D3.8

WP3 Extended Executive Summary

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Abstract:

The goal of this deliverable is the comparison and critical evaluation of the quantitative results obtained across the different tasks of WP3. WP3 has investigated radio resource management and multi-antenna techniques in a separate and independent manner. This deliverable considers the integration of both and examine the potential benefits in terms of spectral efficiency gain versus implementation complexity. In addition, the deliverable reports the deployment guidelines for achieving the spectral efficiency objective of the SANSA project.

Document History

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List of Acronyms

BS	Base station
CSI	Channel State information
HNM	Hybrid Network Management
iBN	Intelligent Backhaul Node
MPTMP	Multi-Point-to-Multi-Point
PTP	Point-to-Point
PTMP	Point-to-Multi-Point
RF	Radio Frequency
RRM	Radio Resource Management
SE	Spectral Efficiency
SINR	Signal-to-Interference plus Noise Ratio

Executive Summary

This document forms deliverable D3.8, which wraps-up the contributions carried out in WP3 by presenting a set of recommendations for the deployment and implementation of the technologies developed within WP3 in the SANSA backhaul network. Namely, it considers the Radio Resource Management (RRM) and the multi-antenna communications, which were evaluated taking into account the spectral efficiency gains only.

For each technology enabler investigated in WP3, we review the pros and cons in terms of spectral efficiency gain versus implementation complexity. Next, we provide implementation guidelines for future SANSA networks, emphasizing on the cost-benefit trade-off of each of the techniques studied in WP3.

In summary, we suggest a two-step implementation based on the performed cost-benefit analysis. As a first step, we suggest the implementation of the RRM techniques, whose software-based functionality provides limited spectral gain (approximately 2x) with relatively low cost. As a second step, the backhaul operators may consider the implementation of multi-antenna technology on the backhaul nodes. The magnitude of the benefits in terms of spectral efficiency that arise from the use of multi-antenna technology are significant, reaching close to 9x for multi-streaming communications, but at the expense of substantial operator expenditure in new hardware equipment.

Therefore, WP3 results are close to the 10x SANSA objective in terms of Spectral Efficiency (SE). This results can be further improved in future backhaul deployments, which are expected to be much denser, with higher number of links sharing the same spectral resources. In addition, the proposed techniques allow the use of satellite terminals performing backhaul services in the Ka-band, sharing the spectrum with the terrestrial stations. This is particularly important for SANSA, where the satellite segments improve the resiliency and offloading capacity of the conventional backhaul networks. The multi-antenna technology plays also a key role in the topology reconfigurability, which is one of the innovative ideas proposed in SANSA. However, reconfigurability as well as the satellite resiliency and offloading capabilities are considered in WP4. Here, we focus on SE results, as the objective of WP3.

It should be noted that the aim of this deliverable is not to drive a detailed cost-benefit analysis, which will be part of the exploitation plan conducted in WP7, but to extract an overall and joint conclusion about the techniques developed within WP3.

1 Introduction

The SANSA project aims at demonstrating the feasibility of integrated terrestrial-satellite backhaul networks where the satellite and the terrestrial segments share the same spectral resources. Hence, one of the main objectives is to demonstrate that these bands can be efficiently used by both segments, while increasing the spectral efficiency (SE) of the integrated system and without compromising the quality of the existing satellite and terrestrial services. Moreover, aggressive frequency reuse will be also considered among the terrestrial links so that the SE is boosted.

In WP3, we investigated the technological enablers that allow sharing the spectral resources over the SANSA backhaul network in an efficient manner. We put special emphasis in the design of large antenna arrays with null-steering capabilities for interference mitigation [1] and in the design of smart Radio Resource Management (RRM) for mitigation of intra-system [2] and inter-system [3] interference.

The performance analysis carried out in WP3 has already shown large benefits in terms of overall network SE. However, these benefits were observed by studying the additional multi-antenna capabilities and the proposed RRM techniques separately. The objective of this deliverable is to derive a recommendation about the benefits and costs related to the combination of the multi-antenna capabilities and the RRM proposed in the context of WP3.

Therefore, this deliverable does not aim to provide an exhaustive performance analysis of the combination of these two technological enablers, but rather seeks to focus on a high-level qualitative cost-benefit analysis based on the technical outcomes achieved in WP3. In fact, the main goal of this deliverable is to provide insights into recommendations for future implementation of the SANSA backhaul network, with a special focus on the PHY layer performance.

