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Review Article

Advancements in Cooperative Communication: A Comprehensive Review of Techniques, Challenges, and Future Directions

[1]Abonyi, D.O. and *[2]Odo, K.O.

[1]Department of Electrical and Electronic Engineering, Enugu State University of Science and Technology, Enugu State, Nigeria.
[2]Department of Electrical and Electronic Engineering, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria.
*kayceebby@yahoo.co.uk; abonyi.dorathy@esut.edu.ng

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ABSTRACT

Wireless networks are increasing at a tremendous rate in the current era and becoming essential for information sharing. With the expansion in the activities requiring internet connectivity, the growth in the number of connected devices and the demand for coverage extension of network connectivity, different techniques to improve capacity and coverage in wireless networks has emerged. Cooperative communication is one of the advanced techniques that have emerged as a promising paradigm to enhance not just coverage and capacity but also reliability and spectral efficiency of wireless communication systems. This paper presents a comprehensive review of the advancements in cooperative communication techniques, challenges, and future directions. The areas covered include; an overview of the fundamental principles and benefits of cooperative communication; various cooperative communication techniques, including relay selection, power allocation, and coding schemes, highlighting their advantages and limitations; key challenges in implementing cooperative communication, such as synchronization, channel estimation, and relay selection criteria; the impact of practical considerations, such as hardware constraints and network topology; and the future research directions, including the integration of cooperative communication with emerging technologies such as machine learning and blockchain. This review provides researchers and practitioners with a comprehensive understanding of the state-of-the-art in cooperative communication and inspires new avenues for research and development in this field.

1. INTRODUCTION

Cooperative communication involves using mobile terminals as relay stations to enhance the quality of transmission, increase performance of network and minimize consumption of energy. Also, different wireless communication systems enable cooperative transmission. Cooperative transmission is using terminals as relay stations to minimize power consumption of mobile terminals, leading to elongated functional times. Also, cooperative transmission can upsurge the capability, data rates and performance of wireless networks. Moreso, it can support to increase the transmission coverage area of both mobile networks and ad-hoc networks, (Alam et al, 2017).

Cooperative communication and networking is one of the evolving technologies that promise meaningfully greater reliability and spectral efficiency in wireless networks. Contrasting conventional point-to-point communications, cooperative communication is a new method of diversity that lets users or nodes to share resources to produce collaboration via distributed transmission and message processing. This cooperative diversity concept is comparable to the multiple-input multiple-output (MIMO) system but is used in a networked setting. Therefore, it is often known as a distributed MIMO or network MIMO. It signifies a paradigm change from a network of conventional point-to-point links to network cooperation, (Zhang et al, 2011).

The quality of received signal level in wireless environment reduces due to path-loss and shadowing from several obstacles in propagation path. Moreso, quality of signal undergoes fading due to constructive and destructive interferences of multi-path components which makes it hard for the receiver to remove the message properly. It is usually the case that multiple sources and multiple relays cooperate to send their data to destination in cooperative wireless networks. A relay helps an alternative channel for flow of replica information corrupted by any kind of error, (Sonkar et al, 2016).

Transmit diversity widely requires more than one antenna at the transmitting end. Conversely, several wireless devices are inadequate by size or hardware complexity to one antenna. Presently, a novel technique known as cooperative communication has been projected that allows single antenna mobiles in a multi-user environment to divide their antennas and produce a virtual multiple-antenna transmitter that permits them to accomplish transmit diversity. The benefits of multiple-input multiple-output (MIMO) systems have been extensively recognized, in so far that definite transmit diversity techniques (i.e., Alamouti signaling) have been integrated into wireless standards. Even though transmit diversity is obviously beneficial on a cellular base station; it may not be applied for other situations. Precisely, due to size, cost, or hardware restrictions, a wireless agent may not be able to take care of multiple transmit antennas. Instances comprise most handsets (size) or the nodes in a wireless sensor network (size, power). Cooperative communication permits single-antenna mobiles to acquire some of the advantages of MIMO systems. The main knowledge is that single-antenna mobiles in a multi- user situation can split their antennas in a way that produces a virtual MIMO system, (Shah and Islam, 2014).

