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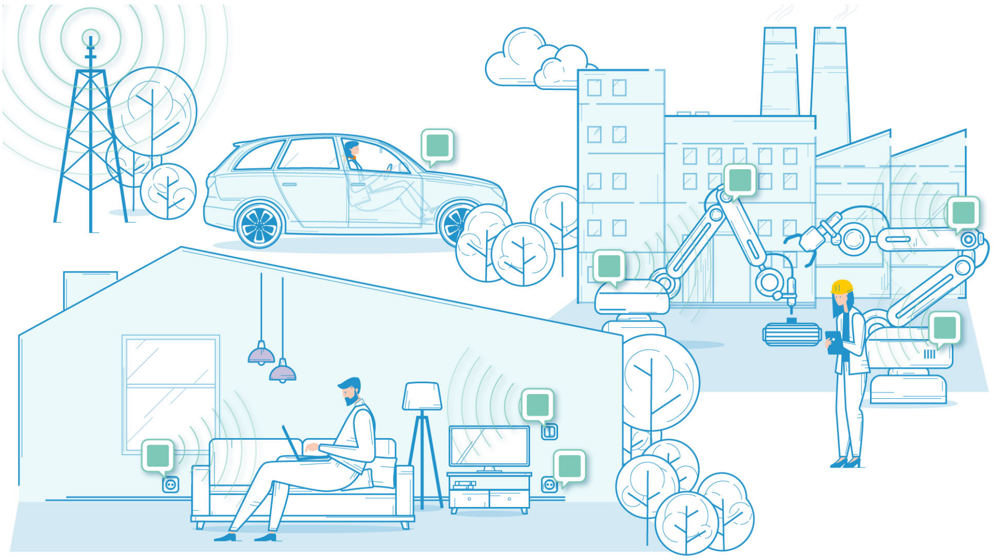
ENHANCING INDOOR MOBILE COVERAGE WITH SUDAS

Potential applications and deployment options for a Shared UE-side Distributed Antenna System (SUDAS)



Fraunhofer Institute for Integrated Circuits IIS
Am Wolfsmantel 33
91058 Erlangen, Germany

Contact
Thomas Heyn
communicationsystems@iis.fraunhofer.de

www.iis.fraunhofer.de/sudas

Why SUDAS?

SUDAS (Shared UE-side Distributed Antenna System) is a technology designed for delivering very high reliability and throughput that can be flexibly tailored to end user data rate needs. It is a highly scalable solution for mobile reception mainly in indoor environments like residential areas, industrial facilities, vehicles, fast trains and many more [1–5]. SUDAS technology is particularly suitable for enhanced mobile broadband (eMBB) use cases in 5G and beyond. By using millimeter wave (mm-wave) spectrum, SUDAS can be configured to deliver high-performance communication links for ultra-reliable low-latency communication (URLLC) scenarios as well.

The concept of a SUDAS infrastructure is based on many low-cost, low-power, and small form factor sub-6 GHz to mm-wave relays distributed in an indoor environment and shared among multiple user equipment (UEs). It does not require any fiber or other cables for backhauling and is thus easy and flexible to install, while it exploits the full potential of mobile communication in terms of improved coverage and extremely high data rates. While the SUDAS concept is even capable of handling multiple mobile network operators (MNOs), deployment in practical scenarios would initially be considered and based on a solution delivered by a single MNO.

SUDAS mainly brings three benefits for MNOs and their customers:

- Coverage extension
- Throughput enhancement
- Reliability improvements

Traditional approaches for in-building mobile coverage

Currently, 80 percent of mobile use is derived from outdoor-to-indoor communication, which suffers greatly from penetration losses in the order of 15 to 26 dB in the sub-6 GHz range and 35 to 53 dB for mm-wave frequencies [6]. Consequently, indoor environments usually present coverage blind spots or dead spots with very poor signal reception if any.

