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Abstract

This deliverable provides the final results of the RISE-6G proposals on architectures, control, signalling, and data flow related to work package 6 “RIS for Enhanced Sustainability and Security”.

Keywords

Beyond-5G, 6G, RIS, Security, Sustainability, Energy Efficiency, EMF exposure.

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List of Acronyms

2D	Two-dimensional
AN	Artificial noise
AP	Access Point
AWGN	Additive white Gaussian noise
BF	Beamforming
BS	Base station
CN	Core network
CSI	Channel state information
CRKG	Channel reciprocity-based key generation
DL	Downlink
DMA	Dynamic metasurface antenna
EE	Energy efficiency
EMF	Electromagnetic field
EMFE	Electromagnetic field exposure
EMFEU	EMFE Utility
FDD	Frequency division duplex
I-UE	Intended User Equipment
I-EMFEU	Inter EMFEU
LOS	Line-of-sight
MIMO	Multiple-input multiple-output
mmWave	Millimeter wave
mMIMO	Massive MIMO
MISO	Multiple-input Single-output
MU-MIMO	Multi-User MIMO
MRT	Maximum ratio transmission
NI	Non-intended
NLOS	Non-light-of-sight
PL	Path-loss
QoS	Quality of service
RAN	Radio access network
RIS	Reconfigurable intelligent surface
RISC	RIS controller
RISE	RIS-empowered
RX	Receiver
S-EMFE	Self EMFE
S-EMFEU	Self EMFEU
SSE	Secrecy spectral efficiency
SNR	Signal-to-noise ratio
SU-MIMO	Single-User MIMO
TDD	Time division duplex
UE	User equipment
UL	Uplink
UT	User terminal

1 Introduction

RISE-6G is a 5G-PPP project funded by the European Commission under the H2020 framework. The project's vision hinges on the latest advances on reconfigurable intelligent surfaces (RISs) technology for radio wave propagation control, with the aim of improving this technology, and conceiving sustainable, programmable, and goal-oriented wireless environments. The main objectives of RISE-6G are: (i) the definition of novel architectures and control strategies incorporating multiple RISs; (ii) the study of the fundamental limits of the RIS technology based on realistic and validated radio wave propagation models; (iii) the design, by three different workpackages (WPs), of algorithmic frameworks based on RIS-empowered smart wireless environments providing enhanced connectivity and reliability (WP4), enhanced localisation accuracy (WP5), and enhanced sustainability and security (WP6); (iv) the prototyping of the proposed innovation via two complementary trials with verticals. Deployment scenarios and use cases are defined by WP2.

Within RISE-6G, WP6 proposes innovative PHY-MAC technical enablers to improve the sustainability and security of wireless networks. More precisely, WP6 proposes solutions to boost the performance of wireless networks in terms of energy-efficiency (EE), electromagnetic-field exposure (EMFE) utility (EMFEU), and secrecy spectral efficiency (SSE) metrics, as defined in Deliverable D2.4 [D2.4]. WP6 aims at improving these metrics focusing on spatially localised areas. Such performance "boosted areas" have been defined in Deliverable [D2.3] and identified for various deployment scenarios and use cases listed in the same deliverable. It is expected that the EE, EMFEU, and SSE metrics require specific and novel network architectures & deployment strategies with RISs, as well as novel assessment methods of their consideration.

This deliverable is an **updated version of D6.1**, taking into account recent advances of the project. This current deliverable provides **the final results from WP6, on network architectures and deployment strategies with RIS to boost the EMFEU and SSE metrics** defined in Deliverable D2.4, for the use cases listed in [D2.3].

The impact of the presented solutions for RIS-enabled/-boosted EMFEU and SSE on the EE performance metric is also discussed; explicit solutions for RIS-enabled/-boosted EE will be present in the upcoming Deliverable D6.4.

The deliverable lists several architectural options, RIS control strategies, as well as related data flows and control signalling, all derived from various technical contributions and innovations proposed within WP6.

To summarise, the following concepts apply to both EMFEU- and SSE-boosted networks and guide the way we design our solutions:

- Radio waves are *desirable* at the position of an *intended* entity (device, user, person, or object), because this entity is receiving data from the network or is sensed by the network;
- Radio waves are *undesirable* at the position of a *non-intended* entity (device, user, person, or object) which can be either an *exposed* entity with undesirable EMFE or an *eavesdropper* to whom signal reception is undesirable;
- A *non-intended* entity (device, user, person, or object) can be either *not helping* or *helping* the network to boost the EMFEU or the SSE;
- In the case of EMFEU, the *helping non-intended* entity can help *intentionally* by participating to the protocol reducing the EMFE; and
- In the case of SSE, the *non-intended* entity is always helping in a *non-intentional* manner. The network simply exploits an existing connection between the *non-intended* entity and itself.

Time diagrams and flowcharts for the considered schemes for SSE and EMFEU improvements present the designed protocols (including control signalling and data transmission), which are mainly devised to perform within the channel coherence time. Therefore, in most cases, the proposed schemes apply to low mobility or static UEs.

1.1 Deliverable objectives & methodology

The current deliverable follows a bottom-up approach:

- First of all, the various Physical Layer-Medium Access Control (PHY-MAC) solutions or innovations proposed by WP6 to boost SSE or EMFEU are all briefly described and analysed, in terms of deployment, architecture and control signalling requirements. Hence, for each proposed scheme, separately, one option of architecture and control signalling is derived. In addition, for each scheme, the impact on the EE metric is briefly analysed. Note that detailed description of the proposed schemes and their performance is not in the scope of this current deliverable. They will be provided in the upcoming Deliverable D6.4.
- Then, all requirements from all proposed schemes are gathered into a single set of requirements.

Each of the proposed schemes aimed at boosting EMFEU, is based on general principles explained hereafter. First of all, the control of EMFE towards humans, other living beings as well as certain objects that should have a limited EMFE needs to be reflected in specific protocol operations that take place in a RIS-aided communication system. In general, the communication system needs to differentiate between spatial points where the radiation is *desirable* and *undesirable*, respectively. The spatial points with *desirable* radiation are the ones occupied by an *intended* entity: an *intended* receiver (for instance hold by an *intended user* of the communication link) that will receive the radio waves, an *intended* object or person that needs to be illuminated by radio waves to be sensed by the network. Hence, radio waves are *desirable* at the position of *intended* receivers, *intended* users and *intended* sensed humans or objects. At the spatial points with *undesirable* radiation, the EMFE needs to be kept below a certain value. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) [ICNIRP] provides recommendation regarding such threshold, based on the analysis of scientific studies. However, it can happen that some countries or cities adopt more constraining limits than the ICNIRP guidelines [GSMA]. Also, some use cases presented in D2.3 and D2.4 propose to provide "EMFEU boosted areas" as a service, for instance, in a Train Station. Therefore, the threshold can be set arbitrarily low, either by a city, a country, or a building owner. Note that according to the local regulation, the threshold usually has to be ensured in a statistical sense (for instance on average and during a given pre-defined period) [TFC+17][DTT16][XZY+19][PCE+18][C+19][CZA21]. The spatial points with *undesirable* radiation are the ones occupied by a *non-intended exposed* entity: a *non-intended exposed* user (a user of the communication network having subscribed to a low EMFE service), a *non-intended exposed* person or object. There are two main ways in which the communication system can detect and control *undesirable* EMFE at the *non-intended exposed* entity (user, person or object), depending on the level of participation of *non-intended exposed* entity to the communication system protocol:

- The *non-intended exposed* entity is *not helping:* In this case the *non-intended* entity does not provide information about its positioning or status of EMFE, such that the communication system needs to infer it based on its own sensing capabilities, or by interfacing to application programming interface (APIs) and systems that can provide such information. For example, there could be a different system that measures room occupancy and based on that information the communication system can adjust the calculation of the induced EMFE.
- The *non-intended exposed* entity is *intentionally helping:* This is the case in which the *non-intended exposed* entity explicitly provides information to the communication system to assist the control of EMFE. For example, the device associated with a *non-intended exposed* user can use some of its signalling messages to indicate the level of EMFE or, simply, to make itself known to the communication system in order to force it to limit the EMFE at that spatial location. Such active methods for EMFE control may require dedicated protocol messages that can initiate certain action, such as change of the RIS pattern or decrease of the transmit power.

Our proposed design solutions for boosted SSE are based upon the same general principles as for EMFEU boosting. Indeed, an *eavesdropper* is similar to a *non-intended exposed* user. Again, there are two main ways in which the communication system can detect and control *undesirable* signal at the *eavesdropper*, depending on the level of participation of the *eavesdropper* to the communication system protocol:

- The *eavesdropper* is *not helping:* In this case the *eavesdropper* does not provide information about its positioning or status of received signal, such that, as for the exposed user, the communication system needs to infer it based on its own sensing capabilities. In the worst case, i.e. without any knowledge regarding the eavesdropper, the network would simply try to reduce the level of signal in general; note that such eavesdropper is sophisticated.
- The *eavesdropper* is *non-intentionally helping:* This is the case in which the *eavesdropper* is itself a User Equipment (UE), such as a smartphone, connected to the communication network. In this case, like any UE connected to the network, the eavesdropper exchanges data, control signals and pilots with the network. However, contrary to a normal UE, the eavesdropper tries to demodulate messages sent over radio resources allocated to another user equipment. To avoid such type of eavesdropping, the network could use pilot, control and data signals circulating between itself and the eavesdropper. In this case, the eavesdropper *non-intentionally helps* the network to improve its SSE; note that such eavesdropper is less complex as it is very close to a standard commercial device.

Figure 1-1 below illustrates the aforementioned concepts with one example where a RISE network emits radio waves with the Intended User as a target, in the presence of four Non-Intended entities:

1. A *Non-Intended User* who uses his/her UE (connected to the network) to *eavesdrop*; the network uses the connection with the *eavesdropper* to avoid eavesdropping, and thus the eavesdropper *unintentionally helps* the network;
2. A *Non-Intended User* who is *exposed* to the radio waves emitted by the RISE network, and who uses his/her UE (connected to the network) to *help intentionally*, the network to reduce his/her exposition;
3. A *Non-Intended* person, who is *exposed* to the radio waves emitted by the RISE network but is *not helping* the network to reduce his/her exposition;
4. A *Non-Intended* person, who uses a device (which is not connected to the network) to *eavesdrop*, *without helping* the network to prevent him/her from eavesdropping.

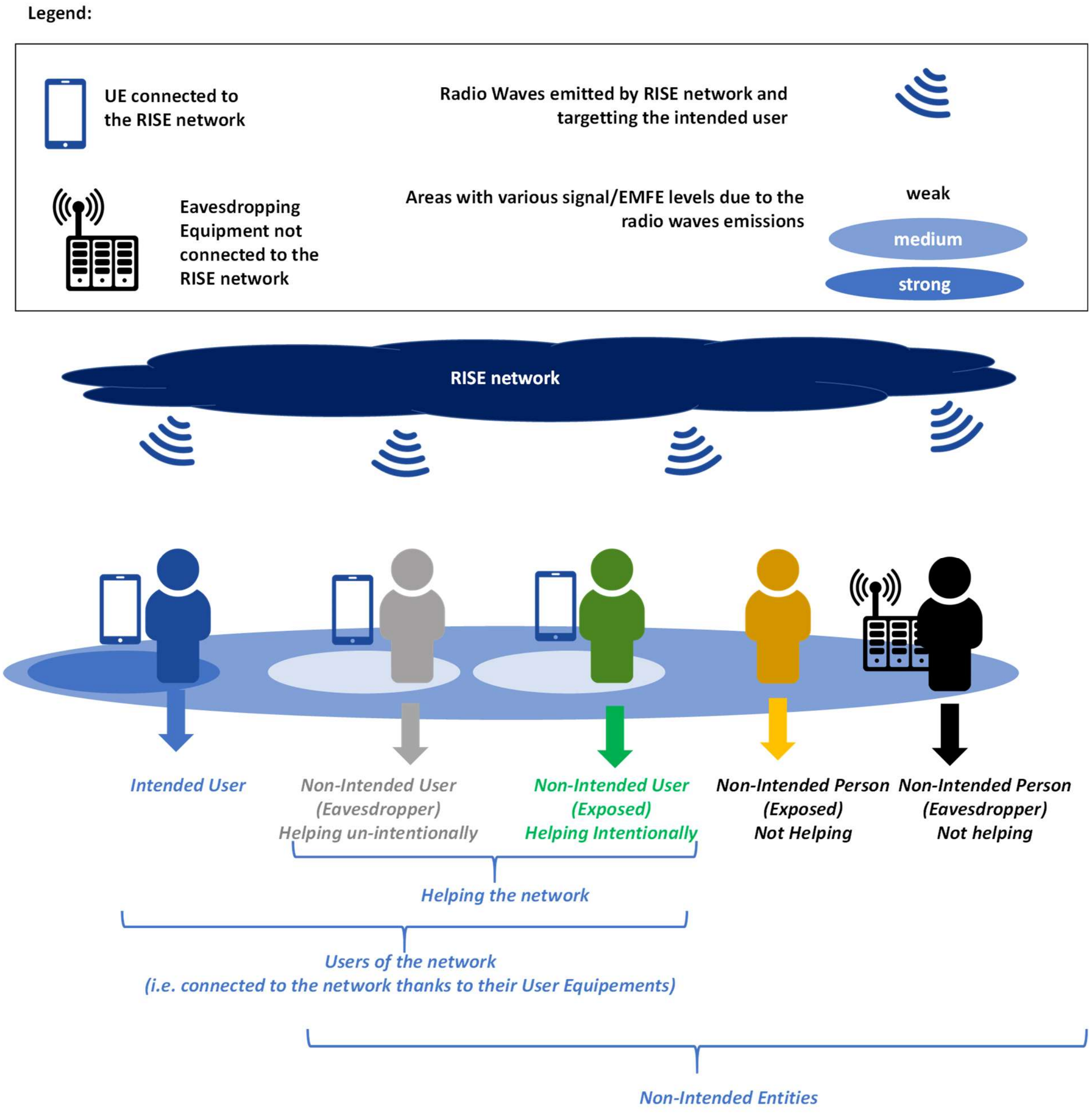


Figure 1-1 – Example where the RISE network emits radio waves with the Intended User as a target, in the presence of four different types of Non-Intended entities.

