Advanced Wireless Cooperative Communication Technology Postprint

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Abstract

The contradiction between limited wireless resources and continuously growing wireless service demands is becoming increasingly acute. Further improving spectrum utilization efficiency has become a critical research issue for future wireless technologies. Limited by spectrum resources and independent optimization architectures, existing wireless networks will struggle to further enhance air interface spectrum efficiency and overall network performance. To fundamentally enhance wireless spectrum utilization efficiency, intelligent collaboration among various network elements is required, thus achieving network resource sharing, improved transmission reliability and system throughput, and effective enhancement of user Quality of Service. This constitutes advanced wireless cooperative communication technology. This paper presents a systematic overview and introduction of wireless cooperative communication technology.

Full Text

Preamble

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Abstract

The limited availability of wireless resources and the continuously growing demand for wireless services have become an increasingly prominent contradiction. How to further improve spectrum utilization efficiency has emerged as a critical research topic for future wireless technologies. Constrained by spectrum resources and independent optimization architectures, existing wireless networks will struggle to enhance air interface spectral efficiency and overall network performance. To fundamentally improve wireless spectrum utilization efficiency, intelligent cooperation among various network elements is required to achieve network resource sharing, improve transmission reliability and system throughput, and effectively enhance quality of service. This is the essence of advanced wireless cooperative communication technology. This paper provides a systematic summary and introduction to wireless cooperative communication technologies.

Keywords: wireless systems, cooperative communication, cooperative mutual assistance, broadband communication

1 Introduction

Wireless networks, represented by mobile communications and broadband wireless access, have become important pillar industries of high-tech development. However, existing and upcoming systems exhibit limitations in comprehensive optimization and utilization of wireless resources, and still cannot adequately resolve the contradiction between limited spectrum resources and rapidly growing service demands. The resulting bottleneck in wireless communications has become increasingly prominent. Traditional wireless communication architectures are primarily based on independently optimized resource usage patterns. Technologies evolved and developed on this foundation exhibit characteristics of local optimization, leaving very limited room for further improvement in spectrum utilization efficiency. Solving the wireless communication bottleneck problem requires fundamentally improving the effectiveness of wireless spectrum resource utilization. Advanced wireless cooperative communication technology, which rationally utilizes resources including space, frequency, time, signals, power, terminals, and networks to maximize spectral efficiency and shared system capacity, has become the most promising approach to address broadband wireless communication bottlenecks.

The scope of cooperative communication is very broad. Based on the different network elements involved in cooperation, it can be broadly categorized into inter-base station cooperation, base station-terminal cooperation, inter-terminal cooperation, and heterogeneous network cooperation services.

Cooperative transmission represents the specific signal transmission technology under wireless cooperative communication, encompassing many aspects such as establishment mechanisms, transmission strategies, coding strategies, cooperative objectives, and diversity utilization, as shown in Figure 1 [Figure 1: see original paper]. The objective of cooperative transmission can be user-centric—improving the performance of a specific user link—or system-centric—enhancing overall system performance. Cooperation can be performed statically or through dynamic adaptive cooperation, with the latter obviously achieving better performance.

Wireless communication systems are interference-limited systems. Taking LTE/LTE-Advanced (LTE-A) as examples, inter-cell interference represents the greatest obstacle to further improving system spectral efficiency. LTE is the evolution of third-generation mobile systems (3G), often called 3.9G technology, which improves and enhances 3G air interface technology using OFDM and MIMO as the sole standards for wireless network evolution. LTE-A is the evolution of LTE, a 4G technology that meets ITU-R IMT-Advanced requirements and is backward compatible with LTE. Due to the impact of inter-cell interference, the services provided by the network exhibit extreme location-dependent variations, making network capacity and user fairness irreconcilable contradictions. Cooperative communication breaks the traditional mechanism of independent network optimization and can effectively improve or resolve these challenging issues. The following sections will systematically introduce advanced wireless cooperative communication technologies, primarily using LTE-A systems as examples.

2 Inter-Base Station Cooperation

With the proposal of LTE-A, increasing attention has been paid to both average cell spectral efficiency and cell-edge spectral efficiency, with the latter receiving the most concern. This is primarily because LTE-A systems, both uplink and downlink, are frequency-division systems based on Orthogonal Frequency Division Multiplexing (OFDM) as the fundamental multiple access scheme. OFDM is a multi-carrier modulation technology that divides the channel into several orthogonal sub-channels, converting high-speed data signals into parallel low-speed sub-data streams modulated onto each sub-channel for transmission. Unlike third-generation mobile communication systems (3G) that use Code Division Multiple Access (CDMA) as the basic multiple access scheme, LTE-A systems have no processing gain. CDMA is an interference-limited system where multiple users share wireless resources through code division, used in 2G IS-95 and 3G systems. Within a cell, due to complete frequency-domain orthogonality, there is almost no interference problem, but interference handling at the cell edge is relatively challenging.

