Chapter 3

# Network Coding for Distributed Antenna Systems

Rafay Iqbal Ansari, Muhamad Arslan Aslam,
Syed Ali Hassan and Chrysostomos Chrysostomou

Additional information is available at the end of the chapter

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**Abstract**

The mushroom growth of devices that require connectivity has led to an increase in the demand for spectrum resources as well as high data rates. 5G has introduced numerous solutions to counter both problems, which are inherently interconnected. Distributed antenna systems (DASs) help in expanding the coverage area of the network by reducing the distance between radio access unit (RAU) and the user equipment. DASs that use multiple-input multiple-output (MIMO) technology allow devices to operate using multiple antennas, which lead to spectrum efficiency. Recently, the concept of virtual MIMO (VMIMO) has gained popularity. VMIMO allows single antenna nodes to cooperate and form a cluster resulting in a transmission flow that corresponds to MIMO technology. In this chapter, we discuss MIMO-assisted DAS and its utility in forming a cooperative network between devices in proximity to enhance spectral efficiency. We further amalgamate VMIMO-assisted DAS and network coding (NC) to quantify end-to-end transmission success. NC is deemed to be particularly helpful in energy constrained environments, where the devices are powered by battery. We conclude by highlighting the utility of NC-based DAS for several applications that involve single antenna empowered sensors or devices.

**Keywords:** network coding, D2D, opportunistic networks, cooperative communication, energy-efficiency

## 1. Introduction

The evolution of 5G networks will open up numerous new opportunities in terms of applications that require higher data rates, reliability and low latency. Spectrum limitation is one of the obstacles that could impede the growth of 5G networks. Several solutions have been proposed to overcome the spectrum scarcity. The efficient utilization of available spectrum resources has gained attention of the research community. Distributed antenna systems (DAS) are considered as one of the solutions for ensuring efficient utilization of spectral resources [1] and providing high data rates. DAS are based on a dense deployment of remote access units (RAUs) in a cellular network, thereby reducing the distance between the users and the RAUs. The RAUs are connected to a central control module through high rate dedicated links. The presence of the users in a close vicinity allows the RAUs to transmit at low power, which leads to energy savings. One of the underlining features of 5G networks is the concept of *green communications* [2]. DAS can help in realizing green communications by ensuring energy-efficient network operation. Several works can be found in literature that addresses the energy-efficiency (EE) of DAS [3, 4]. Another key technology is the multiple-input multiple-output (MIMO), which signifies the presence of multiple antennas in the form of an antenna array [5]. MIMO-assisted DAS provides a robust solution for network connectivity by mitigating the impact of interference and allowing the transmission of multiple data streams simultaneously.

Recently, the concept of virtual MIMO (VMIMO) has been explored for dense network environments. In VMIMO, the single antenna sensors or user equipments cooperate to form a cluster. The cluster is then considered as a single MIMO system that transmits packets to the adjacent cluster in a multi-hop manner [6]. In this chapter, we consider the VMIMO-assisted DAS and employ network coding (NC) to gauge the network performance. NC techniques can further improve the performance of the network with regards to EE and spectral-efficiency (SE) by avoiding packet retransmission. Packets sent by the source nodes can be combined to form coded messages, which are then sent to the destination. NC is particularly helpful in energy constrained environments, where the devices possess limited battery power. NC can be employed in DAS to enhance the network throughput and improve the end-to-end success of the network [7]. In DAS involving multi-hop transmissions, NC can minimize the transmission delay by allowing cooperation between nodes. In this chapter, we consider two DAS environments (1) Low-density DAS, and (2) High-density DAS. Applications for low-density DAS include device-to-device (D2D) communications, where a few antenna elements in the form of user equipments (UEs) are trying to connect to each other. On the other hand, a typical wireless sensor network, where a large number of nodes are deployed in an area, provides an example of high-density DAS. The remainder of the chapter is organized as follows. First, we enlist the benefits of DAS and applications that utilize DAS to enhance coverage and quality-of-service (QoS). Next, we discuss MIMO-assisted DAS and the concept of VMIMO, which is followed by the evaluation of NC in the aforementioned DAS environments. The results quantify the end-to-end transmission success and probability distribution at different network parameters, providing a designerâ€™s perspective for VMIMO-assisted DAS.

## 2. Applications, benefits and limitations of DAS

DAS can help in realizing several new applications. There are several benefits associated with DAS; however, there are also some limitations that need to be taken into consideration while designing networks based on DAS. Multi-service indoor DAS (MS-IDAS) is a class of DAS, which is particularly helpful in applications that involve indoor environments, such as shopping malls, restaurants and bus stations. The hardware modules for such environments are manufactured by keeping in view the esthetics of the environment [8]. DAS are helpful in network applications that involve mobility. Similarly, DAS allow the expansion of coverage to areas, which cannot be covered by the traditional network due to the blockage by physical structures. The geographical areas that undergo blockages are referred to as *coverage holes*. DAS can alleviate the situation with regards to coverage holes and can help in realizing the concept of ubiquitous connectivity. For example, the network connectivity can be ensured on a high speed train by employing the concept of DAS [9].