The importance of this review is to improve system performance, energy efficiency and overall reliability in cooperative communication by allowing nodes to collaborate and share resources, thereby overcoming the limitations associated with traditional point-to-point communication such as signal fading, interference and power constraints. Recent studies in cooperative communication have led to the development of some techniques such as adaptive relay selection, network coding and cognitive radio integration, all of which significantly enhance the performance of modern wireless networks. Ahmed et al (2021) explored power allocation strategies in relay-assisted communication, demonstrating that cooperative communication improves network longevity, particularly in wireless communication. Zhang and Liu (2022) proposed novel distributed space-time block coding techniques that reduce computational overhead while maintaining diversity gain. Rahman et al (2023) introduced energy-aware protocols for wireless sensor networks that dynamically select cooperative nodes based on residual energy levels and network conditions. Despite these improvements, challenges remain in areas such as security, energy efficiency and integrating with emerging technologies such as block chain, edge computing, machine language and AI-enabled cooperative communication.

Therefore, this review stands out by synthesizing the latest advancements in cooperative communication with a forward-looking perspective on emerging technologies like 5G and beyond, AI-driven cooperative systems and security. It goes beyond merely summarizing some existing literatures, instead offering new insights and identifying critical research challenges associated with cooperative communication and future research directions in cooperative communication.

2. OVERVIEW OF THE HISTORY OF COOPERATIVE COMMUNICATION IN WIRELESS SYSTEMS

The origin of cooperative communication could be attributed to an article earlier published on the relay channel by Cover and Gamal back in 1979. They based their work on the analysis of the capacity of a three-node network consisting of a source, a relay, and a receiver. The postulation was that all nodes function in the similar band; hence the system could be disintegrated into a broadcast channel with respect to the source and a multiple access channel with respect to the destination. They developed a relay channel that comprises a source node, a relay node and a destination node, as depicted in the Figure 1.

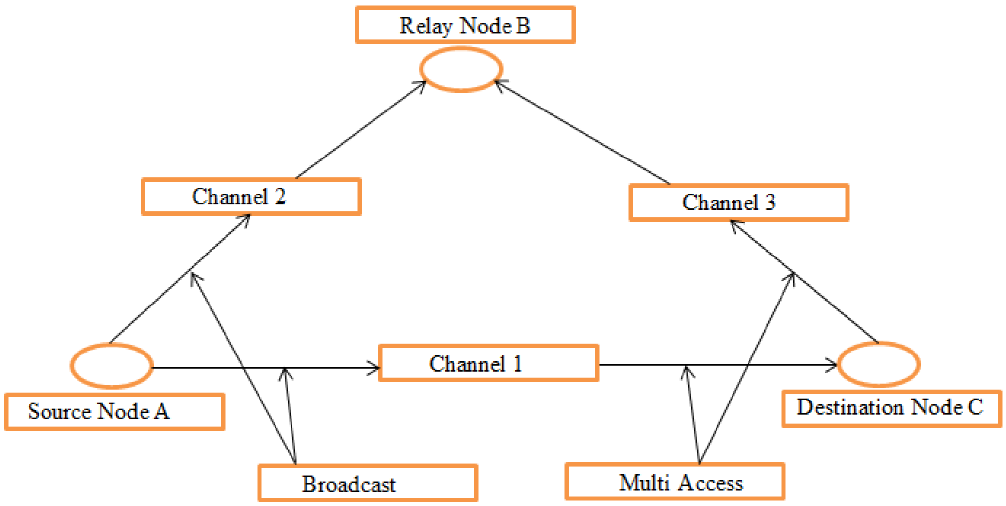

Figure 1: The relay channel

a. Early concepts (2000s): The concept of cooperative communication in wireless systems emerged in the early 2000s as researchers explored ways to lessen the adverse causes of fading and interference in wireless channels. Initial studies focused on simple relay-based schemes, where intermediate nodes (relays) assist in forwarding data between the source and destination nodes, (Sendonaris et al, 2003).

b. Relay networks (Mid 2000s): In the mid-2000s, researchers on cooperative communication expanded to include relay networks, where multiple relays collaborate to improve coverage and reliability. Studies investigated various relay selection algorithms, cooperative protocols and resource allocation strategies to optimize performance in relay-assisted communication scenarios, (Jiang et al, 2013).

