enables the collection of richer contextual information. Integration of sensors with higher accuracy and sensitivity expands the scope of context-awareness in various domains, from environmental monitoring to healthcare [50,51].
Multimodal Sensing. Combining data from multiple sensors (e.g., cameras, microphones, temperature sensors) allows IoT systems to create a more comprehensive understanding of the environment. Multimodal sensing enables robust context representation and enhances the accuracy of CA applications [52-54].

4.2 Context Representation and Modeling

Ontologies and Knowledge Graphs. By creating a common vocabulary and hierarchical relationships, CA IoT systems can efficiently interpret and reason with contextual data..
ML for Context Modeling. Applying ML algorithms to model context enables IoT applications to learn and adapt from contextual patterns. ML models can handle complex context representation and improve CA decision-making.

4.3 Context Fusion and Reasoning.

Context Fusion Techniques. Integrating context from multiple sources (e.g., sensor data, user profiles, historical data) through context fusion techniques enhances thecompleteness and accuracy of contextual information. CA IoT systems can use fusion methods like data fusion, decision fusion, and feature fusion [55].

Reasoning Engines. Implementing intelligent reasoning engines empowers IoT systems to infer higher-level context from raw data. Logical reasoning, probabilistic reasoning, and fuzzy logic can aid in making intelligent decisions based on context.

4.4 Context-Awareness in Dynamic and Heterogeneous IoT Environments

Edge Intelligence (EI). Exploiting EC capabilities enables context-awareness to occur closer to the data source, reducing latency and improving responsiveness in dynamic environments [56].

Adaptive Algorithms. Developing algorithms that can adapt to varying environmental conditions and device capabilities ensures CA IoT systems can operate efficiently in heterogeneous settings [57,58].

By capitalizing on these opportunities, CA IoT systems can create adaptive and personalized user experiences, optimize RU, and drive innovation across various industries. Moreover, the integration of context-awareness in IoT applications paves the way for a more sustainable and interconnected world, where technology proactively caters to human needs and preferences. As research in this area progresses, CA IoT systems are poised to revolutionize industries, improve quality of life, and shape the future of the IoT.

5. Potential Applications and Benefits of CA IoT Systems

CA IoT systems have the potential to transform numerous domains, offering significant benefits through personalized, efficient, and proactive services. Here are some of the potential applications and the associated benefits [59]:

5.1 Healthcare Domain

In the healthcare domain, CA IoT systems have the potential to revolutionize patient care, improve medical processes, and enhance overall healthcare outcomes. The integration of context-awareness in healthcare IoT deployments offers various benefits and opportunities:

Remote Patient Monitoring. CA IoT devices can continuously monitor patient vitals, activity levels, and environmental conditions in real-time. This data enables remote patient monitoring, allowing healthcare providers to track patients' health status, detect anomalies, and provide timely interventions, especially for chronic disease management [60].

CD Alerts and Notifications. IoT systems equipped with context-awareness can generate relevant alerts and notifications based on patient conditions and healthcare guidelines. Doctors are notified about critical events, such as abnormal vital signs or medication adherence reminders, facilitating prompt medical attention [61].

CA Medication Management. CA IoT systems can ensure safe and accurate medication management. Smart pill dispensers can provide reminders and dispense medications as per the patient's schedule and adherence history, reducing medication errors and improving compliance [62,63].

Personalized Treatment Plans. Contextual patient data, such as medical history, lifestyle, and environmental factors, can be used to create personalized treatment plans. [64].

Ambient Assisted Living. CA IoT deployments enable ambient assisted living for elderly and disabled individuals. Smart homes equipped with CA devices can adapt to the resident's preferences and mobility, ensuring a safe and comfortable living environment [65].

Predictive Healthcare Analytics. CA IoT systems can analyze historical patient data and current context [66] to predict health risks and trends, thereby better anticipating health complications.

CA Telemedicine. Context-awareness enhances telemedicine by providing additional contextual information to remote healthcare providers. Real-time context, such as patient location [67] and vital signs, enhances the accuracy of telemedicine consultations and enables better-informed decisions.

Hospital Workflow Optimization. In hospital settings, CA IoT systems can optimize workflows by monitoring the availability of medical equipment, patient occupancy, and staff location. This streamlines patient care, reduces wait times, and improves resource allocation.

CD Rehabilitation. IoT-enabled rehabilitation devices can adapt their intensity and activities based on the patient's progress and physical capabilities. Context-awareness ensures personalized and safe rehabilitation plans, promoting faster recovery.