Massively DAS (MDAS) lead to higher network diversity but at the cost of higher computational complexity. A coordinated antenna selection (CAS) is required to control the operation of a MDAS [10] by selectively activating the antenna elements that provide the best link quality. CAS can help in mitigating the impact of co-channel interference by coordinating the antenna activation; however, one of the limitations of designing a CAS for MDAS is the perfect channel state information (CSI) that is required for scheduling the transmissions. The practical limitations with regards to acquiring perfect CSI restrict the MDAS operation by allowing it to serve less number of users. Channel estimation or prediction techniques are required for smooth operation of a MDAS.

The geographical distribution of RAUs allows spatial degrees of freedom but at the cost of higher computational complexity. In a multi-user DAS-based network, the users with the best channel conditions are served while the users suffering from adverse channel conditions are not scheduled, leading to unfairness in resource allocation [11]. The concept of ubiquitous connectivity for 5G networks is also compromised due to unfair resource allocation. A fair scheduling mechanism is necessary to ensure that the QoS requirements of all the users are met with efficient utilization of resources. Moreover, in an internet-of-things (IoT) environment it is imperative that all the devices and users are able to connect to the network. Concluding, the benefits of DAS include

- spatial diversity,
- efficient spectrum utilization,
- energy-efficiency,
- higher network rate,
- enhanced end-to-end success,
- ubiquitous connectivity,
- interference mitigation.

DAS can go a long way in realizing new applications that would arise with the introduction of 5G networks. An illustration of a DAS based network is shown in **Figure 1**, where the DAS nodes are connected through fiber links to the central processing unit. DAS allows to extend the coverage to geographical areas which are not covered by the traditional networks due to physical blockages.

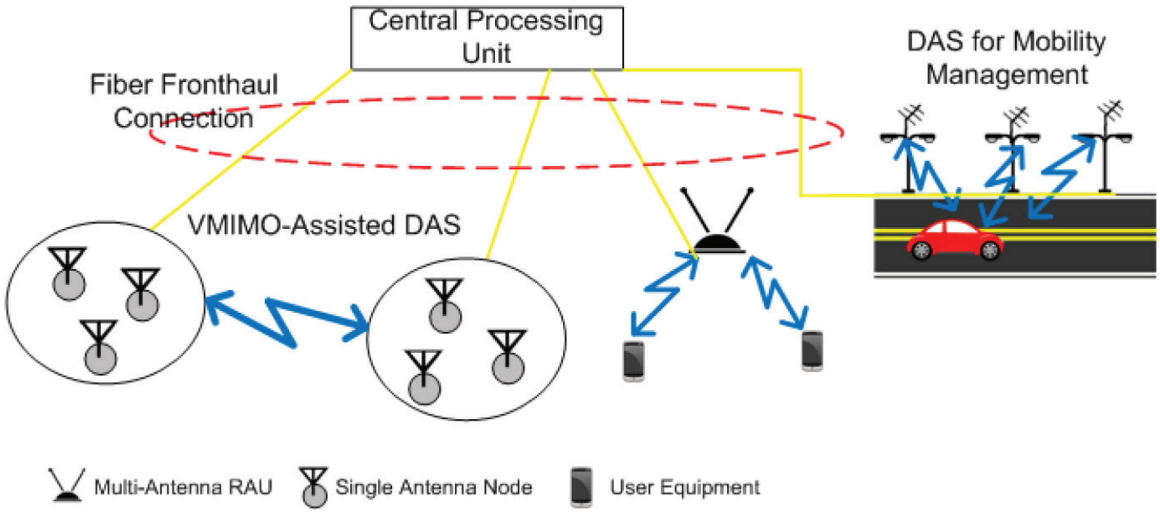


**Figure 1.** Example of DAS-based network.

## 3. MIMO-assisted DAS

Based on the number of antenna elements, the DAS can be further categorized as

- DAS based on single-antenna RAU
- DAS based on multiple-antenna RAU

Initially, the research related to DAS focused on single-antenna RAU [12]. However, the introduction of MIMO technologies opened up a new arena with regards to spectrum utilization. The integration of the concept of DAS empowered by MIMO envisioned significant gains in terms of network reliability. The presence of multiple antennas at the RAUs and users allows multiple links to be established between the user and the RAU, leading to higher rates. Moreover, the number of users also impact the performance of the MIMO assisted DAS. If there are multiple users within the coverage range of the RAU, beamforming is conducted to serve all the users. The network performance is impacted by the increase in the antenna elements at the RAU [13].

MIMO can be categorized into: (1) single-user MIMO (SU-MIMO), (2) multi-user MIMO (MU-MIMO). The impact of channel environment on the network performance is less pronounced in case of MU-MIMO, as compared to SU-MIMO. The reason for such behavior lies in the multi-user diversity that can be achieved through MU-MIMO [14]. In SU-MIMO, the resources are dedicated to a single user for achieving higher capacity. Spatial multiplexing and beamforming aid in forming high capacity transmission links. Spatial multiplexing allows the transmission of multiple streams, where these streams undergo spatial processing at the receiver [15]. On the other hand, MU-MIMO allows allocation of resources to multiple users leading to multi-user diversity and performance gains as compared to SU-MIMO. MU-MIMO is particularly helpful in scenarios marked by high traffic. MU-MIMO leads to increased throughput, increased diversity gain and reduced costs as compared to SU-MIMO.