c. Distributed antenna systems (DAS) (Late 2000s): The late 2000s saw the emergence of distributed antenna systems (DAS) as a form of cooperative communication architecture. DAS employs multiple distributed antennas deployed across a geographical area to enhance signal coverage, capacity and spatial diversity in wireless networks. Research efforts focused on designing efficient coordination and cooperation mechanisms for distributed antenna deployments, (Gesbert et al, 2010).

d. Multi-hop networks and mesh networks (2010s): In the 2010s, cooperative communication gained traction in multi-hop networks and mesh networks, where nodes collaborate to relay data over multiple hops. These networks offer increased coverage, improved reliability and better throughput compared to traditional single-hop communication schemes. Research in this era focused on developing distributed routing algorithms, power control mechanisms and medium access protocols for cooperative multi-hop communication, (Yun et al, 2010)

e. Cognitive Radio and Dynamic Spectrum Access (2010s): Cooperative communication became an integral part of cognitive radio and dynamic spectrum access (DSA) systems in the 2010s. Cognitive radio network leverage spectrum sensing and sharing techniques to opportunistically access underutilized spectrum bands, while cooperative communication enables nodes to collaborate in spectrum sensing, spectrum access and data transmission tasks, (Zhao and Tong, 2003).

f. 5G and Beyond (Present and Future): Cooperative communication continues to play an important part in the development of 5G and beyond wireless systems. 5G networks leverage cooperative techniques such as coordinated multipoint (CoMP) transmission, network densification and device-to-device (D2D) communication to improve spectral efficiency, coverage and user experience. Looking ahead, cooperative communication will remain a key enabler of future wireless technologies, including 6G and beyond, as researchers explore new paradigms such as massive MIMO, intelligent reflecting surfaces and cooperative edge computing, (Andrews et al, 2014).

3. FUNDAMENTAL THEORY OF COOPERATIVE COMMUNICATION IN WIRELESS SYSTEMS

The fundamental theory of cooperative communication in wireless systems revolves around leveraging the spatial diversity provided by multiple distributed nodes. The key principles and theories underlying cooperative communication include:

a. Relay channels: The theory of relay channels describes the transmission of information from a source to a destination with the help of one or more relay nodes. Various relay strategies such as amplify-and-forward, decode-and-forward and compress-and-forward have been developed to optimize performance based on channel conditions and network constraints, (Laneman et al, 2004).

b. Network coding: Network coding enables nodes in a network to combine and process information from multiple sources before forwarding it to the destination. By performing coding operations at intermediate nodes, network coding can improve throughput, reliability and energy efficiency in cooperative communication networks, (Hunter and Nosratinia, 2006). Equation 1 shows the network coding which according to Jaggi et al, 2008 involves linear combinations of packets, often represented using matrices and vectors given by:

$$y = G.x + n \qquad (1)$$

where y is the received signal vector, G is the coding matrix, x is the transmitted signal and n is the noise vector

c. Optimization theory: Optimization techniques are employed to design cooperative communication protocols that optimize different performance metrics such as throughput and energy efficiency. Optimization frameworks consider factors such as channel conditions, node capabilities and network topology to derive efficient cooperative strategies, (Yang and Yuan, 2009).

d. Game theory: Game theoretical approaches are utilized to analyze and design cooperative communication protocols in scenarios involving multiple self-interested nodes. Game theory provides insights into the strategic interactions among nodes and helps in devising incentive mechanism to encourage cooperation and mitigate selfish behaviour, (Saad et al, 2013).

3.1. Types of Cooperative Communication in Wireless Systems

The types of cooperative communication that can be used in various wireless communication scenarios, comprising cellular networks, ad hoc networks, sensor networks and Internet of Things (IoT) deployments to enhance performance and meet the demands of emerging wireless applications according to Akyildiz et al, 2015 are;

a. Relay-based cooperative communication: Amplify-and-Forward, Decode-and-Forward and Compress-and-Forward are prominent relay-based protocols, (Laneman et al, 2004). These protocols utilize intermediate relay nodes to assist in signal transmission, thereby enhancing reliability and coverage, (Sendonaris et al, 2003). The amplify-and-forward method of relay based protocol is shown in Figure 2.

