Ambient IoT Connectivity Topologies: Technology Enablers, Applications, and Challenges

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***Abstract*—Sustainability and energy efficiency are anticipated to be foundational goals of sixth-generation (6G) networks, motivating the development of ultra-low-power communication solutions. The emerging concept of ambient Internet of things (A-IoT), currently under study by the third generation partnership project (3GPP), aims to enable ultra-low-power, battery-free connectivity over cellular networks to support the massive deployment of Internet of things (IoT) devices. Leveraging backscatter communication as a key enabler, A-IoT introduces a new class of devices designed to operate at ultra-low power levels, making it a promising candidate for sustainable 6G applications. In this article, we investigate the connectivity topologies of A-IoT based on backscatter communication. We analyze the enabling technologies in the context of each topology, highlighting how deployment constraints influence their design and feasibility. A comparative performance evaluation is presented, with an emphasis on the outage probability across the different topologies. Furthermore, we explore a range of applications specific to each topology and provide insights into practical challenges, alongside prospective solutions.**

I. Introduction

The rapid expansion of connected devices, fueled by the advent of Internet of things (IoT) applications, is a key driver for the development of energy-efficient measures essential for the sustainability of wireless communication. Fifth-generation (5G) networks have enabled large-scale, low-power IoT connectivity through massive machine-type communications (mMTC). Building on this, 6G is expected to further enhance scalability, energy efficiency, and support for diverse IoT applications. The main contemporary machine type communications (MTC) standards are narrowband IoT (NB-IoT), long term evolution MTC (LTE-M), and reduced capability (RedCap) new radio [1]. These standards support cost-effective, low-complexity devices, offering low power consumption and wide-area coverage. They also have efficient power saving mechanism allowing over ten years of battery life in certain favorable conditions (low duty cycles, not located on the cell edge). However, several low-end IoT applications—particularly those that require ultra-low power consumption, ultra-low cost, longer lifespans, or operation in harsh environments—face requirements that contemporary MTC solutions are unable to meet. Batteries can also be bulky and expensive, increasing the size and complexity of these devices. Additionally, the environmental and safety risks posed by the hazardous materials in batteries, such as lithium-ion, highlight the need for alternative solutions. Eliminating these batteries could significantly enhance device longevity, reduce costs and size, and advance sustainability goals in next-generation IoT systems.

In order to overcome the above mentioned limitations and provide low-cost battery-free connectivity for IoT, third generation partnership project (3GPP) has recently started study items on ambient IoT (A-IoT) in both use cases and service requirements [2], and in radio access network (RAN) aspects [3]. In the recent 3GPP Release 19 [4], standardization efforts have begun to support A-IoT deployment. In the IoT context, ambient devices obtain their energy from surrounding sources, enabling them to monitor the environment in which they are deployed. By using energy harvesting and small energy storage such as supercapacitors, these devices overcome the limitations of battery-based IoT solutions in constrained deployment scenarios. Backscatter communication techniques [5] are considered the primary enabling technology for A-IoT [3]. Combined with mobile communication systems, these zero energy devices (ZED) would enable the next evolutionary step for MTC [6]. Although research into ZEDs and the potential applications is available [6], [7], [8], [9] the literature still lacks a comprehensive exploration of how these technologies integrate with connectivity topologies, along with their potential applications and challenges.

To fill this gap, this article presents a systematic analysis of A-IoT connectivity topologies, which form the foundation for deployment strategies and communication models. We categorize A-IoT links into four representative topologies: direct communication with the base station (BS), denoted as Topology 1 (T1), relay-assisted backscattering (T2), user equipment (UE)-assisted backscattering (T3), and direct communication with the UE (T4). These topologies align with the ongoing 3GPP standardization efforts [3], [4]. While prior work such as [8] has introduced A-IoT concepts, this paper provides a comparative evaluation of these topologies, exploring how key enablers—such as energy harvesting, wake-up radios (WuRs), and device types—map to each topology, supported by performance evaluation and practical application scenarios. The main contributions are summarized as follows:

- We present a unified framework centered on representative A-IoT connectivity topologies and conduct a comparative evaluation using outage probability as a baseline metric to highlight key performance trade-offs.
- We highlight key enabling technologies for A-IoT and discuss how their integration and associated trade-offs vary across different topologies and deployment contexts.
- We explore emerging A-IoT use cases and applications, mapping each to suitable topologies and identifying practical challenges that merit further research for scalable deployment.

II. A-IoT Connectivity Topologies

Inspired by 3GPP's exploration of deployment strategies for A-IoT in the RAN plenary [3], we consider a set of representative network topologies, as illustrated in Fig. 1. In T1, the A-IoT device communicates directly with the BS; in T2, it communicates with the BS via a relay; in T3, a UE assists in providing connectivity with the BS; and in T4, the A-IoT device communicates directly with the UE.

