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Functionalization, Evolution, Challenges and Applications of Cooperative Communication in 6G Wireless Communication

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Abstract: The start of 6G wireless communication letters a transformative leap in connectivity, offering unparalleled rapidity, ultra-low latency, and massive capacity. Central to this evolution is cooperative communication, which leverages collaborative strategies among multiple nodes to enhance network performance. This paper provides a comprehensive exploration of the functionalization, evolution, challenges, and applications of cooperative communication within 6G networks. By examining the underlying principles, potential benefits, and inherent challenges, we aim to shed light on the critical role cooperative communication will play in the advancement of wireless technology. Our analysis underscores the transformative impact of these collaborative approaches, highlighting their potential to address key issues in connectivity, reliability, and efficiency, thereby paving the way for a more robust and versatile 6G network infrastructure.

Keywords: Cooperative Communication, 6G, Wireless Communication, Wireless Networks

I. INTRODUCTION

The emergence of 6G wireless communication is set to revolutionize the landscape of connectivity, bringing about significant advancements in speed, latency, and capacity. A fundamental aspect of this evolution is the concept of cooperative communication, where multiple nodes work together to optimize signal transmission and reception.

This paper explores the foundational principles of cooperative communication, its benefits and challenges, and its potential applications in various domains.

II. TRANSITION TABLE FROM 1G TO 6G USING RELEVANT PARAMETERS

This table captures the evolution of mobile communication technologies from 1G to 6G across various parameters.

Parameter	1G	2G	3G	4G	5G	6G
Introduction Year	Late 1970s - Early 1980s	Early 1990s	Early 2000s	Late 2000s	2020s	Expected 2030s
Network Technology	Analog	Digital (GSM, CDMA)	UMTS, CDMA2000	LTE, WiMAX	NR (New Radio)	Advanced NR, THz Communications
Data Rate	Up to 2.4 kbps	Up to 64 kbps	Up to 2 Mbps	Up to 1 Gbps	Up to 20 Gbps	Up to 1 Tbps
Bandwidth	30 kHz	200 kHz	5 MHz	20 MHz	100 MHz - 1 GHz	1 GHz - 10 GHz
Latency	500 ms	300 ms	100 ms	10 ms	1 ms	Sub-ms (as low as 100 µs)
Core Network	PSTN	PSTN	Packet-switched + Circuit-switched	All-IP Network	All-IP Network	AI-Driven All-IP Network

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Parameter	1G	2G	3G	4G	5G	6G
Spectrum Efficiency	Low	Medium	Medium	High	Very High	Extremely High
Mobility	Up to 60 km/h	Up to 120 km/h	Up to 350 km/h	Up to 500 km/h	Up to 500 km/h	Up to 1000 km/h
Key Features	Voice Calls	Voice, SMS, MMS	Mobile Internet, Video Calls	HD Video Streaming, VoIP	Ultra-Reliable Low Latency Communication (URLLC), Enhanced Mobile Broadband (eMBB)	Holographic Communication, Integrated AI/ML, Extended Reality (XR)
Service Type	Voice Only	Voice and Text	Voice, Text, and Data	High-Speed Data, Multimedia	Enhanced Mobile Services, IoT, Critical Communications	Enhanced Mobile Services, Ubiquitous Connectivity, Advanced IoT
Device Connectivity	Basic Mobile Phones	Feature Phones	Smartphones	Advanced Smartphones, Tablets	IoT Devices, Smart Devices	Hyper-Connected Smart Devices
Energy Efficiency	Low	Medium	Improved	Good	Very Good	Excellent
Security	Basic	Improved	Better Encryption	Advanced Security Protocols	Enhanced Encryption, Security by Design	Quantum Security, Blockchain Integration
Use Cases	Voice Communication	Voice, SMS	Mobile Internet, Video Calls	Streaming, Gaming, VoIP	Smart Cities, Autonomous Vehicles, Remote Surgery	Smart Cities, Holographic Telepresence, Autonomous Systems

Table 1. 1G TO 6G wireless communication transition

Key evolutions:

- **Data Rate and Bandwidth:**
  - From basic voice services in 1G with very low data rates, each generation has progressively increased data rates and bandwidth capabilities. 6G is expected to reach data rates up to 1 Tbps and utilize bandwidths in the range of 1 GHz to 10 GHz, facilitating ultra-high-speed internet and real-time applications.

- **Latency:**
  - Latency has significantly decreased from 500 ms in 1G to potentially sub-millisecond levels in 6G, making applications like holographic communication and real-time control of autonomous vehicles feasible.

- **Core Network:**
  - The transition from PSTN in 1G and 2G to packet-switched networks in 3G and all-IP networks in 4G and beyond has been fundamental. 6G networks will likely be driven by AI and offer even more integration and efficiency

- **Mobility:**
  - The ability to maintain communication at high speeds has improved, with 6G networks expected to support seamless connectivity even at speeds up to 1000 km/h, catering to high-speed transport systems.

- **Security:**
  - From basic security measures in 1G, the evolution has led to advanced encryption and security protocols in later generations. 6G will likely incorporate quantum security and blockchain technology to safeguard data integrity and privacy.

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- **Use Cases:**
  - The progression from voice-only services in 1G to complex, high-speed data applications in 6G highlights the vast expansion of potential use cases, including smart cities, autonomous systems, and immersive technologies like XR.

This comprehensive overview demonstrates how each successive generation of wireless communication has built upon its predecessors, culminating in the advanced, multifaceted capabilities anticipated with 6G technology.

