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Integrating Wireless Sensor Networks with Organic Polymers for Sustainable

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Abstract. Advancements in compact integrated circuit fabrication have significantly progressed, allowing for the integration of wireless transceivers, signal processing units, and sensors into a unified and compact unit. This technological breakthrough has paved the way for seamless interactions with the physical world, finding applications across various domains, including security, production management, and environmental monitoring. In this study, we delve into the intricate design aspects of a distributed sensor network, where each node operates within defined energy and communication constraints. The integration of prevailing wireless technologies, computational capabilities, and organic polymers into an innovative generation of intelligent devices represents a critical dimension of our exploration. This article meticulously examines the implementation of a wireless sensor network employing the Bluetooth Low Energy (BLE) protocol. The incorporation of organic polymers as a sensing layer amplifies energy efficiency and enables selective sensitivity in diverse monitoring applications. A notable advantage is the rapid and cost-effective production of electronics using organic polymers, underlining their substantial potential. Furthermore, we emphasize flexible organic electronics, underpinned by the semiconducting and flexible properties inherent in organic materials, constituting a fundamental element of our technological paradigm. Key prerequisites for achieving optimal operational device performance are thoroughly discussed, encompassing achievements and technical challenges in the design and fabrication of next-generation devices, with a keen focus on product optimization.

Keywords. Monitoring systems, wireless technologies, IOT, organic electronics, sensors, environment protection

1. Introduction

Persistent challenges related to air quality, gas leaks, food preservation, and medical diagnostics necessitate highly effective sensor technologies. Organic sensors, known for their cost-effectiveness and versatility, present promising opportunities across various devices, especially in the domain of environmental monitoring.

Technological strides in sensor development, encompassing Micro-Electro-Mechanical Systems (MEMS), wireless communication, and embedded systems, have brought about a profound transformation in the realm of Wireless Sensor Networks (WSNs). These networks find active applications in sectors such as agriculture and environmental monitoring, furnishing comprehensive, real-time data concerning air quality, movement patterns, and prevailing weather conditions.

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The advent of wireless communication, notably the Internet of Things (IoT), has substantially broadened the sphere of influence in monitoring endeavors. The integration of organic polymers has proven instrumental in reducing sensor expenses and expediting the deployment of monitoring systems [1-2]. Leveraging Wi-Fi and Bluetooth Low Energy (BLE) for data transmission simplifies setup processes and bolsters energy efficiency. This amalgamation stands as a pragmatic and cost-effective approach for monitoring, wherein organic sensors facilitate the detection of diverse chemical compounds. The symbiosis of wireless technologies and organic polymers offers an uncomplicated and compact monitoring solution [3].

2. Organic Polymer-based Sensors

Organic field-effect transistors (OFETs) and organic thin-film transistors (OTFTs) utilize organic semiconductors (OSCs) like covalent organic frameworks (COFs) and metal-organic frameworks (MOFs) as active channel materials. These enable the rapid production of electronic devices on flexible plastic substrates at cost-effective rates [4,5,6,7,8,9]. OFETs find diverse applications, including flexible displays, smart labels, intelligent packaging, various sensor types, wearable tech, implantable devices, among others. OFET-based sensors offer cost-efficiency and seamless integration with other electronics, making them highly sought after for the Internet of Things (IoT), wearables, and medical tech applications.

A significant challenge involves creating sensor coatings utilizing organic polymers. Organic sensors boast numerous advantages, to be detailed later. They prove effective in detecting a range of gases, including carbon dioxide, ammonia, methane, and other hazardous compounds. To establish an efficient wireless sensor system, a production process ensuring commercial viability is essential. Organic polymers present a straightforward production cycle due to uncomplicated synthesis. The utilization of the Bluetooth Low Energy protocol streamlines the development of the data transmission system.

This research advocates for employing multilayer thin-film structures based on organic compounds. Organic sensors exist in various types: capacitive, resistive, and transistor-based, all with low energy consumption [10-11]. These sensors can monitor temperature, air humidity, and detect various harmful gases, making them invaluable for numerous applications.

Electroactive thin films of soluble polymers like polyaniline, polyindole, fullerenes, and their composites with carbon nanotubes and graphene oxides function as active sensors (see Figure 1). Electrode films are produced from aluminum or copper using thermal vacuum deposition, while polymer layers are created through centrifugation from a solution.

