INNOVATIVE SMART SYSTEMS

Wireless Sensor Network

MAC protocols dedicated to WSN / IoT

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Introduction :

This report is part of the Wireless Sensor Networks (WSN) course in the 5th year of the Engineering program at INSA Toulouse, specializing in Innovative Smart Systems (ISS). It focuses on the role of Medium Access Control (MAC) protocols in Wireless Sensor Networks (WSN) and the Internet of Things (IoT), with an emphasis on their efficiency, functionality, and applicability in modern systems. As IoT and WSN technologies continue to gain prominence across various fields, optimizing communication for low-power, scalable, and reliable systems is more important than ever. MAC protocols are essential for managing access to shared communication channels, minimizing data collisions, and ensuring energy efficiency while supporting network scalability. This report aims to explore various MAC protocols, such as CSMA/CA, B-MAC, L-MAC, and more advanced protocols like GAF, comparing them based on factors such as synchronization, energy efficiency, security, mobility, and localization. By starting with basic multiple access techniques such as FDMA, TDMA, and CDMA, we progress to more advanced methods, highlighting their relevance for modern IoT and WSN applications.

1.How multiple Access Works : FDMA, TDMA and CDMA

Multiple access refers to a method that allows several users to communicate simultaneously without interference by sharing multiplexed channels. The main types of multiple access, arranged from simpler to more advanced techniques, include:

• Frequency-division multiple access (FDMA)
• Time-division multiple access (TDMA)
• Code-division multiple access (CDMA)

The functioning of each of these methods is described below, accompanied by conceptual diagrams. Modern wireless communication technologies, such as 4G-LTE and recent Wi-Fi standards like Wi-Fi 6/6E and Wi-Fi 7, adopt an advanced approach known as orthogonal frequency-division multiple access (OFDMA). This technique relies on orthogonal frequency-division multiplexing (OFDM) for modulation and multiplexing.

1.1 Frequency-Division Multiple Access (FDMA)

FDMA works by assigning each user's data stream to a distinct frequency band, ensuring that all streams are transmitted over a shared medium without interference. This approach was first used in the 1980s for handling cellphone and car phone calls in analog first-generation mobile communication systems.

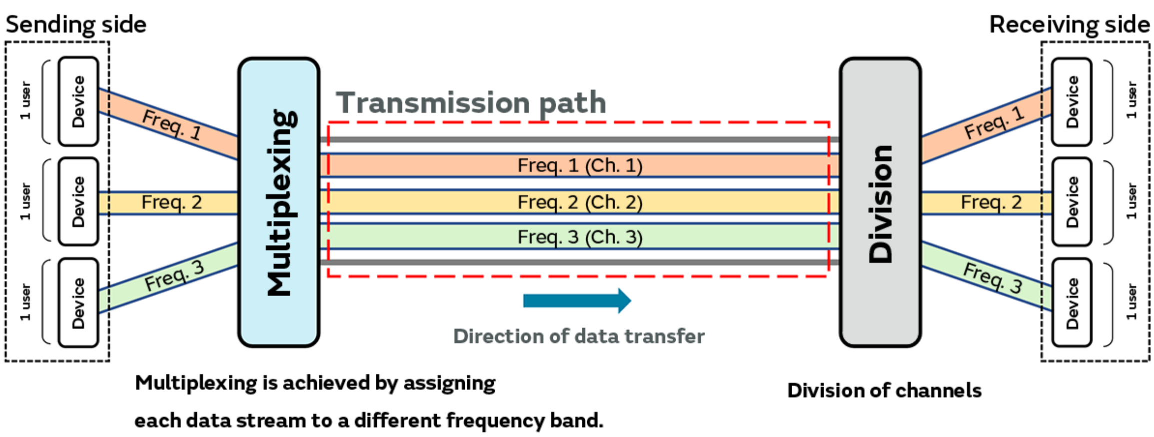

Fig 1 : FDMA

- **Clock Synchronization:** FDMA does not include built-in clock synchronization, as each node operates on a fixed frequency. However, external synchronization may be necessary in certain systems to ensure accurate frequency allocation.
- **Localization Capability:** FDMA does not offer native localization features, so additional protocols or systems must be used to enable localization.
- **Security Mechanisms:** Security is not part of the FDMA protocol. Measures like encryption and authentication must be implemented at higher layers of the network.
- **Mobility Support:** FDMA has limited support for mobility, as its static frequency allocation can cause interference or inefficient spectrum use when nodes move.
- **Power Consumption:** FDMA can be relatively power-efficient since it avoids channel contention. However, nodes still need to remain

powered for both transmission and reception within their assigned frequency band.