Need for Cooperative Communication in 6G Wireless Communication

As wireless communication technology evolves towards the 6G era, the demand for enhanced network performance, efficiency, and reliability has never been higher. Cooperative communication emerges as a critical paradigm to address these demands, offering solutions that go beyond the capabilities of previous generations. This section explores the necessity of cooperative communication in 6G wireless networks, emphasizing its role in achieving ultra-reliable, high-speed, and ubiquitous connectivity.

Enhancing Network Reliability and Coverage

One of the primary needs for cooperative communication in 6G is to enhance network reliability and coverage. In traditional communication systems, network coverage and reliability are often limited by the constraints of signal strength and interference. Cooperative communication mitigates these limitations by employing multiple nodes (such as relay nodes) to assist in signal transmission.

These nodes collaborate to forward signals from the source to the destination, effectively extending coverage and improving reliability. This collaborative approach helps overcome issues related to signal degradation and dead zones, ensuring more consistent and robust connectivity across diverse environments.

Improving Data Rates and Bandwidth Efficiency

As 6G networks aim to support unprecedented data rates and bandwidth requirements, cooperative communication becomes essential for optimizing these parameters. Techniques such as Decode-and-Forward (DF), Amplify-and-Forward (AF), and Compress-and-Forward (CF) play a pivotal role in managing and enhancing data transmission. DF improves data rates by decoding and re-encoding signals, which enhances error correction and data integrity.

AF boosts signal strength by amplifying received signals, thus supporting higher data rates over longer distances. CF reduces the amount of data transmitted by compressing signals, optimizing bandwidth usage and efficiency. These methods collectively contribute to achieving the high data throughput and bandwidth efficiency required for applications such as high-definition video streaming, virtual reality, and massive Internet of Things (IoT) deployments.

Facilitating Advanced Applications and Use Cases

The advent of 6G brings with it a host of advanced applications and use cases that demand significant improvements in communication performance. Cooperative communication supports these requirements by enabling new functionalities and enhancing existing ones. For instance, in autonomous driving, cooperative communication ensures seamless vehicle-to-vehicle and vehicle-to-infrastructure communication, improving safety and operational efficiency.

In smart cities, cooperative communication facilitates the integration of various IoT devices, ensuring reliable and synchronized data exchange. Additionally, in scenarios such as remote surgeries and real-time augmented reality, cooperative communication provides the low-latency and high-reliability needed to deliver critical and immersive experiences. The ability of cooperative communication to support these advanced applications underscores its importance in realizing the full potential of 6G technology.

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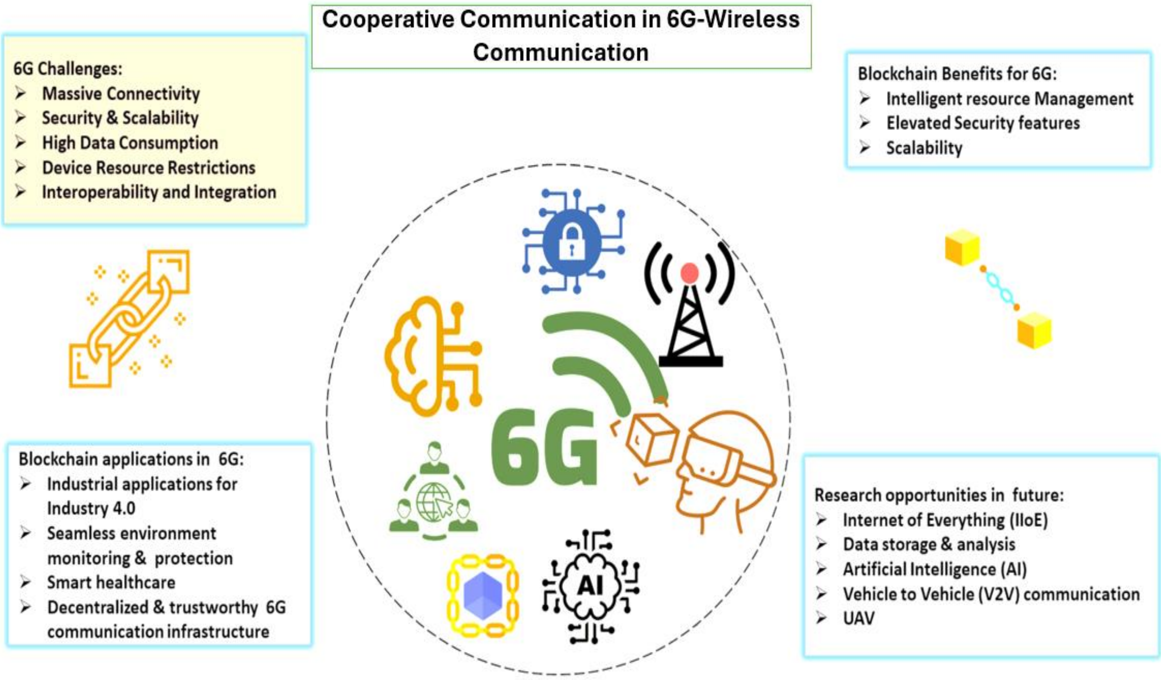
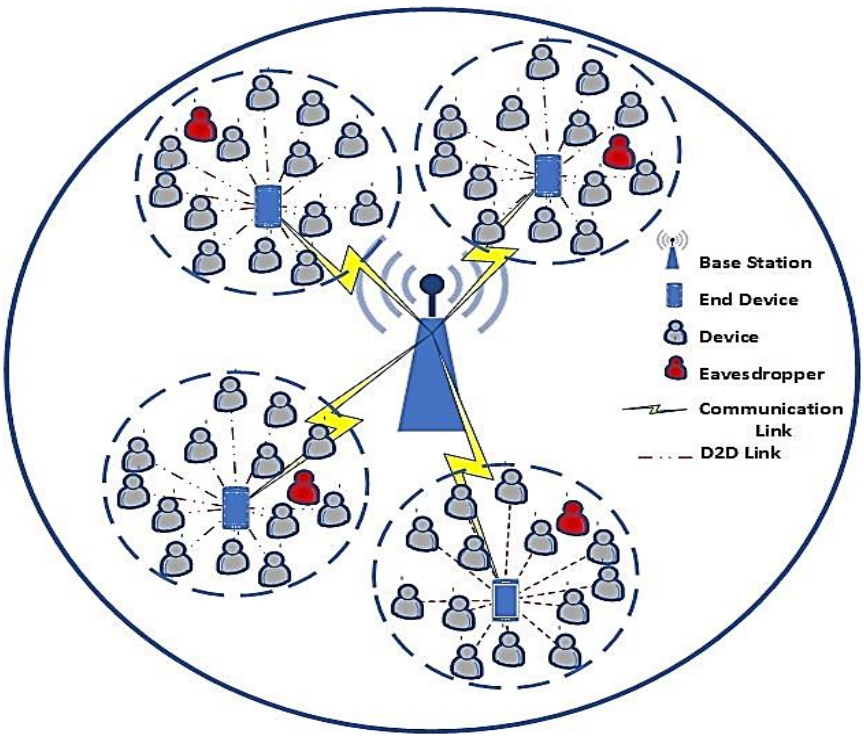