Topology 1 (T1): The A-IoT device communicates directly and bidirectionally with a BS-type node. This corresponds to monostatic backscatter communication (MoBC), where the same BS transmits a carrier and simultaneously receives the backscattered signal using a full-duplex transceiver—denoted

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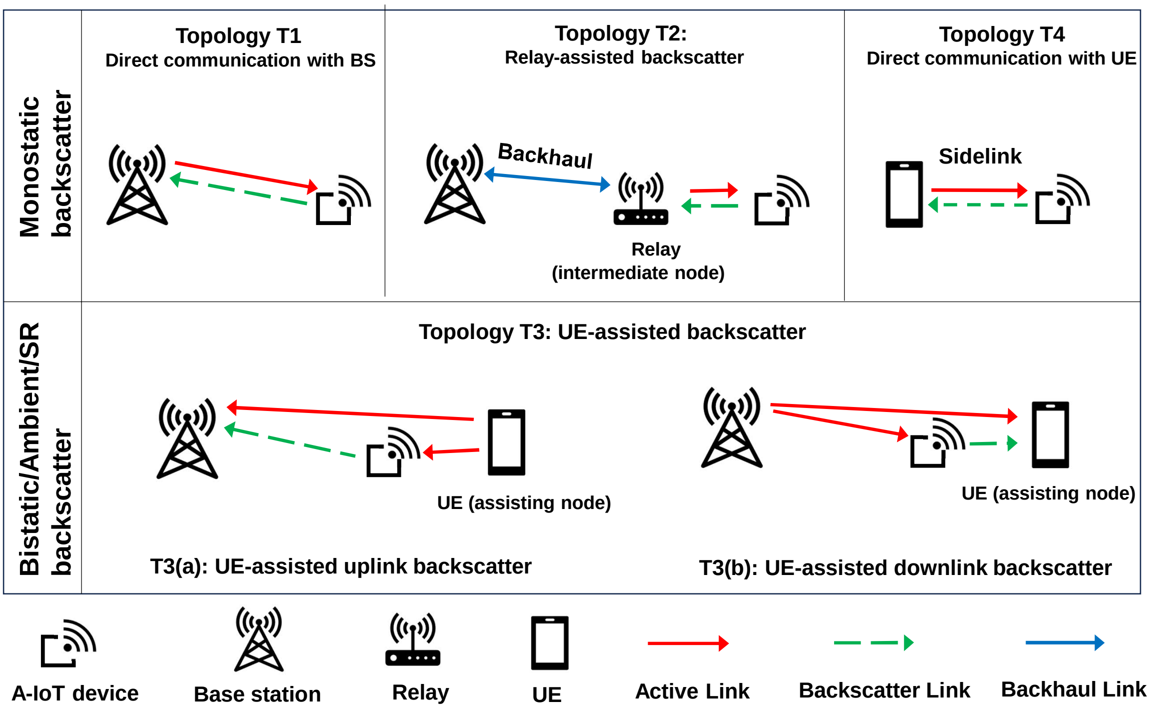

Fig. 1. Illustration of the different A-IoT connectivity topologies

as T1(a). In T1(b), the A-IoT device uses a mixer-based modulator to shift the backscattered signal to a different frequency band. This frequency-shifted approach supports frequency division duplexing (FDD)—where uplink and downlink operate on separate bands—without requiring hardware changes at the BS. However, it increases device complexity. T1 is well-suited for indoor settings, such as warehouses or industrial facilities, where picocells can be placed near A-IoT devices.

Topology 2 (T2): The A-IoT device communicates bidirectionally with a relay, as illustrated in Fig. 1. The relay acts as an intermediate node that processes the backscattered signal and forwards it to the BS via a backhaul link. While this paper considers the use of a relay, other possible intermediate nodes include UE, repeaters, or integrated access and backhaul (IAB) nodes. Depending on its hardware capabilities, the relay can operate in either half-duplex or full-duplex mode. T2 is especially relevant for industrial applications such as smart agriculture and large-area industrial monitoring, where direct BS coverage may be sparse, and localized relays (e.g., picocells or edge nodes) help extend connectivity.

Topology 3 (T3): In T3, a UE can assist A-IoT device transmission in several ways. In UE-assisted uplink backscattering, denoted T3(a), the UE transmits a dedicated carrier to illuminate the A-IoT device—a setup analogous to bistatic backscatter communication (BiBC), where the carrier emitter and backscatter receiver are at different nodes [5]. Alternatively, the UE may transmit its own uplink signal to the BS, which also illuminates the A-IoT device. In this case, the BS concurrently decodes data from both the UE and the A-IoT device—a technique known as symbiotic radio (SR). SR allows backscatter devices to modulate existing wireless signals, enabling simultaneous primary (UE) and secondary (A-IoT) communication [10], [11]. Another approach allows the A-IoT device to leverage known signals, such as the UE's uplink sounding reference signal (SRS), enabling the BS to decode the A-IoT message using the UE-specific channel estimator.

Analogous to T3(a), in UE-assisted downlink backscattering (T3b), the BS transmits either a dedicated carrier or a downlink signal to illuminate the A-IoT device. In the latter case, the UE must jointly decode both the downlink data and the A-IoT message—simplified by using known signals like long term evolution (LTE) cell-specific reference signals (CRS) [12].