Coordinated Multi-Point transmission and reception (CoMP) utilizes multiple cells' transmit antennas for cooperative transmission to enable wireless links at cell edges to support higher capacity and reliable transmission, effectively solving the cell-edge interference problem while improving average system spectral efficiency. CoMP is a complement and extension to traditional single-base station MIMO technology, improving cell throughput, especially cell-edge throughput, to enhance cell-edge coverage and transmission rates. Multi-point cooperative joint transmission methods can be mainly divided into two categories: signal-correlated transmission methods and signal-non-correlated transmission methods. Correlated transmission methods require that signals transmitted from various nodes have certain correlation characteristics at the receiver, enabling the signals to achieve greater combining gain. Non-correlated transmission does not need to consider correlation characteristics of signals at the receiver, primarily obtaining diversity gain.

For solving inter-cell interference problems in cellular networks, whether downlink or uplink, inter-base station cooperation is an extremely promising technology. In the downlink, multiple base stations perform coordinated multi-point signal transmission, while in the uplink, multiple base stations perform coordinated multi-point reception and joint signal processing. Multi-point cooperative transmission technology requires sharing certain information among multiple base stations, such as channel information and data information, thus requiring extremely low-latency reliable link connections between base stations to achieve millisecond-level information interaction among multiple cooperating base station nodes. Based on different information acquisition methods, multi-point cooperative transmission technology architectures can be divided into centralized CoMP architecture and distributed CoMP architecture, as shown in Figure 2 [Figure 2: see original paper].

In the centralized CoMP architecture, as shown in Figure 2(a), a central unit collects channel state information and user data for all users within the cooperative base station coverage area, and performs global optimization decisions based on this user state information, including user scheduling, resource allocation, and signal transmission methods. The central unit calculates the optimized transmission signals for each cooperating base station and transmits these optimized signals to each base station via backhaul links for transmission, requiring high time synchronization among cooperating base stations. The main challenge of the centralized architecture is that it requires high-capacity, low-latency, and high-reliability backhaul link connections between cooperating base stations and the central unit, along with the design of corresponding information interaction communication protocols.

The distributed CoMP architecture assumes that each base station scheduler has equal status and that cooperating base stations can obtain channel state information for all cooperative users, thus eliminating the need for backhaul communication links between base stations. As shown in Figure 2(b), each cooperative user reports channel state information to all base stations in the cooperation set. The greatest advantage of the distributed architecture is reduced infrastructure construction and additional signaling protocol overhead, requiring minimal changes to existing systems. Its disadvantages are twofold: first, performance is inferior to the centralized architecture; second, wireless feedback links are extremely unreliable, requiring handling mechanisms for feedback errors.

Additionally, many multi-point cooperative transmission technologies exist between these two extreme architectures to achieve optimized trade-offs between overhead and performance. The 3rd Generation Partnership Project (3GPP), a standardization organization established in December 1998 with members including ETSI, ARIB, TTC, CCSA, TTA, and ATIS, considers an approach that eliminates the central unit entity but retains information backhaul links between different base stations, with cooperative decisions made jointly by cooperating base stations, and due to the high-speed transmission capability of backhaul links, enabling synchronized signal transmission among cooperating base stations.

3 Base Station-Terminal Cooperation

Cooperation between base stations and terminals mainly has two modes: one is where multiple base stations and multiple terminals form a virtual Multiple-Input Multiple-Output (MIMO) mode for cooperative signal transmission and joint signal processing, and the other is dedicated relay-based wireless cooperative communication networks.

Multi-base station multi-terminal virtual MIMO mode cooperative signal transmission is primarily applicable in areas with multi-cell overlapping coverage. Since users in these areas have roughly equivalent distances to both the serving base station and interfering base stations, they suffer from significant multi-cell interference, resulting in degraded service quality. By performing cooperative signal transmission with nearby user terminals and base stations in the form of cooperative MIMO, as shown in Figure 3 [Figure 3: see original paper], multi-cell interference can be effectively transformed into inter-stream interference, achieving significant spatial diversity and signal processing gains through appropriate joint signal processing. MIMO is an effective space diversity utilization technology that places multiple antennas at both the base station and mobile station to form a MIMO communication link. Under MIMO antenna configurations, information transmission rates can be multiplied compared to single-antenna systems with the same bandwidth, greatly improving spectrum utilization efficiency. Multi-base station multi-terminal virtual MIMO cooperative transmission mode requires sharing certain information among base stations, thus also requiring high-speed data communication link connections between base stations.