Figure 1 Cooperative Communication in 6G Wireless Networks



III. PRINCIPLES OF COOPERATIVE COMMUNICATION

Cooperative communication in 6G wireless networks represents a paradigm shift aimed at leveraging collaboration among multiple nodes to enhance network performance. The structure of cooperative communication involves key components such as the source node, relay nodes, and destination node, interconnected through various communication channels.

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The source node initiates the transmission, while relay nodes—employing techniques such as Decode-and-Forward (DF), Amplify-and-Forward (AF), or Compress-and-Forward (CF)—assist in forwarding the signal to the destination. Each method has distinct processes: DF decodes, corrects errors, re-encodes, and forwards the signal; AF amplifies the received signal and noise before forwarding; and CF compresses the signal to reduce data size before transmission. These components and methods work synergistically to optimize signal transmission and reception, thus ensuring efficient and reliable communication.

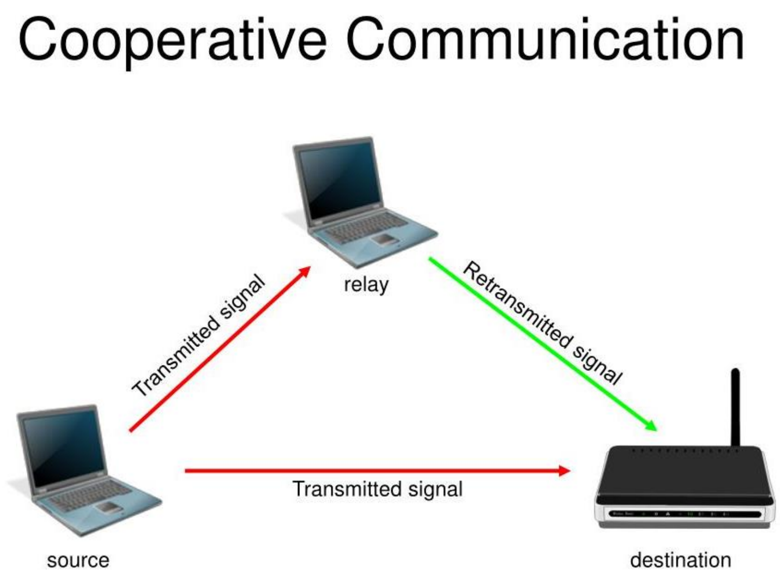

Figure 2 Basic Structure of Cooperative wireless communication single user module

The functionalization of cooperative communication involves various processes tailored to maximize the benefits of the chosen relay method. DF enhances reliability by correcting errors during the decoding process, making it ideal for scenarios requiring high signal quality. AF simplifies implementation by amplifying the signal, though it also amplifies noise, potentially compromising signal quality. CF, on the other hand, reduces data transmission load through compression, beneficial in bandwidth-constrained environments but requiring complex processing. Key parameters influencing these processes include transmission power, data rate, encoding schemes, channel state information (CSI), signal-to-noise ratio (SNR), and bandwidth. Efficient management of these parameters is crucial to achieving the desired performance improvements in 6G networks.

Enhancing Network Reliability, Coverage, and Efficiency through Cooperative Communication

1. Enhancing Network Reliability:
Cooperative communication improves network reliability by employing multiple nodes to assist in data transmission. This collaborative approach allows for redundancy and error correction, which significantly mitigates the impact of network failures and signal degradation. By using techniques like Decode-and-Forward (DF), relay nodes can decode, correct errors, and re-encode the data before forwarding it to the destination. This ensures that errors introduced during the initial transmission are corrected, thereby enhancing the overall reliability of the network. Additionally, Amplify-and-Forward (AF) and Compress-and-Forward (CF) methods, though simpler, also contribute to reliability by extending the transmission range and improving the data integrity, respectively. These methods collectively ensure that data reaches its destination accurately, even in challenging conditions.

2. Improving Coverage:
Cooperative communication extends network coverage by deploying multiple relay nodes strategically throughout the network. These relays work together to forward signals from the source to the destination, effectively overcoming obstacles and mitigating coverage gaps. This technique is particularly beneficial in scenarios where the primary communication path is obstructed or where signal strength is insufficient. For instance, in urban environments with high building density or in rural areas with sparse infrastructure, cooperative communication ensures that signals can traverse longer distances and reach locations that would otherwise be out of range. By enhancing coverage in both dense and remote areas, cooperative communication provides more comprehensive network access.