Solving this issue is one major challenge in order to deliver the promised 5G and 6G coverage as well as eMBB and URLLC services to end users. Not surprisingly, several approaches are currently being pursued in order to mitigate present limitations for mobile indoor reception:

Distributed antenna systems

Distributed antenna systems (DASs) provide extensive indoor coverage by amplifying and splitting the received signal throughout the building. DASs are deployed in different flavors ranging from legacy networks of analog splitting stages with coaxial cables to evolved architectures with digital functionalities.

For 5G scenarios, the evolved architecture typically involves a network of fiber or Ethernet cables, a baseband unit (BBU), control units, and several remote radio heads (RRH) installed in different rooms of a building. It improves indoor capacity by supporting connectivity from multiple MNOs. However, the overall solution is quite expensive, difficult to scale, and not very flexible due to the need to install an abundance of cables and related hardware.

mm-wave small cells

Network densification by means of macro cells can be very expensive and may not even provide better indoor coverage. In contrast, deploying small cells powered by low-power indoor base stations can essentially increase network capacity, quality of service (QoS), and general performance by provisioning high data rates to end users.

However, indoor small cells require wired backhaul to the core network. Due to high penetration losses of mm-waves and limited indoor coverage, every room in a building requires its own small cell, which consequently increases the overall complexity of the backhaul fiber installation.

With the emergence of integrated access and backhaul (IAB) in Release 16, deployment effort for mm-wave cells has been relatively alleviated since it provisions wireless backhaul. This involves single hop or several stages of multi-hop wireless links between base stations until the connection with the so-called "IAB donor" cell is established, which communicates with the 5G core through fiber. 3GPP requires the access and backhaul frequencies to be the same. As a result, IAB is more suitable for the deployment of mm-wave cells in outdoor scenarios. For indoor scenarios, a mm-wave backhaul link between indoor and outdoor base stations would suffer from extreme penetration losses. Apart from this, indoor coverage enhancement would require a complete protocol overhead of a 5G base station (gNB).

Relay-based approach

Relays extend the outdoor and indoor network coverage of a serving macro cell without requiring additional wired backhaul, and they act as an intermediate node between the base station and a UE. A repeater is its simplest implementation, which involves an amplify-and-forward (AF) relay scheme. Regenerative relays with compress-and-forward (CF) and decode-and-forward (DF) functionality add network robustness at the cost of increasing complexity and latency. 3GPP standardizes relays for different use cases with fixed and mobile scenarios.

One bottleneck for traditional relays is that they communicate with both base station and UE within the same frequency range – either in sub-6 GHz or mm-wave. The relaying operation in low bands extends coverage but doesn't suffice indoor users with demanding data needs. Meanwhile, mm-wave relays suffer from very high penetration losses and require line of sight (LOS) from outdoor-to-indoor environments. To combat penetration losses, antennas or antenna arrays can be installed on the rooftop of cars or buildings from where the relaying operation can be realized by shifting the signals from a lower band to a higher band (for the downlink) and vice versa (for the uplink). But this approach is not very flexible in residential areas due to the need for antenna cables, which limits the scalability options.

SUDAS as a mobile reception booster

Looking at these three traditional approaches, it appears that the best imaginable way to enhance indoor mobile coverage would literally be to mix their constituent elements and thereby eliminate the occurring drawbacks. Consequently, the ingredients of such a magic potion have to be:

- Deploying a system of – virtual – distributed antennas
- Using mm-wave, but not for the complete cell range
- Applying a relaying technique that shifts mobile signals to higher frequencies

This kind of solution is within reach: a Shared UE-side Distributed Antenna System (SUDAS) forming an indoor mm-wave relay network that improves mobile coverage inside buildings and enhances vehicle connectivity. The basic concept of SUDAS is shown in Figure 1, where multiple relay elements referred to as "SUDACs" (Shared UE-side Distributed Antenna Components) are installed in distributed fashion in an indoor environment using 5G New Radio (NR) frequency bands.