1.2 Time-Division Multiple Access (TDMA)

TDMA works by dividing data streams from multiple users into equal time slots, with each user assigned a specific slot for transmission. This method was widely adopted in the 1990s for digital second-generation mobile communication systems such as GSM, PDC, and PHS.

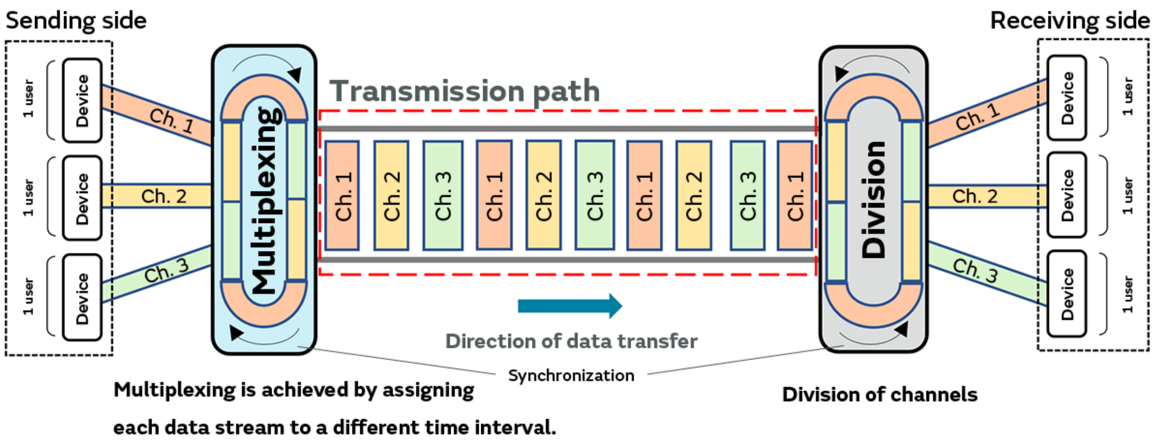

Fig 2 : TDMA

- **Clock Synchronization:** TDMA requires strict synchronization among nodes to ensure that each node transmits within its designated time slot. Accurate synchronization is crucial for the protocol's efficiency.
- **Localization Capability:** TDMA does not provide inherent localization features. As with FDMA, localization must be handled by higher-layer protocols or additional systems.
- **Security Mechanisms:** TDMA does not include security mechanisms by default. Encryption, authentication, and integrity checks must be incorporated at higher layers of the network.

- **Mobility Support:** TDMA is less suitable for mobile nodes due to its reliance on precise time synchronization. Movement can disrupt time slot allocations, leading to delays or collisions in communication.
- **Power Consumption:** TDMA can be energy-efficient because nodes are active only during their assigned time slots. However, maintaining synchronization and precise timing can increase energy overhead.

1.2 Code-Division Multiple Access (CDMA)

CDMA operates by assigning unique identifier codes to user data streams, allowing signals from multiple users to overlap within the same frequency band while sharing a single transmission channel. This technique, introduced in the 2000s, became the foundation for mobile phone calls in third-generation (3G) mobile communication systems.