The remainder of this document is structured as follows. Section 2 presents the analysis in terms of spectral efficiency gain versus implementation complexity for the two key groups of technologies investigated in WP3, namely the multi-antenna communications and the RRM, as well as for SANSA systems considering both. Section 3 provides implementation guidelines for future SANSA backhaul networks, where the overall network spectral efficiency gain is compared to the introduced additional cost in investment and in operational expenses for the system exploitation. Finally, Chapter 4 concludes the document by summarizing the main findings.

2 WP3 technological enablers

In this section we review the main outcomes of WP3 in terms of spectral efficiency gains. These gains will be considered as a baseline for the cost-complexity-gain discussion of Section 3.

2.1 Multi-Antenna Transceivers

The outcomes of the interference mitigation techniques considering backhaul nodes equipped with multi-antenna capabilities have been presented in [1]. In particular, the aim was to increase the spectral efficiency of the system by allowing high frequency reuse on both satellite and terrestrial links through the use of interference mitigation and beam steering capabilities. The high frequency reuse enables simultaneous transmissions by multiple links through the same frequency band. The drawback in this case is that the performance of the existing systems will be degraded due to the interference corruption. This degradation occurs because the existing backhaul networks are based on single antenna structures that employ high directive drums as the RF front end of the system. Such a type of antenna can be seen in Figure 2-1. To that end, we considered replacing the drum antennas with multi-antennas at the SANSA nodes. A schematic of a multi-antenna node can be seen in Figure 2-2.

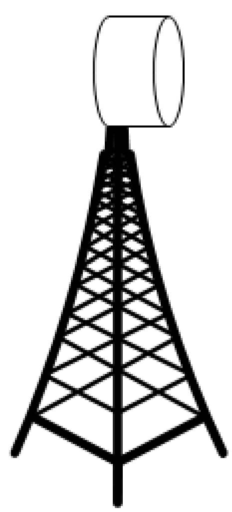

Figure 2-1. Schematic of a backhaul station equipped with a drum Antenna [1]

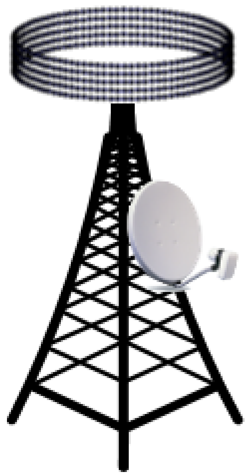

Figure 2-2. Schematic of a multi-antenna SANSA backhaul node [1]

A multi-antenna architecture enables the use of beamforming / pre-coding techniques that can be used to mitigate the generated interference due to the frequency reuse. Moreover, it improves the SINR of the links via the array gain and finally, enables the satellite-terrestrial coexistence thus enhances the SANSA overall network performance. The most promising terrestrial transceiver architecture was found to be a hybrid analog-digital one, as described in [1]. Since the employed number of antennas is very large and thus, a fully digital approach would require high hardware complexity and power consumption, we opted for a hybrid analog-digital architecture.

In particular, in [1] we investigated the aggressive frequency reuse schemes in three different terrestrial multi-antenna communication setups; namely, the Point-to-Point (PTP), the Point-to-Multi-Point (PTMP) and the Multi-Point-to-Multi-Point (MPTMP) setups. The three different multi-antenna communication setups are illustrated in Figure 2-3. The performance of the proposed approaches was studied in detail by simulations on random environment and by simulations on a real topology with data extracted from an area close to the city of Helsinki in Finland [1].