Finally, this deliverable focuses on the main signalling aspects of layers 1 and 2 in the 5G protocol stack to support EMFEU and SSE boosting during data transmission. Therefore, it is not an exhaustive analysis of all aspects of control signalling (i.e., the 5G layer 3 signalling, random access, mobility, etc. are not treated).

1.2 On potential functional/architectural splits of RIS control

The following draft taxonomy is ordered according to increasing complexity and computational capabilities. The final taxonomy will be devised in D2.6.

RIS: it is the device based on reflect-array or meta-material technology that is directly controlled by an associated RIS actuator. In some scenarios, the RIS actuator may be embedded into the RIS device. In such a case, we envision a resulting new RIS device directly controlled by the RIS controller (RISC) function.

RIS actuator (RISA): it is the element in charge of actuating the logical commands received by the RISC, i.e., of translating them into physical configurations to be applied to the RIS device. In particular, such configurations might be envisioned as phase shifts or ad-hoc meta-material state changes. In addition, the RIS actuator can provide feedback or limited sensing input when considering different RIS devices. The RISA is controlled by the RISC.

RIS controller (RISC): the controller associated to an RIS actuator or an RIS function. It is responsible for generating the logical commands associated to the switching operations between the configurations/states of the RIS elements (e.g., predefined phase shifts); RISCs may have different levels of complexity and capabilities and can embed third-party apps to implement smart algorithms. An RISC may either be controlled by other elements in the network, in which case it simply acts as an interface that configures the RIS elements based on external explicit instructions (Controlled RIS), or it may operate on its own (Autonomous RIS).

RIS orchestrator (RISO): the orchestrator is placed on a higher (hierarchical) layer and it coordinates multiple RISCs.

Warning regarding RISA/RISC/RISO concepts.

RISE-6G project builds a new architecture for RISE networks with the following stepped approach:

- Step 1: during the first half of the project, WP4/5/6 have reported intermediary requirements in terms of architecture and control signalling to support their innovations, in D4.1/5.1/6.1, respectively.
- Step 2: all the aforementioned requirements have been used to derive an intermediary RISE network architecture in D2.5.
- Step 3: During the second half of the project, D4.1/5.1/6.1 are updated to D4.3, D5.3 and D6.3) to report the final requirements in terms of architecture and control signalling, taking into account latest and additional innovations.
- Step 4: at M30 of the project, almost all HW RIS prototypes of the project are made available to the consortium. The project lists the different practical ways to control a RIS. The project lists the different practical ways to split the control of the RIS in a functional and physical architecture.
- Step 5: D2.6 provides the final RISE network architecture, taking into account:
  - requirements on architecture and control signalling to support innovations from WP4/5/6, from step 3;
  - the analysis of practical splits based on existing RIS prototypes, from step 4;

As a consequence, the concepts linked to the split of control in the functional and/or physical architecture, such as RISA, RISC and/or RISO, will reach their final definitions only in step 5. Therefore, the definitions of these concepts are local to each deliverable proceeding D2.6, and may potentially vary between deliverables proceeding D2.6.

Note also, that in the current deliverable we do not use the concepts of RISA/RISC/RISO in the descriptions of our schemes, as they are still under definition.

1.3 Deliverable structure

The deliverable is organised as follows:

- In Section 2, we briefly present Spectral Security Efficient schemes proposed in the project, and for each scheme, separately, we analyse the requirements in terms of network architecture and control signalling; the impact on the EE metric is studied;
- In section 3, we briefly present EMFE Utility schemes proposed in the project, and for each scheme, separately, we analyse the requirements in terms of network architecture and control signalling; the impact on the EE metric is studied;
- In section 4, we briefly present an EE scheme (i.e. not optimising other metrics apart from EE) proposed in the project, with its requirements in terms of network architecture and control signalling;
- Section 5 summarises our recommendation regarding network architecture and control signalling for enhanced sustainability and security;
- Section 6 concludes this deliverable.

As this deliverable analyses many different schemes, for the comfort of the reader, we give these schemes (or group of similar schemes) a short name with a number: “Technical Component” TC#1, 2 etc.

2 Secured RISE networks

In this section, we briefly present Spectral Security Efficient schemes proposed in the project. For each scheme, separately, we derive the requirements in terms of network architecture and control. Such SSE oriented schemes are presented in Section 2.2 and try to maximise the SSE metric, whose definition is recalled in Section 2.1.

2.1 SSE metric

The SSE metric has been defined in Deliverable [D2.4]. We recall hereafter its definition.

The ***secrecy spectral efficiency*** (SSE) metric is defined as the difference between the intended receiving UE (RX)'s rate R_I, referring to the legitimate link, and the non-intended RX's rate R_{NI}, referring to the link between the legitimate transmitter and the eavesdropper. When this difference results in a negative number, it means that no security is guaranteed, and the SSE is defined as zero.

Putting all above together, the mathematical definition of SSE is given by

$$\boldsymbol{SSE} = \mathbf{max}(\mathbf{0}, \boldsymbol{R_I} - \boldsymbol{R_{NI}}) \quad (\mathbf{bits/s/Hz})$$

where $R_I = \log_2(1 + SNR_I)$ and $R_{NI} = \log_2(1 + SNR_{NI})$ with SNR_l being defined as in sub-section 2.1 of D2.4, while SNR_{NI} is defined in a similar way by considering the BS to the non-intended UE direct channel $\mathbf{g}_d$ and the RIS to the non-intended UE channel $\mathbf{g}$.

Note that, in these definitions, the waves impinging on non-intended users fall into the category of *undesirable* waves, whereas the waves impinging on intended users, can be seen as *desirable*, as defined in Section 1.1.

2.2 SSE-oriented architecture and control signalling requirements

In this section, we derive the requirements in terms of network architecture and control signalling to support Spectral Security Efficient schemes proposed in the project. For each scheme, we provide:

- The objective of the scheme and the deployment scenario.
- The Architecture Requirements (i.e., which nodes must be connected).
- Data Flow and Control Signalling Requirements (i.e., a protocol description).
- The impact of energy efficiency.

The detailed specification of the proposed schemes and initial performance results are not in the scope of this deliverable; they will be provided in the future D6.4 deliverable.

2.2.1 TC#1: SSE with Full CSI knowledge

This sub-section presents the architecture and control signalling required to support the scheme detailed in [AKW+21]. The detailed description and performance of the scheme are out of the scope of this deliverable and will be provided in the future D6.4 deliverable.

Objective & Deployment Scenario

The considered secrecy-oriented system [AKW+21], illustrated in Figure 2-1, comprising three multi-antenna nodes (an intended RX UE, a non-intended eavesdropping UE, and a BS) and two multi-element RISs, one serving the non-intended RX UE (eavesdropper E) and the other the intended RX UE (legitimate BS-RX link). The two UEs are connected to the BS. The BS is assumed to be unaware of the existence of the malicious RIS and the same is assumed for E regarding the legitimate RIS. Time division duplex (TDD) air interface is assumed. Channel reciprocity can be exploited to acquire full CSI. Finally, it is assumed that there is no propagation path between the BS and the intended UE passing by the malicious RIS, and there is no propagation path between the BS and the non-intended UE passing by the legitimate RIS.

