A Survey of Distributed Radio Systems

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Abstract

Distributed Radio System (DRS) has been studied for almost 15 years. The concept of DRSs includes topics such as distributed wireless networks, distributed multiple input multiple output (MIMO) systems and distributed antenna systems. In this article, we do not concentrate on introducing the concepts or implementations of the system in detail. Instead, some brand new technologies and applications about wireless radio systems are introduced and discussed. The newly gained advantages of distributed wireless network technology are discussed thoroughly in this survey, such as system components diversity improvement, cross-layer cooperation in the network, higher energy efficiency, higher spectral efficiency, higher network capacity and lower delay. As top essential parts of DRS, distributed MIMO system and distributed antenna system attract more and more attention among researchers. In this survey, the current advances and applications of these topics are introduced systematically one by one.

Keywords

Distributed Radio System (DRS), Distributed Wireless Network, Distributed Network Emulator, Distributed MIMO, Distributed Antenna System (DAS), Energy Efficiency (EE), Spectral Efficiency (SE), Capacity Gain, Railway Communications.

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1 Introduction to Distributed Radio System

Distributed Radio Systems include distributed antenna systems, distributed MIMO, distributed wireless networks and distributed spectrum sensing. Distributed Radio System or distributed communication system has been studied for almost 15 years. As Zhou and Zhao published in 2003 [zhou03], distributed wireless communication system (DWCS) is an architecture for future public wireless access.

Figure 1. a) is the traditional tree structure of a cellular system. Mobile terminals or antennas send the signal to base transceiver station (BTS). Then the handoff is controlled by the radio network controller (RNC). As the cell size decreases, the handoff frequency increases and the interference from other cells may become extremely strong. There are two solutions to this problem: (1) Limit the capacity of the communication system; (2) use another architecture such as DWCS. The distributed wireless communication system is shown in Figure 1. b). The system consists of 3 main parts: distributed antennas, distributed signal processing, and distributed high-layer control. In another survey paper of this research group [wangyya02], they divided DWCS into 3 parts: distributed antennas, distributed processing network, and distributed core network.
Distributed wireless network technology offers many advantages that centralized wireless networks cannot achieve, such as system components diversity improvement, cross-layer cooperation in the network, higher energy efficiency, higher spectral efficiency, higher network capacity and lower delay. Distributed MIMO system and distributed antenna system are top essential parts of a DRS. Most of the advantages of a DRS are gained by these two parts. Therefore, in this article we will discuss the current advances of these parts one by one.

The rest of this article is organized as follows. Section 2 presents the recent advances in distributed wireless networks. In Section 3, the main progresses of the distributed MIMO system is introduced. Then, we review the current and future applications of DRS in Section 4. The article concludes with Section 5.

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2 Distributed Wireless Networks

The core technology of distributed wireless networks is DRS. In this chapter, the recent advances in distributed wireless networks are introduced. A macroscopic view of distributed wireless network can be obtained through these achievements, such as system components diversity improvement, cross-layer cooperation in the network, and tradeoff between energy efficiency and network properties.

2.1 Receiver and Sender Diversity

The diversity of nodes is an intrinsic property of wireless networks, especially distributed networks. For example, in IEEE 802.11n-2009 standard MIMO is supported. In IEEE 802.11ac, Multi-User MIMO is supported. Figure 2 shows the diagram of Multi-User MIMO. In this figure, the multiple inputs here mean beams of multiple antenna in one sender or Access Point (AP). While in distributed wireless systems, multiple access points can transmit jointly to one or more users, as is shown in Figure 3.

![Figure 2. Beamforming with Multi-User MIMO](http://www.cse.wustl.edu/~jain/cse574-16/ftp/dist_rdo/index.html)
More details about MIMO and distributed MIMO are discussed in Section 3. In the rest of this section, we will focus on the design and implementation to exploit sender diversity in distributed wireless networks. The architecture for exploiting sender diversity is the contribution of Rahul and Hassanieh [rahul11].