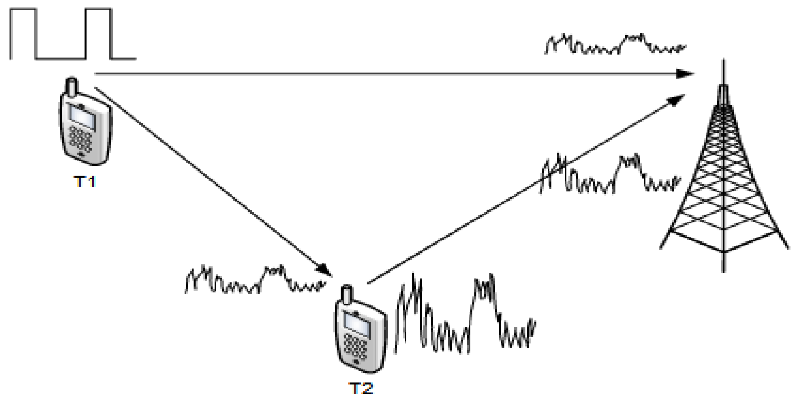

Figure 2: Amplify-and-Forward Method. (Marczak, 2017)

The received signal at the relay, y_R is given in Equation 2 as (Goldsmith, 2005).

$$y_R = h_{SR} \times x_S + n_R \quad (2)$$

where h_{SR} is the channel gain from source to relay, x_S is the transmitted signal from the source and n_R is the noise at the relay.

Some of the advantages of amplify-and-forward technique are simple implementation, low complexity and suitability for multi-hop relay networks. Its limitations include susceptible to noise and interference amplification, relay amplification may not fully compensate for channel losses, (Nosratinia et al, 2004). The decode-and-forward method of relay based protocol is shown in Figure 3.

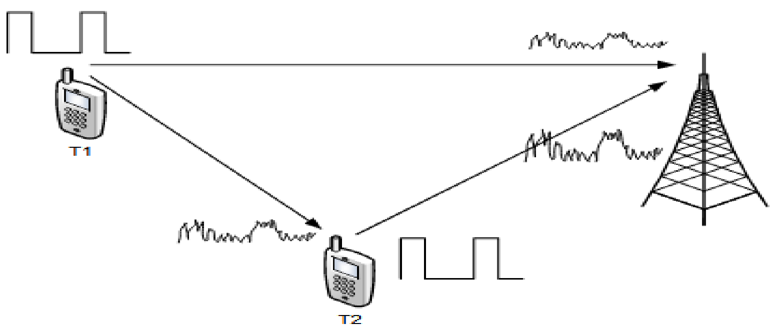

Figure 3: Decode-and-Forward Method. (Source: Marczak, 2017)

The received signal at the destination y_D in decode-and-forward method is given in Equation 3 as:

$$y_D = h_{RD} \times x_R + n_D \quad (3)$$

where h_{RD} is the channel gain from relay to destination, x_R is the relayed signal and n_D is the noise at the destination.

The advantages of decode-and-forward technique are potential for error correction at the relay, improved reliability and security against eavesdropping while its limitations are higher complexity compared to amplify-and-forward, requires accurate decoding and re-encoding at the relay, which may introduce latency, (Sendonaris et al, 2003).

Compress-and-Forward relay compresses the received signal before forwarding it to the destination. The advantages of compress-and-forward include lower relay complexity compared to decode-and-forward, especially for high-dimensional signals and efficient use of relay resources. However, compress-and-forward is limited to scenarios where signal compression is flexible and sensitivity to compression errors, (Koetter and Medard, 2003).

b. Coordinated direct communication: Coordinated Beamforming and Coordinated Multipoint (CoMP) are examples of coordinated direct communication strategies. These techniques enable nodes to coordinate their transmission to optimize signal quality and mitigate interference, (Yang and Caire, 2013).

c. Distributed antenna system (DAS): Spatial Diversity and Spatial Multiplexing are key features of distributed antenna systems. By employing multiple antennas distributed across the coverage area, distributed antenna systems improve signal reception diversity and increases data rates, (Gesbert et al, 2010).

d. Collaborative MIMO: Virtual MIMO and Cooperative Beamforming are examples of collaborative MIMO techniques. These techniques leverage cooperation among distributed nodes to create virtual MIMO systems, enhancing spectral efficiency and coverage, (Ghrayeb and Alouini, 2015).

e. Physical layer network coding (PLNC): Nodes exploit interference to perform network coding at the physical layer, improving throughput in multi-hop relay networks, (Zhang et al, 2006).

f. Interference alignment: Nodes align interference in such a way that it cancels out at the receiver, increasing spectral efficiency and capacity, (Cadambe and Jafar, 2008).

g. Cognitive radio networks: Secondary users cooperate to utilize spectrum white spaces opportunistically while avoiding interference with primary users, (Garg et al, 2013).