A practical demonstration of T3(b) is presented in [12], where A-IoT messages are decoded using downlink LTE-CRS without infrastructure modifications. A low-frequency oscillator in the A-IoT device introduces a slight frequency shift beyond natural Doppler, enabling detection via the receiver's channel estimator after Doppler filtering. This confirms the feasibility of supporting A-IoT communication using existing cellular signals with minimal hardware. Additionally, [7] demonstrates battery-free asset tracking in warehouse environments using smartphone-assisted detection, further validating the real-world applicability of these topologies.

Topology 4 (T4): In T4, the A-IoT device communicates bidirectionally with a UE using a sidelink—the device-to-device (D2D) interface introduced in LTE and extended in 5G—enabling infrastructure-free interaction. The UE acts as a reader—analogous to radio-frequency identification (RFID) in a monostatic backscattering setup—by emitting a carrier signal, which the A-IoT device modulates and backscatters to transmit its data. Alternatively, the A-IoT device (e.g., Device 2b, see Section III) may actively generate its own radio frequency (RF) signal and transmit directly to the UE via the sidelink, allowing autonomous updates even in the absence of a UE transmission. T4 is well-suited for applications such as indoor positioning and contextual information delivery in public environments, including museums and shopping malls [2].

Table I summarizes key properties of the A-IoT topologies, further detailed in Section III. "Frequency shift" refers to the offset applied by the A-IoT device—"small" indicates a few hundred hertz, while "large" refers to tens of megahertz. Energy harvesting feasibility is also shown; "maybe" indicates dependence on the proximity of the RF source. For MoBC,

TABLE I
KEY PROPERTIES OF A-IOT DEPLOYMENT TOPOLOGIES.

Topology	Backscatter type	Frequency shift	A-IoT data rate	RF energy harvesting	Transceiver operation	New HW needed	Advantages	Disadvantages/ Challenges
T1 (a)	MoBC	no	low	yes(small cell) no(macrocell)	full-duplex	yes	low A-ioT device complexity	round-trip path loss, requires full-duplex
T1 (b)	MoBC	large	moderate	yes(small cell) no(macrocell)	FDD	no	infrastructure reuse, good performance	increased complexity at A-IoT device
T2	MoBC	no	moderate	maybe	full-duplex	yes	extended coverage, high reliability	increased complexity
T3 (a)	BiBC	small	low	no	carrier suppression	yes	extended coverage	energy overhead, spectral inefficiency
	AmBC/SR	small/no	very low	no	UL channel estimator/SIC	no	reuse uplink reference signals	timing, interference, limited scalability
T3 (b)	BiBC	small	low	yes	carrier suppression	yes	extended coverage	energy overhead, spectral inefficiency
	AmBC/SR	small/no	very low	yes	DL channel estimator/SIC	no	reuse downlink reference signals	timing, interference, limited scalability
T4	MoBC	no/small	high	yes	full-duplex	yes	direct D2D interaction	short range, reader integration in the UE

A-IoT: ambient IoT
AmBC: ambient backscatter communication
BiBC: bistatic backscatter communication
D2D: device-to-device
FDD: frequency division duplexing
HW: hardware
MoBC: monostatic backscatter communication
RF: radio frequency
SIC: successive interference cancellation
SR: symbiotic radio
UE: user equipment

the "Transceiver operation" column specifies whether a full-duplex or FDD transceiver is required. In T3, it identifies the receiver decoding the backscattered signal—"channel estimator" means decoding via legacy reference signal-based channel estimation. A-IoT data rates are categorized as follows: "high" (megabits per second), "moderate" (tens or hundreds of kilobits), "low" (kilobits), and "very low" (a few hundred bits per second). The "New hardware (HW) needed" column indicates whether additional components beyond standard cellular BSs and UEs are required. For instance, in T1(b), the A-IoT device's frequency shift allows decoding by an FDD-enabled BS without hardware modifications. Likewise, in T3(a) and T3(b), existing LTE reference signals enable decoding without the need for extra hardware.

III. TECHNOLOGY ENABLERS FOR A-IOT

To realize the full potential of A-IoT, integrating key technology enablers is essential. Rather than revisiting their general principles, this section highlights how each enabler—namely device types, energy harvesting, WuRs, and backscatter communication—is applied and distinguished across the different A-IoT connectivity topologies.

A. A-IoT Devices

According to 3GPP Release 19 report [4], A-IoT devices are classified into three types based on power consumption and communication capabilities. Device 1 has minimal energy storage, operates at $\sim 1\ \mu$W peak power, relies entirely on external RF carriers for backscattering, and lacks active amplification. Device 2a has energy storage, consumes $\sim 100\ \mu$W peak power, and supports active amplification, though it still depends on external carrier. Device 2b also consumes around 100 μW, can generate its own RF carrier, enabling greater autonomy at the cost of added complexity.

