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Offline Node-to-Node Communication in Infrastructure-Restricted Environments: A Thematic Review

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Abstract

Communication can become unreliable in infrastructure-restricted environments when cellular coverage, internet access, or local Wi-Fi is unavailable or attenuated by physical structures and industrial equipment. This review examines a selected corpus of 17 research papers covering Bluetooth Low Energy (BLE) mesh networking, smartphone-based peer-to-peer communication, Wi-Fi Direct, opportunistic networking, emergency communication, and cross-technology integration. Rather than treating these technologies as interchangeable, the review distinguishes discovery from data transfer, direct links from multi-hop forwarding, standardised mesh protocols from application-layer overlays, and simulation results from physical-device evaluations. The literature indicates that BLE is attractive for low-energy discovery and short messages, while Wi-Fi Direct can provide a higher-capacity local link but introduces group formation, group-owner, platform API, and multi-hop coordination challenges. Opportunistic and Internet of Things (IoT)-assisted designs can extend reach or preserve messages across intermittent contacts, but they require explicit routing, duplicate suppression, message expiry, persistence, and energy-management policies. Cross-technology physical-layer communication demonstrates that BLE and Wi-Fi signals can be bridged under specialised conditions, but this should not be confused with a ready-made application-layer gateway. The review then derives a staged architecture and evaluation agenda for ResQNet, a prototype intended for communication in digester-area environments. The currently reported implementation is limited to BLE scanning and nearby-device discovery on Android phones; custom messaging, relaying, store-and-forward, Wi-Fi integration, and fixed IoT relays are treated as future work. The principal research need is an empirically evaluated, safety-aware hybrid system whose performance is measured under realistic obstruction, mobility, interference, and power constraints.

Keywords: offline communication; Bluetooth Low Energy; Bluetooth Mesh; Wi-Fi Direct; opportunistic networking; store-and-forward; industrial safety; ResQNet

1. Introduction

Reliable communication is a basic operational requirement in industrial facilities, including wastewater-treatment and biogas installations where workers may move between tanks, digesters, pipes, reinforced-concrete structures, and machinery. In such locations, ordinary mobile connectivity may be weak or unavailable, and a site Wi-Fi network may not cover every work area. The result is not simply a loss of internet access: workers may be unable to pass a short status update, request assistance, or relay an alert to a nearby colleague. An offline communication system therefore needs to prioritise local reachability, predictable behaviour, low operational overhead, and graceful handling of intermittent links.

Research relevant to this problem spans several fields that are often discussed separately. BLE and Bluetooth Mesh studies focus on low-power communication and many-to-many networking; Wi-Fi Direct studies examine direct device-to-device links and multi-group networking; emergency-network studies consider communication after infrastructure failure; and opportunistic networking explores how devices can exchange data when contacts are intermittent. Cross-technology communication adds another layer by examining whether information can pass between otherwise distinct radio systems. These strands offer complementary ideas, but the assumptions and evidence in one strand cannot automatically be transferred to another.

This paper synthesises a corpus of 17 papers to clarify the design trade-offs most relevant to ResQNet, a prototype intended for node-to-node communication in digester-area environments, of which only the discovery stage is

implemented. The current implementation reported by the authors is BLE scanning and nearby-device discovery on physical Android phones. The review therefore separates what the literature demonstrates from what ResQNet has implemented and from features that remain proposed. This distinction is important: a design proposal for multi-hop communication is not evidence of working multi-hop delivery, and a simulated performance result is not a field measurement.

The review makes four contributions. First, it organises the selected literature into four connected themes plus supporting literature: BLE mesh, Wi-Fi Direct and mobile peer-to-peer networking, emergency/opportunistic communication, and cross-technology/IoT-assisted designs, with general peer-to-peer and wireless-mesh studies included as supporting literature. Second, it compares the evidence types and limitations rather than listing technologies descriptively. Third, it identifies gaps for infrastructure-restricted industrial environments, particularly Android platform constraints and the absence of a validated end-to-end application protocol in the current prototype. Fourth, it proposes a staged evaluation agenda for ResQNet without claiming that planned features have already been implemented.