MIMO involves an integration of multiple antenna elements at access points (APs) and base stations (BSs), leading to higher network capacity. Transmission beams with high directivity are formed through beamforming, leading to low interference and high transmission gain communication links. The concept of MIMO has been included in several wireless network standards such as IEEE 802.11n, 802.11 ac WLAN, 802.16e (Mobile WiMAX), 802.16 m (worldwide interoperability for microwave access (WiMAX), 802.20 mobile broadband wireless access (MBWA), 802.22 (WRAN), 3GPP long-term evolution (LTE) and LTE-Advanced evolved universal terrestrial radio access(E-UTRA) [16]. Resource allocation techniques for massive MIMO have been devised to ensure efficient utilization of resources. The resource allocation is conducted by keeping in view the requirements of the desired QoS of the individual users. Moreover, the MIMO is backed by spatial diversity and multiplexing techniques to improve the network performance. Spatial multiplexing is required in multi-user MIMO to enjoy the gains of spatial diversity. In multi-user MIMO, simultaneous data streams are sent to multiple users to increase the network capacity. Below, we list some challenges related to massive MIMO:

- manufacturing low cost base stations
- ensuring hardware compatibility
- designing lower antenna size
- acquiring CSI
- designing low power base stations

Third generation partnership project (3GPP) has defined the key features of MIMO and refers to two-dimensional (2D) antenna array structures as full dimensional MIMO (FD-MIMO). FD-MIMO involves 3D channel propagation, where the path loss is dependent upon the height and distance of the user from the AP. The elevation angle is also one of the aspects that is included in the 3D channel model. An increase in the number of antennas allows a simple interference management by using a precoder [17]. The presence of a dense antenna array also allows network robustness in case of hardware failures [18]. SE and EE can be achieved by utilizing antenna arrays at the user and the BS, but the size of antenna array depends on the hardware compatibility and size of the device.

### 3.1. Virtual MIMO for multi-hop networks

5G networks would involve densification of devices and D2D networks are considered as one of the technologies that could alleviate the burden on the BS. The BS can be equipped with multiple-antennas but the D2D UE is limited to having a single-antenna capability due to size limitations. However, in the up-link transmission mode, multiple users can coordinate with each other to use the same sub-channels and create a virtual antenna array, leading to the concept of VMIMO [6]. The concept of VMIMO is also helpful in multi-hop networks involving cluster environments, e.g., D2D cluster networks [19]. Each cluster contains multiple nodes having single antennas. The cluster acts as a multi-antenna node and helps in transmitting the information cooperatively to the adjacent clusters [20]. The relay mechanisms that can be utilized to realize multi-hop transmission between clusters or nodes include amplify-and-forward (AF), compress-and-forward (CF) and decode-and-forward (DF). Another VMIMO architecture that has been proposed is the multi-hop relaying based on coding techniques. The relay node collects the information sent by the transmitters and forms a coded message that is shared with the destination in the next time slot [21].

## 4. Network coding for DAS

In Section 1.4, we built the case for DAS by presenting their advantages with regards to 5G networks and also discussed MIMO assisted DAS. In this section, we signify the utility of employing NC in DAS. We divide the study into two environments:

1. Low density DAS (D2D multi-hop networks)
2. High density DAS [opportunistic large array (OLA) multi-hop networks]

In the proceeding, we first provide a brief overview of the NC techniques that have been discussed in literature. Next, we describe the system models of both environments and quantify the performance gains achieved through NC in terms of end-to-end transmission success.

### 4.1. Network coding in low density DAS (D2D multi-hop networks)

D2D networks are based on a peer-to-peer (P2P) network between devices instead of relying on the BS for data transmission. The BS is responsible for supporting the control plane, while the devices establish a direct link to share the message with each other. Cooperative diversity could be exploited by D2D networks for ensuring reliable communication. NC-aided cooperative D2D networks enhance the success probability of end-to-end data delivery. In [22], NC is employed in BS-assisted D2D networks. **Figure 2** shows the system model, where the BS operates as a relay between the two D2D users. The D2D users transmit in the first two time slots. In the third time slot, the BS applies exclusive OR (XOR) to form a coded message and transmits it to the D2D users.

Generally, interference is considered as an impairment, but [23] introduces the concept of physical layer NC (PNC) in D2D networks, where interference is maneuvered positively to form coded messages. PNC scheme simply superimposes electromagnetic waves and forms a code. **Figure 3** highlights the PNC operation in a two-source, one-relay scenario. The first time slot is reserved for transmission of the messages $X1$ and $X2$ by the D2D users. The relay performs PNC to form a coded message $X3$ in the second time slot. The conventional two-source relay networks utilize four time slots to complete information exchange. However, PNC-assisted two-source relay network realizes information exchange in two time slots, thereby enhancing the network capacity.

NC can be utilized to enhance performance in mobile cloud scenarios [24]. The authors highlight the diversity gains that can be achieved in high node density D2D networks. The results also show the benefits of D2D networks assisted by NC for providing live data transmission. The devices form a cooperative network and share chunks of data cooperatively to complete the downloading process. The proposed technique leads to energy savings and helps in avoiding delay in transmissions.