Seamless Healthcare Data Exchange. CA IoT deployments can facilitate secure and CD healthcare data exchange among different healthcare providers and systems [68]. This interoperability enhances care coordination, reducing duplicate tests and improving the accuracy of diagnoses.

By integrating context-awareness into healthcare

IoT systems, the healthcare domain can achieve significant advancements in patient care, healthcare efficiency, and cost-effectiveness. Contextual patient insights empower healthcare professionals to deliver personalized and proactive care, ultimately leading to improved patient outcomes and a more patient-centric healthcare experience.

5.2 Smart Cities Domain

Traffic Management. CA IoT systems can optimize traffic flow by considering real-time traffic conditions, weather, and events, leading to reduced congestion and improved transportation efficiency [69].
Energy Management. IoT applications can adjust energy consumption in buildings based on occupancy patterns and environmental conditions, promoting energy conservation and sustainability [70].
Waste Management. CA IoT solutions can optimize waste collection routes based on fill-level sensors, reducing operational costs and enhancing waste management efficiency [71].

5.3 Industrial Automation Domain.

Predictive Maintenance. CAIoT systems can predict equipment failures and schedule maintenance proactively, minimizing downtime and optimizing production processes [57].
Worker Safety. IoT devices equipped with context-awareness can monitor worker conditions and alert them to potential hazards, enhancing workplace safety and reducing accidents [72].
Inventory Management. CAIoT solutions can track inventory levels, demand, and environmental conditions to optimize inventory control and supply chain management [57].

5.4 Other Applications (e.g., agriculture, environmental monitoring).

Precision Agriculture. CA IoT systems can optimize irrigation, fertilizer usage, and crop management based on soil conditions and weather forecasts, leading to improved crop yield and resource efficiency [73].
Environmental Monitoring. IoT devices with context-awareness can monitor pollution levels, air quality, and natural resources, facilitating timely actions for environmental preservation [74].
Smart Home Automation. CA IoT applications can create intelligent and adaptive home environments by adjusting lighting, temperature, and other parameters based on user preferences and activities [44].
The benefits of CA IoT systems include improved RU, enhanced user experiences, optimized decision-making, and increased efficiency across various sectors. By leveraging context-awareness, IoT applications can address specific user needs and dynamically adapt to changing environmental conditions, ultimately shaping a smarter and more sustainable future.

6.Innovation and Improved User Experiences through Context Leveraging

6.1 Opportunities for Innovation in IoT Deployments.

Some key areas for innovation in IoT deployments include:[34].
EC and Fog Computing. Leveraging EC and fog computing paradigms can bring processing and intelligence closer to IoT devices. This approach reduces latency, conserves bandwidth, and enables real-time decision-making at the edge, enhancing overall system performance.
Hybrid Cloud-Edge Architectures. Exploring hybrid cloud-edge architectures can optimize the balance between cloud-based data processing and edge-based computations. Integrating the strengths of both approaches enables efficient RU and seamless scalability.
Artificial Intelligence (AI) and ML Integration. Advancements in AI and ML can empower IoT devices with context-awareness and predictive capabilities. Integrating AI algorithms into IoT deployments opens opportunities for automation, anomaly detection, and proactive decision-making.
Blockchain for IoT Security and Data Integrity. The integration of blockchain technology can enhance the security and integrity of IoT data by providing a tamper-resistant and decentralized data ledger. Implementing blockchain in IoT deployments can ensure trust, transparency, and data provenance [75].
5G and Next-Generation Communication Technologies. The advent of 5G and other advanced communication technologies promises faster and more reliable connectivity for IoT devices. Innovating with these technologies can unlock new possibilities in real-time applications and massive IoT deployments.
Energy Harvesting and Sustainable IoT. Developing energy harvesting solutions and optimizing power consumption in IoT devices fosters sustainable deployments. Innovations in energy-efficient sensors and low-power communication protocols extend the lifetime of battery-operated IoT devices.
CA User Interfaces. Designing CA user interfaces can enhance the user experience by adapting to real-time context and user preferences. CA

interfaces can simplify interactions with IoT systems and make them more intuitive and responsive.

Ubiquitous Sensing and Environmental Monitoring. Expanding the use of ubiquitous sensing and environmental monitoring in IoT enables comprehensive data collection for various applications, such as smart agriculture, air quality monitoring, and disaster management.

IoT in Cross-Domain Integration. Exploring IoT deployments across different industries and domains, such as combining healthcare data with smart city infrastructure or integrating industrial IoT with transportation systems, can lead to innovative cross-domain solutions.