SUDAC nodes talk with the UEs at high frequencies in the mm-wave range (FR2) whereas base stations (gNB) send spatial streams to the relay nodes using mobile signals in the conventional sub-6 GHz range (FR1). The outdoor base stations are based on massive MIMO technology and equipped with a large number of antennas to provide large spatial multiplexing. However, besides the worse indoor reception conditions, UEs have so far also suffered from a limited number of antennas, meaning they eventually become the main bottleneck in attaining the target throughput envisioned for 5G and 6G systems. SUDAS solves this problem by virtually extending the number of distributed antennas on the UE side in a cooperative fashion, which is referred to as virtual MIMO.

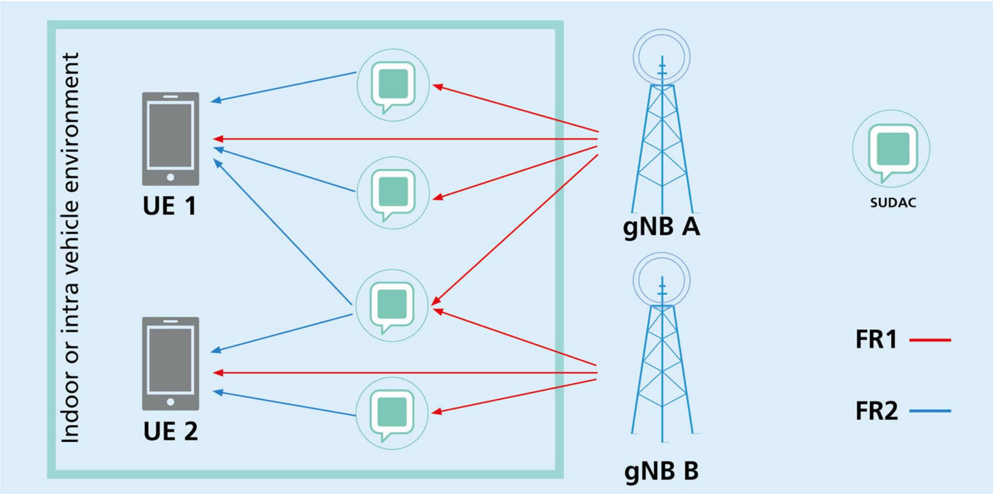


Fig. 1: Basic concept of SUDAS for mobile indoor communications

FR1 = sub-6 GHz
FR2 = mm-wave, >24.2 GHz

SUDAS thus combines the virtues of massive MIMO from the base station and virtual MIMO of SUDACs to transform large spatial multiplexing in FR1 bands into frequency multiplexing in FR2 bands. The higher the number of installed SUDACs, the better the ratio in the spatial-to-frequency translation gets. The throughput on the UE side gets enhanced linearly by the number of SUDACs. An example of the spectrum occupation spread over frequencies in both lower and higher bands as a result of a relaying operation is illustrated in Figure 2. In this example, four SUDACs are deployed, which results in at least four times more bandwidth on the UE side.

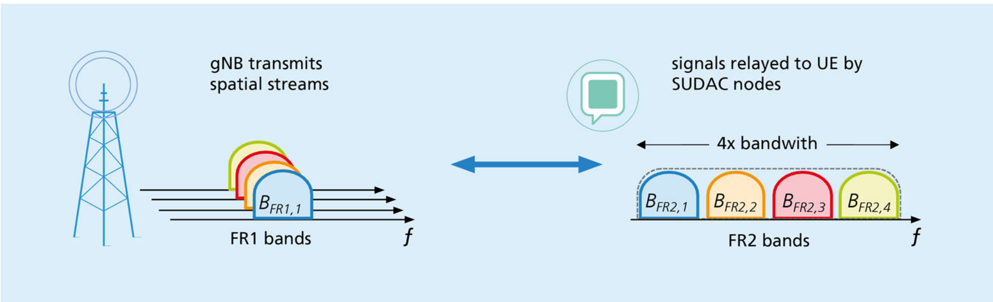


Fig. 2: Exemplary spectrum occupation in FR1 and FR2 bands

SUDAS technology is very flexible in how it achieves this, allowing the relaying operation to be realized in any band. The full potential of SUDAS can be realized by FR1-to-FR2 relaying. FR1 signals have good penetration properties and form a large coverage cell but suffer from spectrum scarcity, whereas FR2 signals provide high bandwidth but are highly attenuated by building walls and short-range cells. SUDAS combines the benefits of both low- and high-frequency bands, which results in coverage extension as well as extremely high throughput.