3.2. Benefits of Cooperative Communication in Wireless Systems

Some of the benefits of cooperative communication in wireless systems include;

a. Increased coverage and range extension: Cooperative relaying extends the coverage area beyond the range of direct communication, enhancing connectivity in remote or obstructed regions, (Liu et al, 2013).

b. Improved reliability and robustness: Cooperative communication mitigates fading, shadowing and multipath effects, improving link reliability and reducing error rates, (Xiao et al, 2011).

c. Enhanced spectral efficiency: Cooperative transmission exploits spatial diversity and multiplexing gains, enhancing spectral efficiency and throughput without requiring additional bandwidth, (Li et al, 2012).

d. Energy efficiency and battery life: Cooperative strategies optimize energy consumption by leveraging nearby nodes for relay assistance, reducing transmit power and extending battery life, (Chayawardana et al, 2018).

e. Flexibility and adaptability to dynamic environments: Cooperative protocols adapt to changing channel conditions, node mobility and network topology, offering resilience and adaptability in dynamic wireless environments, (Suraweera et al, 2015).

f. Resource sharing and load balancing: Cooperative communication allows for efficient resource sharing among nodes, balancing the network load and improving overall system performance, (Cui et al, 2018).

3.3. Key Challenges in Implementing Cooperative Communication in Wireless Systems

Implementing cooperative communication in wireless systems faces several key challenges, which researchers and engineers have been actively addressing. These main challenges include

a. Relay selection and cooperative strategy: Selecting suitable relays and determining optimal cooperation strategies considering dynamic channel conditions and relay availability possess a big threat in implementing cooperative communication, (Wang et al, 2019).

b. Resource allocation and power control: Efficiently allocating transmit power, bandwidth and other resources among source, relay and destination to maximize system performance, (Cui et al, 2017).

c. Synchronization and timing: Achieving adequate synchronization and timing alignment between multiple nodes in cooperative communication systems to avoid interference and ensure coherent reception, (Abdallah et al, 2019).

d. Relay cooperation overhead: Minimizing the overhead introduced by relay cooperation, including signaling, feedback and coordination between nodes, (Zhang et al, 2019).

e. Security and privacy: Ensuring security and privacy of transmitted data in cooperative communication networks, especially in the presence of eavesdroppers and malicious nodes, (Bloch et al, 2011).

f. Energy efficient and battery constraints: Designing energy-efficient cooperative communication protocols considering the limited life of mobile devices and energy constraints in wireless networks, (Zhang et al, 2016).

3.4. Techniques used in Cooperative Communication in Wireless Systems

Cooperative communication in wireless systems involves techniques aimed at improving reliability, coverage and spectral efficiency. Some of these techniques include;

a. Relay selection algorithms: These algorithms select the best relay (nodes) to assist in data transmission, considering factors like channel conditions, energy efficiency and relay location. Their advantage includes exploiting channel diversity by selecting the best relay dynamically and improves system performance under varying channel conditions. However, it requires accurate channel state information and overhead for relay selection and feedback, (Zhang et al, 2009).

b. Power control and resource allocation: Optimizing transmit power levels and resource allocation among cooperative nodes to minimize interference and maximize throughput. Their advantages are minimization of interference and improvement in network efficiency. This technique is limited by complexity in dynamic environments and challenges in real-time optimization, (Wang et al, 2019).

c. Physical layer cooperation: Utilizing techniques such as distributed space-time coding, network coding and joint signal processing to enhance reliability and diversity gains. Their advantages are exploiting space and time diversity gains suitable for multi-antenna relay networks. However, it requires synchronization and coordination among distributed antennas and increases complexity with the number of antennas, (Ikki and Ahmed, 2019).