2. Review Methodology

This manuscript uses a structured thematic review of 17 papers assembled by the authors. The corpus includes peer-reviewed journal and conference publications, including a conference paper on an offline emergency application, and one arXiv preprint. The source set was organised by primary topic and by the kind of evidence reported: conceptual or survey analysis, simulation, software prototype, physical-device testbed, or cross-technology physical-layer experiment.

The review is not presented as a comprehensive systematic literature review (SLR), nor does it claim compliance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. The corpus was assembled before this manuscript was drafted, and no complete database search log, screening counts, duplicate-removal record, or formal exclusion log was retained. Accordingly, the findings are bounded by the selected corpus and should be interpreted as a thematic synthesis rather than an exhaustive estimate of the state of the art. A documented search of IEEE Xplore, ACM Digital Library, Scopus or Web of Science, and Google Scholar, with recorded search dates, exact query strings, inclusion criteria, and a screening log, is left to future work (Section 6).

For each paper, the synthesis considers: (i) the communication problem and assumptions; (ii) the technology and networking layer addressed; (iii) the evaluation method; (iv) the main contribution relevant to offline communication; and (v) the limitation that constrains transfer to ResQNet. Particular care is taken to avoid comparing unlike metrics or presenting simulation results as physical deployment results. The selected papers also vary in direct relevance: BLE mesh surveys and emergency communication systems are central, while general peer-to-peer resource sharing and vehicular-network papers provide supporting concepts rather than direct evidence for industrial-worker communication.

3. Thematic Review of Literature

3.1 BLE discovery, Bluetooth Mesh, and low-energy communication

BLE is attractive for a first-stage offline prototype because contemporary smartphones include BLE radios and can discover nearby devices without an access point or internet connection. Discovery, however, is not equivalent to a communication service. A scan can reveal that an advertisement is present, but it does not by itself provide reliable message delivery, application identity, acknowledgement, persistence, or multi-hop forwarding. A complete system must define how nodes are identified, how messages are framed, what happens when a peer disappears, and how duplicate or expired messages are handled.

Darroudi and Gomez (2017) survey BLE mesh approaches and explain the central limitation of the original BLE star-oriented model: a direct link does not inherently provide mesh reach or end-to-end path diversity. Their review describes the range of approaches used to construct mesh-like behaviour and identifies open design issues. Ghori et al. (2020) extend the discussion to communication and security protocols, emphasising that broader participation in BLE mesh systems also creates security concerns and that robust intrusion detection and practical auto-configuration

remain challenging. Natgunanathan et al. (2023) review Bluetooth Mesh applications and practical considerations, including the protocol's many-to-many design and managed flooding. Taken together, these surveys suggest that Bluetooth Mesh is a protocol and network-design choice, not a capability that should be assumed merely because an application performs BLE scans.

A relevant distinction is between BLE advertising used for discovery and the Bluetooth Mesh standard. Advertising-based discovery may be a useful first milestone for ResQNet, but it does not establish that the application implements the standard's provisioning, network/security keys, relay behaviour, publish/subscribe model, or managed flooding. The manuscript and project demonstration should name the implemented level precisely. If the current build only scans for nearby devices, it should be described as a BLE discovery prototype rather than a completed BLE mesh network.

The literature also cautions against treating mesh capacity as a simple function of radio range. Managed flooding can increase reach and robustness, but message repetition creates airtime overhead and contention. In a metal-rich or obstructed facility, multipath and attenuation may alter reception in ways that are not captured by a generic range statement. For ResQNet, the practical question is not whether BLE is universally superior, but whether it can reliably discover and exchange short messages at the distances and through the obstructions present in the target environment.