Another important effect – especially under difficult indoor propagation conditions – is the higher reliability of the transmissions because of the higher statistical probability of being connected to at least one SUDAC, compared to the traditional approach of directly connecting from the UE to the base station. More details about the increased reliability of SUDAS for industrial use cases are described below.

Use cases and deployment aspects

Industrial communications use case

SUDAS not only provides high throughput gains for residential applications, but it is also suitable for industrial applications. In order to achieve ultra-high reliability, as required for smart factories, SUDAS can be configured with a certain diversity-multiplexing trade-off (DMT).

All SUDAC transmitters can be used to send the same data stream to the machine nodes, which refers to a full-diversity mode suitable for URLLC. In contrast to this, when running SUDAS in full-multiplexing mode, all SUDAC transmitters send distinct streams to the UE. This reduces the reliability aspect but is perfectly suited for eMBB services shared by a larger number of users. A trade-off between diversity and multiplexing makes this a widely applicable and scalable solution as illustrated in Figure 3.

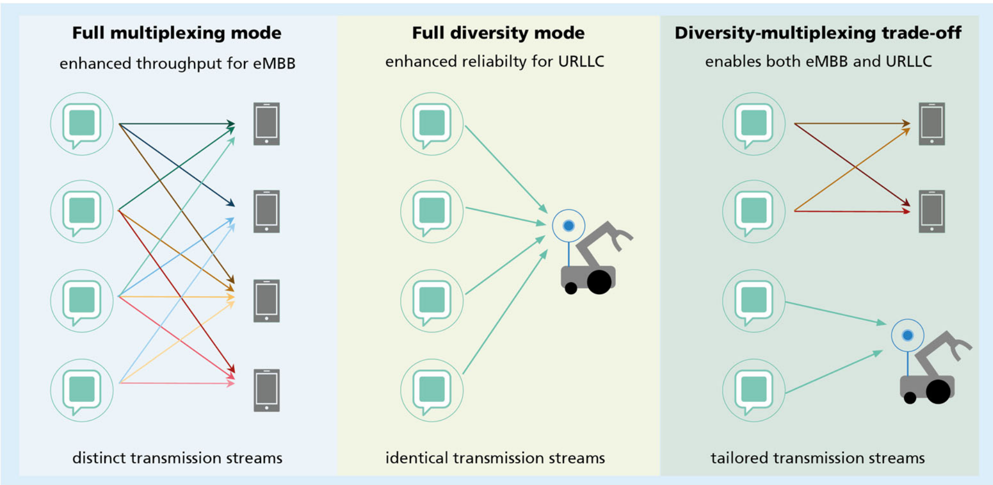


Fig. 3: Diversity-multiplexing trade-off suitable for both eMBB and URLLC

Vehicle connectivity

To provide uninterrupted data connectivity in cars, buses, and fast-moving trains, manufacturers can install a completely wireless infrastructure of SUDAS mm-wave relays. This enables continuous and fast wireless connectivity for passengers' infotainment systems and general mobile connectivity with a seamless connectivity experience.

Through vehicle-to-everything (V2X) communication links, SUDAS services can be shared among other nearby vehicles and devices. In addition to the original FR1-to-FR2 relaying concept, another advantageous configuration and enhancement of SUDAS for vehicle environments would be FR2-to-FR2 relaying operation, where in the first hop a base station sends spatial streams in lower FR2 bands and the SUDACs translate them to a relatively higher FR2 band. While this approach results in massive throughput gains, it suffers from penetration losses since the operating bands are all in mm-wave. To combat this issue, antennas or antenna arrays can be installed on the rooftop of cars or buildings from where the relaying operation can be realized by shifting the signals from a lower band to a higher band. This approach is less flexible in residential areas due to the need for antenna cables. However, in vehicles, cabling is easier to handle and automotive manufacturers can even integrate RF cables right from the start to provide the basis for wireless connectivity with high peak data rates. This setting is illustrated in Figure 4. Alternatively, SUDAC nodes can also be further developed with regard to possibilities for self-installation on building or car windows using an adhesive material, which would eliminate the need for antenna cables.