4. APPLICATION OF COOPERATIVE COMMUNICATION IN WIRELESS SYSTEMS

The vital idea in user-cooperation is that of resource-sharing among multiple nodes in a network. The motive behind the investigation of user-cooperation is that the readiness to share power and computation with nearby nodes can result to savings of overall network resources. The three important applications of cooperative communication in wireless systems are:

a. Cognitive radio: Cognitive radio technology has been widely explored for its potential in enhancing spectrum utilization and efficiency in wireless communication systems. One significant application of cognitive radio is in cooperative communication, where multiple cognitive radios collaborate to improve overall system performance. Cognitive radios can collaborate in spectrum sensing tasks to detect and utilize vacant spectrum bands opportunistically, thereby improving spectrum utilization, (Zhao and Brian, 2007). The cognitive radio operation is shown in Figure 4.

b. Wireless ad-hoc and mesh network: Cooperative communication is essential in ad hoc and mesh networks, where nodes collaborate to relay data and extend network coverage. Multi-hop relaying and cooperative routing algorithms optimize network throughput, mitigate interference and improve fault tolerance in dynamic and decentralized network environments, (Jiang et al, 2012). The wireless Ad-hoc network is shown in Figure 5.

c. Wireless sensor networks (WSN): Cooperative communication enables energy-efficient data transmission and reception, extending network lifetime and coverage in wireless sensor networks. Cooperative relaying and data aggregation techniques decrease the energy consumption of individual sensor nodes, mitigating the hotspot problem and network operation, (Sharma and Kumar, 2016). Figure 6 shows the wireless sensor networks.

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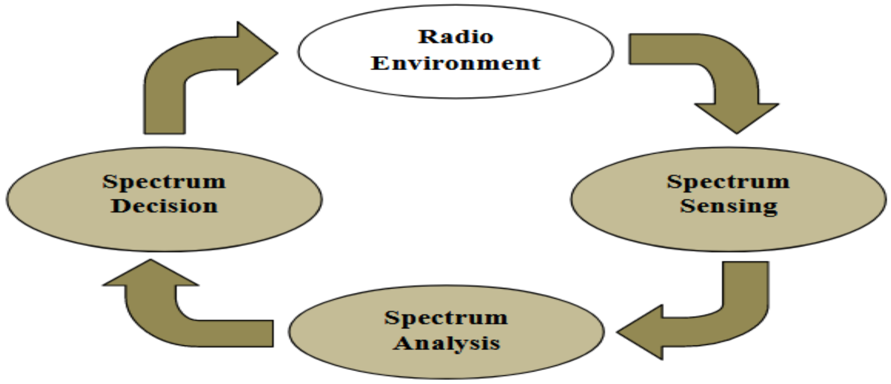

Figure 4: Cognitive radio operation (Danna and Onwuli, 2010)

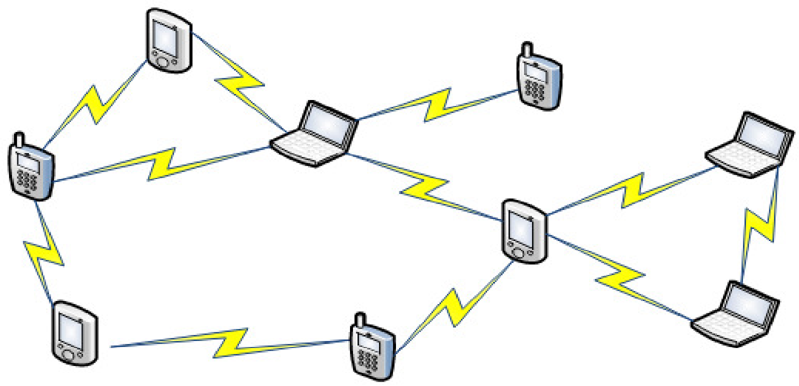

Figure 5: Wireless Ad-hoc Network. (Danna and Onwuli, 2010)