3.2 Wi-Fi Direct and smartphone peer-to-peer networking

Wi-Fi Direct provides a mechanism for devices to form a local group without a conventional access point. It can offer higher data capacity than BLE, but the group-based model introduces coordination that is significant for a multi-hop application. Shahin and Younis (2014) discuss the limited Android APIs available for group formation and management and demonstrate a peer-to-peer framework through a chat application on multiple Android devices. Their work highlights that the radio capability alone does not guarantee that an application can discover every peer, exchange group-member addresses, or construct an arbitrary peer-to-peer topology.

Lee et al. (2017) describe a Wi-Fi Direct mobile ad hoc network with a routing layer intended to support communication within and across Wi-Fi Direct groups, with an implementation on four Samsung mobile devices. Casetti et al. (2014) similarly examine content-centric routing across multiple Wi-Fi Direct groups, including intra-group and inter-group communication primitives and an Android testbed. These studies are important because they demonstrate that multi-hop communication requires an overlay or routing layer above the device-to-device link. They do not imply that a stock Wi-Fi Direct group automatically behaves as a general-purpose mesh.

Iskounen et al. (2016) study Wi-Fi Direct for offloading access points in dense wireless networks and evaluate clustering, power control, and scheduling, reporting simulation-based download-time improvements in their target scenario. The result supports the broader point that local device-to-device links can be useful, but its objective—offloading a dense Wi-Fi network—is different from safety messaging in an infrastructure-restricted industrial area. El Alami et al. (2017) propose a Wi-Fi Direct-based device-to-device framework to provide hotspot support through multi-hop routes. Caballero-Gil et al. (2015) examine the merging of vehicular ad hoc sub-networks and identify practical interoperability problems such as IP-address conflicts and channel differences. These works reinforce that multi-group operation and network merging need explicit address management and link coordination.

Uzayisenga and Priyambodo (2020) implement peer-to-peer communication between computers and smartphones over Bluetooth and Wi-Fi Direct and report functional and usability evaluation. Their study supports the need for application software on top of a wireless link. Nevertheless, an application-level success test does not establish reliability under long periods of disconnection, industrial interference, device sleep, or moving relay nodes. For ResQNet, Wi-Fi Direct is therefore best treated as a possible higher-throughput secondary transport whose availability, permissions, group negotiation, reconnection behaviour, and background execution must be verified on the actual Android devices used.

3.3 Emergency communication, opportunistic networking, and fairness

Emergency communication research is especially relevant because it considers conditions where conventional infrastructure is unavailable. Alvarez et al. (2019) introduce Bluemergency, a post-disaster communication concept that combines Bluetooth Mesh with surviving IoT infrastructure. The design recognises that some powered or fixed IoT devices may remain operational even when conventional communication services fail. This is a useful

architectural insight for an industrial facility: fixed relays could provide predictable coverage in selected areas, but their availability, power source, placement, and failure modes must be established for the specific site. Chempavathy et al. (2025) describe SafeHaven-FOSS, an offline emergency communication application that combines Bluetooth Mesh and Wi-Fi Direct. It is the closest published counterpart to the hybrid combination discussed in Section 4.2, but this review treats it as supporting context rather than comparative evidence because its evaluation conditions are not analysed here.

Banerjee et al. (2021) propose SOS (Self-Organisation for Survival), which focuses on participatory fairness in emergency communication, including the unequal initial battery state of participants' phones. Their work makes an important point for safety systems: connectivity is not the only objective. A protocol can deliver messages while consuming energy unfairly or exhausting the devices of a small number of participants. The reported analysis is based on a designed peer-to-peer model and simulation; its outcomes should therefore be cited as model-based evidence, not as a field validation of smartphone communication in a digester facility.