The other mode is dedicated relay-based wireless cooperative communication networks. To improve system service quality and overall system performance, relays will play an increasingly important role in future wireless communication networks. 3GPP has defined Type 1 relays (Layer-3 relays) and Type 2 relays (Layer-2 relays) in LTE-A. For Rel-8 terminals, Type 1 relays appear as a base station; for LTE-A terminals, Type 1 relays may have more performance enhancements than Rel-8 base stations. Figure 4 [Figure 4: see original paper] shows a relay-assisted enhanced cellular wireless network. The main functions of relays are to improve link transmission quality and expand network coverage. In relay-assisted wireless networks, base stations, relays, and terminal users can perform optimized cooperative transmission together to improve user service quality and enhance system capacity. Relay-assisted cooperative scenarios can be divided into three types: two-way cooperative relay, multiple-access cooperative relay, and broadcast cooperative relay. Combining these three typical scenarios, advanced network coding technology can be employed to further improve overall system performance. Network coding, proposed in 2000, is an information exchange technology that integrates routing and coding, aiming to maximize network capacity. Its core idea is to process information received on various channels at each node in the network before forwarding it to downstream nodes, with intermediate nodes acting as encoders or signal processors. Taking uplink multiple-access relay channel cooperative transmission as an example: in the first phase, cooperative terminal users transmit signals, which are received by the cooperative relay and base station; in the second phase, the cooperative relay processes the received terminal signals (such as through network coding) and forwards them to the base station. The base station performs joint signal processing on signals directly received from terminal users and signals forwarded by the relay, detecting and decoding information from each terminal user. In this scenario, the relay and terminals perform certain cooperative transmission, with specific cooperative transmission methods requiring optimization design based on objectives and scenarios. Additionally, different relay cooperation methods have different applicable environments. From a network optimization perspective, relay cooperative transmission methods also require intelligent adaptive selection to maximize network performance optimization.

4 Inter-Terminal Cooperation

The multipath fading characteristics of wireless channels are one of the main obstacles to increasing channel capacity and improving service quality. MIMO technology, by placing multiple antennas at both the receiver and transmitter to form a MIMO channel structure, can effectively combat fading while fully utilizing spatial resources to substantially increase channel capacity. In future wireless communication systems, base stations will have increasingly powerful functions and processing capabilities. However, due to limitations in actual processing capability, power, and physical size, the number of antennas at user terminals is far smaller than that configured at base stations. To enhance overall system throughput or improve service quality for cell-edge users, terminal cooperation can construct virtual MIMO transmission, fully utilizing MIMO channel spatial characteristics to reduce multi-cell interference and increase user throughput and overall system capacity.

Traditional wireless communication networks provide services through system equipment (base stations, dedicated relays, etc.), where system equipment accounts for only a small portion and bears enormous pressure. Relying solely on system equipment makes it difficult to achieve a good trade-off between system capacity and user fairness. Meanwhile, the system also contains a large number of user equipment. If user equipment can also provide mutual assistance relay functions or cooperative transmission capabilities, it will greatly enhance overall network system capacity, improve service quality at cell edges, and enable green communication networks with lower overall power consumption.

Figure 5 [Figure 5: see original paper] shows a schematic diagram of terminal cooperative transmission in a cellular network scenario. Terminal cooperative transmission can be divided into two modes: non-relay terminal cooperative transmission and relay-based terminal cooperative transmission. Non-relay terminal cooperative transmission adopts multi-user MIMO mode. One end of the MIMO channel is the base station' s multi-antenna array, and the other end is the multi-antenna array composed of multiple users. Multiple users share the same time and frequency resources, improving system spectrum utilization efficiency. The other mode is relay-based terminal cooperative mode. This mode not only utilizes MIMO channel characteristics but also leverages the different geographical locations of different terminals. Using mutual assistance signal cooperative transmission can greatly improve service quality for user terminals and network coverage range. As shown in the figure, according to certain strategies, different numbers of users form terminal cooperative transmission groups. Terminals within the group perform information interaction before conducting mutual assistance information transmission.