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3. Increasing Efficiency:
Cooperative communication enhances network efficiency through various mechanisms. By reducing the need for higher transmission power and improving spectrum utilization, cooperative communication lowers energy consumption and optimizes bandwidth usage. Techniques like CF reduce the amount of data that needs to be transmitted by compressing the signal, thereby alleviating bandwidth constraints and improving overall throughput. Furthermore, cooperative communication enables better resource allocation by dynamically adjusting the roles of different nodes based on network conditions and traffic demands. This adaptability ensures that network resources are utilized effectively, minimizing congestion and maximizing data transfer rates.

Addressing Critical Issues
1. Coordination Complexity:
The coordination of multiple nodes in a cooperative communication network introduces complexity, as it requires seamless interaction and synchronization between relays and the main nodes. Advanced algorithms and protocols are essential to manage this complexity, ensuring that nodes collaborate efficiently without introducing excessive overhead. Techniques such as distributed coordination protocols and network management systems are employed to facilitate effective coordination and maintain overall system performance.

2. Security Risks:
Cooperative communication introduces additional security risks due to the involvement of multiple nodes that interact and share data. Ensuring the confidentiality, integrity, and authenticity of transmitted data is crucial. Security measures, including encryption, secure key management, and authentication protocols, are implemented to safeguard against potential threats such as eavesdropping, data tampering, and unauthorized access. Robust security frameworks are necessary to protect the network and maintain trust among cooperating nodes.

3. Resource Management:
Efficient resource management is critical in cooperative communication networks to balance the load among nodes and optimize the use of available resources. This involves managing spectrum allocation, energy consumption, and computational resources. Techniques such as resource scheduling, load balancing, and power control are employed to ensure that network resources are utilized effectively. Dynamic resource management strategies help adapt to changing network conditions and user demands, thereby maintaining high performance and service quality.

In summary, cooperative communication enhances network reliability, coverage, and efficiency while addressing the complexities of coordination, security, and resource management. Through sophisticated techniques and protocols, it ensures that 6G networks can deliver superior performance and meet the evolving needs of users and applications.

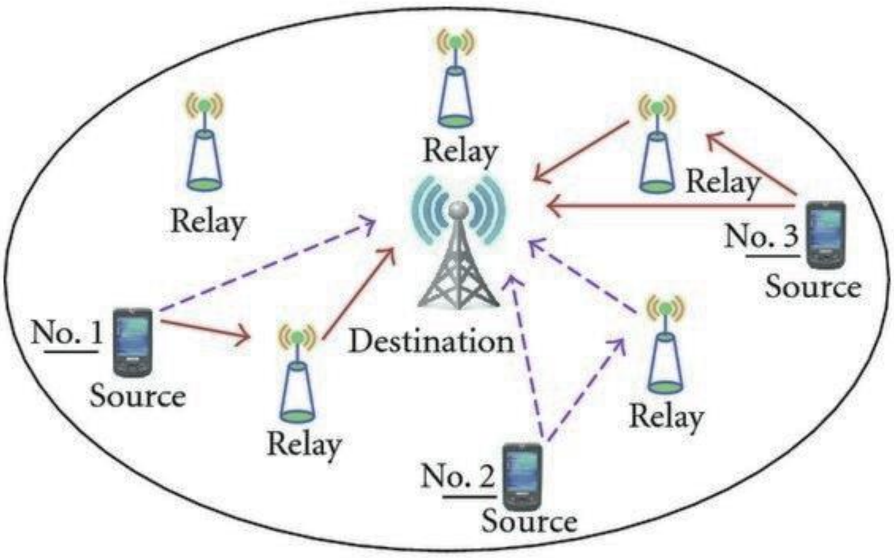

Figure 3 Basic Structure of Cooperative wireless communication multi user module

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Comparative analysis of DF, AF, and CF reveals trade-offs that must be considered when designing cooperative communication systems. DF, with its high implementation complexity and error correction capabilities, offers superior signal quality at the cost of increased computational load and latency. AF, being simpler and more energy-efficient, is suitable for scenarios where minimal processing is preferred, albeit at the risk of noise amplification. CF strikes a balance by offering high bandwidth efficiency and variable signal quality, contingent on the compression ratio and processing capabilities. Understanding these trade-offs and the detailed mechanisms underlying each method is essential for optimizing the performance of cooperative communication in 6G wireless networks, ensuring robust, efficient, and reliable connectivity in the next generation of wireless communication. In a typical cooperative communication scenario, a source node transmits a signal to a destination node with the help of one or more relay nodes. The relays receive the signal, process it, and then retransmit it to the destination. This cooperation can occur in various forms, including:

Decode-and-Forward (DF)

In the Decode-and-Forward (DF) approach, relay nodes decode the received signal, re-encode it, and then forward it to the destination. The DF process involves the following steps:

1. Reception: The relay node receives the signal transmitted by the source node.
2. Decoding: The relay node decodes the received signal to retrieve the original data. This step involves error detection and correction mechanisms to identify and correct any errors introduced during the initial transmission.
3. Re-encoding: After decoding, the relay node re-encodes the data into a new signal.
4. Forwarding: The relay node transmits the re-encoded signal to the destination node.

The key advantage of the DF method is its ability to correct errors, enhancing the overall reliability of the communication. By decoding and re-encoding the signal, the relay node ensures that the forwarded signal is as error-free as possible, even if the initial transmission was corrupted.

