

There re HUNDREDS of these kinds of studies. Here are just a few Nano technology MUST be incorporated into any standards created by FCC, FDA or any regulating body...

https://journals.mesopotamian.press/index.php/BJIoT/article/view/1147?fbclid=IwY2xjawUx9CVleHRuA2FlbQlzMABwZG9mAWJyaWQRMVp4YndocW9ZbVdFOXNmRExzcRjBmFwcF9pZBAyMjIwMzIxNzg4MjAwODkyAAEepqm8EzmFNul6pB2C2ZHziPwcyRfdxxVtYppjiorgOC7i7DPeNE1usgXJkfY_aem_PM9jlEsdncsng8Tgn1-AOw

Internet of Bio-Nano Things (IoBNT) Security: A Comprehensive Survey of Threat Models, Protocols, Mitigation Strategies, Technological Integrations, Tools, and Performance Metrics

Abstract

The Internet of Bio-Nano Things (IoBNT) constitutes a transformative paradigm to support applications in precision medicine, environmental monitoring, and bio-hybrid cyber-physical systems. However, it faces a complex security landscape. Existing research typically examines isolated threats, individual protocol layers, or specific communication modalities, rather than providing a unified perspective on security vulnerabilities, threat models, and mitigation strategies across the entire IoBNT stack. This study provides a comprehensive, structured, and security-centric overview of IoBNT systems by identifying and classifying security threats; analyzing existing and emerging security protocols and mitigation techniques; examining enabling technological integrations that support secure IoBNT operations; and establishing coherent performance metrics and evaluation criteria. The study adopted a comprehensive review methodology, examining 153 research papers retrieved from Frontiers, ACM Digital Library, Wiley Online Library, Nature, Springer Nature, ScienceDirect, MDPI, IEEE Xplore Digital Library, and Google Scholar, with a focus on publications from 2023 to 2026 that addressed

security aspects of the IoBNT. The survey examines contemporary security challenges and defenses in the IoBNT ecosystem. It synthesizes state-of-the-art mitigation strategies alongside reinforcing technological integrations for predictive bio-cyber risk assessment and quantum-safe mechanisms that support long-term resilience. The analysis also surveys tools, simulation frameworks, testbeds, and experimental platforms used to model, validate, and benchmark IoBNT security solutions, while consolidating standardized performance metrics. Finally, it maps the current research landscape, identifies open challenges, and outlines future directions for developing secure, reliable, and ethically aligned IoBNT systems. This survey offers important implications for both researchers and practitioners by delivering a holistic security perspective that informs the design of robust, interoperable, and trustworthy IoBNT systems.

<https://www.itu.int/pub/S-JNL-VOL7.ISSUE2-2026-A14>

Beyond digital twins: The rise of cognitive twins in 6G and beyond wireless systems

Abstract:

Digital twins have emerged as a key enabler for monitoring, simulation, and optimization in complex systems. However, existing approaches remain fundamentally centered on state replication and prediction, lacking the ability to systematically reuse experience, interpret system behavior, and support interactive decision-making under dynamic conditions. In this article, we introduce the cognitive twin as a new system paradigm that extends state synchronization with structured cognitive capabilities, including perception, memory, causal reasoning, and interaction. Unlike traditional digital twins and their learning-based extensions, a cognitive twin maintains an evolving cognitive state that supports experience-aware reasoning, causal interpretation, and context-aware interaction, enabling a transition from data-driven monitoring toward understanding-driven operation. We develop a four-layer reference architecture that captures how cognitive processes are distributed across device, edge, and cloud domains and realized through the

continuous exchange of structured state, contextual knowledge, and inferred decisions. A central insight is that this paradigm fundamentally reshapes the role of communication. Rather than solely supporting data exchange, communication directly influences the formation, synchronization, and evolution of cognitive state under heterogeneous constraints on latency, bandwidth, reliability, and synchronization. A key hypothesis explored in this article is that communication impairments affect cognitive fidelity asymmetrically with respect to semantic importance, such that degradation of semantically critical information may produce disproportionately large reasoning errors relative to equivalent losses in redundant or low-impact data streams. This perspective motivates wireless-native system designs in which communication, computation, memory, and cognition are jointly optimized rather than treated as independent subsystems. [...]

<https://www.itu.int/pub/S-JNL-VOL2.ISSUE3-2021-A08>

Internet of Bio-Nano Things: A review of applications, enabling technologies and key challenges

Abstract:

Internet of Bio-Nano Things (IoBNT) is envisioned to be a heterogeneous network of nanoscale and biological devices, so called Bio-Nano Things (BNTs), communicating via non-conventional means, e.g., molecular communications (MC), in non-conventional environments, e.g., inside human body. The main objective of this emerging networking framework is to enable direct and seamless interaction with biological systems for accurate sensing and control of their dynamics in real time. This close interaction between bio and cyber domains with unprecedentedly high spatio-temporal resolution is expected to open up vast opportunities to devise novel applications, especially in healthcare area, such as intrabody continuous health monitoring. There are, however, substantial challenges to be overcome if the enormous potential of the IoBNT is to be realized. These range from developing feasible nanocommunication and energy harvesting techniques for BNTs to handling the big data generated by IoBNT. In this survey, we attempt to provide a comprehensive overview of the IoBNT framework along with its main components and applications. An investigation of key technological challenges is presented together with a detailed review of the state-of-the-art approaches and a discussion of future research directions.

<https://ieeexplore.ieee.org/document/11505856>

Chemo-Hydrodynamic Transceivers for the Internet of Bio-Nano Things

Abstract:

The Internet of Bio-Nano Things (IoBNT) requires mobile nanomachines that navigate fluidic environments while exchanging molecular signals under external control. We propose a chemo-hydrodynamic transceiver for catalytic Janus particles in which a single optical input jointly controls molecular emission and self-propulsion, unlike standard models that decouple communication from mobility. The resulting stochastic channel contains an actuation-dependent variance term scaling as $1/4$, which creates a nonmonotonic reliability tradeoff. Stronger actuation increases emission but also amplifies motion-induced fading. In a reduced single-link setting, exact-BEP analysis reveals a finite optimal actuation level, and comparison with Brownian-mobility baselines shows that neglecting active motility can markedly underestimate BEP, especially at high actuation and short link distances. These results provide physical-layer guidance for mobility-aware actuation and link design in IoBNT.

Chemo-Hydrodynamic Transceivers for the Internet of Bio-Nano Things, Modeling the Joint Propulsion Transmission trade-off

Abstract—The Internet of Bio-Nano Things (IoBNT) requires mobile nanomachines that navigate complex fluids while exchanging molecular signals under external supervision. We introduce the chemo-hydrodynamic transceiver, a unified model for catalytic Janus particles in which an external optical control simultaneously drives molecular emission and active self-propulsion. Unlike common abstractions that decouple mobility and communication, we derive a stochastic channel model that captures their physicochemical coupling and shows that actuation-induced distance jitter can dominate the received-signal variance,

yielding a fundamental trade-off: stronger actuation increases emission but can sharply reduce reliability through motion-induced fading. Numerical results reveal a unimodal reliability profile with a critical actuation level beyond which the signal-to-noise ratio collapses, and an optimal control level that scales approximately linearly with link distance. Compared with Brownian-mobility baselines, the model exposes a pronounced estimation gap: neglecting active motility noise can underestimate the bit error probability by orders of magnitude. These findings provide physical-layer guidelines for mobility-aware IoBNT protocol design and closed-loop control of nanorobotic swarms.

Internet of bio-nano things: An analytical path loss model for hybrid communications