Each topology aligns differently with device capabilities and power constraints. T1 can be supported by Device 1 and Device 2a in indoor-to-indoor deployments, where both the A-IoT device and BS (e.g., in a picocell setting) are located indoors. In outdoor-to-outdoor deployments, however, T1 may be supported by Device 2b [3]. T2 is ideal for Device 1, benefiting from strong, nearby relay signals. T3 and T4 can be supported by Device 1 and Device 2a; however, they depend on intermittent transmissions from UEs or BSs to provide carrier signals, making energy availability for communication and harvesting less predictable.

This paper primarily focuses on Devices 1 and 2a, which differ significantly from traditional MTC solutions. Device 2b, however, may also be required—particularly in T1 for outdoor deployments or in T3, where carrier availability is opportunistic. Its ability to generate an RF carrier allows for more autonomous operation. Device 2b is also applicable in T4 (see Section II), enabling periodic data uploads and logging when a UE is nearby, without the need for continuous illumination or a dedicated reader.

B. Energy Harvesting

Energy harvesting is central to A-IoT, enabling battery-free operation. Its feasibility depends not only on ambient sources—like RF signals, light, motion, or heat [13]—but also on the connectivity topology, which shapes device–network interaction. The energy harvested by an A-IoT device, as commonly adopted, can be approximated as $E = \eta P_r T$, where η is the RF-to-electrical energy conversion efficiency, P_r is the received RF power, and T is the harvesting duration.

T1: Devices harvest RF energy primarily from cellular BSs. Small-cell deployments improve feasibility due to shorter distances, while macro/microcell setups may suffer from path loss, reducing received power below -30 dBm, making direct RF harvesting more challenging. Advances in RF harvesting circuits, wireless power transfer (WPT), and BS beamforming can help extend range. Multi-source harvesting can also supplement limited RF power: nearby devices or infrastructure can act as auxiliary RF sources, while solar, thermal, or light-based energy can be leveraged depending on the environment.

T2: Relays serve as intentional RF sources near devices, improving energy availability. This can be supplemented with ambient sources like vibration or heat—particularly useful in low-light environments such as warehouses or factories. T2 is thus well-suited for multi-source harvesting, combining reliable RF with complementary ambient sources.

T3: Harvesting relies on opportunistic RF sources, such as smartphones (T3a) or BSs (T3b). A nearby UE can deliver –10 to –20 dBm, sufficient for brief power bursts. However, these sources are sporadic and proximity-dependent. T3 devices typically supplement with ambient sources (e.g., light or motion) to maintain basic functionality between communication events.

T4: The smartphone functions as both reader and power source during close-range interactions, similar to RFID. While suited for short, burst-mode communication, devices with autonomous functions (e.g., sensing or logging) may need additional energy harvesting, such as from solar or motion.

Energy harvesting efficiency is a critical factor in practical A-IoT deployments. At low input power levels (e.g., below –30 dBm), efficiency degrades sharply, often rendering the harvested energy insufficient for device operation—particularly in macrocell scenarios. This can lead to higher outage probability or reduced availability. Robust A-IoT performance thus relies on both sufficient RF power and efficient harvesting, underscoring the importance of multi-source energy harvesting and energy-aware system design.

C. Wakeup Radio and Receiver Sensitivity

WuRs are ultra-low-power receivers that keep A-IoT devices in deep sleep until triggered by a specific signal, enabling on-demand communication without idle listening—crucial for battery-free or energy-constrained devices [14]. WuR design requires balancing power consumption and sensitivity, a key trade-off that directly impacts performance across topologies.

In macrocell T1, high path loss may prevent low-sensitivity WuRs (e.g., > –60 dBm) from detecting BS signals, limiting effectiveness. Small-cell T1 improves conditions but may still require dense BS deployment or repeated wake-up signaling. T2 is well-suited for WuRs, as nearby relays can deliver strong wake-up signals, even for ultra-low-power designs. BS–relay coordination ensures efficient activation.

In T3, wake-up strategies are more varied. In T3(a), the UE may embed a wake-up tone in its uplink; in T3(b), the BS or a nearby UE can deliver the wake-up signal. In T4, wake-up functionality is seamlessly integrated into the device-reader interaction with short-range interactions allowing WuRs to be simple and reliable—though proximity to the user is required.

State-of-the-art WuRs achieve sensitivities in the range of -60 dBm to -80 dBm, with power consumption ranging from a few to tens of microwatts. Advances using subthreshold CMOS and ultra-low-power envelope detectors have pushed consumption below 1 μW, supporting integration in fully passive A-IoT devices [14]. However, improving sensitivity increases circuit complexity and cost, necessitating careful optimization based on the target topology.

D. Backscatter Communications

Backscatter communication, a well-established technique for ultra-low-power wireless connectivity [5], underpins the A-IoT topologies. Each topology corresponds to a specific backscatter mode—MoBC, BiBC, ambient backscattering (AmBC, where existing modulated RF signals are reused), or SR—each with distinct trade-offs and implementation challenges (Fig. 1). T1 and T4 primarily use MoBC, simplifying system design but suffering from double path loss and self-interference. In T2, the communication between the device and the relay typically follows MoBC. However, when a direct device–BS link is available during the first phase of relay transmission—as will be considered in the next section—BiBC also becomes relevant.

