



The Strategic Advantages of 60 GHz Millimeter-Wave Technology in Drone Communications

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1. Introduction

The rapid proliferation of unmanned aerial systems (UASs), particularly in defense and security applications, has exposed fundamental limitations in traditional radio frequency (RF) communication systems. Legacy sub-6 GHz links—while robust and long-range—are increasingly congested, vulnerable to detection, and susceptible to jamming in contested electromagnetic environments. As modern warfare and commercial drone operations evolve toward autonomy, swarm coordination, and real-time data exchange, communications infrastructure must evolve accordingly.

Millimeter-wave (mmWave) technology, particularly within the 60 GHz band, offers a transformative solution. Operating in an unlicensed portion of the electromagnetic spectrum, 60 GHz systems provide uniquely advantageous characteristics: high bandwidth, directional beamforming, inherent low probability of intercept and detection (LPI/LPD), resistance to jamming, and compact hardware footprints. These attributes collectively enable a new class of resilient, secure, and high-performance communication networks tailored for UAS applications.

This paper explores the benefits of 60 GHz mmWave technology in drone communications, with a focus on LPI/LPD properties, anti-jamming capability, size-weight-and-power (SWaP) advantages, and its role in Identification Friend-or-Foe (IFF) systems. The analysis demonstrates that 60 GHz is not merely an incremental enhancement but a foundational enabler for next-generation UAS operations.

2. Background of UAS Communications

The Evolution of Drone Communication Technologies: From Basic RF Links to Resilient, Multi-Domain Networks

The evolution of drone wireless communication technology mirrors the broader transformation of both unmanned systems and the electromagnetic battlefield. Early UASs were relatively simple platforms requiring only basic command-and-control. Modern drones, by contrast, are data-intensive, sensor-rich, increasingly autonomous systems that must operate in congested and contested spectrum environments. As a result, UAS communications have progressed through several distinct phases: analog RF control, digital ISM-band links, satellite-enabled beyond-line-of-sight networks, fiber-optic alternatives, and now high-frequency directional systems such as 60 GHz mmWave.

Early Systems: Analog Control and Low-Frequency RF

The earliest UAS and radio-control systems relied on relatively simple analog links operating in low-frequency bands. These systems were often derived from hobbyist radio-control architectures and used basic amplitude modulation or frequency modulation for line-of-sight control. Legacy RC systems used bands such as 27 MHz, 35 MHz, 40 MHz, and 72 MHz, with relatively short operating ranges and limited data capability.

These systems were sufficient for basic remote control but were poorly suited to modern mission demands. They offered limited bandwidth, minimal security, and little resistance to interference. At this stage, the

communications requirement was largely functional: keep the vehicle under control within visual or near-visual range. There was little need for high-definition video, encrypted networking, autonomous coordination, or electronic warfare resilience.

As UASs moved from experimental platforms to operational military and commercial tools, this model became inadequate. Drone communications needed to support not only control signals, but also telemetry, sensor data, video feeds, positional information, and eventually machine-to-machine coordination.

Digital RF and the Rise of ISM-Band Drone Communications

The next major transition occurred with the adoption of digital RF systems and the widespread use of Industrial, Scientific, and Medical (ISM) bands. The 900 MHz, 2.4 GHz, and 5.8 GHz bands became especially important for commercial, industrial, and tactical drone platforms. 900 MHz systems are commonly associated with longer-range control links because of better propagation and obstacle tolerance, while 2.4 GHz became a dominant control band for commercial drones and 5.8 GHz became widely used for video transmission and higher-bandwidth applications.

This period introduced the multi-link drone architecture that remains common today. A typical UAS may use one path for command-and-control, another for video downlink, another for telemetry, and a passive GNSS receiver for navigation. These functions may operate across different bands and protocols, creating a layered communications environment. One source describes modern drones as relying on up to four RF-related systems: command-and-control, video downlink, GPS/GNSS reception, and telemetry.