Compared with sender diversity, receiver diversity is unlikely to be interfered by other receivers at the same time. Thus, the protocols that exploit receiver diversity, such as Multi-User MIMO in 802.11ac, is often studied more than sender diversity. According to [rahul11], there are three main challenges of sender diversity:

1. Synchronization among senders: there is no shared clock or centralized controller. Therefore, senders may use packet reception as a reference. However, the measurements of delays are challenging since there is also a random delay in detecting the packet reception.

2. The received signal is interfered by other signals from other senders. Attenuation varies even in a single packet because of signal combination in the medium.

3. Transmitted signals are complex numbers: Transmitted signals from different senders may add constructively or destructively instead of being carefully orchestrated as is the case with only one sender.

It is designed for OFDM and contains three main components that address these challenges one by one. The components of SourceSync include Symbol Level Synchronizer, Joint Channel Estimator and Smart Combiner. The implementation and testbed evaluations show that the

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synchronization of senders are accurate, and SourceSync improves the throughput while reducing bit errors.

2.2 Cross-layer Cooperative MAC Protocol

The idea of cooperative communications is that some nodes can act as helpers to help deliver packet from source to destination [shan11]. It is obvious that in a centralized wireless network, it is much easier to implement cooperative communications. There is a network manager or coordinator node in the network, which knows the situations of other nodes in the network. The network manager can make decisions on cooperation between nodes before or during the runtime of a wireless network. As is discussed before, there are limitations of centralized wireless networks regards to capacity and efficiency. Thus, it is important to study the cooperative communication in a distributed wireless network. However, it is difficult for distributed wireless network to realize cooperative communication until two fundamental issues are addressed: when to cooperate and whom to cooperate in a distributed wireless network?

In [shan11], Shan and Cheng address these two issues from a cross-layer protocol design perspective. Their purpose is to design and implement a MAC protocol that can exploit beneficial node cooperation by increasing link utilization. Link utilization of the network will be increased. The network with a low effective payload transmission rate (EPTR) is replaced by a cooperative network with a higher EPTR. Thus the two issues: when to cooperate and whom to cooperate with can be interpreted as:

1. When to cooperate: Find the maximum link utilization difference and achieve the improvement via cooperative MAC.

2. Whom to cooperate with: Given a group of helpers, find the optimal helper that has the highest EPTR with cooperation in a distributed way.

The performances of cross-layer cooperative MAC Protocol are evaluated by simulations. Figure 4 shows the network performance simulation results. N is the number of nodes. Figure 4 shows

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the mean throughputs and delays of the networks, respectively. We can see that the distributed network with cooperation is better than the non-cooperative network in regards to throughput and delay performance.

2.3 Distributed Network Emulator

In order to come up with a protocol for wireless distributed system, precise and realistic emulators are essential for theoretical evaluations. Tsutsumi and Koizumi discuss the features of a time-based distributed network emulator based on the IEEE 1588 PTP Version 2 standard. They analyze the influences of various system load conditions on emulator performance [tsutsumi13]. The IEEE 1588 PTP V2 standards describe a hierarchical master slave architecture for clock distribution. Under this architecture, a time distribution system consists of one or more communication media (network segments), and one or more clocks [wikipedia01].

![Figure 5. Configuration of a distributed wireless network emulator [tsutsumi13]](image)

The configuration of a distributed wireless network emulator is shown in Figure 5. The time synchronization network is used for synchronizing the PTP Grand master with the PTP Network Interface Card (NIC). Agent nodes perform emulation processing. Manager node is in charge of managing the whole emulator. All of these components are connected by a backbone network.

The emulator introduced by Tsutsumi and Koizumi uses the high-precision time synchronization features of the protocol. And they can convert mobility scenario into a time-based wireless link schedule, which saves the cost of the emulation of high-speed mobility. The idea of emulating wireless distributed network with a wired network is inspiring since it is more accurate and realistic than simulation on a PC.