In T3, BiBC is particularly relevant, as separating the carrier emitter and receiver avoids round-trip path loss and enables extended coverage. However, it requires a dedicated emitter, increasing cost and introducing interference and synchronization issues. Nevertheless, T3 can leverage a more advanced form of BiBC and AmBC known as SR. Unlike traditional AmBC, which suffers from direct link interference (DLI), SR systems co-design the receiver and the ambient signal source to enable reliable data extraction, using techniques like successive interference cancellation (SIC). Notably, leveraging LTE reference signals (e.g., SRS and CRS), as discussed in Section II, enables a hybrid AmBC–SR approach, enhancing A-IoT viability in opportunistic or infrastructure-light scenarios [12].

IV. A-IoT Topologies: Performance Insights

This section provides a comparative performance assessment of the A-IoT topologies using outage probability—a key metric for evaluating reliability in low-power, intermittent communication. The goal is to highlight trade-offs between reliability and complexity, supporting practical deployment decisions across diverse scenarios. For a fair comparison, node distances are set as shown in Fig. 2, where A-IoT devices transmit data to the BS. d_1 denotes the backscatter link distance common to all topologies, whereas d_2 denotes the relay–BS distance in T2 and the UE–BS distance in T3. In T3, the A-IoT device is positioned between the BS and the UE, and its backscattered signal is superimposed on the primary signal, forming an SR transmission. In T2, the A-IoT device is typically near the relay node, placing both at distance d_2 from the BS. A half-duplex, two-phase decode-and-forward (DF) relay transmission is assumed [15]. In T3(b), the decoded A-IoT signal is forwarded to the BS via a backhaul link. T4 is excluded from the simulations, as it exhibits performance similar to T1 under identical distance and power constraints. The energy harvesting model is excluded from the outage analysis for two reasons: (1) the focus is on comparing topology performance, and including harvesting would add unnecessary complexity; and (2) even if included, it would not affect the relative comparison, as all topologies would be impacted similarly.

Unless otherwise stated, we consider $d_1 = 10\,\text{m}$, $d_2 = 3d_1$, the transmit power $P = 30$ dBm, the reflection coefficient of the A-IoT device $\alpha = 0.5$, the target information transmission rates of the A-IoT device and UE are $R_o = 0.2$ bps/Hz and $R_1 = 1$ bps/Hz, respectively. The noise variances for detecting the ambient and UE signals are defined as functions of bandwidth: $\sigma_o^2 = N_o B_o$, and $\sigma_1^2 = N_o B_1$, where $N_o = -174\,\text{dBm/Hz}$ is the thermal noise power spectral density, $B_o = 10\,\text{kHz}$, and $B_1 = 1.4\,\text{MHz}$. Rayleigh fading is assumed along with free-space path loss, where the transmission frequency is $f = 915\,\text{MHz}$ and path loss exponent is set to 3. The outage probability measures the likelihood that the achievable rate falls below the required transmission rate, i.e., $P_{\text{out}} = \Pr\left[R^{(\tau)} < R_{\text{a}}\right]$, where $R^{(\tau)}$ is the achievable rate under topology $\tau \in \{\text{T1(a)}, \text{T1(b)}, \text{T2}, \text{T3(a)}, \text{T3(b)}\}$, and $R_{\text{a}} \in \{R_0, R_1\}$ is the corresponding target rate.

Fig. 3 shows the outage probability versus P for all topologies, with theoretical and simulation results in close agreement. Asymptotic analysis at high P reveals the diversity orders for T1(a), T1(b), T2, T3(a), and T3(b) as $\frac{1}{2}$, 1, $\frac{3}{2}$,

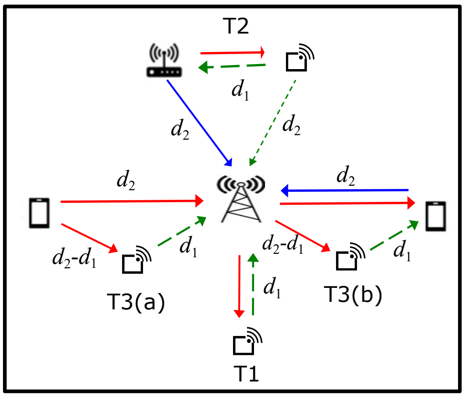

Fig. 2. Illustration of the simulation setup of the different A-IoT topologies, indicating the distances of the different links.

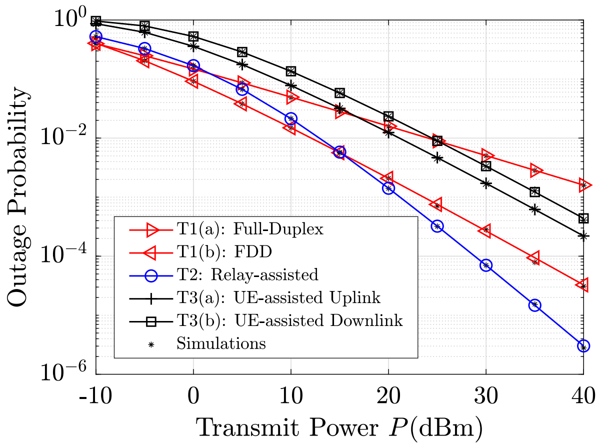

Fig. 3. Outage probability versus the transmit power P for the different topologies.