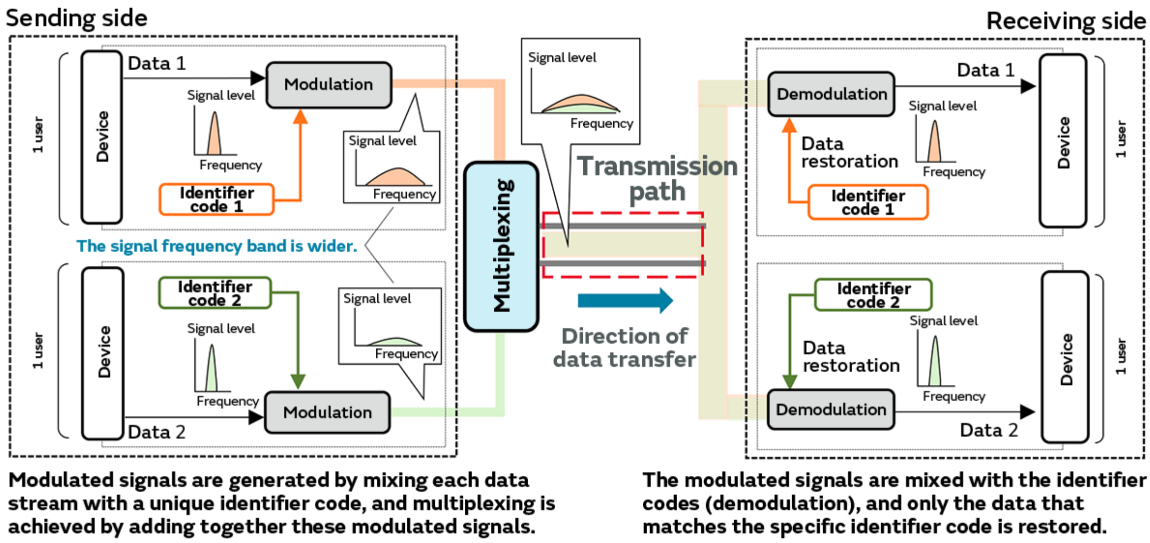

Fig 3 : CDMA

- **Clock Synchronization:** CDMA does not require strict synchronization between nodes. Instead, each node is assigned a unique code, and communication is decoded by correlating the received signal with its corresponding code.
- **Localization Capability:** CDMA does not offer inherent localization features. Localization must be handled through external systems or higher-layer protocols.
- **Security Mechanisms:** CDMA can offer security through its unique spreading codes, which provide a form of privacy. However, additional encryption protocols may be needed for stronger security.
- **Mobility Support:** CDMA is well-suited for mobile networks. It allows nodes to transmit over the same frequency band, making it more resilient to mobility than FDMA or TDMA. However, mobility can still introduce challenges related to signal interference or handoff between cells.
- **Power Consumption:** CDMA can be energy-intensive because it uses spread-spectrum transmission, which requires more power than narrower-band systems. Despite this, it offers robustness against interference and enables simultaneous transmissions from multiple users.

Carrier Sense Multiple Access with Collision Avoidance (CSMA/ CA)

In a local area network (LAN), all devices share a common transmission medium, typically a cable referred to as a "bus." In wireless networks, there is no physical medium like a cable, but instead, all devices rely on a shared radio frequency. In this sense, Wi-Fi (IEEE802.11) operates similarly to early half-duplex Ethernet networks. Consequently, a protocol is necessary in wireless networks to manage access to this shared medium.

The fundamental rule in such systems is that only one device can transmit data at any given time. If multiple devices attempt to transmit simultaneously, data collisions occur, rendering the transmitted information unreadable. To minimize these collisions, the CSMA/CA protocol provides mechanisms to manage access and handle collisions when they do occur. This is particularly important in wireless networks, where transmission rules differ from those in wired networks. In decentralized systems, adherence to common rules is essential for effective communication.

The core concept of CSMA/CA is the "Listen before Talk" principle. This means that a device must first check if the channel is idle before attempting transmission. Additional mechanisms further reduce the likelihood of collisions during data transfer.

- **Clock Synchronization:** CSMA/CA does not require precise clock synchronization. The nodes do not need synchronized clocks to function, and synchronization is handled at higher protocol layers on an ad-hoc basis.
- **Localization Capability:** CSMA/CA does not provide built-in localization features. Any localization functions must be implemented through higher network layers.

- **Security Mechanisms:** CSMA/CA does not include native security features. To ensure secure communication, external security protocols, such as encryption and authentication, must be implemented.
- **Mobility Support:** CSMA/CA is best suited for static networks, as it does not handle node mobility well. Movement can disrupt transmission synchronization and lead to increased collisions.
- **Power Consumption:** CSMA/CA follows a simple approach but can be power-intensive, especially during the channel listening periods. However, active listening techniques can help reduce energy consumption during idle times.

Berkeley MAC (B-MAC)

In the B-MAC protocol, nodes perform Clear Channel Assessment (CCA) by setting a threshold, called the CCA threshold, to determine if the channel is available. If the noise level exceeds this threshold, the channel is considered busy. B-MAC also utilizes duty cycling with periodic channel sampling or Low Power Listening (LPL), which allows nodes to assess the channel status without fully activating their transceivers. When a node has data to transmit, it sends an extended preamble before the data packet, slightly exceeding the receiver's sleep period. This ensures that when the receiver wakes up and detects the preamble, it stays active to receive the data.