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2.4 Trade-off between Throughput, Delay, Energy Cost and Link Reliability

The four most important properties of a wireless network are throughput, delay, link reliability and energy cost. This is also true for a distributed wireless network. In recent years, researchers have done their best to get higher throughput and link reliability, lower the delay and at the same time lower the energy cost as much as possible.

Abouei and Bayesteh [abouei12] present that the main challenge in a wireless network with real-time services is to use an efficient energy allocation scheme to minimize the delay and at the same time achieve a high throughput. And they theoretically study the trade-off between them. Rango and Guerriero [rango12] introduce that there is a trade-off between link-stability and energy cost. Unlike most routing protocols that select shorter routes without taking energy consumption into consideration, they design a novel routing protocol that guarantees link-stability and minimizes the energy cost in a distributed wireless network. A biobjective integer programming (BIP) optimization model is formulated to provide the route. Smith and Portmann present a dynamic non-cooperative repeated game theory to optimize both packet delivery ratio and transmit power [smith14].

3 Distributed MIMO System

Distributed MIMO system and distributed antenna system are top essential parts of DRS. As mentioned in 2.1, distributed MIMO is not totally independent from distributed wireless network. But since it is a significant part of DRS, it is receiving a lot of attention from researchers. Thus, this chapter will discuss topics about distributed MIMO that researchers are currently interested in.

3.1 Spectral Efficiency of Distributed MIMO Systems

A distributed MIMO system (D-MIMO) consists of several APs connected to a central server and operating as a large distributed multi-antenna AP [balan12]. Figure 6 shows the structure of distributed antenna system (DAS). In DAS, remote antenna units (RAUs), which are only used to send and receive signals, are distributed over a wide range. RAUs are connected with baseband processing unit (BPU). BPU uses advanced signal processing methods to process the signals from RAUs. The D-MIMO system combines the advantages of MIMO and DAS.
Therefore, D-MIMO system can improve the spectral efficiency and power efficiency, as a result, it can provide a much higher data rate service to a larger number of users without increasing the transmit power and bandwidth. However, is D-MIMO always better than traditional Collocated MIMO (C-MIMO) in spectral efficiency and power efficiency? The spectral efficiency of (M, L, N) D-MIMO and C-MIMO are compared in Wang's research [wangyyb13]. M is the number of antennas of the mobile terminal, L is the number of antennas per RAU, and N is the total number of RAUs.

The theoretical analysis shows that D-MIMO is not always better than C-MIMO in spectral efficiency, since D-MIMO has different degrees of path losses and shadowing fading caused by
different access distance to different distributed antennas. The relationship between \((M, L, N)\) and mean the spectral efficiency of a MIMO system can be summarized in the following formula.

\[
\begin{cases}
\text{MSE of DMIMO is larger; } M \leq L \text{ and } N \text{ is very large} \\
\text{MSE of CMIMO is larger; } M \geq NL
\end{cases}
\]

For both systems, the mean outage spectral efficiency of the D-MIMO system is higher than that of the C-MIMO system.

### 3.2 Capacity Gain of the System

Besides improving the spectral efficiency, another feature of the MIMO system is achieving higher capacity. In single input single output (SISO) system, there is only one sender and receiver pair. On the other hand, in MIMO system, there can be many pairs of senders and receivers. If we can separate the signals from different sender and receiver pairs, the system's capacity will be enlarged greatly. However, in traditional MIMO system, multiple antennas are located densely in hand-held devices so that there is severe interference between signals. Besides, limited number of nodes are allowed in such small devices. This is the main reason why the idea of a D-MIMO system came to be. In D-MIMO system, wireless users with single transmit and receive antenna cooperate in clusters to form DAS. There can be up to \(n\) users in \(n\) sender and receiver pairs, and the system can be distributed over a larger area \(A\) to make the nodes be located further apart.