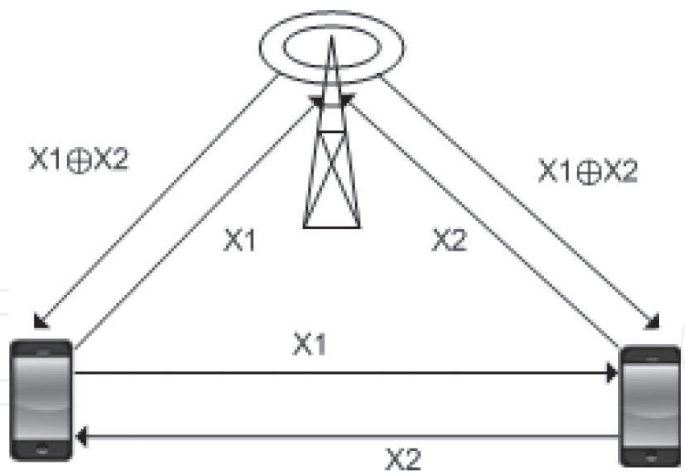


**Figure 2.** Network coding assisted D2D cooperative network [22].

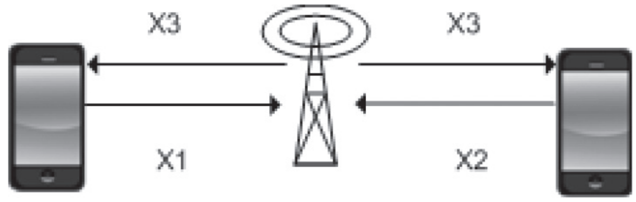


**Figure 3.** Physical layer network coding assisted D2D communication network [23].

In [25], the authors present the integration of caching techniques and NC-assisted D2D communication networks. Such networks are particularly helpful in realizing the proximity services. D2D users that require similar content can utilize such networks receive the desired content, cooperatively. Ref. [26] presents a comparison between D2D aided by space–time analog NC (STANC), traditional D2D networks and D2D aided by analog NC. The system model comprises of a relay that has two antennas and three D2D pairs. The relay employs amplify and forward technique to transmit the message to the destination. The desired information is recovered at the destination through zero forcing detection. The average sum rate is computed to highlight the utility of STANC as compared to other techniques.

*4.1.1. Evaluation model*

In our analysis, we consider a DAS with 3-D2D pair network aided by a relay node as shown in **Figure 4**. One transmission cycle comprises of four time slots. The source $S_1$ transmits in the first time slot. Sources $S_2$, $S_3$ and relay $R$ transmit in the next three time slots, respectively [27]. The transmission is considered successful if the received SNR is greater than a threshold $\tau$. The source $S_1$ broadcasts its message $X_1$ in the first time slot, which is received by all other receivers and sources, as shown in **Figure 4(a)**. In the next time slot, source $S_2$ formulates a coded message by employing NC, i.e., $a_1 X_1 + a_2 X_2$, and broadcasts the coded message as shown in **Figure 4(b)**. Linearly independent codewords are formed by choosing the coefficients $a_1$ and $a_2$ from a finite Galois field. In the same manner, $S_3$ forms a coded message $a_3 X_1 + a_4 X_2 + a_5 X_3$ and transmits in the third time slot (**Figure 4c**), followed by the transmission from relay $R$ in the fourth time slot (**Figure 4d**). The destination receives multiple codewords and it can recover the intended information by utilizing Gaussian elimination technique.