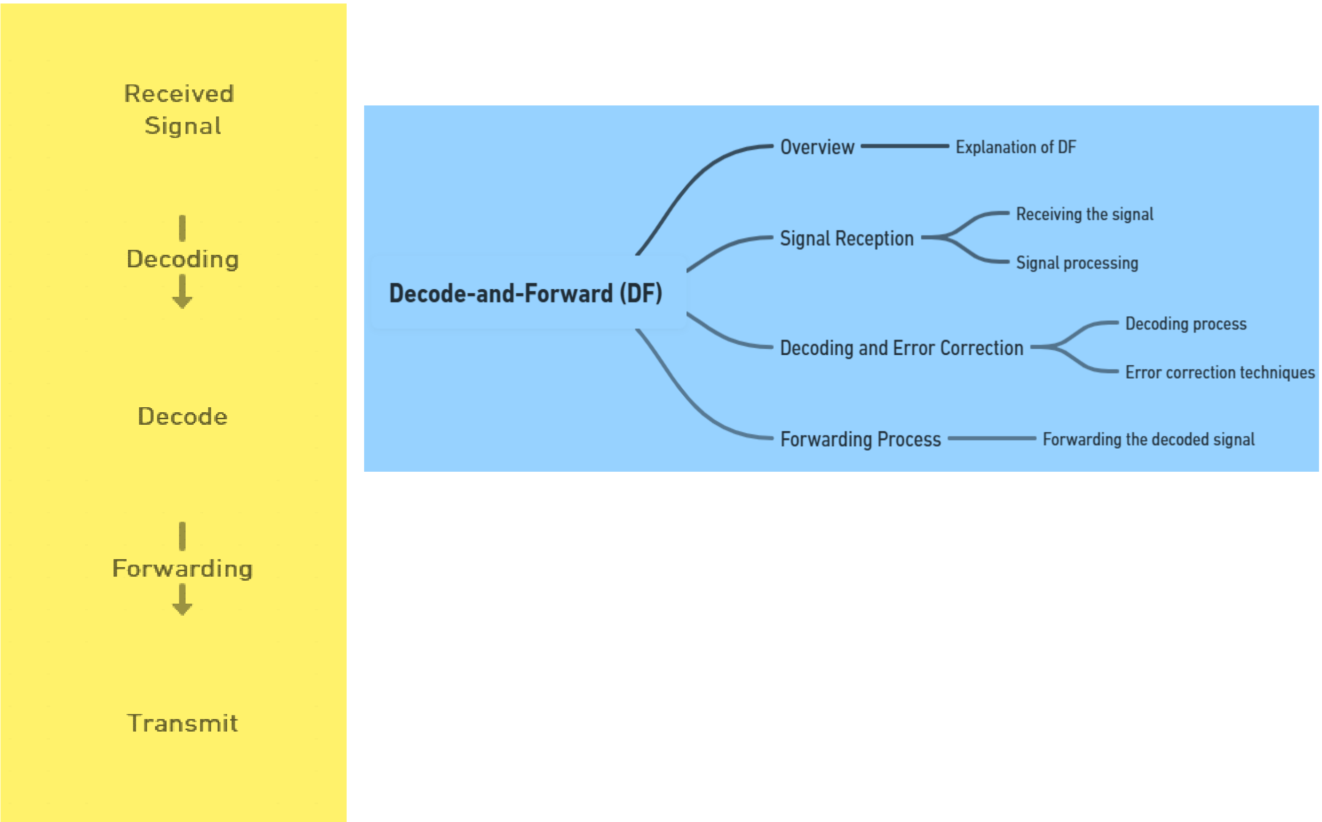

Figure 4. Decode and forward Algorithm and Characteristics

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Amplify-and-Forward (AF)
The Amplify-and-Forward (AF) technique involves relay nodes amplifying the received signal, including any noise, before forwarding it to the destination. The AF process involves the following steps:

1. Reception: The relay node receives the signal transmitted by the source node.
2. Amplification: The relay node amplifies the received signal, which includes both the desired signal and any noise that was introduced during transmission.
3. Forwarding: The amplified signal is then transmitted to the destination node.

The AF method is simpler to implement compared to DF, as it does not require decoding and re-encoding. However, a significant drawback is that the noise present in the received signal is also amplified, which can degrade the quality of the forwarded signal.

Compress-and-Forward (CF)
In the Compress-and-Forward (CF) approach, relay nodes compress the received signal and forward a compressed version to the destination. The CF process involves the following steps:

1. Reception: The relay node receives the signal transmitted by the source node.
2. Compression: The relay node compresses the received signal using compression algorithms to reduce its size. This step aims to reduce the amount of data that needs to be transmitted.
3. Forwarding: The compressed signal is transmitted to the destination node.