Niebla-Montero et al. (2025) present an opportunistic communications protocol based on Bluetooth Mesh and libp2p and include practical evaluation. This line of work is close to ResQNet's longer-term objective because opportunistic communication accepts that peers may not remain continuously connected. It also highlights a design boundary: an application needs more than scanning to carry messages between nodes. It must define message identity, routing or forwarding policy, retry behaviour, duplicate suppression, expiration, and what is stored locally when no destination is reachable.

A store-and-forward system can allow node A to retain a message and pass it to node B when they meet, even if the final destination is not currently reachable. Yet persistence introduces operational requirements: bounded storage, message time-to-live (TTL), deduplication, priority rules, acknowledgement semantics, and privacy protections. If these are absent, a system can flood a local network with repeated or stale alerts. If storage is not durable, messages can be lost when an app process is killed or a device reboots. If message authentication is omitted, false alerts or spoofed node identities may be possible. The current ResQNet discovery prototype should not be described as store-and-forward until these behaviours are implemented and tested.

3.4 Cross-technology communication and IoT-assisted designs

Gao et al. (2025) investigate physical-layer cross-technology communication from BLE to Wi-Fi using IEEE 802.11ax-compatible hardware. Their approach exploits signal-level techniques so Wi-Fi receivers can recover information conveyed through BLE-related waveforms. This is a specialised physical-layer result. It is valuable evidence that cross-technology communication can be explored, but it is not equivalent to a software gateway that receives a BLE application message and forwards it over Wi-Fi. The distinction matters because the latter depends on ordinary OS networking APIs, pairing or connection semantics, packet formats, and application routing.

IoT-assisted designs such as Bluemergency suggest that fixed nodes can be used to improve coverage or provide a bridge between local devices and a wider network when part of the infrastructure remains available. In a digester area, fixed relays could be mounted at known locations and powered independently, potentially reducing the need for every worker's phone to relay messages. However, adding ESP32-class devices or other fixed relays would introduce new engineering tasks: radio coexistence, enclosure and environmental protection, power continuity, maintenance, node authentication, and the handling of relay failure. These are plausible extensions, not demonstrated ResQNet capabilities at the current stage.

The general peer-to-peer literature adds supporting concepts. Liu et al. (2005) show why logical peer relationships should consider physical proximity rather than choosing neighbours without regard to underlying topology. Canali et al. (2010) adapt peer-to-peer resource sharing to wireless mesh networks and report benefits from location awareness and MAC-layer cross-layering in their simulated setting. Such results suggest that network topology and link cost matter; however, an overlay strategy developed for resource lookup cannot be transplanted unchanged into a safety-message system. ResQNet will need a routing objective appropriate to short, time-sensitive messages, and its forwarding policy should be evaluated under mobility and partial connectivity.

3.5 Comparative synthesis of the selected corpus

Table 1 summarises how the selected papers contribute to the design space. The table intentionally distinguishes the kind of evidence reported. It does not rank technologies universally because the studies use different scenarios, devices, objectives, and evaluation methods.

Table 1. Thematic comparison of representative papers from the selected corpus.