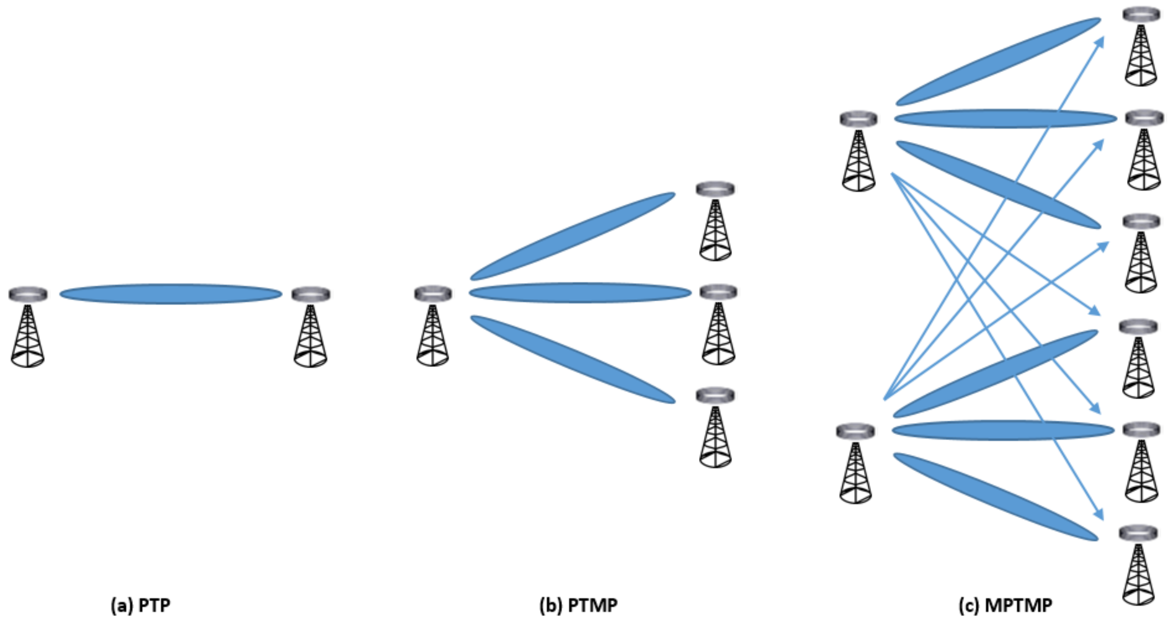

Figure 2-3. Multi-Antenna communications setups proposed in [1]

In general, we concluded that all techniques allow maintaining the link rates to a similar level as when low frequency reuse is employed, even in the case of aggressive frequency reuse. We also showed how these techniques allow the coexistence of both satellite and terrestrial links operating on the same frequency band. The later refers to the interference management capabilities brought by beamforming.

In some special cases, the spatial statistics of the channel allows spatial multiplexing and diversity gains. In particular, this happens in the presence of multiple clusters of paths such as the ones encountered in dense urban deployments. For the PTP case, it was observed that multiplexing combined with interference nulling provides an 8.9x spectral efficiency improvement, which falls very close to the overall SANSA SE objective of 10x. For further information and comparisons of the performance of the different techniques, the interested reader may check [1].

This section is concluded by discussing the implementation aspects of the examined approaches. The majority of the techniques require the Channel State Information (CSI), which can be estimated by standard channel estimation techniques. This is a typical requirement in pre-coding beamforming techniques and it is among the existing functionalities of a wireless network. The required CSI can be transmitted to any of the SANSA nodes that require it, since efficient feedback mechanisms have been already considered an integral part of wireless networks. The computational complexity of the majority of the techniques is negligible, given the fact that the SANSA nodes are backhaul stations managed by the Hybrid Network Manager (HNM), which is assumed to have high computational capabilities. As a final part of this section, we will comment on the number of required RF chains. An additional RF chain offers the possibility to use an additional stream for transmission and hence increase the spectral efficiency of the system. On the contrary, the maximum number of streams that a system can transmit is bounded by the rank of the channel matrix between the transmitter's and the receiver's antennas. Thus, the optimal number of the employed RF chains is related to the channel conditions, as a number of RF chains that is quite large compared to the expected rank of the channel matrix would significantly increase the hardware complexity and power consumption without providing significant gains on the performance.

2.2 Radio Resource Management

The outcomes on the RRM techniques have been presented in [2], and adapted to inter-system interference in [3]. In particular, we assessed the performance and adaptation of new RRM technologies for terrestrial and satellite link scheduling, carrier allocation, power and flow control. The different setups addressed by the RRM techniques proposed in [2] are illustrated in Figure 2-4.

In [2], we showed that PTMP scheduling and power allocation combined with the multi-antenna beamforming designs of [1] can provide up to 2.83x improvement in terms of spectral efficiency, compared to conventional terrestrial-only backhaul networks. Scheduling is useful when there is a limited number of RF chains, but there is a need to serve a high number of backhaul nodes using the same spectral resources. In particular, this 2.83x gain mentioned in [1] can be interpreted as the frequency reuse gain, since the considered scenario serves 3 links with a single carrier frequency.