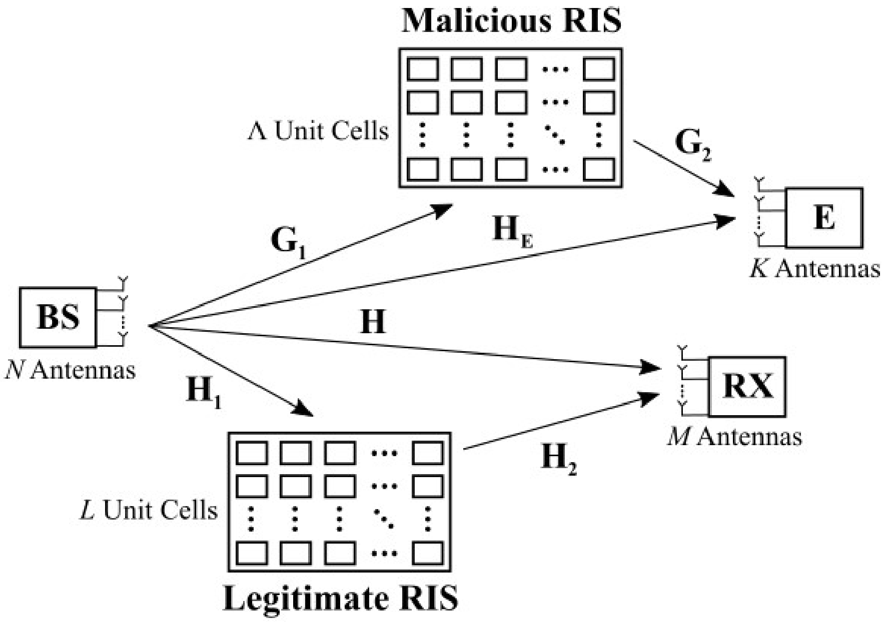


Figure 2-1 Considered deployment scenario for the secrecy spectral efficiency with full CSI knowledge.

Architecture requirements

For the above model illustrated in Figure 2-1, the following architecture requirements are assumed: we consider full CSI knowledge for both legitimate and eavesdropping sides, regarding the channels that each side needs to possess in order to design its free parameters, such as RIS configuration, beamforming vectors/matrices and receive combiners. We assume that the BS acquires the channel matrices $\mathbf{H}$, $\mathbf{H}_1$ and $\mathbf{H}_2$, while it is also assumed that the BS and the non-intended UE cooperate to estimate the BS-to-non-intended UE channel $\mathbf{H}_\mathrm{E}$ based on the following channel estimation scheme: BS transmits pilot signals to non-intended UE that estimates $\mathbf{H}_\mathrm{E}$ and then feeds this estimation back to BS. This cooperation may apply to the case where the non-intended UE plays the dual role of an intended receiver and of an eavesdropper. BS is unaware of the existence of the malicious RIS; hence, it has no knowledge on the BS-to-malicious RIS channel $\mathbf{G}_1$ and the malicious RIS-to-non-intended UE channel $\mathbf{G}_2$. However, the latter two channels are assumed available at the eavesdropping side.

The RIS nodes are assumed to be hybrid [ASA+21] and able to switch between several modes: transmission mode, reflection mode and transparent mode (where they are transparent to impinging waves). Note that such transparent mode could be obtained for instance by loading the unit cells with a switchable impedance very far from the adapted impedance for the carrier frequency of interest.

Data Flow and Control Signalling Requirements

For the described scheme above, the necessary protocol and the associated requirements for control signalling are summarised below:

1. The BS sends pilots in the downlink (DL) and the UEs estimate $(\mathbf{H}, \mathbf{H}_\mathrm{E})$. During this step, the two RISs are assumed to be in a “transparent state”, for instance, their unit cells are loaded with large impedances (close to an open circuit).

2. The UEs send pilots in the uplink (UL) and the BS estimates $(\mathbf{H}, \mathbf{H}_{\mathrm{E}})$. During this step, the two RISs are assumed to be in a “transparent state”, for instance, their unit cells are loaded with large impedances (close to an open circuit).
3. Next, the BS turns on the legitimate RIS, to estimate the cascaded channel, that is, $\mathbf{H}_1$ and $\mathbf{H}_2$. In parallel, the eavesdropper E turns on the malicious RIS and estimates the cascaded channels of the malicious RIS $(\mathbf{G}_1$ and $\mathbf{G}_2)$.
4. The BS computes the weights for the BS BF and for the legitimate RIS, optimised for SSE, only based on the knowledge of $\mathbf{H}, \mathbf{H}_{\mathrm{E}}$, $\mathbf{H}_1$ and $\mathbf{H}_2$. In parallel, the eavesdropper E compute the RIS weights for the malicious RIS only based on the knowledge of $\mathbf{H}_{\mathrm{E}}$, $\mathbf{G}_1$ and $\mathbf{G}_2$.
5. The BS sends the weights to the legitimate RIS. In parallel, the eavesdropper E sends the weights to the malicious RIS.
6. The legitimate RIS configures itself according to the received weights. In parallel, the malicious RIS configures itself according to the received weights.
7. The BS sends confidential data using the BF weights. Hopefully, the intended UE receives and demodulates the data successfully, and the non-intended UE demodulates it unsuccessfully.

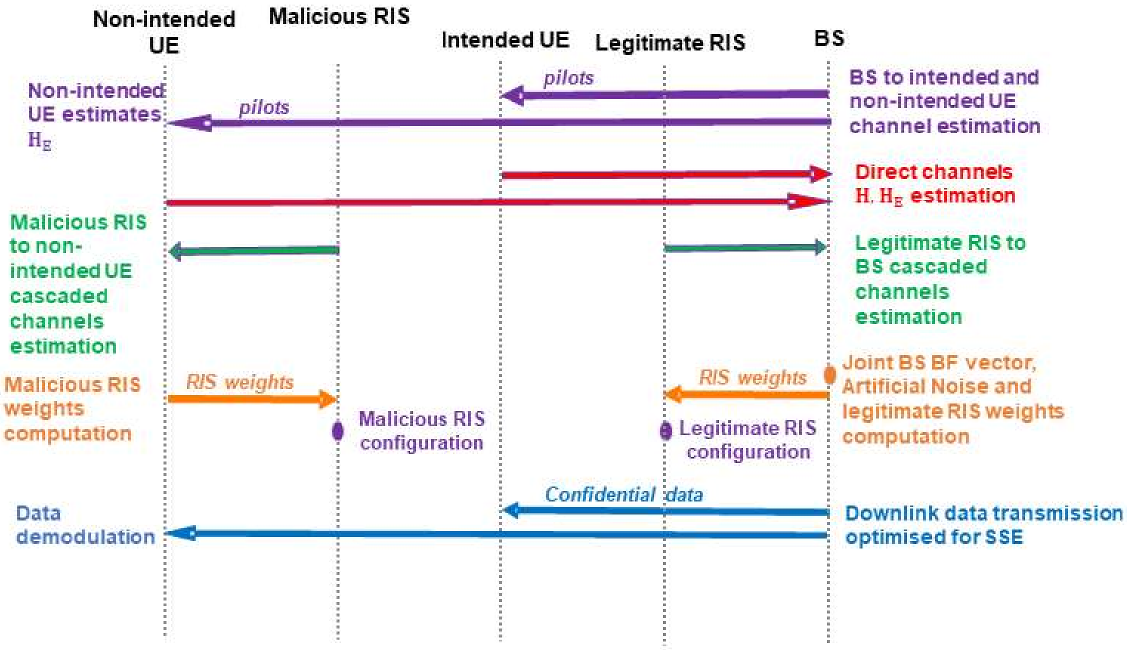


Figure 2-2 Data flow and control signalling for the secrecy spectral efficiency scheme with perfect CSI.