Theme / representative studies	Primary contribution	Evidence type in source	Implication and limitation for ResQNet
BLE mesh surveys: Darroudi & Gomez (2017); Ghori et al. (2020); Natgunanathan et al. (2023)	Taxonomy, protocol operation, application and security considerations	Survey/review; selected practical observations	Supports BLE as a low-energy building block, but scanning alone is not a mesh implementation.
Emergency networking: Alvarez et al. (2019); Banerjee et al. (2021); Chempavathy et al. (2025)	Infrastructure-failure communication, IoT assistance, fairness and energy-aware participation, offline emergency application	Architecture proposal and model/simulation; application description (evaluation not analysed)	Useful requirements and design ideas; results must not be presented as industrial field validation.
Wi-Fi Direct: Shahin & Younis (2014); Lee et al. (2017); Casetti et al. (2014)	Group management, multi-group routing and local content discovery	Software frameworks and Android testbeds	Higher-capacity link is possible, but multi-hop requires additional routing and platform-specific handling.
P2P/Wi-Fi deployment: Iskounen et al. (2016); El Alami et al. (2017); Caballero-Gil et al. (2015); Uzayisenga & Priyambodo (2020)	Device-to-device offloading, hotspot access, sub-network merging and application-level peer-to-peer	Simulation, framework, implementation and functional/usability tests	Useful for link and group design; objectives and conditions differ from worker safety messaging.
Opportunistic / cross-technology: Niebla-Montero et al. (2025); Gao et al. (2025)	Intermittent communication using Bluetooth Mesh/libp2p; BLE-to-Wi-Fi physical-layer communication	Practical protocol evaluation; physical-layer experiments	Supports future hybrid research, but neither result proves ResQNet has application-layer forwarding or a general-purpose gateway.
General P2P topology: Liu et al. (2005); Canali et al. (2010)	Topology-aware neighbour selection and resource sharing in wireless mesh networks	Algorithm and packet-level simulation	Topology and link cost matter; routing policies must be adapted and tested for short safety messages.

4. Discussion: Research Gaps and Design Implications

4.1 Discovery is not end-to-end communication

The clearest implementation gap is the difference between detecting a nearby radio and delivering an application message. A demonstrator that lists nearby BLE devices verifies only the discovery stage. End-to-end communication requires a stable application-level node identifier, a defined message schema, sender and receiver validation, delivery status, and a strategy for disconnection. This gap is not a weakness in an early prototype when stated honestly; it is the

natural next stage of the engineering work. It becomes a research problem when the implementation is evaluated systematically and the resulting trade-offs are reported.

4.2 No single transport satisfies every requirement

BLE and Wi-Fi Direct address different parts of the design space. BLE can support low-power discovery and compact messages, while Wi-Fi Direct can provide a local higher-capacity link. A hybrid design is not automatically better: it adds switching logic, connection setup, failure handling, and more complex testing. A defensible design should first establish a reliable minimum service on BLE, then introduce a secondary transport only when a specific requirement—such as larger payloads or a measured reach limitation—justifies it. Transport selection should be based on observed conditions and measured performance, not on nominal data rates alone.

4.3 Industrial conditions require site-specific evidence

Much of the selected literature focuses on general IoT, disaster scenarios, Android peer-to-peer groups, simulations, or controlled testbeds. These studies do not establish how well a phone-based network performs among digesters, metal tanks, reinforced walls, and moving workers. A site-specific evaluation should measure discovery success, packet delivery ratio, message latency, reconnection time, effective range, battery use, and performance with obstacles and interference. Results should include the tested phone models, Android versions, scan/advertising configuration, physical layout, number of nodes, and repeated-trial counts. A single successful demonstration is not sufficient evidence of reliability for a safety-related context.

4.4 Routing, persistence, and energy fairness

A future multi-hop ResQNet implementation should define a simple and auditable forwarding policy. At minimum, each message needs a unique identifier, source and destination or scope, creation time, TTL, priority, and payload integrity check. Relays should suppress duplicates, expire stale messages, bound storage, and avoid forwarding loops. For store-and-forward, the implementation must specify what happens after an app restart or phone reboot. Energy-aware limits are also necessary: the fairness issue raised by Banerjee et al. (2021) suggests that a small number of relay devices should not be depleted simply because they happen to be well positioned.

4.5 Security and human factors

Offline operation does not eliminate security risks. A local network can still be exposed to spoofed identities, false alerts, replayed messages, unauthorised joining, or disclosure of sensitive location information. The system should use authenticated message formats and, when appropriate, encryption; it should also avoid collecting more personal data than necessary. For a worker-facing tool, interface simplicity and clear delivery state matter: a message should not appear delivered when it has only been queued locally. A future study should evaluate not only network metrics but also usability under time pressure and the clarity of failure notifications.

