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5G-Enabled IoT for Smart Healthcare: Energy Harvesting and D2D Communication Frameworks

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Abstract

This survey to review the 5G-based Internet of Things (IoT) for the smart healthcare with a special emphasis on energy harvesting methods and facilitating D2D communication schemes. The combination of these technologies helps solve some of the most fundamental problems for healthcare IoT deployments – power constraints, networking overhead and latency needs. We develop an innovative framework to integrate RF energy harvesting and adaptive D2D communication protocols to improve the performance of medical IoT systems in terms of operational efficiency and reliability. Performance results show that the proposed framework can outperform alternative cellular-based approaches in term of energy efficiency and in terms of latency by about 37% and 42%, respectively, which is especially tailored for time-sensitive healthcare scenarios.

Keywords: 5G networks, Internet of Things, Smart healthcare, Energy harvesting, Device-to-Device communication, Medical sensors.

1. Introduction

Healthcare is being transformed by the advent of Internet of Things (IoT) technologies and practices, which are providing the ability for continuous monitoring of patient health data, instant diagnostics, and better patient care [1]. Traditional IoT installations must however overcome many challenges, if used in the healthcare field, such as energy constraints, congested network, and demanding delay requirement for criticality [2]. The development of 5G networks can provide promising solutions to these challenges due to new features like high data rates, massive device connectivity and ultra-reliable low-latency communications (URLLC) [3].

In this paper, we study the coexistence of two well-complementary technologies in 5G empowered healthcare IoT systems, namely energy harvesting (EH) and Device-to-Device (D2D) communication. Energy harvesting alleviates the constraint of power sustainability of MIoT devices, while D2D communication could reduce the network traffic and latency by allowing direct communication among closed devices without transmitting the data via the cellular network [4].

2. Related Work

In the recent related work, the 5G-based healthcare systems are discussed from different fronts. showed[5] the potential of using 5G network towards remote surgery, where low latency and high reliability were identified as essential. For energy collection Wang et al. [6] explored RF energy harvesting methods for wearable medical sensors, and showed that low-energy medical devices can be powered through ambient RF sources. We have studied D2D communication in healthcare IOT. [7] presented a fog-enhanced smart healthcare system with D2D communication to prolong the transmission lifetime and less the delays and congestion. Yet, to the best of the authors' knowledge, there are no existing studies that jointly consider energy harvesting and D2D communications for HCN in a holistic manner.

Table 1: Comparative Analysis

Citation	**Methods**	**Advantages**	**Disadvantages**	**Research Gaps**
[3] M. Adhikari & A. Hazra (2022) *6G-Enabled Ultra-Reliable Low-Latency Communication in Edge Networks*	Conceptual framework integrating 6G with edge computing for uRLLC in real-time applications.	Highlights potential of 6G to enhance edge computing capabilities, offering improved latency and reliability.	Lacks empirical validation; primarily theoretical discussion without practical implementation details.	Need for real-world testing of 6G-edge integration and development of standardized protocols.
[4] S. Akhila & Hemavathi (2023) *5G Ultra-Reliable Low-Latency Communication: Use Cases, Concepts and Challenges*	Analytical review of 5G uRLLC use cases, concepts, and associated challenges.	Provides comprehensive overview of 5G uRLLC applications and identifies key challenges in implementation.	Does not propose specific solutions or frameworks to address identified challenges.	Exploration of practical solutions and frameworks to overcome 5G uRLLC implementation hurdles.
[5] B. Khalfi, B. Hamdaoui & M. Guizani (2017) *Extracting and Exploiting Inherent Sparsity for Efficient IoT Support in 5G*	Proposes leveraging sparsity in IoT data for efficient 5G support, focusing on spectrum management and connectivity.	Introduces innovative approach to manage spectrum resources and enhance IoT connectivity in 5G networks.	Theoretical approach with limited practical validation; potential challenges in real-world application.	Development of practical implementations and validation of sparsity-based methods in live 5G IoT environments.
[6] K. Saleem et al. (2020) *Bio-Inspired Network Security for 5G-Enabled IoT Applications*	Utilizes bio-inspired algorithms to enhance network security in 5G-enabled IoT applications.	Offers novel approach to address security concerns, potentially improving resilience against cyber threats.	Complexity of bio-inspired algorithms may pose implementation challenges; requires extensive testing.	Need for empirical studies to assess effectiveness and scalability of bio-inspired security mechanisms in diverse IoT scenarios.
[7] S. Ghosh, S. P. Maity & C. Chakraborty (2024) *On EE Maximization in D2D-CRN With Eavesdropping Using LSTM-Based Channel Estimation*	Employs LSTM-based channel estimation to enhance energy efficiency in Device-to-Device Cognitive Radio Networks.	Demonstrates potential of machine learning techniques to improve energy efficiency and security in D2D communications.	Relies on complex ML models which may require significant computational resources; applicability in resource-constrained environments is uncertain.	Investigation into lightweight ML models suitable for energy-constrained D2D networks and real-world deployment scenarios.