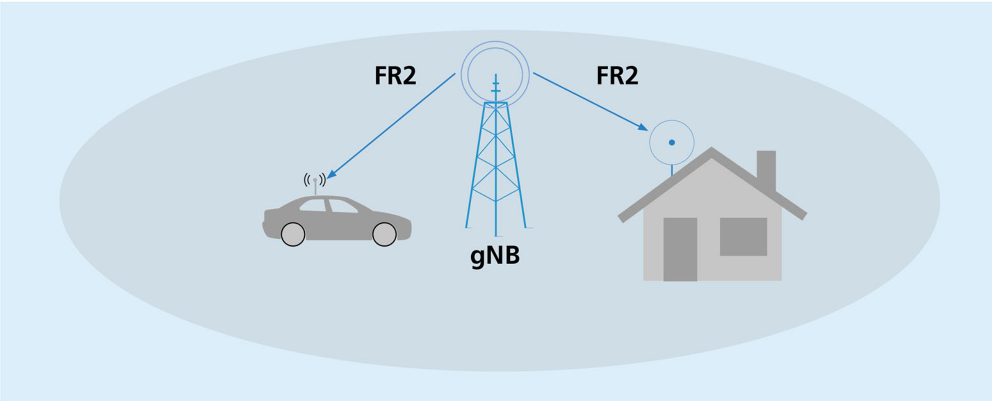


Fig. 4: mm-wave relaying requires rooftop antennas for vehicles and residential buildings

Outdoor coverage enhancement

Beyond conventional indoor scenarios, SUDAS can serve for outdoor coverage enhancements as well. The relay nodes (SUDACs) can be installed near to the cell edges in a sparsely distributed manner on poles, trees, building rooftops, sidewalks, and so on to extend the coverage, thereby lowering the capital expenditure for base stations as depicted in Figure 5.

Similarly, another useful approach would be to deploy SUDAS as a single co-located and unified system of SUDACs (with multiple antennas) at the same place near the cell edge to extend coverage and throughput. This approach can be particularly interesting for MNOs as it offers less installation effort.

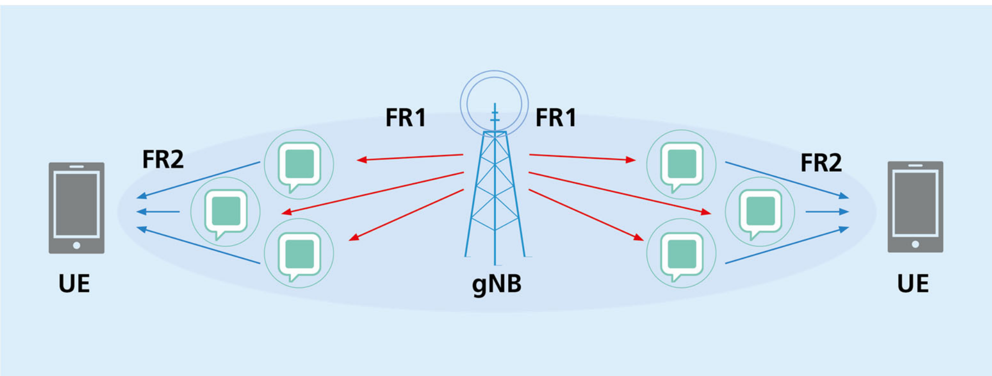


Fig. 5: Outdoor coverage enhancement with distributed SUDACs near the cell edges

SUDAS enhancement options

To enhance seamless coverage and deliver uninterrupted indoor data reception, SUDAS can be combined with existing 3GPP enablers and other technologies as well.

