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Designing a framework for meter reading with an emphasis on the capabilities of the Internet of Things

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Abstract

The Internet of Things (IoT) is a transformative network of physical devices equipped with sensors and connected technologies that efficiently collect and share vital information. Intelligent energy prioritizes using renewable energy sources while significantly enhancing energy efficiency and environmental sustainability. Smart energy is not just an option but essential across all sectors. In smart cities, remote meter reading is a powerful and precise tool for intelligent energy management. This system operates through three critical components: measurement, analysis, and action. This paper introduces an efficient, cost-effective, and highly reliable method for real-time monitoring of AC power consumption for local and remote loads. Understanding household energy consumption is imperative for consumers, as it enables them to pinpoint significant opportunities for energy savings. Our monitoring system is specifically designed to analyze and evaluate household appliances' output voltage, current, frequency, and energy, empowering users to make informed choices about their energy use.

Keywords: Internet of Things, electricity meter, meter reading, smart city

1- Introduction

Building dependable and adaptable IoT-based savvy metering frameworks is fundamental to playing down support costs and contributing to the productivity and maintainability of our basic framework. Shrewd meters increment the effectiveness of essential systems and must resist natural and operational challenges throughout their life cycle. However, administrative and compliance

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necessities at worldwide and neighborhood levels include the specialized challenges of planning savvy metering frameworks based on the Web of Things. Planning for unwavering quality requires careful consideration of equipment and program plans, component determination, and testing and compliance forms (Zhao et al., 2024).

Shrewd meters are settled IoT gadgets that utilize advanced innovation to empower opportune transmission of utilization information to utility suppliers and empower farther meter administration and charging. Unlike conventional meters that require manual perusing, keen meters are prepared with modern two-way communication frameworks. These frameworks encouraged productive information exchange and permitted meters to get firmware upgrades and operational commands, expanding their execution and responsiveness to utility needs (Yalli et al., 2024).

Present-day keen metering frameworks depend on progressed frameworks compared to programmed meter perusing. The progressed metering foundation is a coordinated framework of shrewd meters, communication systems, and information administration frameworks that empower two-way communication between companies and clients (Nozari et al., 2024, Nozari, 2023). Programmed and programmed meter perusing kills the requirement for manual perusing, but programmed meter perusing as it was encourages one-way communication and limits its capabilities. Progressed estimation foundation frameworks regularly incorporate the following:

- A connection that enables data transfer between meters and power tools
- Head-end systems that manage meter data and enable remote meter management

Planning secure and solid savvy metering frameworks requires tending to calculated layers and specialized complexities. Abandoning equipment necessities, joining solid security conventions, and maintaining belief and administrative compliance in an advancing savvy metering framework are a few of the foremost common challenges in savvy metering arrangements (Gharachorloo et al., 2021).

Planning savvy metering frameworks could be troublesome, with numerous contemplations about fabricating past gadgets. A vital rule is to set unwavering quality objectives from the start because they can have far-reaching suggestions for framework execution, versatility, and adaptability (Nozari , 2024).

This research has tried to provide a way to implement a system for meter reading based on the Internet of Things. Therefore, the research framework is as follows: In the second part, the literature review is discussed. In the third part, the research method is presented. The conceptual framework is presented in the fourth part, and finally, the conclusion is presented in the last part.

2- Literature review

The Internet of Things (IoT) has transformed multiple industries, introducing efficient data communication and remote monitoring capabilities. One of the most promising applications of IoT lies in utility management, mainly through IoT-based Automatic Meter Reading (AMR) systems. Traditional meter reading, which often involves manual collection of utility data (for electricity, water, and gas), faces significant challenges, including labor costs, human error, and delays in data processing. IoT-based AMR systems aim to overcome these obstacles by providing an automated, real-time solution for monitoring and transmitting meter data to central systems, reducing costs and improving accuracy (Yalli et al., 2024).