1, and 1, respectively. These trends are reflected in the simulations: T2 outperforms other topologies at $P > 15$ dBm, benefiting from additional diversity via the device-to-BS link. In contrast, T1(a) performs poorly at high P due to limited power scaling. T3(a) and T3(b) show lower reliability than T1(b) and T2 under the given distance configuration. However, T3's performance is sensitive to the A-IoT device's placement relative to other nodes—a factor further explored in Fig. 4. This highlights T2 as achieving the highest diversity gain—though with greater complexity—making it suitable for high-reliability applications such as industrial monitoring, where infrastructure and relays are available. Meanwhile, T1(b) offers a favorable balance between performance and simplicity, highlighting its potential for practical, low-complexity A-IoT deployments.

Fig. 4 shows the impact of backscatter link distance d_1 on outage performance, with d_2 fixed at 40 m. As d_1 increases, performance degrades in T1 and T2, with T2 consistently outperforming T1 across all distances. T1(a) performs the worst, though the performance gap narrows as d_1 grows. The behavior of UE-assisted backscattering (T3) is notably different. At short distances ($d_1 \leq 10$ m), T3 exhibits the poorest performance among all topologies. However, as d_1 increases, T3's performance improves and eventually surpasses the others at longer distances. This improvement is due to the T3 configuration (Fig. 2), where the distance $d_2 - d_1$ decreases as d_1 increases, moving the A-IoT device closer to the signal source. This resembles BiBC, where a stronger illumination improves the backscatter link. Interestingly, the outage probability peaks at the midpoint between the BS

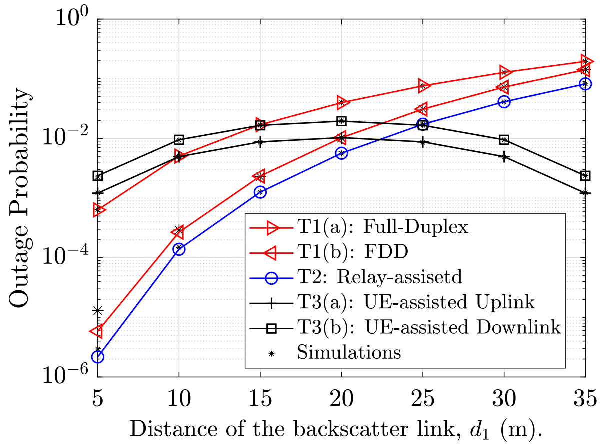

Fig. 4. Outage probability versus the distance of the backscatter link d_1, for the different topologies, with $d_2 = 40$ m.

and the UE—where the combined path loss of the two links is maximized—but improves as the A-IoT device moves closer to either node. Thus, T3 becomes advantageous at longer backscatter distances when the device is near the illuminator. Another noteworthy case is when the A-IoT device is positioned closer to the UE, as in T3(b)—a setup well-suited for applications such as wearables and health monitoring, which can leverage existing cellular infrastructure and opportunistically available UEs.

In summary, each topology reflects a trade-off among reliability, complexity, and flexibility. T2 offers strong outage performance but adds system complexity; T1(b) balances performance and simplicity; and T3, though placement-sensitive, excels at longer ranges by leveraging existing cellular networks and opportunistic UE access.

Beyond outage probability, other critical performance metrics for A-IoT deployment include energy efficiency, latency, and device density. Energy efficiency is especially important for battery-free devices and depends on both the topology's energy demands and device functions. Latency is typically lower in T1 and T4 due to direct communication paths, while T2 and T3 may incur delays from relay operations or reliance on opportunistic UE access. For scalability, T1 and T2 can support higher device densities through localized and optimized RF sources, whereas T3 may require more careful interference and scheduling management. Future work should explore joint reliability–energy models for a more comprehensive performance evaluation.

V. A-IoT Applications

In this section, we explore the potential A-IoT applications, with particular emphasis on the adaptability and relevance of the various topologies discussed earlier. This includes industrial applications, personal applications, and use cases in smart homes and smart cities, as illustrated in Fig. 5.