The ISM-band era greatly expanded drone capability. Digital links enabled more reliable control, greater range, improved video quality, and more sophisticated telemetry. However, it also introduced a new problem: these bands became crowded. The same spectrum used by drones is also used by Wi-Fi, Bluetooth, consumer electronics, industrial equipment, and other wireless systems. For commercial operations, congestion can degrade performance. For defense operations, predictable and widely used RF bands create vulnerabilities that adversaries can exploit.

Anti-Jamming Techniques: Spread Spectrum, Frequency Agility, and Adaptive Control

As drones became more dependent on wireless links, communications resilience became a mission-critical requirement. Early anti-jamming approaches focused on spread-spectrum techniques, especially Frequency-Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). FHSS rapidly changes operating frequencies according to a hopping pattern, forcing a jammer to either follow the hop sequence or jam a much wider portion of spectrum. DSSS spreads a signal across a wider bandwidth, reducing the impact of narrowband interference and making the communication signal more difficult to isolate.

Modern drone systems also use adaptive channel selection and multi-band switching. Commercial drone systems, for example, may operate across 2.4 GHz and 5.8 GHz and dynamically select clearer channels depending on interference conditions. These techniques improved reliability in benign or moderately congested environments and made simple jamming less effective.

However, spread-spectrum and frequency-agile approaches are not complete solutions. They can be effective against basic interference, but they may not provide sufficient protection against more advanced electronic warfare systems. Research on UAS anti-jamming has increasingly focused on adaptive, game-theoretic, and

intelligent strategies that allow UASs to select frequencies or behaviors in response to hostile jamming. Other approaches include multichannel jamming suppression and adaptive beamforming, where receivers attempt to reject interference based on spatial direction rather than frequency alone.

This progression highlights an important trend: anti-jamming is no longer simply a protocol feature. It is becoming a system-level design requirement involving spectrum agility, waveform design, antenna architecture, beamforming, network redundancy, and autonomy.

Satellite Communications and Beyond-Line-of-Sight Operations

As UAS missions expanded beyond direct line-of-sight, satellite communications became essential for larger military and strategic platforms. SATCOM enabled beyond-line-of-sight and beyond-visual-line-of-sight operations, allowing UASs to be controlled over long distances and enabling persistent intelligence, surveillance, and reconnaissance missions. Satellite-enabled UASs can maintain command-and-control and data connectivity when direct terrestrial links are unavailable.

Military and high-end UAS communications may use a variety of bands depending on mission requirements. L-band and S-band are often associated with more robust lower-data-rate connectivity and command-and-control functions, while C-band, Ku-band, and Ka-band support higher-bandwidth applications such as video, sensor data, and beyond-line-of-sight links.

SATCOM fundamentally changed what UASs could do. It enabled remote operations, long-range ISR, and sustained missions far beyond the range of terrestrial control systems. However, it also introduced constraints: reliance on satellite infrastructure, potential latency, cost, spectrum allocation challenges, and vulnerability to electronic attack or denial. In a highly contested environment, SATCOM may itself become a target of jamming, spoofing, cyber attack, or broader anti-access strategies.

Fiber-Optic Drone Systems: A Non-RF Alternative

Recent conflicts and electronic warfare environments have accelerated interest in fiber-optic drone communication systems. Unlike conventional UASs that rely on RF links, fiber-optic drones maintain a physical optical connection between the drone and operator. Control signals, telemetry, and video are transmitted as light through fiber rather than as radio waves through the air.

This architecture offers a powerful advantage: immunity to RF jamming and interference. Sources describing fiber-optic drones note that they can provide high-bandwidth, low-latency communications while avoiding conventional RF vulnerabilities. Fiber-optic drone systems are particularly relevant in environments where radio links are heavily jammed or where RF emissions could make the drone detectable.

Fiber systems also provide low probability of RF detection because they do not emit conventional radio-control signals. They can deliver stable video and control links in dense electronic warfare environments, making them attractive for certain reconnaissance or strike applications. Public reporting has discussed the battlefield use of fiber-optic FPV-style drones in Ukraine and Russia, where the key appeal is resistance to jamming and signal spoofing.