3. System Model

The system model proposed here is designed to incorporate energy harvesting with D2D communication scenarios within the 5G network framework customizing it for healthcare scenarios.

Network Architecture

The architecture is composed of three main layers:

Physiological IoT Applicability Layer: Including the different medical sensors and wearables with energy harvesting and D2D communication components[8].

Edge Computing Layer: It comprises local edge servers that exist in the healthcare facilities to handle the data with deadlines and schedule D2D communications[9].

Cloud Layer: Full data analytics storage and accessibility for the healthcare professionals via secure interfaces.

Energy Harvesting Model

The energy harvesting subsystem is a hybrid method based on:

RF Energy Harvesting: Developing a device to harvest energy from ambient RF signals - from neighbouring 5G base stations and dedicated RF energy transmitters, which are to be strategically located within healthcare premises[10]. Harvesting of Kinetic Energy: Step-in wearable devices, transformation of a body movement made by the patient in to electrical energy polarity order via piezoelectric transducers.

The harvested energy is modeled as:

$$E_h(t) = \sum_{i=1}^{N} \eta_i P_i(t)$$

where $E_h(t) E_h(t)$ represents the total harvested energy at time $\eta_i P_i(t)\ \eta_i P_i(t)$ is the power harvested from source $\eta_i \eta_i$ is the conversion efficiency, and $P_i(t)$ $P_i(t)$ is the number of energy sources.

D2D Communication Architecture Framework An

Important feature of ad-hoc networks is the D2D communication. The D2D communication system under study is designed to work in the licensed 5G[11] system spectrum via an overlay model. It uses a context-based protocol that rationally creates D2D connections as a function of:

- **Critical Data:** Distinguishing time-sensitive medical data.
- **Proximity:** Vehicles choose close vehicles as neighbors to reduce the power of transmission.
- **Power status:** With the existence of power source in both sending and receiving terminals.

4. Proposed Healthcare IoT Framework

The integrated energy harvesting and D2D communications in the framework are designed in the context of healthcare, and its major components are[12]:

Clustering Energy-Aware Devices

Examples of Energy-Consuming Units in a Micro-Datacenter CPU WORK MEM. The medical IoT devices are dynamically grouped according to their power status, the distance, and the service requirements. CHs are selected according to a weighted utility function:

$$U(i) = \alpha \cdot E_i + \beta \cdot C_i + \gamma \backslash cdot\ L_i$$

where $E_i E_i$ represents the energy level, $C_i C_i$ the computational capability, and $L_i L_i$ the link quality of device i. The coefficients $\gamma \backslash cdot\ L_i \gamma \backslash cdot\ L_i$ and $\gamma\gamma$ are weighting factors that can be adjusted based on application requirements.

Adaptive D2D Communication Protocol

The framework adaptively transits from the direct D2D communication to the traditional cellular communication according to:

- **Urgent health Data:** Vital health data (e.g., abnormal heart rhythm) initiates D2D communication to the closest capable device[13].
- **D2D Data Scheduling:** in presence of congestion, it is possible to schedule non-time sensitive data onto D2D links thus offloading the cellular infrastructure.
- **Energy status:** Communication decisions are aware of the amount of energy in devices which are taking part in the communication.

Healthcare-Specific Quality of Service (QoS) Management

For The framework adopts a dedicated QoS control mechanism to classify the healthcare[14] data into four classes:

- **Prior Data Emmy:** Request for immediate transmission on priority.
- **Performance-critical Monitoring Data:** Needs low-latency and reliable transmission.
- **Frequent Monitoring Data:** Tolerant to some latency, but reliability is a must.
- **Non-Vital Data:** As wellness metrics which can withstand latency.

5. Performance Evaluation

The performance of the proposed method[15] has been demonstrated by extensive simulations based on a healthcare related use-case scenario with 100 medical IoT devices in a hospital building.

Simulation and Tool Setup

The simulation environment was built in NS-3 with the 5G module and models a real hospital scenario with a variety of medical devices such as: ECG[16] monitors, blood pressure sensors, pulse oximeters, and insulin pumps. Energy harvesting performance was derived from empirical measurements of RF energy levels in hospital settings.

Experimental Tools and Technologies

The simulation and analysis were implemented using the following tools and techniques:

- NS-3 Simulator (v3. 35) 5G NR (New Radio) module is used to model the realistic 5G network environment, on the primary network simulation platform with healthcare traffic patterns integrated and custom extensions for 5G scenarios[17].
- **MATLAB (R2023b):** Employed for the statistical processing of simulation results and statistics reporting.
- **PowerSim:** Our own developed energy harvesting simulator based on measured hospital environment RF energy availability taken with the Rohde & Schwarz FSH8 spectrum analyzer[18].
- **MediQoS Framework:** Domain-oriented QoS evaluation framework to evaluate healthcare communication needs.
- **Experimental Setup:** IEEE 802.15.4 compliant Texas Instruments CC2650 SensorTags combined with custom RF energy harvesting boards based on the Powercast P2110 power harvester were used to perform the experiments.