Human-Centric IoT Design. Emphasizing human-centric design principles in IoT deployments ensures that technology is developed with the end-users' needs and preferences in mind. User feedback and usability testing can drive innovative solutions that resonate with users.

Seizing these opportunities for innovation will propel the IoT ecosystem forward, creating a more connected, intelligent, and responsive world. By embracing emerging technologies, novel architectures, and user-centric approaches, IoT deployments can continue to evolve, unlocking new potentials and addressing real-world challenges [76].

6.2 Enhanced User Experiences with CA Systems.

CA systems have the potential to revolutionize user experiences, making interactions with technology more seamless, personalized, and efficient. By leveraging contextual information, IoT deployments can enhance user experiences in various ways:

Personalized Services. CA IoT systems can tailor services and recommendations based on individual preferences, location, and past behavior. Users receive personalized content, such as targeted advertisements, smart home automation, or curated healthcare recommendations. [77].

Proactive Assistance. E.g., a CA smart assistant can automatically calibrate temperature, lighting, and music preferences based on the user's occupancy and time of day, enhancing comfort and convenience [78].

Adaptive User Interfaces. CA user interfaces can dynamically switch between touch, voice, or gesture interactions based on the user's preferences or physical limitations, ensuring a seamless and inclusive user experience [79].

Real-Time Recommendations. In dynamic environments, CA IoT systems can offer real-time recommendations and guidance. E.g., a CA navigation system can provide optimal routes based on traffic conditions, weather, and user preferences, enhancing travel efficiency.

CD Automation. CA automation enables smart decision-making based on contextual cues. E.g.,a CA smart home system can automatically adjust energy usage, security settings, and appliance control based on occupancy and user patterns, improving energy efficiency and security.

CA Healthcare. In healthcare applications, CA systems can monitor patient conditions in real-time, detect anomalies, and provide timely interventions. This enhances patient care, reduces medical errors, and empowers individuals to take control of their health.

Immersive Experiences. CA IoT deployments can create immersive and interactive experiences, such as augmented reality (AR) games or location-based storytelling. Context-awareness enriches these experiences by integrating real-world elements, making them more engaging and lifelike.

Adaptive Learning (AL) and Education. CA systems can personalize learning experiences based on the learner's context, learning style, and progress. AL platforms can dynamically adjust content and learning pathways, optimizing knowledge retention and comprehension.

CD Social Interactions. CA IoT systems can facilitate CD social interactions, connecting individuals with shared interests or activities.

Safety and Security Enhancements. CA IoT deployments can enhance safety and security by detecting potential risks and hazards. E.g., CA surveillance systems can raise alerts based on suspicious behavior or unusual patterns, enhancing situational awareness [66].

By focusing on enhancing user experiences through context-awareness, IoT deployments can create meaningful and valuable interactions between users and technology. The ability to understand and adapt to user context empowers IoT systems to provide efficient, relevant, and delightful experiences, driving user adoption and engagement across diverse applications and industries.

7. Future Research Directions and Opportunities

7.1 Identification of Gaps in Current Research.

While CA IoT systems show great promise, several gaps in current research exist, presenting opportunities for further investigation and advancement. The identification of these gaps is crucial for driving the evolution of CA IoT technologies. Some key areas with existing research gaps include:

Context Fusion and Reasoning.

Contextual Data Integration. Research can focus on developing efficient methods for integrating heterogeneous contextual data from diverse sources, such as sensors, social media, and historical records. Effective context fusion techniques will improve the accuracy and completeness of CA decisions.

Hybrid Reasoning Models. Investigating hybrid reasoning models that combine symbolic reasoning, statistical methods, and ML can enhance CA decision-making in dynamic and uncertain environments.

Contextual Privacy and Security.

Privacy-Preserving Context Sharing. Developing privacy-aware protocols and techniques to share context while preserving user privacy will be critical for building trust in CA IoT systems [56].

Secure Context Acquisition. Investigating secure context acquisition methods to prevent tampering and malicious data injection will safeguard the integrity and reliability of CA applications [56].

Resource-Constrained CA. Many IoT devices have limited computational capabilities and energy constraints, making it challenging to implement complex CA algorithms. Investigating lightweight and energy-efficient CA techniques tailored to resource-constrained devices is essential to achieve widespread adoption.

Explainability and Trust. CA AI models often operate as black boxes, limiting user trust and adoption. Research focusing on developing explainable CA algorithms will help users understand how decisions are made and enhance the transparency and accountability of IoT systems.

Context-Awareness in Unstructured Data. While current research often focuses on structured data, a significant portion of contextual information is present in unstructured data, such as natural language or multimedia. Exploring methods to extract and utilize context from unstructured data sources is a fertile area for further exploration [80].