However, fiber-optic drones have inherent trade-offs. The tether limits maneuverability, introduces drag, can snag on terrain or obstacles, and imposes payload and range constraints due to the onboard fiber spool. Some

reporting notes that fiber spools can extend for many kilometers but add weight and operational complexity. As a result, fiber is best understood as a complementary architecture rather than a universal replacement for wireless communication. It is highly compelling for certain high-threat, short-duration, or specialized operations, but less suitable for fully unconstrained swarms or long-endurance untethered missions.

Hybrid Architectures and the Modern Communications Stack

Today's UAS communication environment is increasingly hybrid. Rather than relying on a single link type, advanced systems may combine several layers: sub-GHz control links, 2.4 GHz or 5.8 GHz commercial-style links, SATCOM for beyond-line-of-sight, cellular networks for infrastructure-supported operations, mesh networking for swarms, and in selected cases, fiber-optic links. The goal is resilience through redundancy, adaptability, and mission-specific link selection.

This hybrid approach reflects the operational reality that no single frequency band or communication method solves every problem. Lower frequencies generally provide better range and penetration but lower bandwidth and larger antennas. Higher frequencies provide more bandwidth and smaller antenna structures but require greater attention to line-of-sight, propagation loss, and beam control. Satellite systems extend range but add infrastructure dependency. Fiber avoids RF jamming but introduces physical constraints.

The result is a communications landscape defined by trade-offs. The next leap in UAS connectivity must therefore address several requirements simultaneously: high bandwidth, low latency, low detectability, jamming resilience, efficient SWaP, and scalability to multi-drone networks. This is precisely where 60 GHz mmWave technology becomes strategically important.

The Shift Toward High-Frequency and mmWave Systems

The move toward mmWave communication is a response to the limitations of traditional RF. Sub-6 GHz bands are increasingly congested and face growing electronic warfare pressure. They remain useful and will continue to be part of hybrid UAS architectures, but they are not sufficient for the full demands of next-generation drone operations.

60 GHz mmWave offers a different operating model. Rather than broadcasting energy broadly, it enables highly directional, high-capacity links. The 60 GHz band also benefits from significant atmospheric oxygen absorption, which limits long-distance signal propagation and can reduce the probability of detection or interception outside the intended link path. This creates a natural fit for localized high-capacity drone networks, secure short-range communications, and swarm coordination.

The historical progression of UAS communications can therefore be summarized in four broad phases:

1. **Basic analog RF control** — simple, short-range, vulnerable links.
2. **Digital ISM-band drone communication** — 900 MHz, 2.4 GHz, and 5.8 GHz links supporting control, telemetry, and video.
3. **SATCOM and hybrid networking** — L, S, C, Ku, and Ka-band systems enabling beyond-line-of-sight operation.

4. **Resilient advanced architectures** — fiber-optic systems, adaptive anti-jamming, beamforming, and mmWave links for secure high-capacity operation.

This evolution reflects a fundamental shift in priorities: from basic control, to range, to bandwidth, to survivability. In modern drone operations, the communications link is no longer an accessory to the platform. It is a core determinant of mission success.

Within this broader historical context, beamforming emerges as the critical technology that allows high-frequency systems—particularly 60 GHz mmWave—to deliver practical range, security, and resilience.

3. Technology

3.1 Beamforming: The Foundational Enabler of 60 GHz UAS Communications

A defining attribute of 60 GHz mmWave technology—and the key to unlocking its full operational value—is adaptive beamforming. While often treated as a technical implementation detail, beamforming is in fact a foundational capability that reshapes how wireless communication behaves in drone systems. It is essential to understanding why 60 GHz solutions deliver such significant advantages in security, resilience, and performance.

The Need for Beamforming in High-Frequency Communications

At mmWave frequencies such as 60 GHz, electromagnetic signals experience significantly higher free-space path loss compared to traditional sub-6 GHz bands. Without mitigation, this loss would severely limit the practicality of high-frequency communication links.