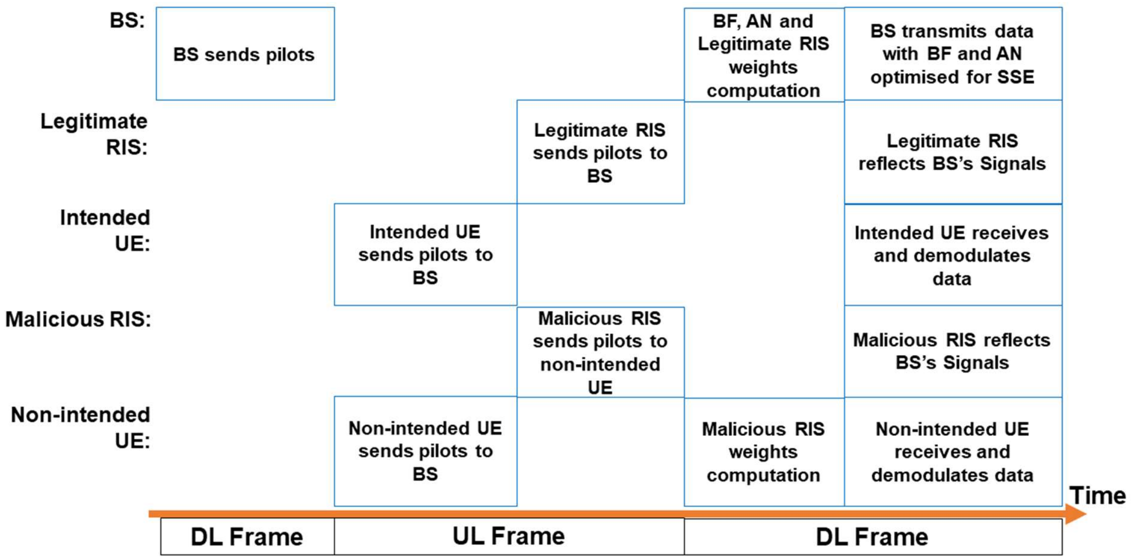


Figure 2-3 Time diagram for the secrecy spectral efficiency scheme with perfect CSI.

Energy Efficiency

Thanks to the proposed SSE scheme, the intended UE will experience higher rates due to the presence of the legitimate RIS, even when the malicious RIS has five times more unit elements than it, according to the results in [AKW+21].

2.2.2 TC#2: SSE with Partial CSI knowledge

Objective & Deployment Scenario

As depicted in Figure 2-4, the considered system [AKW+23], which is similar to the system model of previous section, is consisted of three multi-antenna nodes and two RISs. In contrast to Figure 2-1, there also exists the link between the legitimate RIS and the non-intended user (Eve). It is also assumed that the BS has partial CSI knowledge with respect to the eavesdropping links, that is, between the BS and the non-intended user. The same holds for the link between the legitimate RIS and Eve.

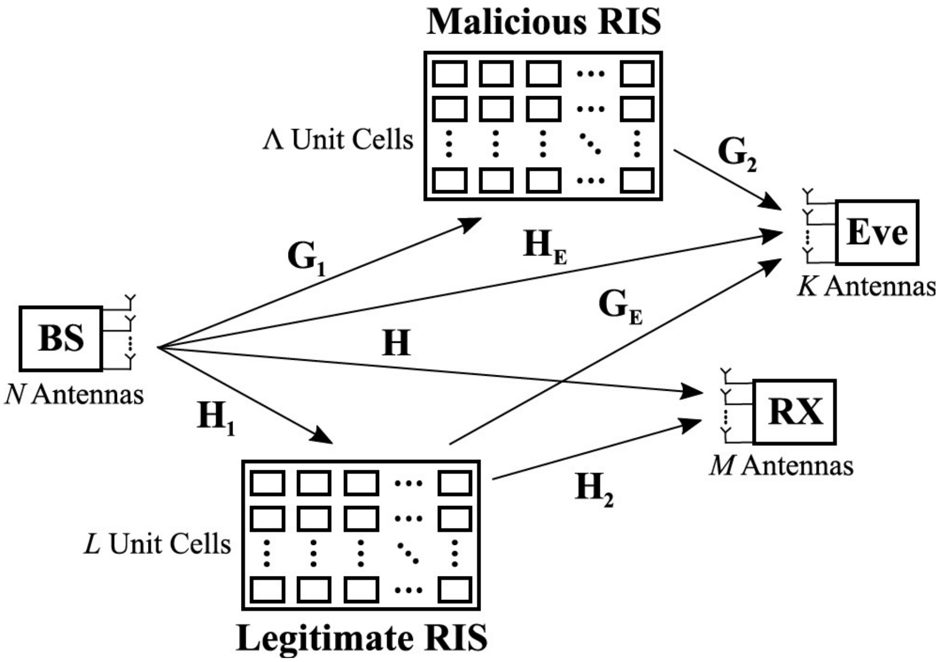


Figure 2-4 Considered deployment scenario for the secrecy spectral efficiency with partial CSI knowledge.

Architecture requirements

The following architecture requirements are assumed: it is considered that the BS acquires the channel matrices $\mathbf{H}, \mathbf{H}_1, \mathbf{H}_2$. However, since the malicious RIS is transparent to the legitimate sub-system, the channel matrices $\mathbf{G}_1, \mathbf{G}_2$ are unknown to the BS. In addition, the channel links $\mathbf{H}_E, \mathbf{G}_E$ are known up to their second order statistics since the unintended receiver does not collaborate with the BS to reveal its presence. Also, the channel matrix $\mathbf{H}_E$ is ignored by the non-intended receiver because it profits from the deployment and control of the malicious RIS to fulfil eavesdropping. Furthermore, the unintended receiver has not perfect knowledge of $\mathbf{G}_1$, but leverages on the line-of-sight placement of the malicious RIS relative to the BS. Hence, Eve composes this channel as the outer product of the array response/steering vectors based on the geometrical parameters (distances of the links and azimuth/elevation angles). It is finally assumed that the non-intended UE can perfectly estimate the channel matrix $\mathbf{G}_2$.