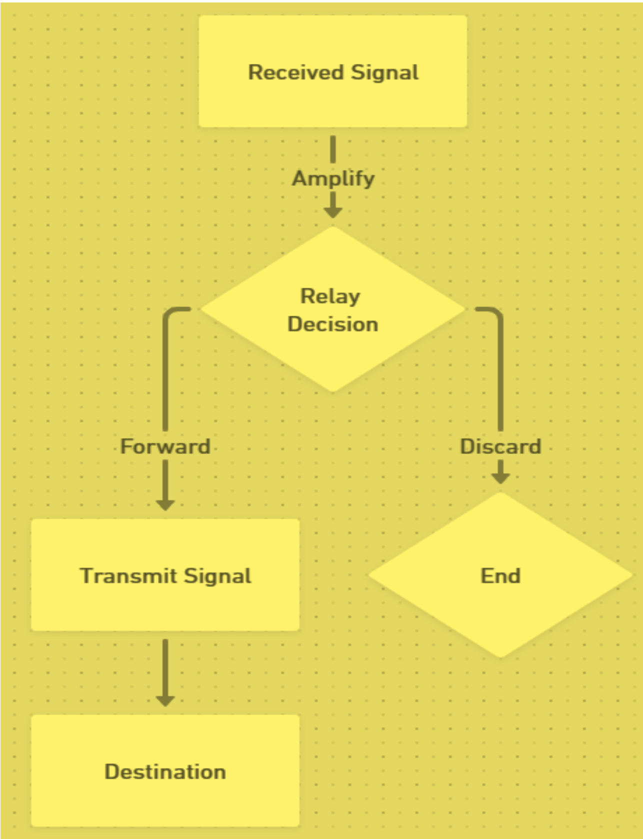

Figure 5. Compress-and-Forward (CF) Algorithm and Characteristics

The CF method reduces the data transmission load, which can be beneficial in bandwidth-constrained environments. However, this approach requires more complex processing to compress and decompress the signal, and there is a potential for loss of information during the compression process.

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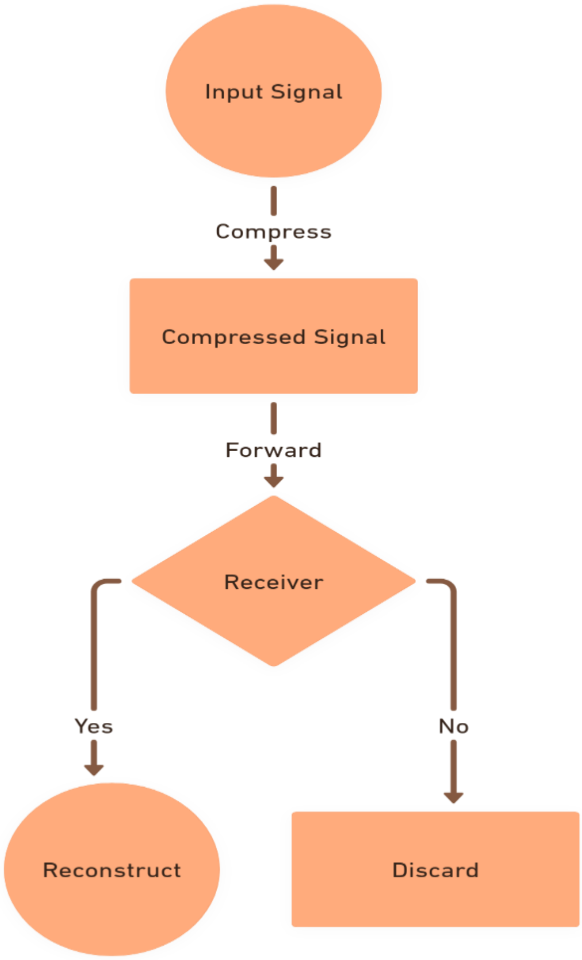

Aspect	Decode-and-Forward (DF)	Amplify-and-Forward (AF)	Compress-and-Forward (CF)
Process	Decode, re-encode, and forward	Amplify and forward	Compress and forward
Error Handling	Corrects errors during decoding	Amplifies both signal and noise	Compression can mitigate noise but may lose information
Implementation	More complex due to decoding and encoding	Simpler, just amplification	Complex due to compression algorithms
Signal Quality	High, due to error correction	Lower, noise is also amplified	Variable, depends on compression efficiency
Bandwidth Efficiency	Moderate	Low, as noise is amplified	High, due to reduced data size
Computational Complexity	High, requires decoding and re-encoding	Low, only amplification	High, due to compression processing
Latency	Higher, due to decoding and encoding steps	Lower, minimal processing	Variable, depends on compression and decompression times

Table 2 Comparison of DF, AF, and CF

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Each method of cooperative communication offers distinct advantages and disadvantages, making them suitable for different scenarios within 6G networks. DF provides high reliability through error correction, AF offers simplicity at the cost of noise amplification, and CF balances data reduction with increased computational complexity. Understanding these methods and their trade-offs is crucial for optimizing 6G network performance.

Benefits of Cooperative Communication in 6G

The implementation of cooperative communication in 6G networks offers numerous advantages, including:

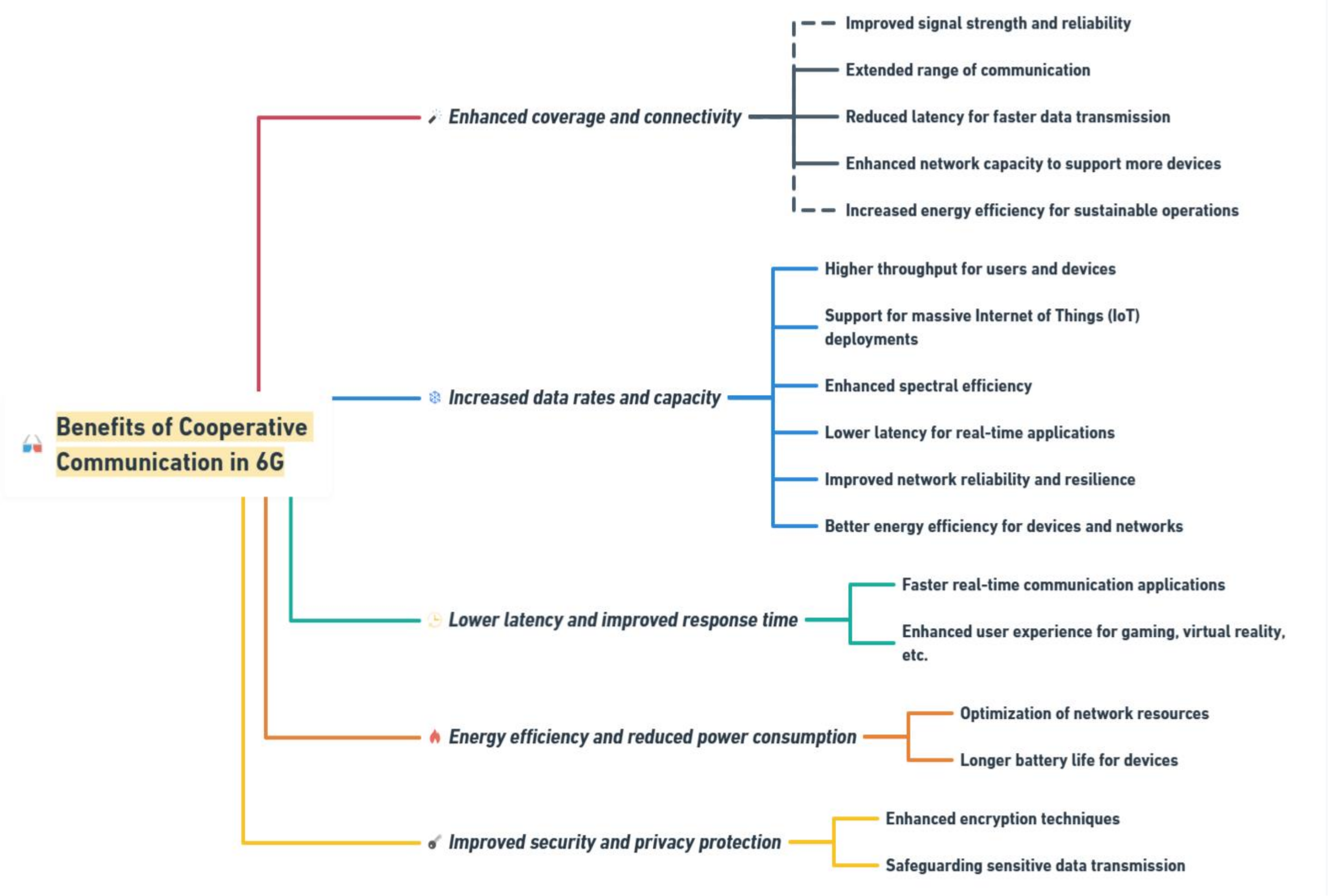
1. **Enhanced Coverage and Capacity:** Cooperative communication can extend the coverage area by leveraging relay nodes, making it possible to reach users in remote or challenging environments. This extension improves overall network capacity and user experience.

2. **Improved Reliability and Robustness:** By utilizing multiple paths for signal transmission, cooperative communication enhances the reliability of data delivery. This redundancy ensures that even if one path experiences interference or blockage, the communication can still proceed through alternate routes.

3. **Energy Efficiency:** Cooperative communication can optimize energy consumption by reducing the need for high-power transmissions. Relay nodes can be strategically placed to minimize the distance between hops, lowering the power required for each transmission.

4. **Interference Mitigation:** The collaborative nature of cooperative communication allows for better interference management. By coordinating transmissions among multiple nodes, the system can reduce interference and enhance spectral efficiency.

5. **Latency Reduction:** Cooperative strategies can decrease end-to-end latency by optimizing the routing of signals through multiple paths, ensuring faster and more reliable data delivery.



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Challenges in Implementing Cooperative Communication

Despite its potential benefits, cooperative communication in 6G faces several challenges:

1. **Complexity in Coordination:** Managing the coordination among multiple nodes requires sophisticated algorithms and protocols. Ensuring seamless cooperation without introducing excessive overhead is a significant challenge.

2. **Security and Privacy Concerns:** The involvement of multiple nodes in the communication process raises concerns about data security and privacy. Ensuring secure transmission and protecting against malicious attacks are critical issues that need to be addressed.

3. **Resource Allocation:** Efficiently allocating resources such as bandwidth, power, and computational capacity among the cooperating nodes is essential for maximizing the benefits of cooperative communication.

4. **Scalability:** As the number of nodes in the network increases, maintaining efficient cooperation becomes more complex. Scalability is a crucial factor in the widespread adoption of cooperative communication in large-scale 6G networks.

5. **Standardization:** Establishing industry-wide standards for cooperative communication is necessary to ensure interoperability and compatibility among different devices and networks.