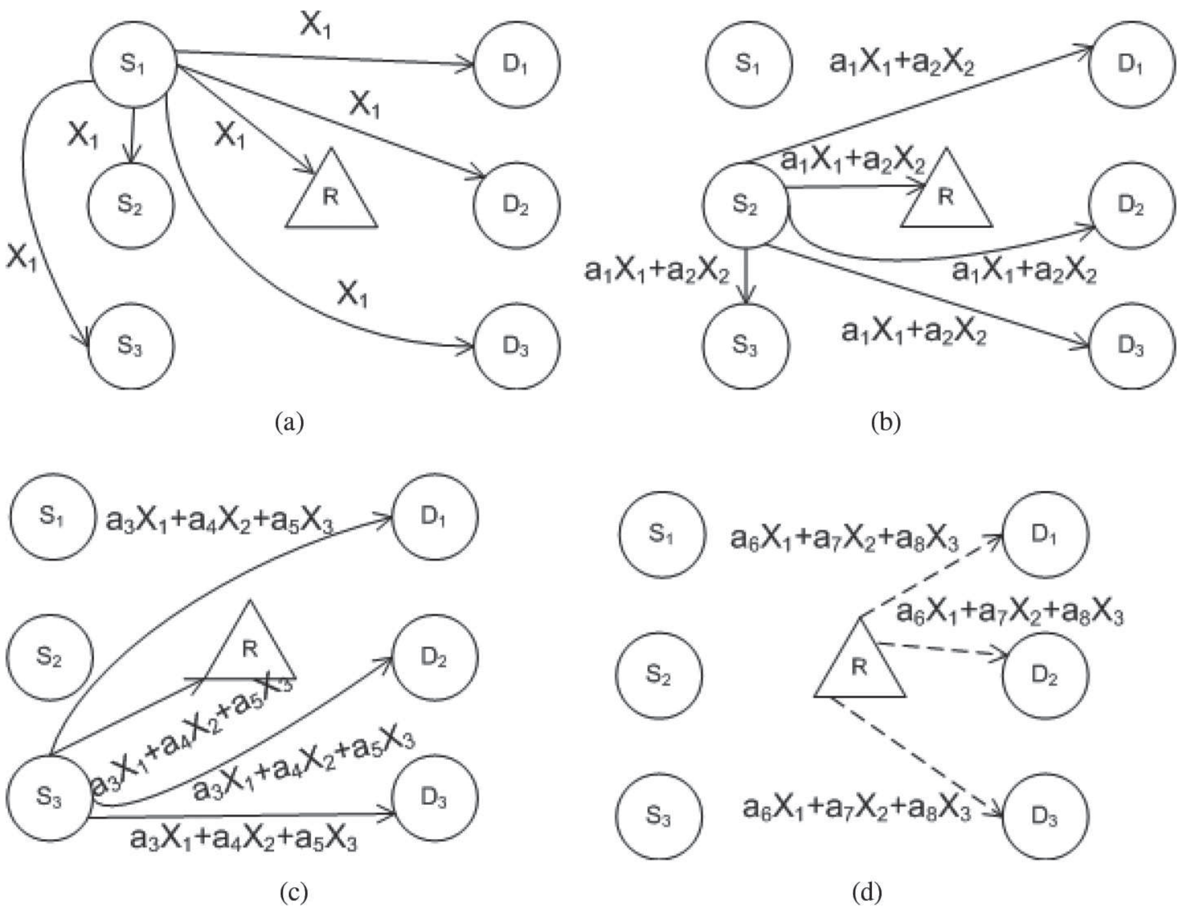


**Figure 4.** Relay-aided-network-coded (RANC) D2D network transmission model [27].

The transmission model presented in **Figure 4** is designed to provide diversity to the channels suffering from weakest links. In the case shown in **Figure 4**, the highest priority $P_1$ is assigned to D2D pair 1, as in the ideal case the destination $D_1$ can receive four codewords that contain the message $X_1$. Similarly, priorities $P_2$ and $P_3$ are assigned to the destinations $D_2$ and $D_3$, respectively. It is pertinent to mention that the transmission flow can be adapted dynamically according to the channel states. For example, if D2D pair 2 suffers from worse channel conditions, then priority $P_1$ could be assigned to it, leading to more diversity and hence an increase in success probability for the transmissions that are destined for $D_2$. Another criteria that drives the assignment of the priorities is the sensitivity of the information that is being shared over the network. If the information being transmitted is sensitive in nature, then a higher priority could be assigned to that D2D pair.

A comparison between traditional relay-aided D2D network and RANC is presented [27]. The aim of the comparison is to ascertain the deployment that best suits the QoS requirements in a particular network setting. **Figure 5** signifies the behavior of simple relay-aided D2D network and RANC versus the signal-to-noise ratio (SNR) margin. SNR margin is defined as SNR normalized by the threshold, $\tau$. In these results, we assume that D2D pair 1 is assigned priority $P_1$. We determine the success probability for two different scenarios:

1. Network model excluding the impact of path loss
2. Network model including the impact of path loss

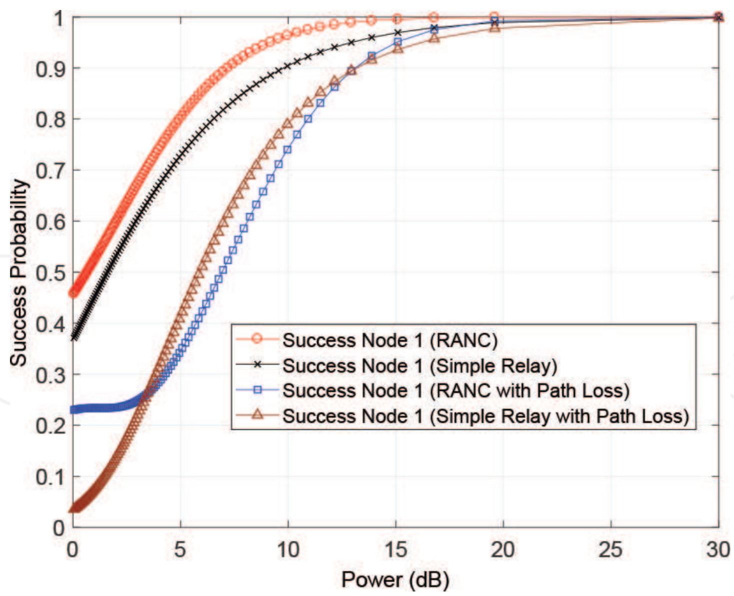


**Figure 5.** Success probability for D2D pair 1.

It can be observed that at a specific SNR margin, e.g., 15 dB, the performance of RANC and simple relay-aided D2D network can be analyzed. In this case, RANC outperforms the simple relay-aided D2D network for both aforementioned scenarios. These results could be particularly helpful in identifying the SNR margins that would be required for maintaining a particular end-to-end success probability in VMIMO-assisted DAS.