Data Flow and Control Signalling Requirements

For the described scheme above, the necessary protocol and the associated requirements for control signalling are summarised as follows:

1. The intended UE sends pilots in the uplink and the BS estimates $\mathbf{H}$, while the non-intended UE, sends limited information about its position, and BS partially estimates $\mathbf{H}_\mathrm{E}$. During this step, both RISs are in "transparent state".
2. The BS sends pilots in the downlink and the intended UE estimates $\mathbf{H}$, while the non-intended receiver estimates the position of the BS.
3. Then, the BS turns on the legitimate RIS, to estimate the cascaded channel $\mathbf{H}_1, \mathbf{H}_2$.
4. The eavesdropper locates the malicious RIS in a near position and partially computes the cascaded channel $\mathbf{G}_1$, whereas the channel $\mathbf{G}_2$ can be perfectly estimated.

5. The BS, computes the weights for the precoding and for the legitimate RIS, optimised for SSE, only based on the perfect knowledge of $\mathbf{H}, \mathbf{H}_1, \mathbf{H}_2$ as well as the statistical CSI knowledge of $\mathbf{H}_\mathrm{E}$ and $\mathbf{G}_\mathrm{E}$.
6. The BS controls the legitimate RIS based on the computed configuration and in parallel the eavesdropper sends the malicious RIS's weights to control it.
7. Both RISs configure themselves according to the received weights.
8. The BS sends confidential data using the precoding weights. The intended UE receives and demodulates the data successfully, while the non-intended UE demodulates them hopefully with errors.

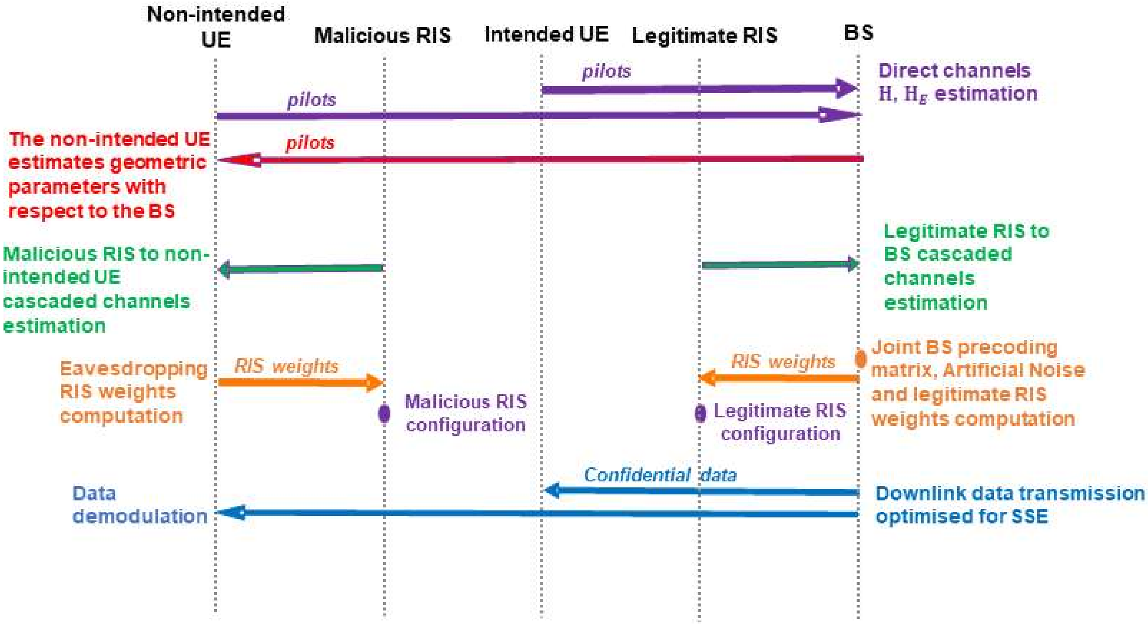


Figure 2-5 Data flow and control signalling for the secrecy spectral efficiency scheme with partial CSI.

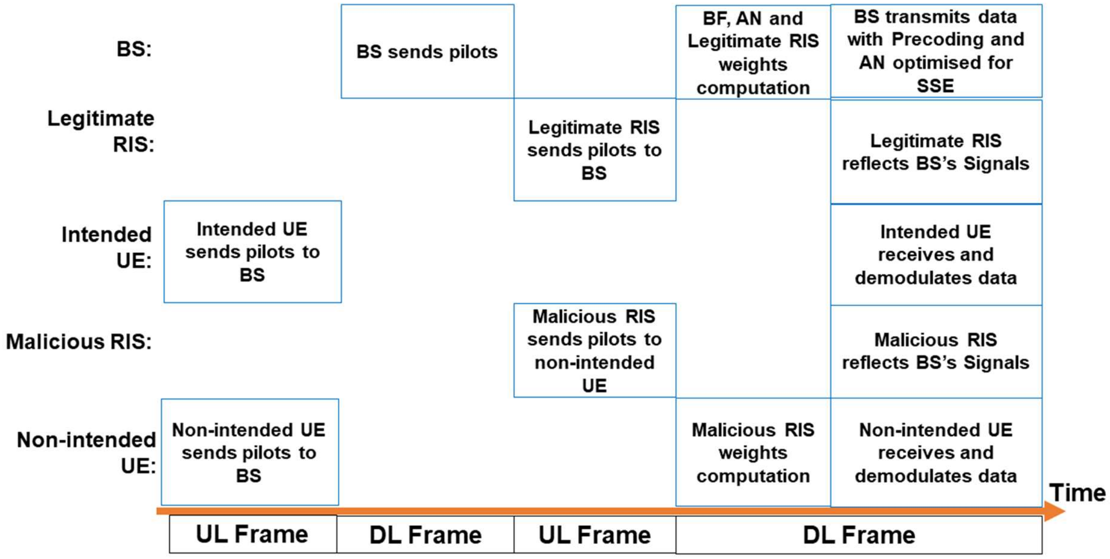


Figure 2-6 Time diagram for the secrecy spectral efficiency scheme with partial CSI.

Energy Efficiency

According to the proposed SSE scheme, the intended UE will experience higher rates due to the presence of the legitimate RIS, especially in the area close to it, according to the results in [AKW+23].

2.2.3 TC#3: On Maximizing the Sum Secret Key Rate for Reconfigurable Intelligent Surface-Assisted Multiuser Systems

This sub-section presents the architecture and control signalling required to support the scheme detailed in [LSX+22]. The detailed description and performance of the scheme are out of the scope of this deliverable and will be provided in the future D6.4 deliverable.

Objective & Deployment Scenario

The tremendous growth in connectivity and the ubiquity of wireless communications have resulted in an unprecedented awareness of the importance of data confidentiality. Traditionally, data confidentiality is guaranteed by using encryption methods in existing upper-layer protocols. Encryption methods require secret keys that are available only between legitimate parties as shown. However, the distribution of the keys is usually challenging, especially in resource-constrained large-scale mobile networks.