Therefore, the RRM gain arises essentially from the effort to pack a high number of backhaul links efficiently into the minimum number of carrier frequencies. In particular, in [2], we showed that carrier allocation by itself can provide a 2.09x improvement in terms of spectral efficiency with respect to the benchmark when considering the overall "Helsinki" topology equipped with few satellite-terrestrial hybrid backhaul nodes. Moreover, when this carrier allocation is combined with power and flow control, taking into account the traffic that each link can support, this gain can be pushed up to 2.47x. However, this implies cross-layer design, where the RRM needs to closely collaborate with the Hybrid Network Management (HNM) in order to route the traffic.

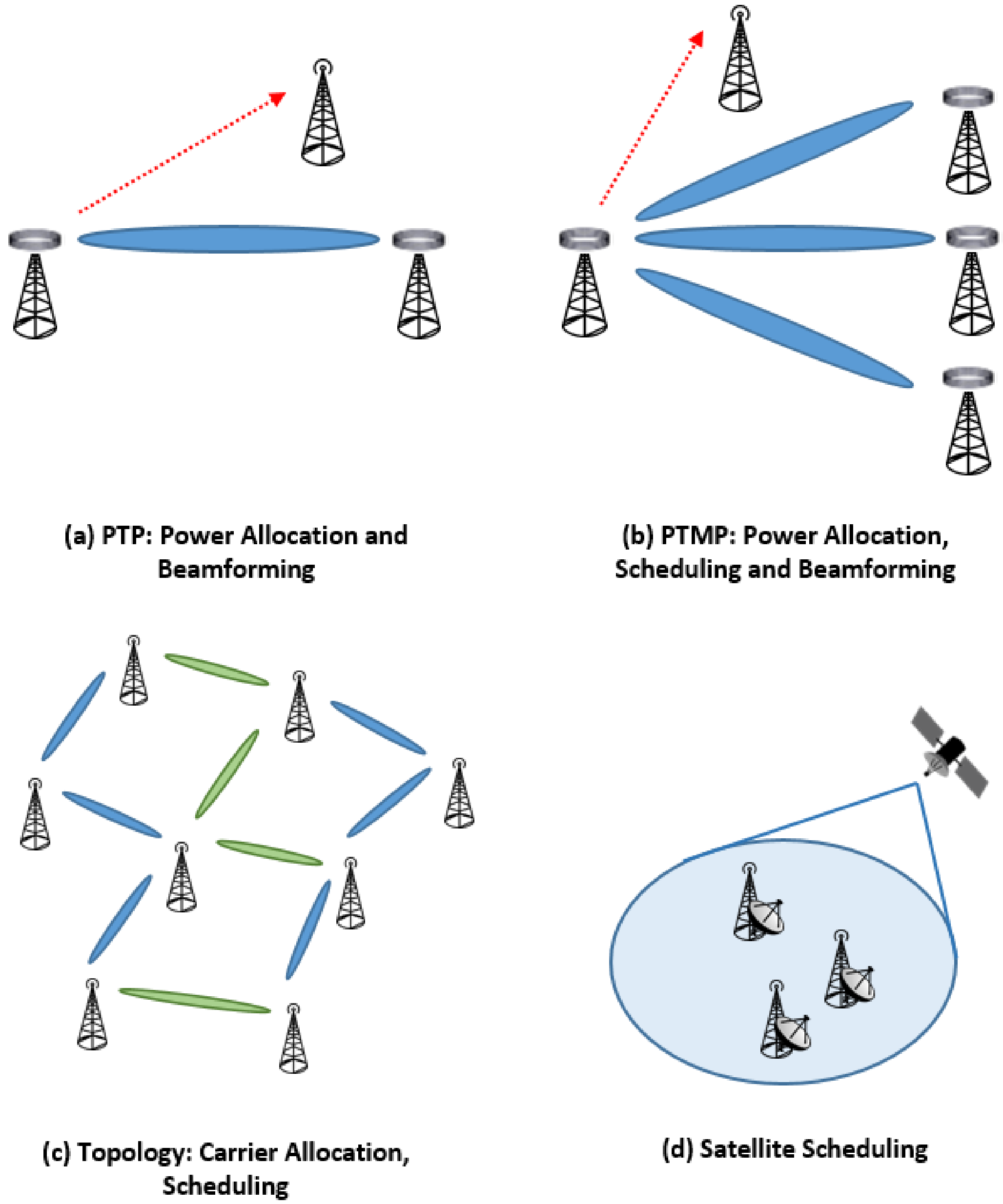

Figure 2-4. Setups addressed by the RRM techniques proposed in [2]