Enhancing throughput and reliability in private industrial networks

Private networks, so called non-public networks (NPN) [8–9] according to 3GPP terminology (Release 16), empower industrial communication and can be realized in two ways:

- Standalone NPNs are independent private networks without any mandatory dependency on a public network operating in licensed frequency bands.
- Public network integrated NPNs are deployed with the support of a public network and with a multitude of options regarding the integration level [7].

NPNs are intended for the sole use of a private entity such as an enterprise and may be deployed in a variety of configurations. SUDAS eases the installation of NPNs and enables industrial communication networks to support positioning, URLLC including enhanced mobility, and many more applications.

Figure 6 shows a proposed implementation architecture suitable for SUDAC relays inside an industrial vertical domain. This architecture is based on a private network that connects with the base station of an outside public network at licensed frequencies in the FR1 range. Some of the SUDAC elements relay these signals to the machine nodes using the private campus network (at 3.7–3.8 GHz in Germany). Some other SUDAC relays communicate with the rest of the machine nodes in unlicensed spectrum (NR-U).

3GPP standardized NR-U in 5G Release 16. Enterprises can thus adopt local as well as unlicensed frequencies for implementation of their non-public networks to guarantee the level of reliability required for the envisioned services. SUDAS can additionally support channel access protocols like listen-before-talk (LBT) to comply with the frequency regulations if and when needed.

A non-standalone gNB provisions the coexistence of LTE and NR in the same band through dynamic spectrum sharing (DSS). SUDACs can be deployed as either amplify-and-forward (AF) or decode-and-forward (DF) relays in industrial environments. Both approaches complement the DSS standard, while DF has the additional benefit of re-encoding the signal. This gives flexibility to decode the LTE and NR signals and retransmit them at faster rates in unlicensed and local bands while enabling both LTE-U and NR-U standards.

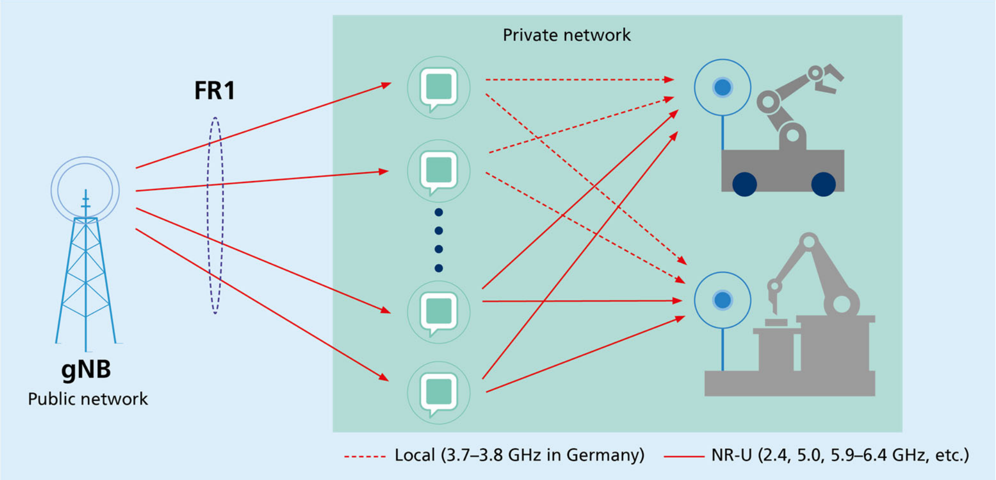


Fig. 6: Industrial communication use case

Network reliability can be further enhanced by increasing the diversity through the addition of numerous SUDAC nodes. SUDAS complements various deployment scenarios for networks with and without dependencies on the public network. This can be accompanied by different levels of radio access network (RAN) and core integrations with the public networks.

Extending the coverage of networks with sidelink-based SUDAS

Release 16 of 5G NR introduced a sidelink (SL) relaying operation that helps UEs communicate with other UEs without the involvement of a RAN interface. Sidelinks provide direct communication links between UEs over a "PC5" interface. The "Uu" interface of the cellular access network is thus not included. This means, sidelinks enable direct device-to-device communications such as two vehicles sharing information, for instance in a vehicle-to-vehicle (V2V) use case. The NR SL operation developed in Release 16 is entirely focused on enhanced V2X services with the provision of unicast, broadcast, and groupcast services [10–11].