To further elaborate the findings, we present the performance comparison between simple relay-aided D2D and RANC D2D at different values of SNR margin. If $P^{D_i}_{s_{RANC}}$ and $P^{D_i}_{s_{relay-aided}}$ denote the success probabilities of RANC and simple relay-aided D2D network when calculated at a particular destination $D_i$, respectively, then the percentage improvement in success probability for RANC is given as

$$\text{percentage improvement} = \frac{P^{D_i}_{s_{RANC}} - P^{D_i}_{s_{relay-aided}}}{P^{D_i}_{s_{relay-aided}}} \times 100. \quad (1)$$

**Table 1** highlights the comparative analysis of simple relay-aided D2D and RANC D2D. The results are presented at different SNR margins in the form of percentages calculated using (1.1). The negative entries in the table signify a performance degradation of RANC, while the positive entries signify the performance gains that can be achieved through RANC.

The performance of RANC at D2D pair 1 is analyzed for different fading characteristics. Note that $\lambda$ characterizes the power of Rayleigh channel in a link. The fading characteristics are varied by changing the values of $\lambda$, where $\lambda = 0.2$ denotes the strongest gain. It can be observed that at higher values of SNR margin, RANC provides significant performance gains as compared to the simple relay-aided D2D network. Similar results are presented in **Table 2** for a scenario involving path loss. The results signify the utility of employing RANC when the links suffer from channel degradation. Dynamic priority assignment can help in increasing the end-to-end transmission success for links suffering from channel degradation.

| SNR margin(dB) | 0 (%) | 10 (%) | 15 (%) | 20 (%) | 25 (%) | 30 (%) |
|---|---|---|---|---|---|---|
| D2D Pair 1 | 23.60 | 6.56 | 2.75 | 0.95 | 0.31 | 0.1 |
| D2D Pair 2 | −17.71 | 3.88 | 2.4 | 0.92 | 0.30 | 0.09 |
| D2D Pair 3 | −4.81 | 1.81 | −4.23 | 0.06 | 0.21 | 0.09 |
| D2D Pair 1, $\lambda = 0.2$ | 29.28 | 8.83 | 3.03 | 0.98 | 0.31 | 0.09 |
| D2D Pair 1, $\lambda = 0.4$ | 28 | 8.2 | 2.9 | 0.90 | 0.31 | 0.09 |
| D2D Pair 1, $\lambda = 0.6$ | 26.6 | 7.67 | 2.89 | 0.97 | 0.30 | 0.09 |
| D2D Pair 1, $\lambda = 0.8$ | 25.18 | 7.11 | 2.82 | 0.96 | 0.30 | 0.09 |

**Table 1.** Analysis of simple relay-aided D2D with RANC D2D (excluding path loss) [27].

### 4.2. NC in high density DAS (OLA multi-hop networks)

Cooperative OLA networks allow a cluster of nodes to share the message with the adjacent cluster through multi-hop communication. OLA can be considered as a variant of DAS in network environments involving high density of nodes. In our analysis, we consider an OLA network which comprises of multiple source nodes that transmit the message to a common destination using a multi-hop topology [28]. We consider two network topologies for evaluation (1) Deterministic topology, and (2) Random topology.

**Deterministic topology** Consider a network topology shown in **Figure 6**, where two sources are deployed at a particular distance from each other. There are $N$ relay nodes in a cluster (hop), where the average distance between each cluster is denoted by $d$. The number of clusters is denoted by $n$, while the destination is denoted by $D$. The source nodes operate at orthogonal frequencies to send the information to the first cluster of nodes. The relays in the first cluster employ DF mechanism to transmit the information to the adjacent cluster, until the information reaches the desired destination. In **Figure 6**, nodes 1, 2 and 4 shown by the filled circles are the first hop nodes that successfully decode the message from both the sources, while the nodes that are not able to decode the message from either of the source nodes are shown by hollow circles. The nodes in the first cluster

| SNR margin(dB) | 0 (%) | 10 (%) | 15 (%) | 20 (%) | 25 (%) | 30 (%) |
|---|---|---|---|---|---|---|
| D2D Pair 1 | 572 | −6.14 | 1.58 | 1.4 | 0.56 | 0.19 |
| D2D Pair 2 | 1258 | −3.39 | 5.15 | 3.08 | 1.16 | 0.39 |
| D2D Pair 3 | 470 | −2.61 | 5.29 | 3.10 | 1.16 | 0.39 |
| D2D Pair 1, $\lambda = 0.2$ | 39.58 | 12 | 5.16 | 1.86 | 0.61 | 0.19 |
| D2D Pair 1, $\lambda = 0.4$ | 93.73 | 7.27 | 4.23 | 1.74 | 0.60 | 0.19 |
| D2D Pair 1, $\lambda = 0.6$ | 196.05 | 2.56 | 3.33 | 1.63 | 0.59 | 0.19 |
| D2D Pair 1, $\lambda = 0.8$ | 361.02 | −1.90 | 2.45 | 1.52 | 0.58 | 0.19 |

**Table 2.** Analysis of RANC D2D with simple relay-aided D2D(including path loss) [27].

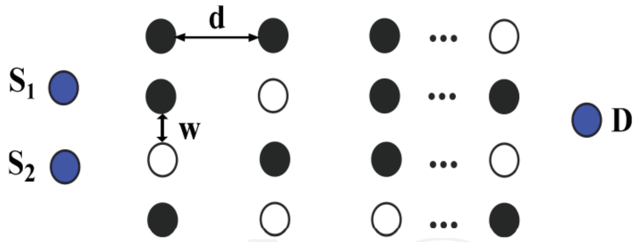


**Figure 6.** Deterministic network topology: $N = 4$ [28].

employ NC by combining the message from the two sources, i.e., the message $I_1$ & $I_2$ transmitted by source $S_1$ and $S_2$, respectively, are network coded at the first cluster nodes to form linearly independent codes at each DF relay. Each relay in the first hop transmits these network codes to next cluster of nodes. Each node in the second hop receives network coded copies of $I_1$ and $I_2$, which can be decoded using Gaussian elimination. Diversity is achieved at second hop nodes as many network coded copies of $I_1$ and $I_2$ are received. The similar process is continued until the transmission are received by the destination. The state of the cluster at each hop is modeled by a Markov chain, as the current state of the system depends only on the previous state of the system.