The representative encryption method for ensuring data confidentiality is referred to as channel reciprocity-based key generation (CRKG) method. This technique is intended for the ad hoc generation of symmetric secret keys out of radio channels between pairs of devices (namely “Alice” and “Bob”), without necessitating key distribution. The general process of CRKG comprises four phases, i.e., channel sounding, quantiation, information reconciliation, and privacy amplification. During the phase of channel sounding, Alice and Bob send pilots to each other in turn, they estimate the channels between them, and they extract appropriate channel features. These features are then converted into binary sequences by using quantisation algorithms. Then, possible disagreements between the two sequences are corrected during the information reconciliation phase. Finally, the privacy amplification phase is employed to distil the key and wipe out possible information leakage in the previous phases. As observed from the process, the security of the CRKG method is ensured by the inherent randomness of the wireless channel, the Tx-Rx reciprocity and the location-dependent behaviour of the radio channel.

Since the CRKG method relies upon the properties of fading channels, it may not guarantee the desired secret key rates in harsh propagation environments. In a factory automation scenario with densely deployed equipment, for example, the radio waves may be blocked by obstacles, leading to an interruption of the communication and the impossibility of generating the secret key. Furthermore, the phenomenon of wave-blockage is more frequent at high-frequency bands. These issues have limited the applicability and scalability of CRKG in wireless networks.

Unlike relay nodes, which require partial or complete information about the secret key, RIS is viewed as a planar array of nearly-passive reflecting elements, which makes it difficult to estimate the instantaneous channel information and derive the secret key. These advantages of RIS make it a perfect helper to assist Alice and Bob in forming an RIS-induced fluctuating channel, which serves as the common randomness for generating secret keys

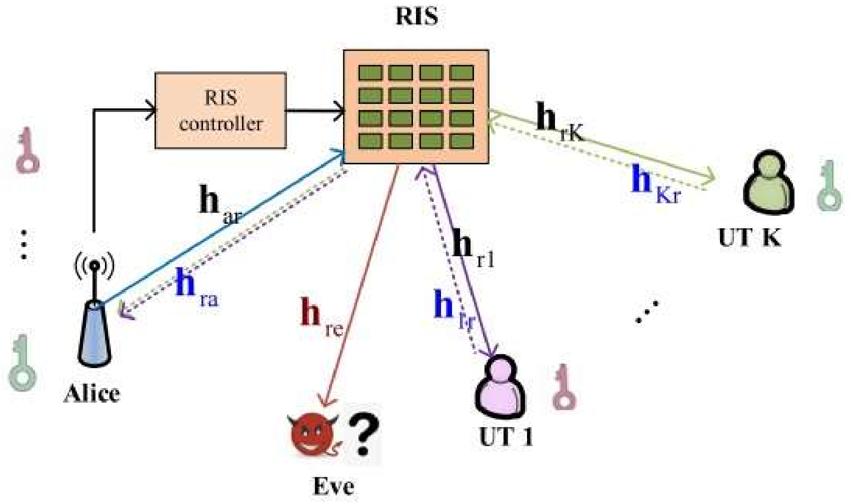


Figure 2-7 Considered deployment scenario for secrecy spectral efficiency.

An RIS-assisted multiuser key generation system, which comprises a wireless access point (AP) called "Alice", an RIS, an eavesdropper called "Eve" and K legitimate user terminals (UTs) as shown in Figure 2-7. All parties, including Alice, Eve and the UTs, are assumed to be equipped with a single antenna. Alice intends to generate secret keys $\kappa = \{\kappa_1, \kappa_2, \ldots, \kappa_K\}$ with the UTs, from the wireless channels between them. The phase shifts of the RIS are programmed and reconfigured via a controller. The keys generated between Alice and the multiple UTs are not the same.

We assume that the direct wireless channels between Alice and the UTs are blocked, therefore an RIS with M elements is deployed to enable the key generation. The RIS-induced downlink channel from Alice to the k-th UT is modelled as h_{ak}. The channel gains are assumed to be zero-mean complex Gaussian random variables and the channel from Alice to the RIS is independent of those from the RIS to the UTs. Similarly, the RIS-induced uplink channel from the k-th UT to Alice is modelled as h_{ak}. A TDD protocol is assumed. Therefore, the channels between Alice and the UT k are equal as well, i.e., $h_{ak} = h_{ka}$, which can be used to generate a pair of symmetric keys.

Architecture requirements

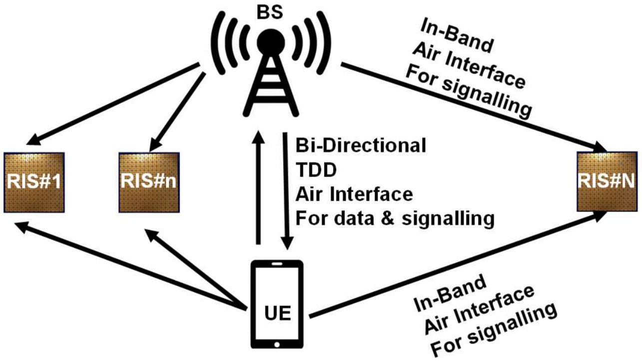


Figure 2-8 Architecture requirements for secrecy spectral efficiency.

The proposed schemes have the following minimum architecture requirements (captured in Figure 2-8): a single BS is serving a single UE at a time, through a bi-directional TDD air interface, with the help of one or several RIS nodes. The BS BF weights and RISs reflected BF weights are optimised for a single UE at a time.

The RIS is hybrid (it has a receiver) and it is connected to the BS and the UE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down.
- it listens to the UE uplink pilots.

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

Data Flow and Control Signalling Requirements

The procedure of key generation between Alice and the UT *k* is illustrated in Figure 2-9. It encompasses five main steps below:

1. The RIS phase shift matrix is configured according to statistical CSI.
2. Alice broadcasts the pilot signal for probing the downlink channel. UT *k* receives the received signal tainted by the additive white Gaussian noise (AWGN). The UT *k* estimates the downlink CSI.
3. For probing the uplink channel, the UTs send pilot signals to Alice simultaneously. Alice receives the received signal tainted by the AWGN at Alice. Alice estimates the uplink CSI of the UT *k*. To distinguish each UT, the pilot signals of different UTs are designed to satisfy the orthogonality condition.
4. Alice and the UT *k* quantise their channel estimates into binary sequences, respectively. Since these binary sequences are not exactly the same due to the impact of noise, they are referred to as initial keys.
5. Alice and the UT *k* obtain, from the initial keys, a consistent secret key through the steps of information reconciliation and privacy amplification.