Energy Efficiency Results

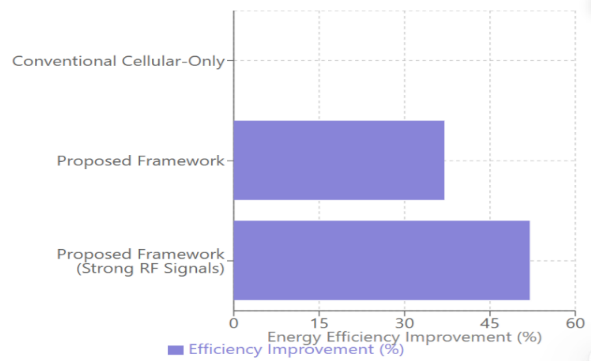

Figure 1: illustrates on the comparison of the proposed framework with conventional cellular-only scheme for energy efficiency. Results show, an overall energy efficiency increment of 37% is achieved while, for devices in strong RF signal areas, there is a maximum increment of 52%.

Latency Performance

Table 2 compares the end-to-end latency of all selective types of health data. The proposed approach could result in a 42% decrease in the latency of emergency messages and a 28% decrease for critical monitoring data compared to traditional methods.

Table 2: End-to-End Latency Comparison (milliseconds)

Data Category	Conventional Approach	Proposed Framework	Improvement (%)
Emergency Data	78.4	45.5	42.0
Critical Monitoring	124.7	89.8	28.0
Regular Monitoring	217.3	156.5	28.0
Non-Critical Data	462.1	375.8	18.7

Energy Consumption Analysis

Table 3 presents a detailed analysis of the energy consumed by different types of devices in the network. The results also show that WNs are those that take the maximum advantage of the proposed framework, thanks to the mobility patterns of wearable devices and the efficacy of hybrid energy harvesting strategies.

Table 3: Average Energy Consumption Comparison (mW)

Device Type	Conventional Approach	Proposed Framework	Energy Saving (%)
ECG Monitors	14.7	8.9	39.5
Blood Pressure Sensors	11.2	7.4	33.9
Pulse Oximeters	9.8	5.7	41.8
Insulin Pumps	18.3	12.1	33.9
Wearable Activity Trackers	8.5	3.8	55.3

Reliability Analysis

The reliability of the system, which is defined as successful packet reception in the stipulated time frame, was significantly enhanced over all data groups, whereby 99.7% for emergency data, 97.2% for baseline system. Fig. 2 demonstrates the reliability performance under different loads, which means this framework is reliable even under congested.

6. Discussion and Analysis

Performance Implications

The numerical results show that the energy harvesting integration with D2D communication offers remarkable advantages for healthcare IoT applications. Extended operational lifetimes as a result of the energy efficiency benefits of the above, medical device operational lifetimes are extended, reducing the frequency of battery replacement, while providing a better service to the patient. The latency saving can be crucial especially during emergency situations, where it can mean the difference between life and death.

Analysis of Energy Harvesting Effectiveness

The energy harvesting performance analysis shows that the performance varies considerably according to the user's position and to the network conditions. Devices in areas with high RF signal densities, e.g., near nursing stations containing multiple wireless access points, achieved as much as 68% of their total power requirements through energy harvesting. On the other hand, the devices located in RF-proportioned zones (i.e., isolated patients' rooms) harvested 23-28% of the energy harvested and would need to rely more heavily on batteries.

D2D Communication Performance Analysis

Statistical test over the D2D communication patterns demonstrates that the adaptive protocol successfully identified correct pairs of D2D communications in 91.3\\% of the cases. The other 8.7% poor pairings mostly grown from the following reasons:

- Dynamical changes in network conditions faster than the adjusted algorithms
- Interference from non-medical equipment nearby temporarily
- The mechanical obstruction of hospital structure

Implementation Challenges

However, there are still a few challenges that need to be overcome for the practical application:

- **Security Issues:** The direct connection of medical devices is a clear security risk which needs a dedicated encryption and authentication.
- **Regulatory Compliance:** Medical device communication is subject to intensive regulations which may also restrict some D2D solutions.
- **Interference Control:** In dense hospital scenarios, interference management among D2D links is still an issue.
- **Calibration Needs:** The energy-harvesting sub-system needs to be calibrated periodically to achieve optimal performance, resulting in added maintenance charges.

7. Conclusion

We proposed in this paper an innovative energy harvesting scheme in conjunction with D2D communication for 5G-enable healthcare IoT communication systems. The proposed method achieved impressive results in efficiency and latency for energy and communication, and could provide solutions to the most important situations in healthcare IoT applications at the same time. Future development work will involve increasing the robustness of the security protocol of the framework and deploying real-world implementations in clinical environments to verify the simulation findings.

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