A key feature of B-MAC is its two-stage backoff mechanism, which balances fairness and optimizes channel throughput. When a node has data to send, it first selects a random backoff duration within a predefined window. During this initial backoff, no CCA is performed to save energy. If the channel remains busy, the node switches to a congestion backoff phase, where CCA is conducted, and the backoff counter is decremented only when the channel is idle. Once the counter reaches zero, the transmission begins.

It's important to note that CCA occurs only during the congestion backoff phase, not during the initial backoff. This leads to different decrement rates for the initial and congestion backoff stages. Consequently, the backoff mechanism in B-MAC cannot be modeled with the discrete-time Markov models typically used in other protocols.

A sender's state can either be idle (when no data is pending) or active (when there are one or more packets awaiting transmission). In this context, the average duration of the active state, which represents the time taken for a single packet transmission or the total service delay, is analyzed.

- **Clock Synchronization:** B-MAC provides basic clock synchronization through periodic synchronization packet exchanges. Although the synchronization is not highly precise, it is sufficient to maintain approximate coordination of node sleep and activity periods.
- **Localization Capability:** B-MAC does not offer built-in localization features. If needed, localization must be integrated via higher network layers or external systems.
- **Security Mechanisms:** B-MAC lacks native security mechanisms. To ensure data security, external solutions such as encryption and authentication must be implemented.
- **Mobility Support:** B-MAC is primarily designed for static networks. It does not support node mobility, as movement would disrupt the management of sleep and wake periods.
- **Power Consumption:** B-MAC is optimized for low power consumption, utilizing Low Power Listening (LPL) and energy management techniques, such as adjusting activity periods based on traffic levels.

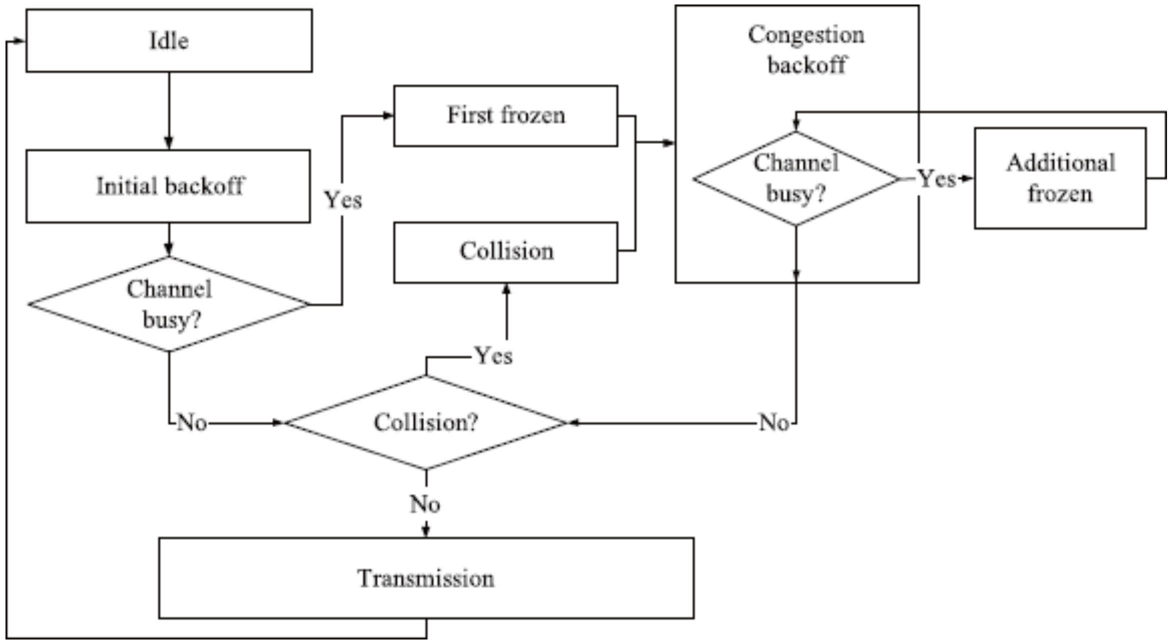

Fig 4 : B-MAC

Lightweight Medium Access Control (LMAC)

The L-MAC protocol is designed to minimize the frequency of transceiver switches, adapt sleep intervals based on data traffic levels, and simplify implementation. It includes basic routing functionality to report data to designated gateways within the network. L-MAC manages transmission and energy efficiency through key components such as wakeup and sleep scheduling, dynamic sleep period calculation, beacon generation, multi-packet modes, retransmission, and radio power management. Clear channel assessment and backoff control are also integral to the protocol, ensuring efficient communication. Beacon retransmission occurs if an initial transmission fails, with preloading adapted for retransmissions to accommodate real-time calculations of active and sleep periods.