IoT-based AMR systems use sensor nodes and communication networks to gather and process consumption data remotely. Numerous studies highlight that IoT enables better data accuracy, timeliness, and reduced operational costs compared to traditional methods. Sensors installed in smart meters continuously capture data and transmit it to the central server using wireless communication protocols like LoRaWAN, Zigbee, or cellular networks (Ali et al., 2020). A significant benefit of IoT-enabled AMR systems is that they can provide near real-time data on utility consumption, which can help utility providers monitor usage patterns, identify leaks or losses, and perform load balancing to improve grid efficiency.

In addition, IoT-AMR systems are scalable and suitable for urban and rural settings, where traditional meter reading processes may face logistical challenges. These systems support integrating various IoT devices, such as sensors and actuators, making implementing both metering and control functions possible. In the event of an anomaly, like excessive water usage or unauthorized access, the system can generate alerts, thus providing consumers with enhanced control over their utility usage (Wang et al., 2021).

Reliable and efficient communication is essential for the success of IoT-based AMR systems. A wide range of studies have examined communication protocols and technologies suitable for AMR systems, each presenting different benefits and trade-offs. LoRaWAN and Narrowband IoT (NB-IoT) are among the most popular choices, particularly for their low power consumption and extensive coverage (Raza et al., 2017). LoRaWAN, a long-range and low-power protocol, is suited for areas with limited cellular connectivity. This protocol also supports bidirectional communication, allowing utility providers to send instructions back to meters for remote updates or resets. NB-IoT, a cellular-based technology, provides high data rates and is compatible with existing mobile infrastructure, which makes it suitable for urban environments with robust connectivity.

Researchers have also explored hybrid networks that combine different technologies to enhance coverage and reliability. For instance, Bui et al. (2019) proposed a hybrid IoT-AMR architecture combining LoRaWAN and Wi-Fi for suburban applications. Such combinations allow for more data collection and transmission flexibility, particularly in areas where connectivity varies. Satellite IoT solutions have also been proposed in remote regions to overcome connectivity challenges. However, they remain costly and may require further technological advancements to be viable on a large scale.

Data management and security are crucial concerns in IoT-based AMR systems. As these systems transmit sensitive consumer data over public networks, the risk of cyber-attacks, unauthorized access, and data breaches is significant. Several studies propose encryption, authentication protocols, and blockchain-based methods to secure data communication and storage within IoT-AMR systems. For instance, Gupta et al. (2018) suggested a blockchain-based architecture for secure and transparent data management, enhancing consumer trust and compliance with data protection regulations. Blockchain technology can help address some of the limitations in traditional security methods by creating a tamper-proof ledger of all transactions, ensuring data integrity and accountability.

Another promising approach involves using lightweight encryption protocols specifically designed for IoT devices, which typically have limited processing power. In particular, AES-based encryption and public-key cryptographic algorithms, like Elliptic Curve Cryptography (ECC), are recommended due to their balance of security and computational efficiency (Singh & Sharma, 2020). Moreover, data anonymization techniques have been explored to protect consumer privacy while allowing utility providers to analyze usage patterns for operational insights.

The energy efficiency of IoT-AMR devices is a critical factor, as these devices are often deployed in large numbers and may not have access to a stable power supply. Low-power communication technologies, such as Zigbee, LoRaWAN, and NB-IoT, are commonly used in AMR systems to optimize battery life. Studies show that low-power wide-area networks (LPWANs) can enable extended battery life extensions of up to 10 years, which is essential for remote or difficult-to-access areas where frequent maintenance is costly (Xiong et al., 2019). Additionally, integrating energy harvesting technologies, such as solar power, can further reduce the dependence on external power sources.

Cost-effectiveness is another primary consideration, especially for large-scale deployment. Initial investments in IoT-based AMR infrastructure can be substantial; however, the long-term benefits often justify the expense. IoT-based AMR systems can offer utility providers a significant return on investment by reducing labor costs associated with manual meter readings and improving billing accuracy. A comparative study by Patel et al. (2020) demonstrated that although IoT-AMR implementation costs are high, the system's potential to reduce operational costs, decrease theft, and improve resource management justifies the investment over time.