Taking two-user terminal cooperative transmission as an example: one user terminal is the source user (S), and the other is the partner user (P). The cooperative transmission process is divided into two phases. Phase 1 is inter-terminal information interaction, where users transmit their information over mutually orthogonal channels, received by cooperative terminals and the base station. Phase 2 is the mutual assistance phase, where the source terminal forwards the partner terminal' s information, and the partner terminal forwards the source terminal' s information to the base station. The base station performs joint processing on all signals received during both phases, detecting and recovering information transmitted by all users in the cooperative terminal group, and can obtain significant spatial and temporal diversity gains. If appropriately combined with channel coding, distributed coding gains can be obtained to better improve link transmission quality. Additionally, more advanced network coding technologies can be introduced to design optimized relay cooperative protocols and transmission methods to further enhance system spectrum efficiency.

Distributed cooperative transmission is a key path to achieving green wireless networks. Green wireless networks aim for energy conservation, emission reduction, reduced environmental pollution and resource waste, and reduced hazards to humans and the environment, seeking harmony between humans and nature and sustainable development. Figure 6 [Figure 6: see original paper] shows an example of user terminal networked cooperative transmission: if a user terminal is located at the cell edge and has a large amount of data exchange demand with the base station, but the direct link quality between the user terminal and base station is very poor, making data exchange difficult. However, if nearby relays and user terminal devices cooperate in communication, the situation will be greatly improved. User terminals, relays, cooperative terminals, and base stations form a mesh communication link network through cooperation, enabling high-speed data interaction between user terminals and base stations. Since cooperative terminals have shorter distances to user terminals, relays, and base stations, resulting in better channel quality, communication can be performed with lower signal energy, achieving green communication objectives. This user terminal networked cooperative transmission can greatly overcome existing bottlenecks in current networks and will be an important research and development direction in the future.

5 Heterogeneous Network Cooperation

People' s demand for wireless communication rates continues to grow, yet wireless spectrum resources are extremely limited. To provide higher-capacity wireless access services, wireless access system bandwidth must increase. LTE-A employs Carrier Aggregation (CA) technology to achieve broadband wireless communication up to 100MHz, which can aggregate discontinuous frequency bands for use, providing an efficient spectrum utilization means. Carrier aggregation is only a means of effectively utilizing spectrum resources within the same network. Achieving spectrum sharing between heterogeneous networks to improve wireless access service quality is another highly attractive technical approach, although this approach has not yet been considered by 3GPP. Since customers for different services may use terminals based on different wireless access technologies, in a specific area, service providers may simultaneously offer several wireless access technologies (such as LTE, WIMAX, HSPA, etc.). Meanwhile, with continuously improving device integration, terminals supporting multiple wireless access technologies will become popular in the future. This enables service providers to potentially implement inter-heterogeneous network cooperation, optimizing decisions on which wireless access technology to use for multi-mode user terminals while guaranteeing required Quality of Service (QoS), to maximize spectrum utilization efficiency. In this scenario, the spectrum resources required by each wireless access network will vary with time and space, enabling dynamic resource allocation among heterogeneous networks by utilizing this variation characteristic.

Figure 7 [Figure 7: see original paper] shows an example of inter-heterogeneous network cooperation: two networks using different wireless access technologies provide overlapping coverage in a certain area, as shown in Figure 7(a). The two wireless access network base stations (which can be co-located) serve their accessed users using their respective independent Radio Resource Management (RRM) strategies based on predetermined spectrum allocation. RRM aims to provide quality of service guarantees for wireless user terminals within limited bandwidth, flexibly allocating and dynamically adjusting available resources for wireless transmission and networks to maximize wireless spectrum utilization, prevent network congestion, and maintain minimal signaling load. To achieve inter-heterogeneous network cooperation, Joint Radio Resource Management (JRRM) can be introduced at a higher layer to be responsible for spectrum sharing among heterogeneous wireless networks. JRRM is a collaborative approach that optimizes resource allocation across different radio access technologies. The granularity of upper-layer joint radio resource management is typically much larger than that of lower-layer Local Radio Resource Management (LRRM). Taking LTE or LTE-A systems as examples, local radio resource management typically operates at the millisecond level, while upper-layer joint radio resource management typically operates at the second or minute level. Joint radio resource management and local radio resource management cooperate in a hierarchical architecture: joint radio resource management first performs dynamic spectrum allocation among heterogeneous wireless networks based on statistical information reported by local radio resource management and certain external policies, and local radio resource management then performs scheduling and management according to the allocation results from joint radio resource management, thereby achieving more efficient spectrum utilization, as shown in Figure 7(b). Additionally, for services with less stringent real-time requirements, such as file transfer protocol (ftp) services, multi-mode terminals can simultaneously access multiple wireless access networks, providing cooperative access services through multiple heterogeneous networks for multi-mode terminals to further improve user terminal access rates.

6 Conclusion

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Note: Figure translations are in progress. See original paper for figures.