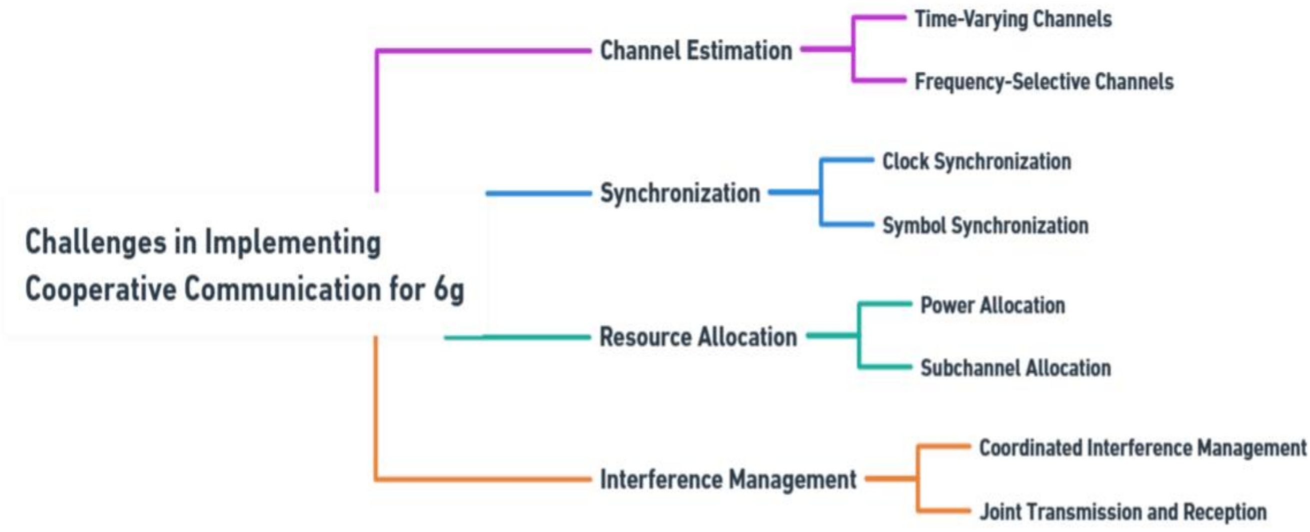

Figure 6 Challenges in Cooperative Communication

Potential Impact of Cooperative Communication on Network Performance and Application Scenarios

1. Impact on Network Performance:

a. Improved Reliability and Robustness:

Cooperative communication significantly boosts network reliability by employing multiple nodes to forward and verify data. This redundancy ensures that data is less likely to be lost or corrupted due to transmission errors or node failures. The use of methods like Decode-and-Forward (DF) not only corrects errors but also provides resilience against various network impairments, leading to a more dependable network overall.

b. Enhanced Coverage and Signal Strength:

By strategically deploying relay nodes, cooperative communication extends network coverage and improves signal strength. This is particularly valuable in areas with challenging topologies, such as urban canyons or rural regions with limited infrastructure. The ability of relays to forward signals over long distances helps in bridging coverage gaps and delivering consistent connectivity across diverse environments.

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c. Increased Efficiency and Throughput:
Cooperative communication optimizes resource usage, reducing the need for high transmission power and improving spectral efficiency. Techniques like Compress-and-Forward (CF) reduce the data volume that needs to be transmitted, thereby easing bandwidth constraints and enhancing overall throughput. This efficiency translates into better utilization of network resources, reduced congestion, and higher data transfer rates.

d. Enhanced Network Scalability:
The collaborative nature of cooperative communication enables networks to scale more effectively. As the number of connected devices and users grows, the network can adapt by incorporating additional relay nodes to handle increased traffic and maintain performance. This scalability is crucial for accommodating the burgeoning demand for high-speed and high-capacity connectivity in 6G networks.

2. Impact on Application Scenarios:
a. Autonomous Vehicles:
In autonomous driving systems, cooperative communication enables real-time vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, enhancing situational awareness and decision-making. This leads to improved safety, more efficient traffic management, and seamless integration with smart city infrastructure. The low-latency and reliable communication facilitated by cooperative strategies are essential for the safety and functionality of autonomous vehicles.

b. Smart Cities:
Cooperative communication supports the development of smart cities by enabling reliable data exchange among various IoT devices and sensors. This connectivity is crucial for applications such as smart grids, environmental monitoring, and intelligent transportation systems. The ability to extend coverage and improve signal strength ensures that smart city services can operate efficiently and provide real-time information and control.

c. Augmented and Virtual Reality (AR/VR):
For AR and VR applications, cooperative communication provides the low-latency and high-bandwidth requirements necessary for immersive experiences. The collaborative nature of the communication enhances the synchronization of data between devices, reducing latency and improving the quality of the virtual environment. This leads to more fluid and interactive AR/VR experiences, crucial for applications in gaming, training, and remote collaboration.

d. Remote Healthcare:
In telemedicine and remote healthcare, cooperative communication ensures reliable and high-quality data transmission for teleconsultations, remote monitoring, and tele-surgery. The ability to transmit large volumes of data with minimal delay is essential for accurate diagnostics and real-time patient monitoring. Cooperative communication enhances the reliability and responsiveness of remote healthcare systems, contributing to better patient outcomes and expanded access to medical services.

e. High-Definition Video Streaming:
The demand for high-definition and ultra-high-definition video streaming continues to grow. Cooperative communication enhances video streaming services by improving bandwidth efficiency and reducing buffering. Techniques like CF help in managing large data volumes, while improved coverage ensures consistent streaming quality even in areas with high user density or challenging conditions.

IV. CONCLUSION

Cooperative communication is set to be a cornerstone in the evolution of 6G wireless technology, leveraging the synergistic capabilities of multiple nodes to significantly enhance network attributes. By enabling nodes to work together in forwarding data, cooperative communication can dramatically improve coverage, reliability, and energy efficiency while optimizing overall network performance. This collaborative approach addresses critical challenges such as mitigating coverage gaps, enhancing signal strength in weak areas, and reducing energy consumption through efficient resource utilization. However, the integration of cooperative communication into 6G networks is not without its complexities. Key challenges include the need for sophisticated coordination mechanisms among nodes to ensure seamless operation, robust security measures to protect against potential vulnerabilities introduced by multiple interacting entities, and effective resource allocation to balance load and maintain quality of service. Additionally, scalability concerns must be addressed to accommodate the increasing number of connected devices and users, while standardization efforts are essential to ensure interoperability across diverse network components and technologies. As research and

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development in 6G advance, addressing these challenges will be critical. Cooperative communication is anticipated to be a pivotal enabler of the next generation of wireless networks, fundamentally transforming how we connect, communicate, and interact in an increasingly digital and interconnected world. By overcoming the hurdles associated with its implementation, cooperative communication will play a vital role in achieving the ambitious performance goals set for 6G technology.

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