The future of IoT-based AMR is promising but faces several challenges. Scalability and interoperability are prominent concerns, as these systems often need to be compatible with multiple devices, platforms, and communication protocols. Additionally, integrating IoT-AMR systems with other smart grid technologies and renewable energy sources presents technical and regulatory challenges. There is ongoing research into AI and machine learning applications within IoT-AMR systems for predictive maintenance, demand forecasting, and anomaly detection, which could further improve the efficiency and resilience of utility networks (Zhou et al., 2021).

Another emerging trend is using edge computing to enhance data processing capabilities close to the source, thereby reducing the need for data transmission and improving system responsiveness. By processing data locally, edge computing can alleviate some security and privacy concerns associated with centralized data storage (Shi et al., 2022). However, more studies are needed to evaluate such solutions' long-term feasibility and cost-effectiveness in large-scale IoT-AMR deployments.

3- Research methodology

In the case of constructing a conceptual framework for an IoT-based meter reading system, metasynthesis can integrate insights from various studies that examine the technology, challenges, user needs, and operational features associated with IoT in utility management. Here's a guide to using metasynthesis for this purpose:

Steps to Using Metasynthesis for Developing a Conceptual Framework for an IoT-Based Meter Reading System

1. **Define the Research Scope and Objectives**
   - **Scope**: Focus on studies related to IoT applications in utility management, particularly those that address meter reading, smart grids, data security, and user interaction.
   - **Objective**: Synthesize insights on the essential components, challenges, and stakeholder needs in IoT-based meter reading systems to create a comprehensive, conceptual framework.
2. **Systematic Literature Search and Selection**
   - **Data Sources**: Identify relevant qualitative studies from academic databases (e.g., IEEE Xplore, ScienceDirect, SpringerLink) and industry reports focusing on IoT in utilities, smart metering, and energy management.
   - **Inclusion Criteria**: Select studies that use qualitative methods (e.g., interviews, case studies, focus groups) and directly address themes like real-time data monitoring, system security, cost efficiency, and user accessibility in IoT-based meter reading systems.
   - **Exclusion Criteria**: Exclude quantitative studies, studies focused solely on non-IoT meter reading systems, and outdated technologies that lack relevance to current IoT infrastructure.
3. **Data Extraction and Coding**
   - **Identify Key Themes**: Extract recurring themes, such as "real-time monitoring," "data privacy," "system interoperability," and "user engagement," across studies.
   - **Coding**: Use qualitative coding methods to organize these themes into broader categories. For example, "real-time monitoring" and "data accuracy" might fall under a "Data Collection and Processing" category, while "data encryption" and "access control" might align under "Data Security."
4. **Synthesize Themes into Higher-Order Constructs**
   - **Identify Patterns and Relationships**: Combine themes from multiple studies to develop higher-order constructs that capture the essential elements of an IoT-based meter reading system. For example, if "user interface design" and "mobile access" are prominent across studies, synthesize these into a broader construct like "User Accessibility and Interaction."
   - **Cross-Study Analysis**: Compare themes across studies to identify patterns, common challenges, and effective solutions. This analysis helps refine the constructs into components that will form the framework's layers.
5. **Develop the Conceptual Framework**
   - **Organize Constructs into Layers**: Arrange the higher-order constructs into framework layers that define the IoT-based meter reading system:
     - **Perception Layer**: Sensors and smart meters for data collection.