3 Implementation guidelines for SANSA systems: Cost-complexity-gain trade-off

In this section, we provide some implementation guidelines for SANSA backhaul networks based on a high-level qualitative cost-benefit analysis related to the techniques developed in WP3. For this analysis, we take into account the spectral efficiency gains summarized in Section 2, along with the cost and complexity of implementing such techniques.

Our goal is to help backhaul operators determine if an investment on the WP3 proposed technologies is sound, by evaluating whether their benefits outweigh the costs.

For the sake of clarity, we split the WP3 techniques' implementation into two steps, according to the implementation cost. As a first step, we will review the RRM module implementation, which offers a relatively low cost solution with limited gain. On top of that, backhaul operators may consider implementing the multi-antenna transceivers as a second step, which boosts the gain, but requires a considerable capital investment.

It should be noted that this deliverable focuses on SE gains and does not consider the gains in terms of resiliency, offloading and reconfigurability of the topology. These are considered in WP4.

In the following, we provide a short section summarizing the SANSA architecture followed by the detailed description of each of the aforementioned implementation steps.

3.1 General SANSA architecture

This section discusses the system architecture of the SANSA backhaul network [4], which is fundamental to understand the investment required to implement the technical solutions proposed in WP3.

In the SANSA architecture, conventional backhaul nodes are replaced by intelligent backhaul nodes (iBNs), which extend the internal architecture of traditional backhaul nodes by introducing new functional blocks and interfaces for the proper management of backhaul satellite and terrestrial resources. Each iBN can be reconfigured by the HNM. It will encompass interfaces to other iBNs, and to the core network either directly (with a radio link) or through other iBNs. Some iBNs may include a satellite dish, thus allowing direct connection to the core through the satellite network. At the same time, the satellite will encompass an interface to other iBNs.

Information such as carrier frequency, channel bandwidth, transmitted power, available data rate and link availability is constantly monitored by the HNM. The HNM is responsible of optimizing the radio resources for both the satellite and the terrestrial segments in such a way that the SANSA network performance is maximized.

3.2 Step 1: RRM implementation

The first step considers the implementation of the RRM module. The RRM module uses context information available at the HNM to optimize the resource allocation across the entire SANSA backhaul network. Therefore, the RRM module is an external component of the HNM that calculates interference levels and performs the resource optimization, thus allowing remote reconfiguration of the radio resources. Essentially, the implementation of the RRM requires additional software with minimal hardware modifications, assuming that the backhaul node modems are already equipped with remote reconfiguration interfaces (e.g. power, bandwidth, channel number). Even if this is not the case, these capabilities can be enabled with a firmware update without the need for upgrading any HW components. Therefore, the RRM can provide a spectral efficiency gain up to 2.47x with a relatively low investment on the backhaul network infrastructure. Note also that the operating cost of such a technology is minimal, since it is based on software commands sent directly from the HNM to the RRM module.

Moreover, the RRM module can be complemented with a database (DB) including the information related to the utilization of the spectral resources by external systems as described in [3]. This allows the design of the RRM module so that the SANSA spectral efficiency is maintained, while protecting external links operating on the same spectral band. In the preliminary stages of deployment, when the SANSA system is surrounded by legacy backhaul networks, a static DB with periodic updates through the national regulator will be sufficient. This is because the legacy systems do not have reconfiguration capabilities and new nodes must be registered in advance with the national regulator. For the later stages, when multiple SANSA systems might operate in adjacency, the SANSA operator can consider the deployment of a network of sensors to complement the database, which will definitely increase the investment and operating cost in order to tightly satisfy the inter-system interference requirements. An alternative solution would be the exchange of real-time information among the backhaul operators to enable dynamic adaptation. However, this is a complicated solution which should probably be coordinated by the regulators to guarantee wide compliance.

Regarding the satellite segment, the proposed RRM techniques can be easily implemented by considering low cost software updates on the current systems, since the hardware components are readily available. As discussed in WP2, the integration and coordination among terrestrial and satellite segments within the SANSA backhaul network will be performed within the HNM module.