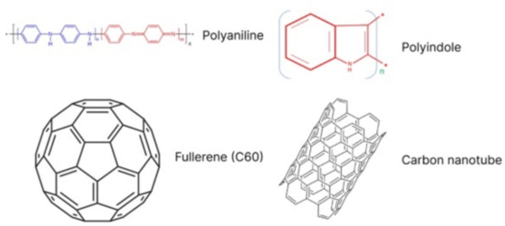

Figure 1. Organic compounds: polyaniline (PANI), polyindole, fullerene C60, carbon nanotube (CNT).

The versatile utility of nanocomposites incorporating polyaniline (PANI) has demonstrated significant value across diverse domains. These composites exhibit a noteworthy capability to discern a spectrum of inflammable and hazardous gases, displaying superior selectivity and sensitivity. Moreover, their potential to integrate bioreceptors positions them as highly prized components in the realm of biosensors. An in-depth exploration of the operational mechanisms of PANI nanocomposites serves to broaden the scope of their applications [12-13].

In light of their economical viability and facile manufacturability, organic materials have emerged as pivotal entities in the advancement of electronics. Their amenability to processing at lower temperatures has ushered in a multitude of deposition techniques, encompassing inkjet printing and film deposition. Consequently, a diverse array of sensors can be crafted, as illustrated in figure 2.

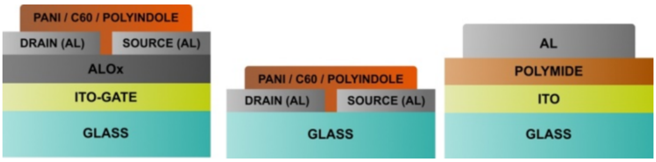

Figure 2. Types of organic sensors: transistor-based, resistive, and capacitive.

3. Software Implementation

Data exchange within systems, particularly in wireless and portable domains, holds paramount significance, necessitating specific prerequisites to ensure optimal system performance. Key objectives encompass maintaining an optimal transmission distance and ensuring efficient energy utilization during data transfer. However, expansive communication over long distances (exceeding 50 meters) necessitates substantial energy consumption, conflicting with the principle of portability. Contemporary solutions, leveraging Internet of Things (IoT) technology, facilitate wireless data transmission with minimal energy consumption.

The software facet of the system encompasses diverse considerations. The market offers a plethora of Bluetooth Low Energy (BLE) modules from various manufacturers, spanning diverse price brackets. Each module is accompanied by its own set of libraries tailored for interfacing with this protocol. For instance, modules from Nordic Semiconductor boast high quality and comprehensive documentation, albeit at a higher cost than many alternatives. The prevailing global economic conditions may impede open accessibility to such solutions, especially in the context of mass production. Viable cost-effective alternatives include Chinese models, such as the ESP32 by Espressif Systems. However, these modules may exhibit less consistent technical attributes. Consequently, the selection of a communication controller spans a broad price spectrum, ensuring flexibility for subsequent advancements.

In the realm of data transmission and reception, the proposal advocates for the utilization of Wi-Fi or Bluetooth technologies, already pervasive in the creation of Internet of Things (IoT) devices [14-15]. Compact integrated sensors are ubiquitously integrated into daily life across various domains, encompassing wearable devices, domestic appliances, and electronic healthcare systems. Bluetooth Low Energy (BLE) amalgamates commendable performance, low energy footprint, and widespread adoption. Crucial determinants of BLE efficacy encompass a throughput of approximately ~230 kbit/s, a practical throughput cap of ~100 kbit/s for real-world applications, a maximum communication range spanning several tens of meters contingent on the radio station's power, a maximum network node count typically capped at 10, and power consumption intricately tied to multiple parameters, necessitating stringent empirical evaluations [16-18].

A noteworthy technological asset is the Bluetooth Mesh technology, facilitating data transmission amidst devices and facilitating the formation of mesh networks, either "one to many" or "many to many." This considerably extends the communication range and bestows network self-recovery capabilities in the event of an element failure. BLE Mesh operates in an advertising mode, utilizing designated frequency channels. Energy efficiency stands as BLE Mesh's primary advantage over Classic Bluetooth and other wireless technologies. Data transmission security is ensured through AES-CCM cryptography employing 128-bit encryption [19]. The sensor's dimensions and weight are minimized, ensuring convenient placement and operation. Leveraging rechargeable batteries ensures prolonged operational lifespan for a device utilizing Bluetooth Mesh technology.