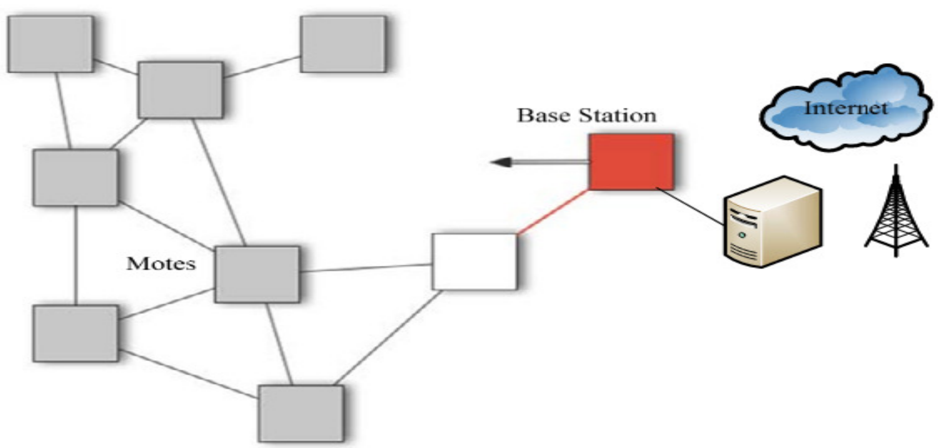

Figure 6: Wireless sensor networks (Danna and Onwuli, 2010)

4.1. Impact of Practical Considerations in Cooperative Communication in Wireless Systems

Practical considerations play a crucial role in the implementation and deployment of cooperative communication in wireless systems. Some impacts of practical considerations are;

a. Hardware constraints: Limited hardware capabilities such as processing power, memory and energy resources can affect the design and complexity of cooperative communication protocols, (Chiani et al, 2007).

b. Channel estimation and feedback overhead: Imperfect channel state information (CSI) estimation and high feedback overhead can degrade the performance of cooperative schemes, requiring practical solutions for efficient CSI acquisition and feedback, (Mallik et al, 2017).

c. Synchronization and timing alignment: Synchronization errors and timing misalignment among nodes can lead to performance degradation necessitating practical synchronization techniques for cooperative communication systems, (Jing et al, 2018).

d. Scalability and deployment flexibility: Scalability issues and deployment constraints (example, node density, and network topology) must be considered for practical deployment of cooperative communication systems, especially in large-scale networks, (Bletsas et al, 2007).

e. Interference management and coexistence: Interference from neighbouring cells or coexisting networks can degrade the performance of cooperative communication systems, necessitating practical interference management techniques, (Ghasemi and Sousa, 2011).

f. Protocol overhead and signaling complexity: Overhead from control signaling, feedback and coordination messages can consume bandwidth and energy resources, impacting the overall system efficiency, (Jayalath et al, 2006).

4.2. Future Research Directions in Cooperative Communication

Various areas aimed to address various challenges and leverage emerging technologies for future wireless systems. These future research directions include;

a. Energy-efficient cooperative communication: Investigating energy-efficient protocols and algorithms to minimize consumption in cooperative communication systems, prolonging the network lifetime, (Zhang et al, 2015).

b. Distributed cooperative beamforming: Developing distributed beamforming techniques for cooperative networks to improve spectral efficiency, coverage and interference management, (Li et al, 2020).

c. Relay selection and optimization: Exploring advanced relay selection algorithms and optimization techniques to adaptively select relays and allocate resources for maximizing system performance, (Liu et al, 2020).

d. Cooperative multi-user communication: Extending cooperative communication principles to multi-user scenarios, enabling collaborative transmission among multiple users for improved throughput and fairness, (Kim et al, 2019).

e. Security and privacy in cooperative networks: Addressing security and privacy challenges in cooperative communication, including authentication, secure key exchange and privacy-preserving data transmission, (Zhou et al, 2019).

f. Machine learning and AI-enabled cooperative communication: Leveraging machine language and artificial intelligence techniques to optimize cooperative communication protocols adapt to dynamic network conditions and enhance system intelligence, (Shi et al, 2018).

g. Integrating with emerging technologies: Integrating cooperative communication with emerging technologies such as blockchain, edge computing and Internet-of-Things (IoT) for enhanced performance and functionality, (Chaturvedi et al, 2020).

5. CONCLUSION

The fundamental idea of cooperative communication revolves around harnessing the spatial diversity inherent in wireless networks by enabling collaboration among distributed nodes. By leveraging the diversity provided by multiple nodes, cooperative communication mitigates the effects of fading, enhances coverage and improves spectral efficiency. Various cooperative communication techniques have been developed and deployed in wireless systems to assist in signal transmission to optimize signal quality and mitigate interference. Therefore, cooperative communication represents a promising paradigm for addressing the challenges of wireless communication systems. Also, by fostering collaboration among distributed nodes and exploiting spatial diversity, cooperative communication enables more robust, efficient and sustainable wireless networks.

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7. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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