3.3 Step 2: Multi-antenna transceivers implementation

If a backhaul operator requires higher spectral efficiency gains and additional spectrum is nonexistent or too expensive, the backhaul nodes have to be equipped with multi-antenna transceivers. In this second step, the increased hardware and computational costs due to the use of very large antenna arrays should be taken into account.

The antenna array concept is nowadays quite expensive for mass market applications such as backhaul networks, since the HW development as well as the testing are quite costly. In terms of adaptive beamforming with phased arrays approach, the "hybrid analog-digital" solution has been identified in WP3 as the most promising in terms of hardware complexity and cost. However, the large number of elements required for sufficient directivity in the Ka-band, means that capital expenditure is needed to develop integrated components, including the digital modem, the analog beamforming network (BFN), the digital interface for controlling the BFN and the large array. Operating expenditure should be commensurate to legacy backhaul networks, including unexpected node failures, upgrades and regular maintenance.

However, the investment in multi-antenna technology might be unavoidable in some cases. Frequency reuse is the key factor to improve the spectral efficiency. Unfortunately, as more and more links are packed in the same carrier frequency, the interference increases dramatically reaching a saturation point where every backhaul link experiences a considerable decrease in data rate. This interference saturation point has been clearly observed in the studies carried out in [2] (see Figure 6.7 of [2]). This saturation, which was already perceived in the "Helsinki" topology, can be aggravated with the forthcoming dense backhaul deployments [5].

This saturation versus frequency reuse can be delayed with the use of backhaul nodes equipped with multi-antenna arrays. This is because the gains reviewed in Section 2 showed that the proposed techniques allow maintaining the link rates even in the case of aggressive frequency reuse.

On top of that, in WP3 we showed that the multi-antenna techniques can boost the spectral efficiency gain in rich scattering propagation environments, such as dense urban scenarios. In particular, heavy-multipath propagation channels allow the exploitation of the spatial dimension of the communication link and hence, allow spatial separation of independent and separately encoded data signals, so called streams. Therefore, multi-antenna technology can be an attractive option for urban backhaul areas, while for rural areas the RRM approach may provide a better cost-benefit balance.

In parallel, the PTMP connections can be exploited independently of the propagation environment, since the spatial separation of the nodes supports a separate stream for each link over the same frequency resources. This has obvious benefits for unicast data streams, but it can also facilitate physical layer multi/broadcast backhauling, which will become considerable in the future. For example, recent evolutions in the LTE Broadcast suggest that the same stream will have to be backhauled towards multiple BSs so that it can be concurrently broadcasted. Similarly, evolutions in the 5G edge caching suggest that content will have to be simultaneously cached in multiple BSs taking into account not only the popularity, but also the mobility patters of the subscribers. As a result, cache placement streams will have to be multicasted to large groups of BSs to minimize the backhaul cost.

It is worth highlighting that this deliverable focuses on the WP3 objectives, i.e. the SE. Nonetheless, the reader should keep in mind that the multi-antenna technology allows the beam-steering capabilities required for the reconfiguration of the network topology, which is carefully studied in WP4. In particular, the self-configuration of the SANSA topology is expected to reduce the cost of installation and management by simplifying operational tasks through automated mechanisms, and this is only possible if the backhaul nodes are equipped with multi-antenna arrays. For example, in legacy networks a node failure entails that all interfaces installed in neighboring nodes to enable the link, become unusable as well. On the other hand, in the SANSA system, these interfaces could be reconfigured to establish links with other nodes and reroute the backhaul traffic, minimizing the impact of the node failure. Also in WP4, the benefits of the satellite system are investigated, namely the resiliency and off-loading capabilities, together with their inherent broadcast capability, which represents another key advantage of the proposed SANSA architecture.

Clearly, the multi-antenna technology requires large initial expenses in backhaul equipment (antennas and modems) and installation costs, which are expected to pay off over many years of operation. However, these updates in modern infrastructure will automatically translate into significant gains in terms of spectral efficiency and at the same time allow the spectral coexistence of satellite and terrestrial backhaul nodes operating at Ka band. In addition, the multi-antenna arrays are mandatory to reconfigure the backhaul topology automatically from the HNM.

The proposed two-step implementation of WP3 technologies is schematically depicted in Figure 3-1, where the balance between benefits and costs has been summarized in bullet form.