Beamforming addresses this challenge by focusing transmitted energy into a narrow, directed “pencil” beam aimed precisely at the intended receiver. Instead of radiating power in all directions, as in conventional RF systems, mmWave transceivers use phased-array antennas to coherently combine signals and create highly directional communication paths.

This capability is not optional—it is intrinsic to mmWave system design. By concentrating energy, beamforming effectively restores link budget and enables reliable communication over practical distances, even in the presence of atmospheric attenuation and dynamic operating conditions typical of UAS environment.

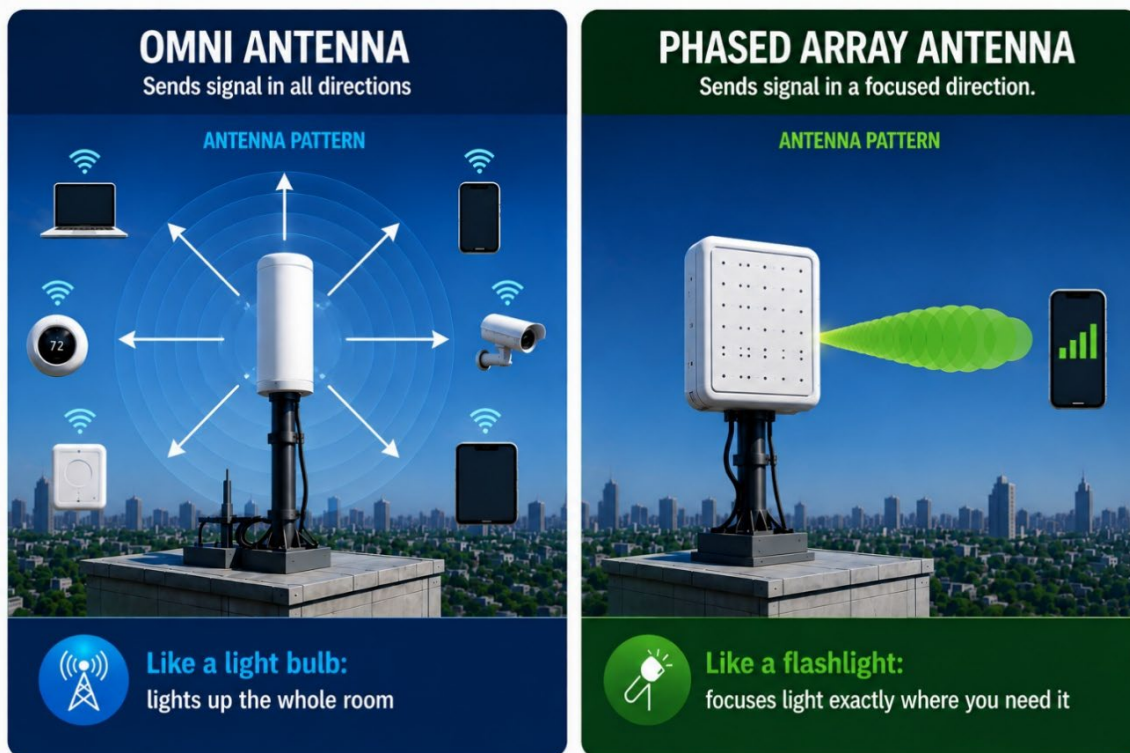


Figure 1 – Broadly radiating omni-directional antenna vs. focused phased-array antenna

3.2 Dynamic Beam Steering: Maintaining Connectivity in Motion

While directional beamforming is fundamental to enabling efficient and secure mmWave communication, its full operational value in UAS systems is realized through **dynamic beam steering**. Unlike fixed wireless infrastructure, drone communication environments are inherently dynamic, with platforms continuously moving in three-dimensional space, often at high speed and with rapidly changing orientation. Maintaining a stable communication link under these conditions requires not only directional transmission, but the ability to **continuously adapt that direction in real time**.