Scalability and Interoperability. As CA IoT systems scale to include a vast number of interconnected devices, ensuring seamless interoperability and communication between heterogeneous IoT platforms becomes a challenge. Investigating scalable and standardized approaches for context sharing and integration is crucial for a cohesive IoT ecosystem.

Real-Time Context Processing. Real-time context-awareness is essential for time-sensitive applications like autonomous systems or healthcare. Research gaps exist in developing high-speed context processing techniques to enable instant responses in dynamic environments.

Ethical and Social Implications. CA IoT systems raise ethical questions concerning data privacy, user consent, and potential biases in decision-making. Further research is needed to address these ethical and social implications and ensure responsible and equitable use of CA technologies.

Long-Term Context Adaptation. Investigating methods to maintain accurate context-awareness over extended periods, considering context drift and changing user preferences, is a critical research area.

Human-Centric Design and Usability. Current research often lacks a strong focus on user-centered design and usability aspects of CA IoT applications. Understanding user needs and preferences and incorporating them into the design process can significantly enhance user acceptance and adoption.

EC for Context-Awareness.

Decentralized Context Processing. It reduces both latency and bandwidth consumption.

Context Distribution and Sharing. Research can focus on efficient methods to distribute and share context information among IoT devices at the edge, ensuring timely access to relevant context for decision-making.

Context-Awareness in Highly Dynamic Environments.

Mobility-Aware IoT Systems. Exploring context-awareness techniques that account for the mobility of IoT devices and users will enable seamless adaptation in dynamic environments, such as vehicular networks.

Real-time Context Updates. Research can focus on efficient mechanisms for real-time context updates, ensuring timely and accurate information for CA decision-making in rapidly changing scenarios.

CA AI and ML.

CD Learning. Investigating how context can influence the learning process in AI and ML models can lead to CA algorithms that adapt to changing environmental conditions.

CA Reinforcement Learning. Research can explore CA reinforcement learning algorithms to optimize IoT systems' decision-making in complex and dynamic environments.

Human-Computer Interaction (HCI) in CA IoT.

Natural User Interfaces. Studying and developing natural user interfaces that facilitate seamless interactions between humans and CA IoT devices will enhance user experiences.

Contextual Feedback and Explainability. Research can focus on providing meaningful feedback and explanations from CA IoT systems to improve user trust and understanding.

CA IoT Applications in Emerging Domains.

Contextual Robotics. Exploring context-awareness in robotics applications can lead to intelligent and adaptive robotic systems that interact effectively in dynamic environments.

AR and Virtual Reality (VR). Investigating CA AR and VR systems can create immersive experiences that respond intelligently to users' physical surroundings.

By delving into these future research directions and opportunities, researchers and practitioners can push the boundaries of CA IoT systems, paving the way for a future where technology seamlessly integrates with human context and needs, ultimately enhancing the efficiency, intelligence, and usability of IoT applications.

Addressing these gaps through interdisciplinary collaboration and rigorous research efforts will advance the field of CA IoT systems and unlock the full potential of intelligent and adaptive IoT ecosystems.

7.2 Emerging Trends and Areas for Further Exploration.

As CA IoT systems continue to evolve, several emerging trends and areas warrant further exploration to unlock their full potential. These trends present exciting opportunities for researchers, practitioners, and industry stakeholders:

EI. The convergence of context-awareness and EC is a promising trend. Exploring how CA algorithms and AI models can be deployed at the edge of the network enables real-time decision-making, reduced latency, and enhanced privacy.

Federated Learning (FL). FL, where CA models are trained across multiple IoT devices while preserving data privacy, holds immense potential. Investigating efficient and secure FL techniques can enhance context-awareness while respecting user privacy [6].

Explainable AI in CA. Developing CA AI models that offer explainability will be crucial, particularly in critical domains like healthcare and autonomous systems. Understanding the decision-making process of CA algorithms fosters trust and adoption.

CD Security. Exploring CA security mechanisms will be vital to address emerging threats and challenges in IoT ecosystems. CA authentication, anomaly detection, and dynamic access control can bolster the security posture of IoT devices [81].

Multi-Modal Context Fusion. Investigating methods to fuse diverse contextual information from multiple sources, such as sensors, cameras, and social media, can lead to richer context representations and more accurate CA decisions.

CA Sustainability. Assessing the environmental impact of CA IoT systems and developing energy-efficient solutions will be critical. Context-awareness can be leveraged to optimize resource usage and promote sustainability in IoT deployments.