        - **Network Layer**: Communication protocols for data transmission.
        - **Middleware Layer**: Data integration and processing.
        - **Application Layer**: Analysis, visualization, and control systems.
        - **User Interface Layer**: Platforms for user interaction and feedback.
    - **Interrelationships**: Identify how these layers interrelate and depend on each other, such as how the network layer supports real-time data transmission from the perception layer to the application layer.
6. **Validation and Refinement**
    - **Feedback from Experts**: Present the framework to IoT, utility, and technology experts to validate its practical relevance and refine the constructs based on their feedback.
    - **Further Literature Cross-Validation**: Review additional literature to ensure that all critical aspects of the IoT-based meter reading system are covered, especially about emerging themes like edge computing or artificial intelligence applications.
7. **Presentation of the Final Conceptual Framework**
    - **Illustration**: Visualize the conceptual framework, showing each layer, key components, and their relationships.
    - **Narrative Explanation**: Provide a detailed explanation of each component and how it fulfills stakeholder requirements, such as data security, accuracy, scalability, and user accessibility.

4- Research Finding

A Conceptual Framework for an IoT-Based Meter Reading System Using Metasynthesis synthesizes insights from multiple qualitative studies to outline the essential components and interactions in the system. A conceptual framework for an IoT-based meter reading system can be divided into several interconnected layers, each handling specific tasks within the system. Here is a breakdown of a typical framework:

- **Perception Layer (Sensing and Data Collection)**

- **Components**: Smart meters, sensors (for electricity, water, or gas), and local processing units.
- **Function**: This layer collects data from various utility meters. Smart meters with sensors measure real-time utility usage (e.g., electricity, water, gas). The meters capture consumption values, timestamps, and potential anomalies.
- **Data Processing**: Some initial data processing, such as filtering or simple aggregation, may be performed here to reduce the volume of data transmitted.

- **Network Layer (Data Transmission and Communication)**

- **Components**: Communication modules (e.g., LoRaWAN, Zigbee, NB-IoT, or Wi-Fi) that enable connectivity and data transfer.
- **Function**: This layer transmits data collected by the perception layer to the central processing server or the cloud. IoT-based meter reading systems often use low-power wide-area network (LPWAN) protocols, which ensure efficient and long-range data transmission.
- **Security**: This layer may also implement encryption protocols to protect data during transmission, ensuring data integrity and confidentiality.

❖ Middleware Layer (Data Management and Integration)

- **Components**: Middleware platform, IoT gateways, data protocols.
- **Function**: Middleware is an intermediary between the network layer and the application layer. It processes, filters, and manages data before it reaches the central server. The layer can integrate data from various types of meters and manage compatibility between different communication protocols and devices.
- **Integration**: This layer ensures interoperability and organizes the data for further processing, often leveraging protocols like MQTT or HTTP to route the data reliably.

❖ Application Layer (Data Analysis, Storage, and Control)

- **Components**: Data analytics software, cloud storage, and control systems.
- **Function**: This layer performs advanced data analysis to extract insights, monitor utility usage patterns, and detect anomalies (e.g., leaks or unauthorized usage).
- **Data Storage**: Cloud storage solutions store historical data, allowing users and utility providers to review long-term usage and trends.
- **Data Visualization**: The processed data is presented on user-friendly dashboards for utility companies and consumers to access in real-time.

❖ User Interface Layer (Access and Interaction)

- **Components**: Web and mobile applications, dashboard interfaces.
- **Function**: This layer enables interaction between the end-users (customers and utility providers) and the system. Consumers can monitor real-time consumption and receive alerts on irregular usage, while utility providers can manage resources more efficiently and make data-driven decisions.
- **Control Features**: Utility providers may also have control functionalities through the interface, such as remotely disconnecting meters or modifying operational parameters.

❖ Security and Privacy Layer (Cross-Cutting Layer)

- **Components**: Encryption protocols, access control mechanisms, and privacy-preserving methods.
- **Function**: Security measures span the entire framework to safeguard data from unauthorized access and ensure consumer privacy. This layer includes data encryption,

user authentication, and anomaly detection methods to protect data integrity and build consumer trust in the system.

Figure 1 shows the conceptual framework for the meter reading system based on the Internet of Things.