However, even though D-MIMO indeed brings higher capacity, the capacity still is limited when the transmit number \(n\) is large. Ozgur and Lévêque present that this is because when the transmit number becomes large, the channels between pairs will be correlated, which will limit the capacity gain \([\text{ozgur13}]\). Thus, they systematically study the relationship between the distributed area \(A\) of clusters, transmit pairs number \(n\), and the carrier wavelength \(\lambda\). \(A^{(1/2)} / \lambda\) is defined as the degree of freedom (DoF) of the D-MIMO system. They compare the D-MIMO system with traditional multi-hop in ad-hoc networks. The conclusion of their results can be summarized in the following formula.

\[
\begin{cases}
\text{adhoc is better than DMIMO; } \frac{\sqrt{A}}{\lambda} \leq \sqrt{n} \\
\text{DMIMO with limitation is better; } \sqrt{n} \leq \frac{\sqrt{A}}{\lambda} \leq n \\
\text{DMIMO performs ideally; } \frac{\sqrt{A}}{\lambda} \geq n
\end{cases}
\]
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(1) When $A^{(1/2)/\lambda} \leq n^{(1/2)}$ the DoF of the system is very small. Thus there is no need to use D-MIMO, which brings extra computation complexity. Thus, D-MIMO performs worse than ad-hoc network.

(2) If $A^{(1/2)/\lambda} \geq n$, there is enough DoF in the system, so there are not any physical constraints to obtain the ideal capacity gains by implementation of D-MIMO. D-MIMO is definitely better than ad-hoc network.

(3) When $n^{(1/2)} \leq A^{(1/2)/\lambda} \leq n$, DoF is smaller than $n$, so there are physical constraints to obtain the ideal capacity gains by D-MIMO. However, at this time, the system can still get larger capacity gains with D-MIMO than with ad-hoc.

3.3 Achieve High Data Rate

In Section 3.2, we discuss that there is a limitation on the capacity gain in the D-MIMO system due to the physical constraints of a wireless system. In this section, a recent research about how to achieve higher data rate based on the fact of limitations is introduced. Balan and Rogalin systematically study the data rate gain that can be obtained by the D-MIMO system [balan12]. The Distributed MIMO testbed was built in University of Southern California. They claim that it is the first time theoretical data rate gain is tested in a real D-MIMO testbed.

Table 1 shows the comparison of different precoding schemes. When full channel state information is available at the transmitters (CSIT), Zero-Forcing Beamforming (ZFBF) and Tomlinson-Harashima Precoding (THP) are used. Blind Interference Alignment (BIA) is used instead when channel state information is unavailable. Their data rate gains are compared with traditional TDMA scheme theoretically and experimentally. Figure 7 shows the experimental results of multiplexing gain of THB and BIA over TDMA. THB and BIA get more gains over TDMA because they provide more degrees of freedom. DoF of D-MIMO system is discussed in Section 3.2. ZFBF is not shown in the figure because its result is similar to THB. Experiments show the data rate results the system gets is very close to the theoretical results.

<table>
<thead>
<tr>
<th>Properties in following condition</th>
<th>Full CSIT</th>
<th>No CSIT</th>
<th>Full/no CSIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>complexity</td>
<td>ZFBF</td>
<td>THB</td>
<td>BIA</td>
</tr>
<tr>
<td>Linear or not</td>
<td>lower</td>
<td>low</td>
<td>-</td>
</tr>
<tr>
<td>High SNR</td>
<td>-</td>
<td>better</td>
<td>-</td>
</tr>
<tr>
<td>Low SNR</td>
<td>better</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Client statistically equivalent</td>
<td>-</td>
<td>-</td>
<td>optimal</td>
</tr>
<tr>
<td>Remove interference</td>
<td>-</td>
<td>-</td>
<td>perfect</td>
</tr>
<tr>
<td>Sum rate in testbed</td>
<td>8bps/Hz</td>
<td>8bps/Hz</td>
<td>5.3bps/Hz</td>
</tr>
</tbody>
</table>

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3.4 Adaptive Distributed MIMO

Besides spectral efficiency, capacity and data rate analysis and improvements, researchers also study how to combine the technology from other modern network systems with the D-MIMO system. Chen and Nijsure [chen13] combine 'feedback adaptive system' with the D-MIMO system in radar detection. Figure 8 shows the architecture of their adaptive D-MIMO radar. A two-step waveform optimization algorithm is used to transfer high quality and suitable signals from transmitter to receiver. The first step of the algorithm is to maximize the mutual information (MI) from transmitter to receiver; and the second step is to minimize the MI between the original signal and backscatter signals.