Phased-array antennas provide this capability through electronic beam steering. By precisely controlling the phase and amplitude of signals across an array of antenna elements, the system can rapidly redirect the beam without any mechanical movement. This allows the communication link to track mobile UASs with high precision and near-instantaneous response, ensuring continuous alignment between transmitter and receiver.

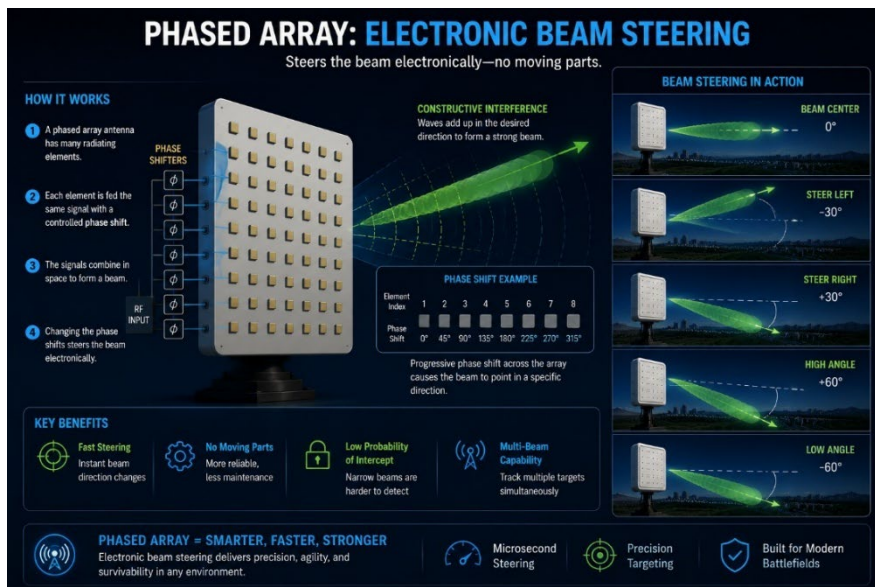


Figure 2 - Electronic Beam Steering Continuously Adapts in Real Time

Real-Time Link Alignment in Dynamic UAS Networks

Drone communication links are characterized by constantly changing geometry. UASs may be maneuvering independently, transitioning across nodes in a mesh network, or coordinating within a swarm. Beam steering enables systems to:

- Continuously track the position of moving drones
- Maintain alignment despite changes in altitude, velocity, and orientation
- Sustain high-performance links under dynamic flight conditions

Without beam steering, the narrow beams associated with mmWave communication would make maintaining connectivity impractical. Beam steering ensures that the benefits of high directionality can be preserved even in highly dynamic operating environments.

Improved Link Stability and Reduced Dropouts

At mmWave frequencies, even small misalignments between transmitter and receiver can degrade signal quality. Beam steering mitigates this risk by continuously adjusting beam direction to compensate for motion.

This results in:

- Reduced link interruption during maneuvering
- Lower packet loss and improved data integrity
- Stable support for real-time video and sensor data transmission

For mission-critical UAS applications, where latency and data continuity are essential, this stability is a key operational advantage.

Adaptive Routing and Environmental Resilience

In complex or obstructed environments, line-of-sight links may be intermittent or degraded. Beam steering enables UAS communication systems to dynamically adapt by:

- Redirecting beams to alternative nodes or relay drones
- Exploiting indirect or reflected paths where available
- Reconfiguring network topology in real time

This contributes to overall system resilience, allowing UAS networks to maintain connectivity even under challenging environmental or operational conditions.

Strategic Significance

Dynamic beam steering transforms beamforming from a static capability into a fully adaptive communication system. It is the mechanism that allows 60 GHz mmWave technology to function effectively in highly mobile, distributed UAS environments.

In practical terms, beam steering ensures that the benefits of mmWave—high data rates, low probability of intercept, and reduced susceptibility to jamming—can be maintained even as the network topology changes in real time.