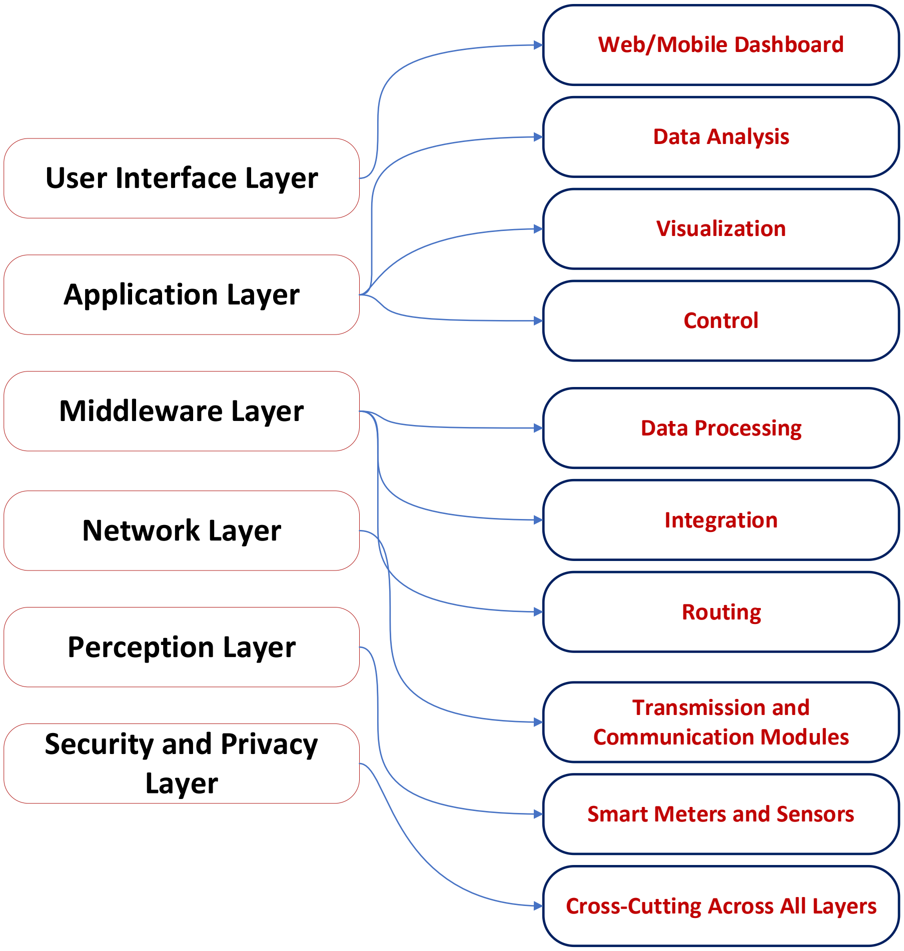

Figure 1: Conceptual framework for the meter reader system based on the Internet of Things

According to the presented framework, it is possible to determine the causal relationships of all active actors in the smart meter reader system based on the Internet of Things. These causal relationships are shown in Figure 2:

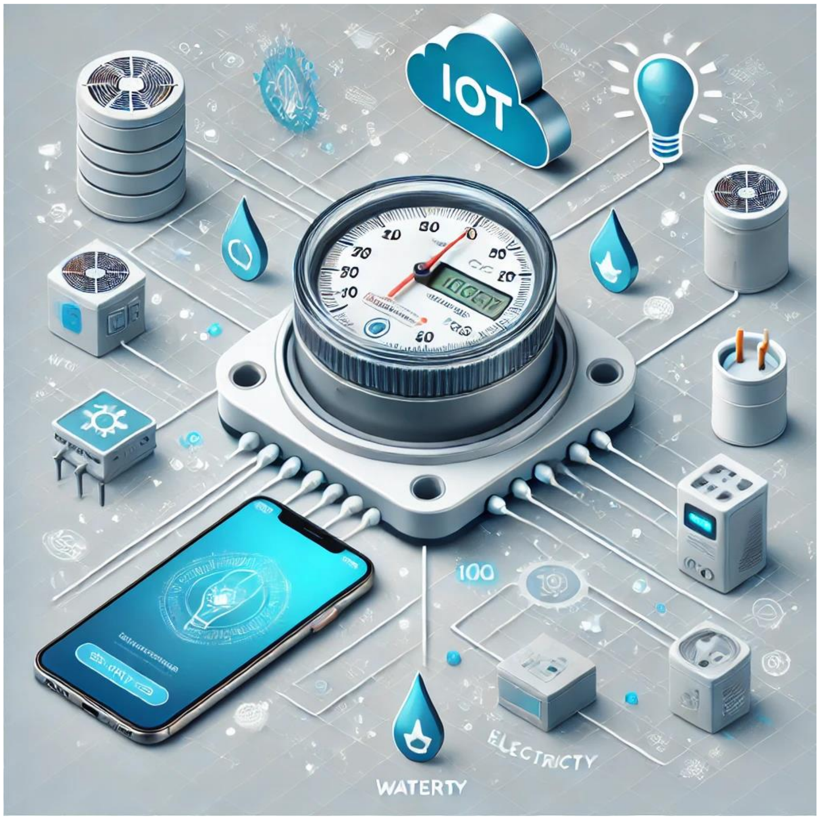

Figure 2: Causal relationships of all active actors in the intelligent meter reader system based on the Internet of Things

Figure 2 represents a conceptual framework for an IoT (Internet of Things) system that monitors and manages utilities like water, electricity, and other resources through interconnected devices. Here is an explanation of its components:

1. **Central Meter or Gauge**:
    - The large gauge in the center acts as a monitoring hub, likely symbolizing a smart utility meter.
    - It displays measurements like water or electricity usage in real-time.
2. **IoT Cloud Connection**:
    - The "IoT" cloud icon indicates that the system operates through the Internet of Things.
    - Data from various devices (sensors, meters, and controllers) is uploaded to the cloud for processing and analysis.
3. **Smartphone**:
    - The smartphone interface illustrates user interaction with the system.
    - Users can monitor and control utilities (like water consumption or electricity usage) through an app.
4. **Sensors and Devices**:
    - The small components, such as water drops, light bulbs, and sockets, represent various IoT devices.

    - Each device is connected to the network to measure and manage specific utilities or functions.
5. **Connectivity Lines**:
    - The lines connecting all devices signify a network that integrates sensors, controllers, and the central hub.
    - These connections enable real-time communication and data sharing.
6. **Icons for Resources**:
    - Water droplets, light bulbs, and electricity sockets symbolize different utilities being monitored or controlled.

Figure 3: Causal and effect relationships of factors affecting the IoT-based meter reader

The applications of this system are:

- ✓ **Data Collection**: Sensors gather real-time data (e.g., water flow, electricity usage) and transmit it to the central meter.
- ✓ **Cloud Processing**: The collected data is sent to the cloud, where it is analyzed for trends, anomalies, or optimization opportunities.
- ✓ **User Access**: Users can access this data on their smartphones, allowing them to monitor usage, set limits, or control devices remotely.
- ✓ **Automation**: The system might automatically adjust settings (e.g., turn off devices or manage water flow) to save resources or respond to conditions.

5- Conclusion

IoT-based AMR systems represent a substantial advancement in utility management, offering enhanced data accuracy, efficiency, and control over traditional meter reading methods. While data security, energy efficiency, and interoperability remain, continued research and technological developments will likely address these issues. The robust communication protocols, advanced encryption techniques, and data management frameworks promise a reliable and scalable future for IoT-AMR systems. As these systems evolve, they are expected to advance smart grid infrastructure and support sustainable resource management in the coming years. The conceptual framework emphasizes real-time data collection, transmission, and management across distributed IoT devices. By integrating security, data management, and user-friendly interfaces, this framework facilitates an efficient, secure, and accessible IoT-based meter reading system. This structure can be adapted as technology evolves, ensuring scalability, efficiency, and robust security in managing utility resources.

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