A. Industrial and Logistics Applications

A-IoT supports a wide range of indoor and outdoor application scenarios. A representative indoor use case is automated warehousing, involving real-time inventory tracking, resource optimization, and material handling. To ensure continuous coverage in large indoor spaces, T1 can be deployed with picocell BSs distributed across the site to collect data from A-IoT-tagged items. Similar indoor use cases include asset tracking in airport terminals and smart agriculture settings

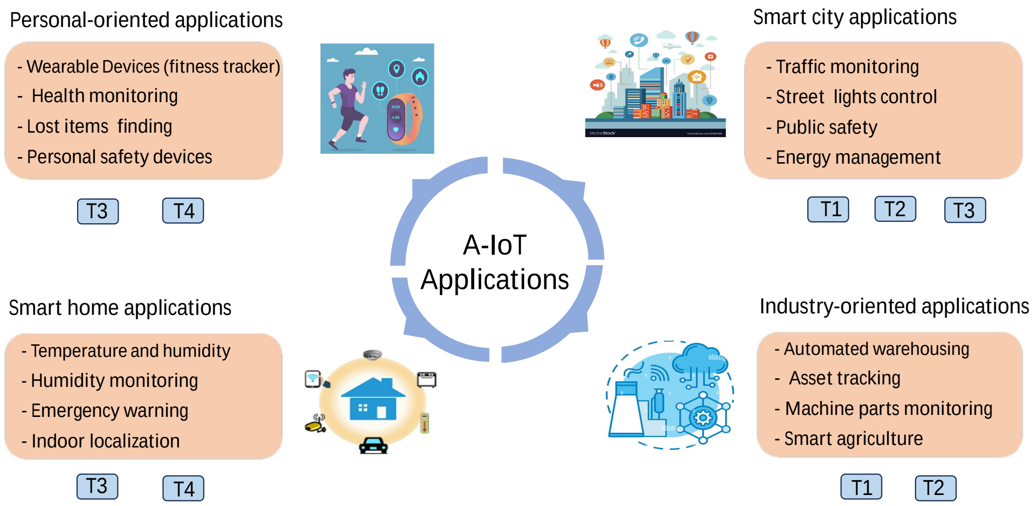

Fig. 5. Representative A-IoT use cases and their main associated connectivity topologies.

such as greenhouses and indoor farms. Additionally, in [7], smartphones are used to detect and track A-IoT devices attached to assets—an approach aligned with T3.

Outdoor industrial and logistics environments can also benefit from A-IoT technologies. Smart agriculture is a concrete example where T2 (relay-assisted) is particularly effective. In such scenarios, battery-free A-IoT sensors monitor environmental conditions across large fields, while edge nodes or picocell gateways act as relays to provide wide coverage and energy-efficient communication.

B. *Personal-Oriented Applications*

A-IoT enables a broad range of personal-oriented applications. One example is wearable devices—such as fitness trackers and health monitors—that interact with smartphones to provide real-time health data. Another use case involves tracking lost items (e.g., keys, wallets, or phones) by attaching A-IoT tags and using a smartphone for retrieval. These applications are especially valuable when the lost item is far from the owner's phone, making direct communication infeasible. T3(b), where the A-IoT device communicates with a nearby UE using existing legacy signals (e.g., LTE downlink), is particularly suited to such scenarios [2]. Alternatively, T4 could also be used, though it may involve higher cost and hardware complexity.

C. *Smart Home and Building-Oriented Applications*

A-IoT sensors can enhance smart home functions by monitoring environmental conditions (e.g., temperature and humidity) and detecting emergencies such as gas leaks or smoke. These sensors can trigger alarms and send notifications to family members via smartphones when they are away. Depending on the use case, different communication topologies may apply. For example, personal devices like smartphones or tablets can serve as intermediaries between A-IoT devices and the BS, aligning with T3. Alternatively, indoor BSs or relays can support building-oriented A-IoT devices, corresponding to T1 or T2, respectively. A compelling smart building application is indoor localization, where A-IoT devices serve as low-cost, maintenance-free alternatives to Bluetooth beacons. In this scenario, T4 enables smartphones to detect nearby A-IoT tags, allowing room-level location estimation for navigation and context-aware services. The same approach is also applicable to localization in environments such as shopping malls and museums [2].

D. *Smart City-Oriented Applications*

A-IoT devices enable real-time monitoring of urban infrastructure and smart grid components, including traffic systems, energy distribution, and public safety. For instance, wireless sensors in power substations can monitor temperature, humidity, or vibrations to detect anomalies and enable predictive maintenance. Similarly, A-IoT sensors deployed across road networks can track vehicle density, speed, and flow patterns in real time. T1 is suitable in these use cases, where sensors can communicate directly with BSs for reliable data delivery. However, in macro/micro BS deployments, long-distance path loss limits both RF energy harvesting and reliable backscatter communication, and enhanced devices like Device 2b may be employed to support T1 [3], [4]. While T1 is suitable for well-covered urban areas, T2 can extend coverage in dead zones, and T3 can offer opportunistic connectivity where infrastructure is limited.

VI. Challenges and Future Research Directions

There are several challenges and open research directions in adopting A-IoT in cellular networks. Addressing these is key to achieving reliable, scalable, and energy-efficient deployments.