On the receiver side, the system not only deals with target detection but also estimates the situation of each channel and dynamics of the system such as channel status, signal quality, noise level. Then the receiver will send the estimation back to the transmitter via a feedback
mechanism. After getting the current situation of the system, the waveform optimization system can dynamically get the optimal solution of waveform according to the environment changing of the system. As shown in Figure 9, the simulation results show that the two-step optimization performs better than only one-step algorithms.

Figure 9. MSE in target response extraction [chen13]

4 Application of Distributed Antenna System

Since the distributed network system has the intrinsic features of high spectral efficiency, capacity and data rate, the application of DAS has been a hot research area in recent years. Thus, DAS techniques have been paid intensive attention in the standardization of the third generation partnership project (3GPP) long-term evolution (LTE) and LTE-Advanced [3gpp01]. In this chapter, the energy and spectral-efficiency tradeoff in application will be discussed first. Then the applications of DAS in high-speed train and subway tunnel environment will be introduced. The discussion demonstrates that DAS can work in high-speed environment and other environments, which are tough for centralized wireless network.

4.1 Energy and Spectral Efficiency Tradeoff in Application
Battery life is one of the most important properties to measure if a wireless radio system is applicable or not. As is mentioned in former sections, in distributed network, researchers tend to find the balance between data rate, delay, throughput, link quality and energy cost. In the application of DAS and D-MIMO, the balance of spectral efficiency (SE) and energy consumption is studied instead.

He and Sheng [he13] present a method to maximize energy efficiency (EE), subject to constraints on power of each RAU, bit-error rate and proportional data rates. The optimization problem can be described as the following formula.

$$\text{MAX: Objective function} = \text{Energy efficiency model}$$

$$\text{subject to: power of each RAU} \geq P_i$$

$$\text{bit error rate} \leq E_i$$

$$\text{Proportional data rate} \geq R_i$$

Figure 10. EE versus SE ( is scalar weight in EE model) [he13]
He and Sheng model the EE function and the constraints. They also convert the optimal problem with a non-convex objective function and non-linear constraints to a simpler single objective problem. As shown in Figure 10, their experimental results show that there is a saturation point in EE. No matter how much power is used, EE cannot be improved when it reaches the saturation point. Thus the optimal solution for EE must exit at the minimum point at which SE satisfies the requirement. The results also show that EE optimization has higher efficiency as compared to rate adaptive optimization with the same SE.

4.2 Application in Mobile Communication in High-speed Train

Since DRS has plenty of advantages, when and where will the system be applied in wireless communication? The hottest application of DAS is mobile communication in high-speed train (HST).

The peak data rate of LTE-Advanced reaches 3 Gbps downlink and 1.5 Gbps uplink [3gpp01]. However, in HST, the speed of which is 300km/h, the data rate supported by global system for mobile (GSM) for rail (GSM-R) is less than 200 kbps. The challenges in achieving high data rate in HST is:

(1) Since mobiles communicate with base station directly, the carriages in the train lead to the attenuation of the signals.

(2) Since the train is moving in a high speed, there will be frequent handoffs and packet drops during the signal transmission.

(3) The physical properties of the network, such as channel quality, noise level will also vary frequently due to the high-speed movement of the mobile.

According to Wang and Zhu [wangyyc12], the application of DAS can address the above mentioned challenges one by one:

(1) A hierarchical two-hop network has been introduced for HST. [wangyyc12] Instead of direct communication between mobiles and base station, one more hop (antenna) is added on the top of the train. Therefore, the influences of carriages are mostly eliminated.