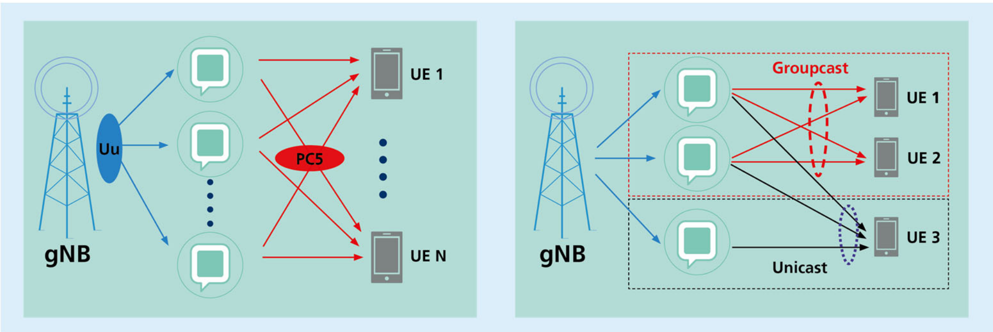


Fig. 7: (left) SUDAS via sidelinks, (right) SUDAS enables groupcast and unicast modes

In addition to V2X applications, sidelink-based relaying with respect to coverage extensions for a wider range of applications is part of Release 17. The supported modes are of two kinds: UE-to-UE and UE-to-network relaying. The focus of Release 17 lies mainly on layer 2 and layer 3 relay operations [12]. With such an advantageous 3GPP enhancement, SUDAS can be implemented using sidelinks as illustrated in Figure 7 (left), where SUDACs act as UEs relaying information to other UEs. The operation is very straightforward: SUDAC nodes receive data streams through the access channel "Uu" from the base station and they forward it to the UEs over the "PC5" channel after appropriate frequency translation into the higher bands.

The sidelink channel can be either FR2 or FR1 with the provision of unicast, broadcast, and groupcast modes, though at present most data in cellular networks is normally provisioned for point-to-point unicast. Nevertheless, SUDAS enables futuristic applications as presented in Figure 7 (right). This shows an example use case where two SUDACs serve two users via groupcasting; this can for instance be multistreaming in vehicle infotainment systems, multiplayer gaming services in residential environments, AR and VR entertainment services, and many more.

In addition to vehicle scenarios, sidelink-based SUDAS potentially fulfills the requirements for various domains including "inHome," "SmartFactories," and "SmartCities," which are identified in [13]. The inHome scenario extends residential coverage through enhanced relays and by employing a single-entry 5G residential gateway (5G-RG) that requires backhauling. A distributed installation of SUDACs replaces the need for a 5G-RG, with the result that SUDAS simplifies the whole deployment effort. There is no need for backhaul cables since the system benefits from the advantages of distributed and virtual MIMO.

Mitigating building penetration losses by using intelligent reflecting surfaces

Despite very high data rates, FR2 suffers from large wall penetration losses. Consequently, a SUDAS arrangement as shown in Figure 1 works well for a single-room scenario, but since walls block mm-waves, there are basically only two feasible options for providing coverage in another room: adding and connecting multiple SUDAS, or using intelligent reflecting surfaces.

SUDACs are low-cost relay components, so they can be scaled up quite easily according to end-user data requirements. A coverage extension across additional rooms, for example, can be achieved via the installation of another independent SUDAS. However, in the event that a UE moves from one room to another, handover procedures are needed to meet indoor reliability requirements. If the required control link for proper handoffs is implemented in FR2 then a cable installation might be needed between separate rooms. A better approach would be to implement the control link in FR1 to avoid cables and to guarantee flexibility. Additionally, the UE can act as relay between involved SUDACs during handover.