A. *Interference and Regulations*

A-IoT devices modulate all signals within their antenna bandwidth, raising interference concerns due to closely spaced cellular bands—operation in one band may unintentionally affect adjacent ones. Mitigating this may require additional RF filters, which increase device complexity and power consumption. Nevertheless, the reflected signal power from A-IoT devices is typically very low—often tens of decibels below other signals—minimizing interference with existing receivers. In fact, it can even be exploited as an additional multipath component in SR setups [10]. However, interference between nearby devices—especially across different operators—remains a key challenge. Future research should explore spectrum-aware backscatter schemes, cross-operator coordination protocols, and joint waveform–antenna design to mitigate interference while maintaining energy efficiency. Additionally, clear certification procedures and regulatory limits aligned with 3GPP inter-site distances are crucial for large-scale A-IoT deployment.

B. *Communication Range*

In T1, the limited range of A-IoT devices poses challenges for macro/micro cellular setups, as maintaining coverage often requires high BS transmit power—undermining energy-saving goals. Outdoor-to-indoor communication is further constrained by wall penetration loss, making T1 more suitable for high BS density areas, ideally with indoor BS placement to reduce attenuation. In contrast, T3(b) offers more flexible device placement, allowing outdoor BSs to serve indoor A-IoT devices. T2 extends range but adds deployment cost.

The communication range of A-IoT systems is largely constrained by the performance of RF harvesters and WuRs. Future research should focus on harvesting circuits with lower activation thresholds and hybrid energy sources (e.g., RF and light) to improve coverage. Improving wake-up radio sensitivity through adaptive low-power designs can extend activation range. While low-noise amplifiers (LNAs) help increase this range, they also raise energy consumption. Therefore, a systematic analysis of the range–energy trade-off will be essential to guide practical A-IoT deployments.

C. *Network Integration and MAC protocol*

As discussed in Section III-D, T3 benefits from SR setups that leverage legacy reference signals (e.g., LTE-CRS, SRS), enabling A-IoT signal decoding via built-in channel estimators [12] and seamless integration into existing cellular infrastructure without requiring dedicated backscatter receivers or added BS/mobile hardware.

Designing medium access control (MAC) protocols for large numbers of uncoordinated A-IoT devices remains a major challenge, due to their limited capabilities and strict energy constraints. Contention-based protocols such as ALOHA offer simplicity, particularly for uncoordinated devices with minimal hardware capabilities, but suffer from high collision rates, idle listening, retransmissions, and poor scalability. In contrast, schedule-based protocols, particularly when paired with wake-up receivers, enhance energy efficiency by enabling deterministic access and minimizing unnecessary radio activity. However, current schemes often lack the flexibility to accommodate the sporadic traffic and variable energy availability typical of A-IoT. To support dense deployments, future MAC designs must integrate energy-aware scheduling with lightweight coordination, while addressing device heterogeneity, fairness, and limited resources. For instance, in T3 scenarios, standardizing how intermediary devices (e.g., smartphones) relay data is also key to ensuring scalability and interoperability.

D. *Security and Device Authentication*

Conventional cryptographic security methods are often impractical for A-IoT devices due to stringent energy and processing limitations. Physical layer authentication offers a lightweight alternative by exploiting unique radio signatures—such as hardware imperfections or channel characteristics—for identity verification without requiring key storage or complex computation. Techniques like physical unclonable functions (PUFs), which leverage manufacturing variability to generate device-specific fingerprints, provide a lightweight and low-cost option for secure identification. WuRs can also enhance security by activating only in response to encrypted signals from authorized sources. In parallel, physical layer security techniques—such as channel-based key generation and artificial noise—enable confidentiality without upper-layer encryption [11]. Furthermore, lightweight blockchain schemes can provide decentralized trust and tamper-proof logging without requiring constant connectivity or centralized authentication. Future research should focus on robust physical-layer security and authentication methods, energy-aware security protocols, and experimental validation across diverse A-IoT deployment scenarios.

E. *Sustainability Considerations*

A-IoT holds strong sustainability potential by eliminating disposable batteries and enabling the use of low-cost, biodegradable materials like printed antennas and organic substrates. However, large-scale deployment raises concerns around end-of-life disposal and recyclability. To maximize environmental benefits, future designs must prioritize eco-friendly materials and sustainable manufacturing.

Moreover, system-level energy efficiency is crucial for sustainable A-IoT deployment, as relying on high-power infrastructure solely to energize passive devices may offset the intended environmental gains. Future research should focus on energy-aware network planning to optimize RF source placement and minimize redundant transmissions. Investigating SR-based topologies (e.g., T3) that reuse existing communication signals can reduce the need for dedicated carriers. Additionally, progress in low-loss WPT and artificial intelligence (AI)-driven resource management will be essential for enabling large-scale, energy-efficient A-IoT systems [9].

VII. Conclusions

This paper provided a study on connectivity topologies for A-IoT, outlining four representative models and analyzing how key enabling technologies—such as backscatter communication, energy harvesting, and WuRs—interact with each topology. By linking deployment scenarios, device types, and application domains to specific topological configurations, we offered a structured framework for understanding A-IoT design trade-offs. This approach can guide future research and deployment strategies toward scalable, energy-efficient integration of battery-free devices into cellular networks. In addition, our characterization offers valuable insights to support the refinement and enhancement of ongoing A-IoT standardization efforts, particularly in aligning topologies with practical deployment needs.

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