To optimize energy consumption, sensor nodes maximize sleep durations and wake only briefly for data transmissions. While this reduces idle listening, it introduces the risk of buffer overflows or outdated data. L-MAC mitigates this by allowing nodes to store a limited number of data packets—either received from neighbors or generated by the node—during specified periods.

Time synchronization occurs at the beginning of each active time slot. Within a time slot, a sensor node may stay asleep if there are no scheduled transmissions or wake to receive and send data if its neighbors are transmitting. These actions can occur within the same time slot, with the number of transmissions determined by the arrival rate, network bandwidth, and data packet size.

- **Clock Synchronization:** L-MAC provides basic time synchronization to ensure nodes activate and deactivate at appropriate times. The synchronization is relatively simple and does not require high precision.
- **Localization Capability:** L-MAC does not offer built-in localization features. If localization is needed, it must be handled by higher network layers.
- **Security Mechanisms:** Like B-MAC, L-MAC does not include security mechanisms by default. External security solutions such as encryption can be added to secure communications.
- **Mobility Support:** L-MAC is designed for static networks and does not support node mobility. Movement can disrupt synchronization and the effectiveness of sleep period management.
- **Power Consumption:** L-MAC is optimized for low power consumption by utilizing extended sleep periods. However, dynamic energy management may introduce some latency, depending on network load.

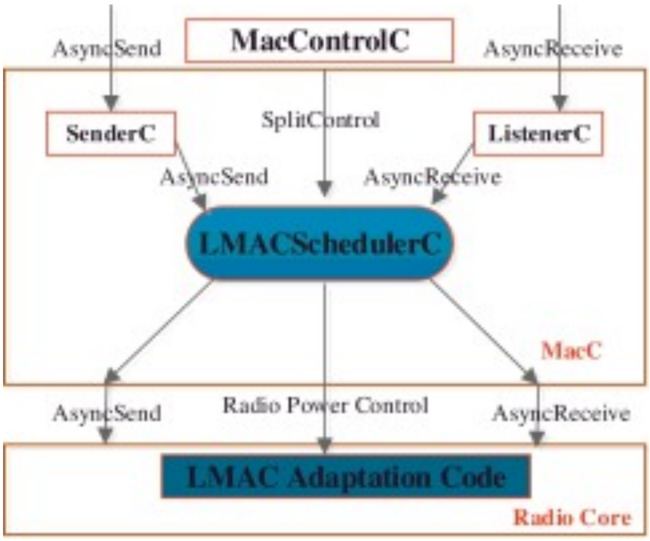

Fig 5 : LMAC

Sensor-MAC (S-MAC)

S-MAC utilizes a contention-based channel access mechanism built on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Nodes monitor the channel and initiate transmission only when the channel is detected as idle.

- **Clock Synchronization:** S-MAC integrates a basic clock synchronization process, where nodes exchange synchronization packets periodically. Although the precision is not highly refined, it is sufficient for maintaining synchronized sleep and wake cycles among nodes.
- **Localization Capability:** S-MAC does not provide built-in localization capabilities. Any localization features must be implemented at higher network layers.
- **Security Mechanisms:** S-MAC does not include native security mechanisms. External security solutions, such as encryption and authentication, must be added to secure communications.

- **Mobility Support:** S-MAC is not well-suited for node mobility. Movement can disrupt synchronization and interfere with the fixed sleep schedules, making it less effective in mobile networks.
- **Power Consumption:** S-MAC is designed for efficient energy management, utilizing scheduled sleep periods and active listening. However, energy consumption increases with mobility or disruption of synchronization, as nodes may need to adjust their schedules more frequently.

Timeout-MAC (T-MAC)

T-MAC, similar to S-MAC, uses a contention-based channel access method based on CSMA/CA. However, T-MAC improves upon S-MAC by dynamically adjusting the active and sleep periods depending on network traffic, offering adaptive duty cycles to optimize energy consumption.