5. Proposed ResQNet Architecture and Evaluation Plan

Based on the reviewed literature, a staged architecture is recommended. Stage 1 is the current BLE discovery prototype: validate repeatable scanning and identify devices using an application-specific identifier rather than treating every nearby BLE advertisement as a ResQNet node. Stage 2 adds direct application messaging between connected or advertising peers, with a documented packet schema and acknowledgement policy. Stage 3 adds bounded store-and-forward with message IDs, TTL, duplicate suppression, persistence, and priority handling. Stage 4 evaluates relay behaviour across multiple physical phones. Stage 5 investigates Wi-Fi Direct as an optional higher-capacity transport. Stage 6 considers fixed IoT relay nodes only after the phone-only design has been characterised.

The architecture should be tested incrementally so that each new feature has an attributable effect. A baseline experiment should record the probability of discovering a peer over repeated trials at fixed distances and orientations. A second experiment should measure successful message delivery and latency with direct peers. A third should introduce obstruction, mobility, and competing radio traffic. Only after direct messaging is stable should relay and store-and-forward tests be conducted. If Wi-Fi Direct is added, the evaluation should include group formation time, group-owner changes, reconnect behaviour, and failures across the Android models selected for the study.

The following metrics are recommended: (i) discovery success rate; (ii) message delivery ratio; (iii) median and 95th-percentile end-to-end latency; (iv) time to reconnect after link loss; (v) duplicate-forwarding rate; (vi) stale-message rejection rate; (vii) energy consumption or battery percentage change under a controlled workload; and (viii) storage overhead. Each metric should be defined before experiments begin. Trials should be repeated and report the number of observations, device models, Android versions, environmental conditions, and uncertainty or variability. Comparisons should be made against a baseline, such as direct BLE communication without relaying, rather than comparing results from unrelated papers with different conditions.

Safety-related claims should remain proportionate to the evidence. Until the system has undergone site testing and an appropriate risk assessment, ResQNet should be described as a prototype intended to support local communication, not as a certified emergency or life-safety system. It should not replace existing plant emergency procedures or approved communication equipment. A responsible field study would require site permission, supervision, and clear operating boundaries.

6. Limitations of This Review

This review is limited by the composition of the 17-paper corpus assembled by the authors. The corpus includes relevant BLE mesh and emergency-communication research but also papers on general peer-to-peer topology, wireless mesh resource sharing, and vehicular networking that provide indirect rather than direct evidence. The review did not perform a fresh, comprehensive database search, and therefore cannot claim that the identified gaps are unique across all published literature. Some papers report simulations or limited testbeds, and their metrics are not directly comparable. Future work should add a reproducible search and additional recent work directly addressing industrial communication, Android BLE background restrictions, delay-tolerant networking, and offline worker-safety systems.

7. Conclusion and Future Directions

The selected literature shows that offline node-to-node communication is a system-design problem rather than a choice of radio alone. BLE provides a practical starting point for discovery and short-range communication, but a BLE scan is not a mesh network. Wi-Fi Direct can support local device-to-device links, yet group management and multi-hop routing require additional software and platform-specific evaluation. Emergency and opportunistic networking studies highlight the importance of resilience, fairness, persistence, and delivery under intermittent contact. IoT-assisted and cross-technology approaches offer possible extensions, but they introduce additional infrastructure and implementation complexity.

For ResQNet, the defensible contribution at this stage is an explicitly scoped Android BLE discovery prototype and a research plan for progressing toward reliable messaging. The next technical milestones are application-specific node identification, direct message exchange, acknowledgement, and controlled performance measurement. Store-and-forward, multi-hop relay, Wi-Fi Direct, and fixed IoT nodes should be presented as future extensions until implemented and validated. A broader, documented literature search and reproducible site-oriented experiments are the necessary next steps. The most useful future contribution would be a transparent empirical evaluation that reports not only successful communication but also failure modes, energy cost, environmental sensitivity, and limitations relevant to industrial digester areas.

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