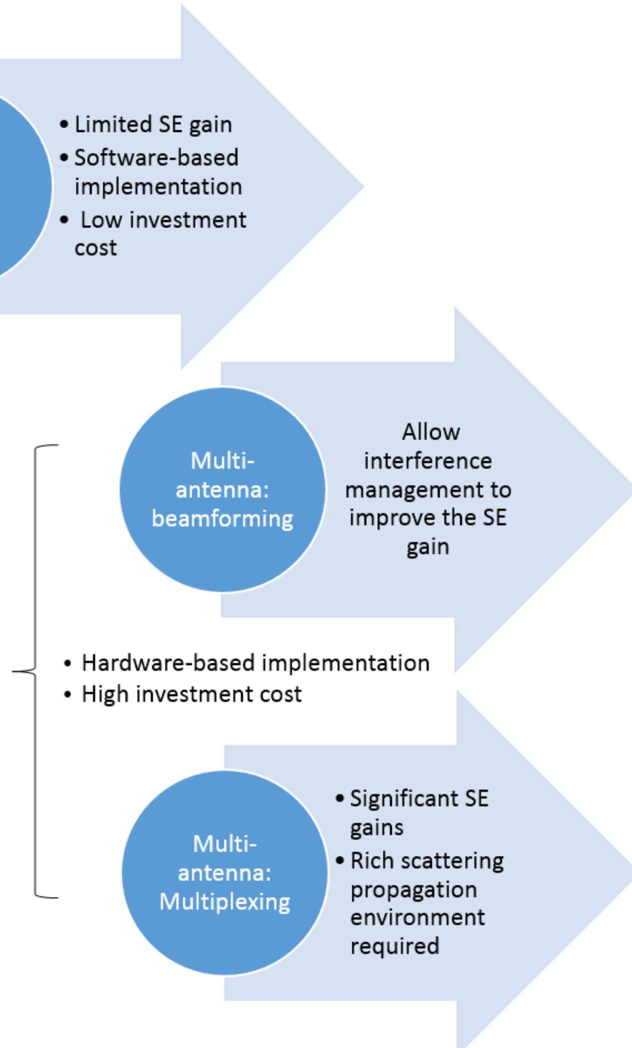

Figure 3-1. WP3 techniques' implementation

4 Conclusions

In this deliverable, we have described the main outcomes of the technological enablers investigated within WP3, namely the RRM and the multi-antenna-based interference mitigation and multiplexing techniques. In previous deliverables, each technology was studied and evaluated independently, with separate conclusions.

In this deliverable, we presented a common basis to evaluate both the potential costs and benefits of these technologies, and the expected performance gains of the SANSA backhaul network after their implementation.

Table 4-1 illustrated a summary of the cost versus SE gain analysis carried out in this deliverable. Weighing investment's costs and spectral efficiency gains, the RRM is the most well-balanced solution. The RRM can provide spectral efficiency gains of approximately 3x with a relatively low investment on the backhaul network infrastructure thanks to its software-based implementation. However, if the telecommunication operators would like to increase this gain by implementing more aggressive frequency reuse, then the multi-antenna technology becomes a requirement. Antenna arrays not only allow interference reduction towards both terrestrial and satellite receivers, but also they can boost the spectral efficiency gains up to 9x in rich scattering propagation environments, which goes in-line with the 10x SE gain objective of SANSA. On the counterpart, multi-antenna solutions are hardware-based upgrades which remain an expensive technology, not only from a manufacturing point-of-view but also for deployment and maintenance.

As a remark, multi-antenna technology is a trending topic in the current telecommunication research community and it is expected that in the future, the maturity of this technology will ease the penetration of smart backhaul networks equipped with antenna arrays due to price reduction in manufacturing and deployment. Apart from the huge SE gains, having backhaul nodes equipped with antenna arrays are mandatory for the SANSA network in order to reconfigure its topology according to the traffic demands. Moreover, the reader should remember that the WP3 technologies are key components to allow the satellite segment to be integrated in a seamless manner with the terrestrial network, and therefore, to achieve the benefits in terms of resiliency, traffic off-loading and broadcast of content. The latter benefits are considered in WP4.

Table 4-1. Cost-benefit analysis of WP3 technologies

WP3 Technology	Spectral efficiency gain	Investment and maintenance cost
RRM	***Medium***	***Low***
Multi-antenna	***High***	***High***

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