- **Clock Synchronization:** T-MAC employs clock synchronization mechanisms similar to S-MAC. While the precision is limited, it focuses on aligning active periods to ensure efficient CSMA/CA operation.
- **Localization Capability:** T-MAC does not include native localization capabilities. Localization features must be implemented at higher layers of the network.
- **Security Mechanisms:** Like S-MAC, T-MAC does not provide built-in security mechanisms. External security solutions, such as encryption and authentication, must be added to ensure secure communication.

- **Mobility Support:** T-MAC, designed for static networks, does not support node mobility effectively. Movement can disrupt synchronization and the active period schedule.
- **Power Consumption:** T-MAC improves energy efficiency by dynamically adjusting sleep and active periods based on network traffic. However, this adaptive approach can result in delays in certain situations.

Geographic Adaptive Fidelity (GAF)

GAF (Geographic Adaptive Fidelity) uses a location-based mechanism for channel access, where the network is divided into a virtual grid. In each grid cell, only one node is selected to remain active and manage communication, helping conserve energy across the network. This approach ensures that only the necessary nodes are activated at any given time, minimizing energy consumption.

One of GAF's key strengths is its support for node mobility. As nodes move between grid cells, the protocol automatically adjusts by assigning new active nodes in the appropriate cells, ensuring continuous communication and coverage. This mobility support allows the network to adapt dynamically to node movements while maintaining efficient communication.

- **Clock Synchronization:** GAF requires synchronization within each grid cell, but precise global synchronization is not needed. Active nodes in neighboring cells must synchronize to relay messages.
- **Localization Capability:** GAF provides basic localization capabilities. Nodes must know their approximate location to determine their grid cell, allowing the network to manage active nodes in each cell for energy optimization.

- **Security Mechanisms:** GAF does not include internal security mechanisms. External security measures, such as encryption and authentication, are required for secure communication.
- **Mobility Support:** GAF supports node mobility. As nodes move between grid cells, the protocol automatically assigns new active nodes in the appropriate cells, ensuring continuous communication and coverage.
- **Power Consumption:** GAF optimizes energy consumption by activating only the necessary nodes in each grid cell, reducing the number of active nodes and conserving energy throughout the network.

Comparison of each Protocol:

Protocol	Clock Synchronization	Localization Capability	Security Mechanisms	Mobility Support	Power Consumption
FDMA	Not required (uses fixed frequencies)	No built-in support	None	Limited	Moderate (depends on active transmission)
TDMA	Strict synchronization required	No built-in support	None	Poor	Efficient (active only in assigned time slots)
CDMA	Not required (uses unique codes for each node)	No built-in support	Partial (via code privacy)	Good	High (spread-spectrum transmission)
CSMA/CA	No precise synchronization required	No built-in support	None	Limited (best for static networks)	High (due to idle listening periods)
B-MAC	Basic synchronization through periodic exchanges	No built-in support	None	Limited (static networks)	Optimized with Low Power Listening (LPL)
L-MAC	Basic synchronization for sleep/wake schedules	No built-in support	None	Limited (static networks)	Highly efficient with long sleep periods
S-MAC	Basic synchronization through periodic packets	No built-in support	None	Poor (static networks only)	Efficient with scheduled sleep periods
T-MAC	Basic synchronization for active periods	No built-in support	None	Poor (static networks only)	Improved with adaptive duty cycles
GAF	Local synchronization within grid cells	Basic (location-based operation)	None	Good (supports mobility)	Highly efficient (activates minimal nodes)

Conclusion

In conclusion, this report highlights the critical role of MAC protocols in the operation of Wireless Sensor Networks (WSN) and the Internet of Things (IoT). These protocols enable efficient channel access and energy management, making them essential for the success of IoT systems. The examination of protocols like CSMA/CA, B-MAC, L-MAC, and GAF illustrates the varied strengths of each: B-MAC's focus on low-power listening and energy efficiency, L-MAC's optimization of transmission schedules, and GAF's balance of energy savings and mobility support. The study also reviewed traditional multiple access methods such as FDMA, TDMA, and CDMA, showing their foundational role in shaping modern access strategies. Ultimately, selecting the most suitable MAC protocol depends on specific network requirements, such as energy efficiency, scalability, security, and mobility needs. This report serves as a guide for making informed decisions when designing IoT and WSN systems that deliver high performance and long operational lifespans, in line with the goals of the ISS specialty at INSA Toulouse.

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