**Random topology** In random topology, instead of placing the relay nodes deterministically, the source nodes and the $N$ relay nodes are randomly distributed in a region of area $L \times L$. **Figure 7** illustrates a network where the network is extended in the form of a strip of $L \times L$ sized contiguous regions. A fixed number of nodes at each hop is considered, resulting in a binomial point process (BPP). The transmission flow is similar to deterministic topology, i.e., the nodes that decode the message in the first hop transmit the information to the next hop. The nodes that are able to decode the message from both sources form a codeword. Moreover, in this topology it is assumed that the nodes that decode either $I_1$ or $I_2$ are also able to forward the message to the next hop. A single node in a cluster can have four possible states

- State 0 = node does not decode anything,
- State 1 = $I_1$ is decoded,
- State 2 = $I_1$ and $I_2$ are decoded,
- State 3 = $I_2$ is decoded.

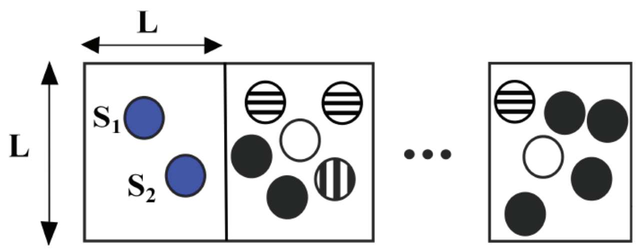


**Figure 7.** Random topology: Nodes at each hop = 6 [29].

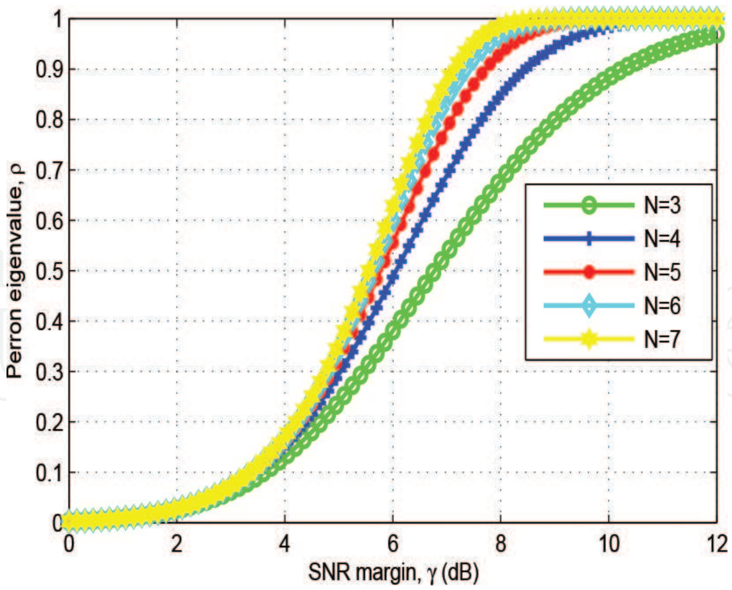


**Figure 8.** Success probability versus SNR margin for different values of $N$; $P_t = 1$, $d = 1$ [28].

It is not feasible to model the state of this topology by Markov chain due to the presence of a high number of states. Therefore, state distribution probability model is employed to model the network.

### *4.2.1. Evaluation model*

First, we present results related to the deterministic topology. **Figure 8** shows the relationship between the Perron eigen value, $\rho$, SNR margin and $\gamma$. $\rho$ is the one-hop success probability that corresponds to a state where at least two nodes in a hop are able to successfully decode a message. It can be observed that for a fixed value of $N$, an increase in the SNR margin leads to an increase in one-hop success probability. Moreover, an increase in the number of nodes, $N$, leads to higher success probability for a fixed SNR margin because the diversity gain increases. Hence, NC provides a way to transmit data to a far off destination by providing diversity.

The number of hops in the network impact the end-to-end success of data delivery, as the probability of successful hop decreases at each hop. If we want to maintain a certain QoS, $\eta$, we need to find the number of nodes in a cluster that would be sufficient for providing the desired QoS. The probability of delivering the message to the $m^{th}$ hop with a constraint that the probability is greater than a threshold $\eta$, can be determined through $\rho^m \geq \eta$, where $m$ represents the number of hops. **Figure 9** shows the results pertaining to the normalized distance denoted by $m \times d$ and the QoS. $d$ is distance between two adjacent hops and the results are presented for values of $N$ and $\eta$. It can be seen that as the QoS criteria is relaxed, the coverage is extended to a higher normalized distance.