An alternate approach for coverage extension is to use intelligent reflecting surfaces (IRSs) inside buildings. An IRS is a passive reflector, and the topic has gained particular attention in the scientific community, where its characteristics are being actively studied for 6G applications. An IRS directs the signals to the UEs that are not in line of sight (NLOS) of the SUDACs, as shown in Figure 8.

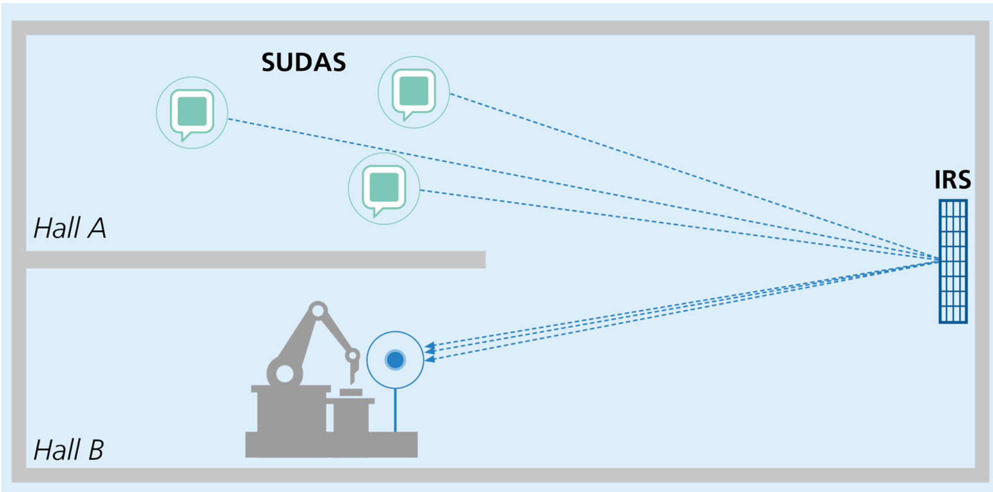


Fig. 8: NLOS mitigation through an intelligent reflecting surface (IRS) in a factory area

The deployment of IRS lowers the number of required relay nodes in a building and thus reduces the capital expenditure for setting up a SUDAS infrastructure. For the best channel gain results, the IRS should be placed near to the UEs.

However, an additional feedback channel is required between SUDAS and IRS. In order to fully exploit its advantages, the reflecting angle of the IRS, which is controlled by a backend baseband unit (microcontroller), has to be optimally determined in addition to the subcarrier and power allocation, based on the throughput requirements of the indoor UEs. The combination of FR1-to-FR2 relay and IRS enhances coverage and increases overall throughput in indoor environments.

Conclusion

In view of our insights into seamless mobile connectivity, we strongly believe that SUDAS is a technological breakthrough designed to cater to eMBB, abolish coverage dead spots, and deliver URLLC services to users in indoor environments for 5G and beyond.

Whereas traditional concepts for network densification in indoor environments always come with lots of installation and backhauling effort for the MNOs, SUDAS lowers the capital expenditure for the base stations, as it is a low-cost infrastructure based on virtual MIMO, and it eases the installation effort without requiring fiber and additional cables.

SUDAS supports both 5G NR frequency ranges, i.e. FR1 and FR2, as well as unlicensed frequency bands, while the operating band at which the SUDAC nodes talk with the UEs is considerably higher than the one at which base stations send their spatial streams to the relay nodes.

Based on the enhancement options reviewed in this paper and in comparison to the traditional technologies, SUDAS can play a significant role in the 5G and future 6G indoor communications market by providing a generalized solution suitable for all outdoor and indoor environments including the deployment of private industrial networks.

Our aim is to enable mm-wave wireless connectivity in indoor environments with a scalable technology that can be tailored according to the use cases and requirements. We strongly encourage MNOs, industrial enterprises, automotive companies and smartphone manufacturers to join us on our journey and share our vision of bringing 5G and 6G indoors with a seamless user experience.

Further information about SUDAS and a simulation package can be found here:
www.iis.fraunhofer.de/sudas

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