Context in AR VR. Integrating context-awareness into AR and VR experiences can enhance immersion and personalization, making virtual environments more responsive to user actions and real-world context.

Collaborative Context Sharing. Exploring methods to enable secure and privacy-preserving context sharing between IoT devices and across domains will facilitate a more interconnected and seamless IoT ecosystem .

CA IoT Standardization. Developing industry-wide standards and protocols for CA IoT systems will promote interoperability and seamless integration across diverse IoT platforms.

Ethical Considerations. Investigating the ethical implications of CA IoT, such as data privacy, bias, and transparency, is required for inclusive deployment.

In addition to working on these fronts, collaborative efforts between academia, industry, and policymakers will be crucial in fostering innovation, addressing challenges, and creating a responsible and human-centric IoT future. Embracing these trends will accelerate the realization of intelligent and CA IoT ecosystems, bringing us closer to a more connected and enriched digital world.

8. Conclusion

8.1 Recap of Key Findings and Contributions.

Throughout this paper, we have delved into the realm of CA IoT systems and their transformative potential. Our key findings can be summarized as follows:

Significance of Context-Awareness. We emphasized the crucial role of context-awareness in IoT. Context like location, time, user preferences, and device characteristics, empower IoT devices to adapt intelligently and dynamically.

Importance of Personalization. CA IoT systems enable personalized and proactive services, enhancing user experiences and engagement.

Research Challenges and Opportunities. We identified various research challenges in developing CA IoT systems, including scalability, interoperability, security, and privacy concerns. Additionally, we highlighted opportunities for advancement in context acquisition, representation, fusion, and reasoning.

Applications. We explored the potential applications of CA IoT systems across domains such as healthcare, smart cities, industrial automation, agriculture, and environmental monitoring.

Human-Centric Design. CA IoT fosters human-centric design by prioritizing user needs and preferences. HCI is enriched through intuitive and context-responsive interfaces.

RO. By tailoring actions based on real-time context, CD decision-making leads to optimized RU and reduced energy consumption. This contributes to sustainability and cost-effectiveness in IoT deployments.

Security and Privacy Considerations. We highlighted the importance of addressing security and privacy challenges to build trust in CA IoT systems[82].

Innovation and Technological Advancements. CA IoT drives technological advancements in sensors, data processing, and ML. These innovations push the boundaries of CA IoT capabilities. In conclusion, our findings underline the transformative potential of CA IoT systems, reshaping industries, enhancing user experiences, and propelling innovation. The integration of context-awareness into IoT technologies has far-reaching implications, accelerating the evolution of a more intelligent, responsive, and interconnected world. Addressing research challenges and leveraging opportunities will drive the future development of CA IoT, revolutionizing how technology seamlessly integrates with human context and needs.

8.2 Implications for the Future of CA IoT Systems.

The incorporation of context-awareness into IoT systems holds profound implications for the future of IoT technologies. As CA IoT deployments continue to evolve, the following key implications are foreseen:

Enhanced User Experience. CA IoT systems have the potential to revolutionize user experiences by delivering personalized and proactive services. Devices can anticipate user needs based on real-time context, leading to seamless and intuitive interactions.

Optimized RU. CD decision-making enables IoT devices to optimize resource usage, leading to more efficient operations and reduced energy consumption.

Expansion of IoT Applications. Context-awareness opens up new horizons for innovative IoT applications across various domains.

Accelerated Technological Advancements. CA IoT systems drive innovation in both hardware and software technologies. Advancements in sensors, data processing, AI , and ML will continue to push the boundaries of CA IoT capabilities.

Realizing the Potential of EC.

Human-Centric IoT Designs. Context-awareness places human needs and preferences at the forefront of IoT design. HCI will be further enriched, creating intuitive and context-responsive interfaces.

CA AI and ML. This will enable adaptive and more accurate decision-making, resulting in smarter and contextually relevant IoT applications.

Industry Transformation. CA IoT systems will reshape industries, streamlining processes and optimizing operations. From healthcare to transportation and agriculture, industries will leverage CA IoT to drive efficiency and innovation.

Societal Impact. As CA IoT technologies become more prevalent, their impact on society will be far-reaching. By facilitating data-driven insights and personalized services, CA IoT will improve people's quality of life and lead to societal advancements. To fully realize the potential of CA IoT systems, ongoing research, collaboration, and standardization efforts will be essential. Addressing challenges related to context data fusion, privacy, and scalability will pave the way for a future where CA IoT technologies seamlessly integrate into our daily lives, bringing forth a more intelligent, responsive, and interconnected world. IoT has been widely studied in the literature [83-95].

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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