For next-generation UAS systems, particularly those operating in contested environments or as part of coordinated swarms, beam steering is not optional. It is a critical requirement for achieving reliable, high-performance, and secure communication.

4. mmWave Technology Benefits

4.1 Anti-Jamming and Electromagnetic Resilience

Traditional RF systems are vulnerable to jamming due to their broad radiation patterns and predictable operating characteristics. In contrast, 60 GHz mmWave systems offer significant resilience.

Key factors include:

- Directional beamforming
- Reduced spectral congestion
- Spatial filtering of interference

Together, these enable a low probability of jamming and improved communication reliability in hostile environments.

Beam steering further strengthens the inherent LPI/LPD and anti-jamming advantages of mmWave systems. By continuously adjusting beam direction:

- Signal energy remains tightly confined to intended receivers
- Exposure to adversaries is minimized
- Interception opportunities are reduced

- Fixed-position jammers become less effective

The dynamic nature of beam steering makes it significantly more difficult for adversaries to detect, track, or disrupt communications.



Figure 3 - 60GHz narrow, steerable beam supports LPI/LPD and anti-jamming

4.2 Low Probability of Intercept and Detection (LPI/LPD)

LPI/LPD capabilities are essential for UAS operation in contested environments. 60 GHz technology inherently supports these characteristics through directional transmission, reduced sidelobes, and rapid signal attenuation.

A key contributor is atmospheric oxygen absorption at 60 GHz, which introduces significant signal loss over distance—approximately 10–16 dB per kilometer. This naturally confines signals to localized regions, making interception beyond short distances extremely difficult.

These characteristics result in:

- Lower emission visibility
- Reduced risk of interception
- Enhanced tactical survivability

Operational demonstrations have validated 60 GHz as providing strong LPI/LPD performance in drone applications.

4.3 Spectrum Availability and High-Capacity Communications

One of the most compelling advantages of the 60 GHz band is its vast available bandwidth. Unlike the congested sub-6 GHz spectrum, the 57–71 GHz band provides multi-gigahertz channels capable of supporting extremely high data rates.

In UAS applications, this translates directly into enhanced operational capabilities. mmWave systems can support multi-gigabit-per-second throughput, enabling real-time high-definition video transmission, rapid sensor data exchange, and seamless coordination between drones.

Higher-frequency bands such as 60 GHz also deliver lower latency and improved communication performance compared to legacy RF systems.

4.4 Stealth Support for Scalable Drone Systems

The directional nature of mmWave communication allows for high spatial reuse, enabling multiple UAS links to operate concurrently without interference.

This supports:

- Scalable drone swarm communications
- High-density network deployments
- Predictable and high-performance link behavior

These capabilities are essential for next-generation autonomous systems.