(2) Different from traditional collocated antenna system, where the antenna units should be centrally collocated, RAU in DAS can be widely distributed and connect to base station via wire. This feature of DAS can obviously shorten the wireless communication distance between mobile and base station. Thus, the frequencies of handoffs and packet drops will be reduced accordingly.

(3) Since the wireless communication distance is shortened, the speed of communication will increase. Thus, the variances of network environment will be reduced. Besides, the data rate of communication will surely increase due to the higher communication speed.
4.3 Distributed Antenna System in Subway Tunnel Environment

Based on the advantages of DAS in HST, we may ask whether DAS can also be applied in subways or tunnels. As we all know, the wireless network environments in subways and tunnels are even more challenging than railways. In most parts of the world, at most of the time, passengers cannot achieve any wireless signals in subway or tunnels. Along with the inconveniences brought to passengers, the low data rate and poor signal may also influence the train's surveillance and control through wireless network. Thus, high-quality radio communication can increase the capacity and reliability of subways.

The modeling and implementation of DAS in subway tunnels was studied 10 years ago [rodriguez07]. Guan and Zhong obtain the measurements of DAS in real subways and tunnels to better statistically model the wireless environments [guan12]. Effects such as near shadowing of long trains, path loss, shadow fading, multimode, and signal attenuation have been systematically measured at high accuracy to permit the modeling, design and implementation of a distributed antenna solution. The accurate statistic obtained by the experiments will help the design of DAS in subway tunnels to meet the service quality requirements for subway systems. I believe the application of DAS will be the starting point for distributed ratio system to gain its popularity in the near future.

5 Conclusion

This survey introduces some current technologies and applications about wireless radio system. The macroscopic view of distributed wireless network can be obtained by introducing the recent advantages of distributed wireless network technology. As one of the essential parts of DRS, D-MIMO system improves the spectral efficiency and power efficiency, so that provides much higher data rate service. Algorithms and solutions to improve the properties of D-MIMO system are systematically presented in this survey. The progresses in D-MIMO system show a great opportunity to improve the performances of wireless networks. The current applications of DAS show that its application in HST or subway tunnels will be the start point for distributed ratio system to gain its advantages and popularities in the near future.

References

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List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>BIA</td>
<td>Blind Interference Alignment</td>
</tr>
<tr>
<td>BPU</td>
<td>Baseband Processing Unit</td>
</tr>
<tr>
<td>C-MIMO</td>
<td>Collocated Multiple Input Multiple Output</td>
</tr>
<tr>
<td>CSIT</td>
<td>Channel State Information is available at the Transmitters</td>
</tr>
<tr>
<td>D-MIMO</td>
<td>Distributed Multiple Input Multiple Output</td>
</tr>
<tr>
<td>DAS</td>
<td>Distributed Antenna System</td>
</tr>
<tr>
<td>DoF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>DRS</td>
<td>Distributed Radio System</td>
</tr>
<tr>
<td>DWCS</td>
<td>Distributed Wireless Communication System</td>
</tr>
<tr>
<td>EE</td>
<td>Energy Efficiency</td>
</tr>
<tr>
<td>EPTR</td>
<td>Effective Payload Transmission Rate</td>
</tr>
<tr>
<td>HST</td>
<td>High-speed Train</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institution of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>MI</td>
<td>Mutual Information</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Spectral Efficiency</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>NIC</td>
<td>Network Interface Card</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>PTP</td>
<td>Precision Time Protocol</td>
</tr>
<tr>
<td>RA</td>
<td>Rate Adaptive</td>
</tr>
<tr>
<td>RAU</td>
<td>Remote Antenna Unit</td>
</tr>
<tr>
<td>SCNR</td>
<td>Signal to Clutter Plus Noise Ratio</td>
</tr>
<tr>
<td>SE</td>
<td>Spectral efficiency</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>THP</td>
<td>Tomlinson-Harashima Precoding</td>
</tr>
<tr>
<td>ZFBF</td>
<td>Zero-Forcing Beamforming</td>
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