Now, we present the results for random topology. **Figure 10** represents the number of nodes that are in state 2 versus $\gamma$, for $N = 8$ and $N = 10$ at the fifth hop. Recall that state 2 is a desired state because a node is in state 2, if it has decoded both $I_1$ and $I_2$. The information sent by the

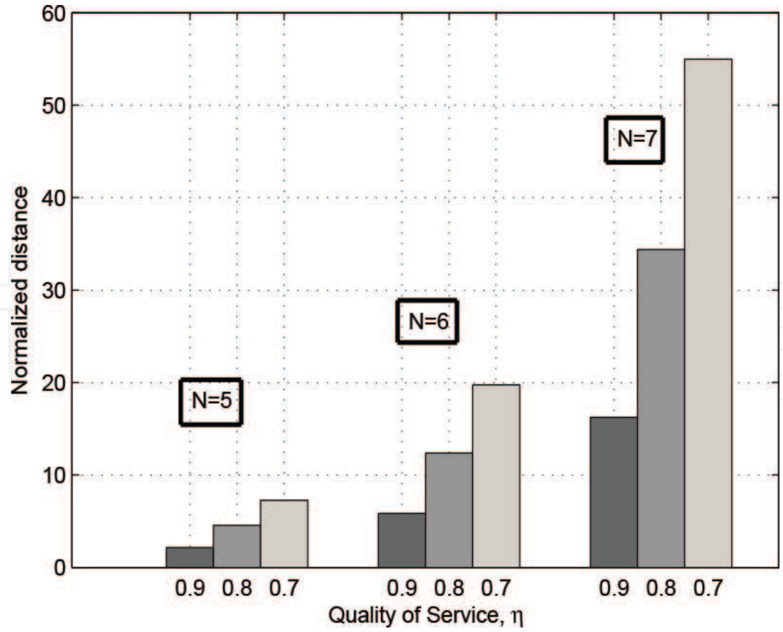


**Figure 9.** Normalized distance; $\gamma = 6\ dB, P_t = 1, d = 1$ [28].

sources can be recovered if a minimum of two nodes are available at each hop. The increase in $\gamma$ leads to an increase in the number of nodes in state 2.

The aforementioned results shown for two multi-hop network topologies empowered by the NC provide a designer's perspective for VMIMO-assisted DAS. The number of nodes that form a part of the VMIMO cluster, and the distance between adjacent clusters impact the network performance. Moreover, NC could help in increasing the end-to-end transmission success probability and therefore increases the coverage area. The network design parameters can be ascertained for VMIMO-assisted DAS to meet the desired QoS criteria.

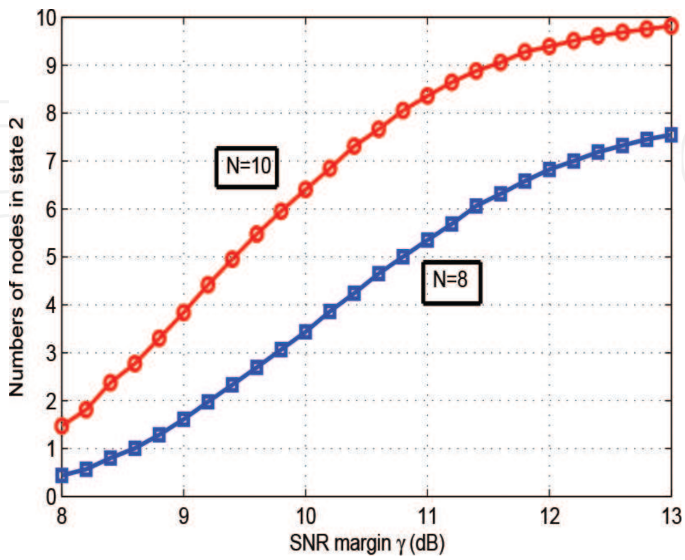


**Figure 10.** Number of nodes in state 2 versus SNR margin at $5^{th}$ hop.

## 5. Conclusion

In this chapter, we presented an overview of the benefits of DAS and the limitations that could arise due to DAS-based network operation. Then, we discussed the concept of VMIMO-assisted DAS and its utility in the network based on single-antenna empowered devices. VMIMO-assisted DAS help in realizing key aspects of 5G technology, i.e., energy/spectral efficiency and enhanced reliability. We analyzed the MIMO-assisted DAS by employing NC and quantify the performance metrics such as end-to-end transmission success probability. We considered a multi-hop environment and based our analysis on two network topologies: (1) Low density DAS (D2D multi-hop networks), and (2) High density DAS (OLA multi-hop networks). We discussed the transmission flow mechanism for both cases and presented results related to network reliability. Moreover, we also quantified the sustainability of the transmissions by determining the maximum distance that could be achieved by operating on particular network parameters. The analysis presented in this chapter provides design insights that could help in identifying the network parameters to achieve the desired QoS. The results highlight the advantages of employing NC in VMIMO-assisted DAS.

## Author details

Rafay Iqbal Ansari[1]*, Muhamad Arslan Aslam[2], Syed Ali Hassan[2] and Chrysostomos Chrysostomou[1]

*Address all correspondence to: rafay.ansari@stud.frederick.ac.cy

1 Department of Computer Science and Engineering, Frederick University, Nicosia, Cyprus

2 School of Electrical Engineering and Computer Science (SEECS), National University of Sciences and Technology (NUST), Islamabad, Pakistan

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