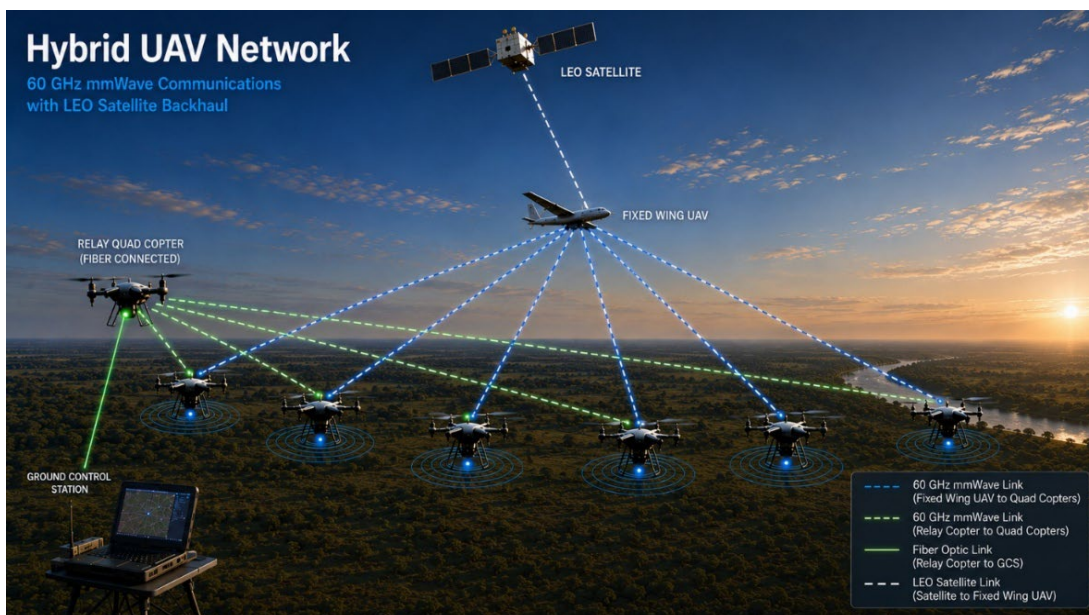


Figure 4 - Directional 60 Ghz links enable stealthy drone swarm coordination

Beam steering is particularly critical for drone swarm operations. In these scenarios, multiple UASs must maintain simultaneous communication links with each other and with command nodes.

Dynamic beam steering enables:

- Rapid link acquisition between nodes
- Time-multiplexed or multi-beam communication across multiple UASs
- Seamless handoff between communication partners

This capability allows networks to scale efficiently without the interference limitations associated with omnidirectional RF systems. As a result, beam steering becomes a foundational enabler of **coordinated swarm behavior and distributed autonomy**.

4.5 SWaP Advantages: Size, Weight, and Power Optimization

SWaP is a critical consideration in UAS design. 60 GHz technology enables:

- Smaller antennas
- Integrated semiconductor solutions
- Lower power consumption

These characteristics support longer flight time, lighter payloads, and greater system flexibility.

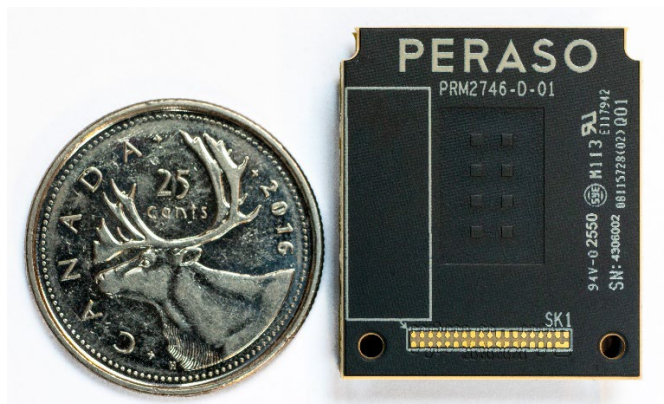


Figure 5 - Single board includes MAC/PHY, RF, antenna

4.6 Identification Friend-or-Foe (IFF) Integration

IFF systems are vital for distinguishing friendly from hostile assets. They operate by sending interrogation signals and receiving authenticated responses.

60 GHz enhances IFF capability through:

- Directional, low-observable communication
- Reduced spoofing risk
- Compact, UAS-compatible form factors



Figure 6 - 60 GHz links enable identification of friendly assets

4.7 GPS-Denied Operations and Network Resilience

In environments where GPS is unavailable or compromised, UASs must rely on alternative coordination mechanisms.

60 GHz networks enable:

- GPS-independent synchronization
- Reliable inter-drone communication
- Continued operation in denied environments

5. Conclusion

60 GHz mmWave technology represents a fundamental advancement in UAS communications. Its combination of high throughput, LPI/LPD characteristics, anti-jamming resilience, and SWaP efficiency provides a compelling solution for modern drone operations.

Crucially, adaptive beamforming serves as the foundation for these benefits, transforming wireless communication into a precise, secure, and resilient capability.

As UAS missions become increasingly complex and contested, 60 GHz mmWave technology will play a central role in enabling next-generation aerial networks—delivering not only improved performance, but a decisive operational advantage.

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