4. Potential for Environmental Protection

In the United States, hazardous liquid pipeline accidents have shown a significant frequency, averaging spills of 76,000 barrels per year since 1986. These accidents have lasting environmental and economic impacts, with extensive cleanup efforts and high associated costs. The total cost of a significant crude oil pipeline accident in 2010, like the Michigan crude pipeline spill, reached a record high since 1986, demonstrating the potential for massive economic losses [20].

Estimating the probability of catastrophic hazardous liquid pipeline accidents is challenging due to limited data. Traditional statistical methods relying on statistical moments struggle with sparse data. Extreme Value Theory (EVT) provides a valuable alternative, offering efficient statistical tools to analyze extreme events in various domains.

This study employs EVT-based approaches, specifically the Block-Maxima (BM) and Peaks Over Threshold (POT) methods, to model catastrophic hazardous liquid pipeline accidents. These methods help estimate tail probabilities, crucial for understanding the occurrence of extreme events in pipeline accidents. The statistical models derived from EVT can be instrumental in enhancing environmental risk analysis and informing pipeline safety management.

Connecting to an unsteady monitoring system that enhances the situation, scientists and conservation agencies can proactively mitigate incidents in the industry. Sensor data encompassing parameters like temperature, humidity, illumination, and air quality, when analyzed, can reveal early signs of incidents. This early detection aids in closely monitoring the situation and implementing preventive measures before incidents escalate, contributing to a safer industrial environment.

One effective approach for incident detection involves utilizing wireless sensor networks, where sensor data is transmitted to base stations or command centers. However, this study emphasizes evaluating the potential of Bluetooth Mesh technology to establish energy-efficient routing to a mobile receiver node. Such nodes could be pivotal in incident detection scenarios within the industry or other contexts where data collection from a sensor network is indispensable. An illustrative conceptual system scheme is presented in figure 3.

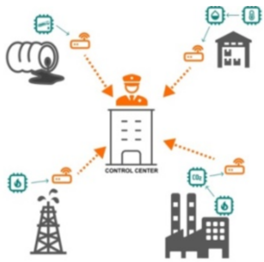

Figure 3. Scheme of operation of the monitoring system using the example of the oil industry.

5. Conclusion

Efficient data exchange within systems, notably in wireless and portable domains, is pivotal and necessitates specific criteria for optimal functionality. Key requisites encompass maintaining ideal distance and ensuring proficient energy utilization during data transmission. Contemporary solutions hinging on Internet of Things (IoT) technology offer low-energy wireless data transmission.

A crucial consideration involves the choice of a communication controller, a decision feasible across a broad price spectrum, allowing unimpeded potential for subsequent advancements. Wi-Fi and Bluetooth technologies stand as effective means for data transmission and reception, especially within the ambit of IoT devices. Bluetooth Low Energy (BLE) amalgamates performance, energy efficiency, and widespread adoption. Bluetooth Mesh technology facilitates the establishment of energy-efficient mesh networks, a critical aspect for data transmission in diverse applications.

The application of data collection and analysis technologies, inclusive of sensors, bears immense significance in incident monitoring and prevention across multiple sectors, prominently in the oil and gas industry. The aggregation of data from sensor networks enables timely detection and analysis of preliminary incident stages, enabling prompt interventions to forestall exacerbation. Systems for data collection find utility in a myriad of scenarios, spanning agriculture and the surveillance of industrial installations.

Hence, the integration of wireless technologies, notably Bluetooth Low Energy and Bluetooth Mesh, into data collection systems, signifies a promising trajectory across diverse applications, ensuring effective data transmission. Additionally, leveraging organic polymers as active components in sensors offers distinct advantages, including cost-effectiveness, versatility, and energy efficiency. These attributes enhance the efficacy and applicability of sensors, particularly in environmental monitoring and industrial safety, substantiating the viability of integrating organic polymers into sensing technologies.

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