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Communication technologies: Bridging the nano-to-macro gap

While the previous section discussed the functional classifications, performance advantages, and limitations of nanosensors across various applications, their effective integration into real-world systems demands more than advanced sensing capabilities. One of the key challenges lies in ensuring reliable and efficient data transmission from the nanoscale domain to macroscopic ICT systems. The following subsection explores Communication Technologies that address this challenge by bridging the nano-to-macro gap, ensuring that sensor data are efficiently captured, transmitted, and utilized in broader networks. The data output of nanosensors must be efficiently communicated, interpreted, and acted upon a task that demands equally advanced communication technologies.[69] Conventional wireless protocols like ZigBee and Bluetooth Low Energy offer low-power operation and are suitable for wearable or indoor nanosensor applications.[70] However, their limited data throughput and short-range capabilities constrain broader deployments, especially in smart cities or precision agriculture.[71] LoRa (Long Range) technology has emerged as a promising alternative, offering extended coverage with minimal energy consumption.[72] While ideal for sporadic data transmission from nanosensor nodes in remote areas, its low

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