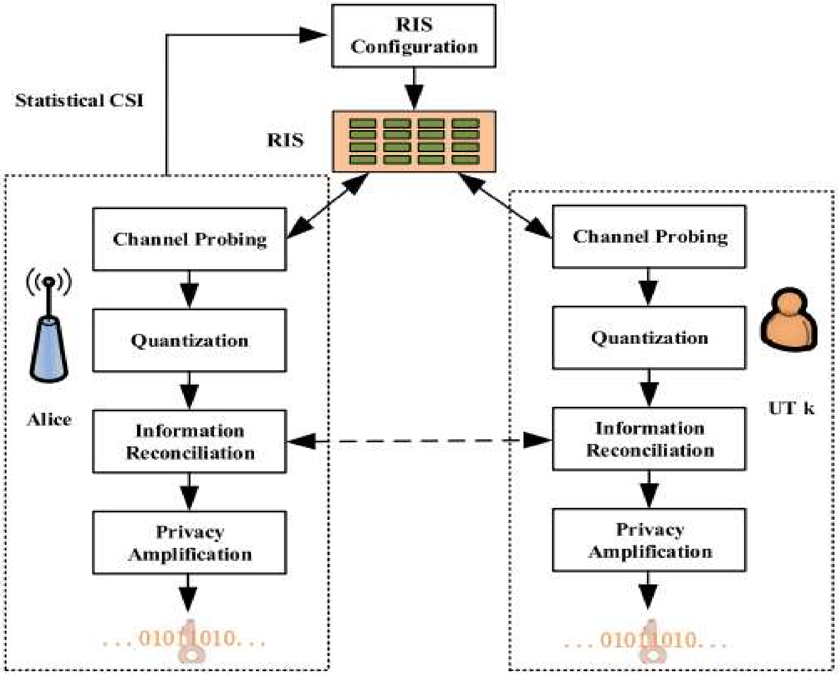


Figure 2-9 Procedure of secret key generation

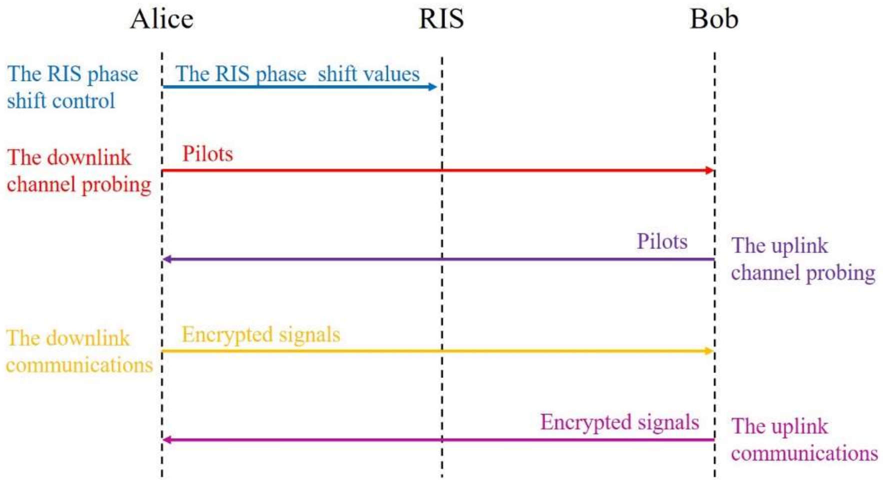


Figure 2-10 Data flow and control signalling for secrecy spectral efficiency.

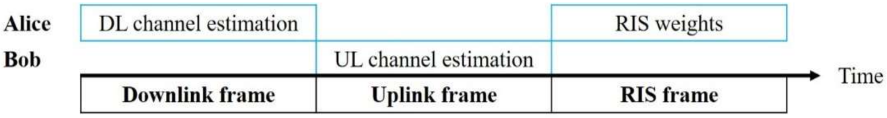


Figure 2-11 Time Diagram for secrecy spectral efficiency

2.2.4 TC#4: Spatial SSE

Objective & Deployment Scenario

The considered system [KA23] is consisted of two single-antenna receivers (an intended RX UE and a non-intended eavesdropping UE), a multi-antenna BS. It is assumed that the direct links between the BS and the UEs are blocked due to obstacles in the area that separates them. Therefore, a multi-antenna RIS is deployed to assist downlink communications. It is also assumed that the BS has partial CSI knowledge with respect to the two UEs, that is, both channels are known up to their second-order statistics. Then, the BS designs the linear precoder and the RIS passive beamforming vector to guarantee secrecy over the geographical areas where each UE is assumed to be located.

Architecture requirements

For the described system model above, the following architecture requirements are considered: It is assumed that BS perfectly estimates the channel matrix corresponding to its connection with the RIS, whose elements can be hybrid operating among various modes, such as transmission mode, reflection mode and transparent mode. However, the channels that connect the RIS with both UEs are not perfectly known at the BS’s side but partially, since both UEs lie in areas blocked with respect to the BS and the cooperation between them is hard.

Data Flow and Control Signalling Requirements

The necessary protocol and control signalling requirements for the considered scheme are summarised as follows:

1. Both intended and non-intended UEs send limited information about their position through the RIS. During this step the RIS operates in a hybrid mode.
2. The BS receives the signals from the UEs through the RIS and partially estimates the geographical areas where the UEs are located.
3. Then, the BS computes the precoding weights and the RIS’s passive beamforming vector.
4. The BS controls the RIS based on the computed configuration per element.
5. The BS transmits confidential data through the RIS using the precoding weights. The intended UE receives and demodulates the data successfully, while the non-intended UE demodulates them hopefully with errors.

The above process ideally results in secure guarantees for both the geographical areas where the UEs are located.

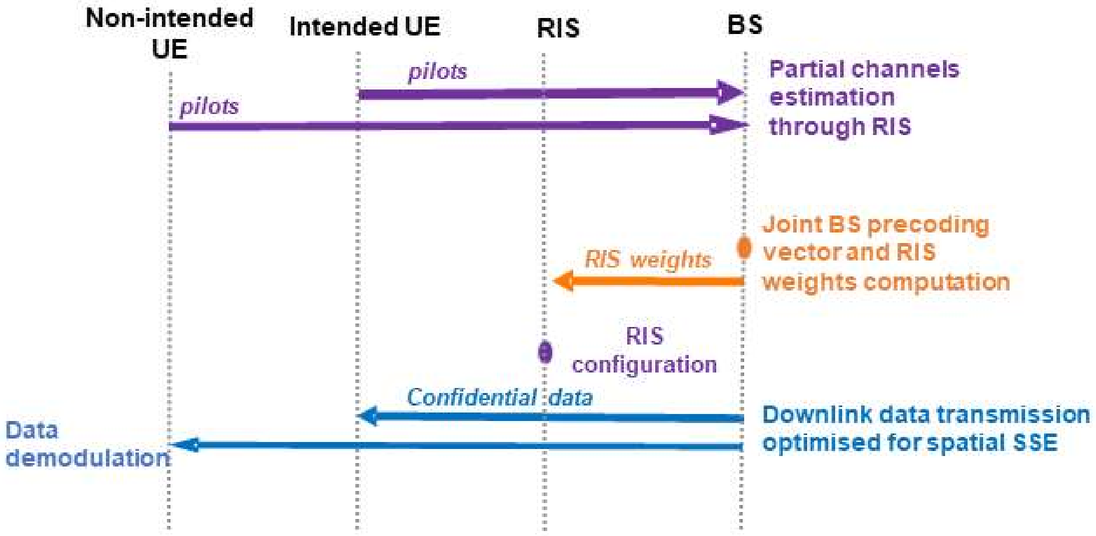


Figure 2-12 Data flow and control signalling for the spatial SSE scheme with partial CSI.

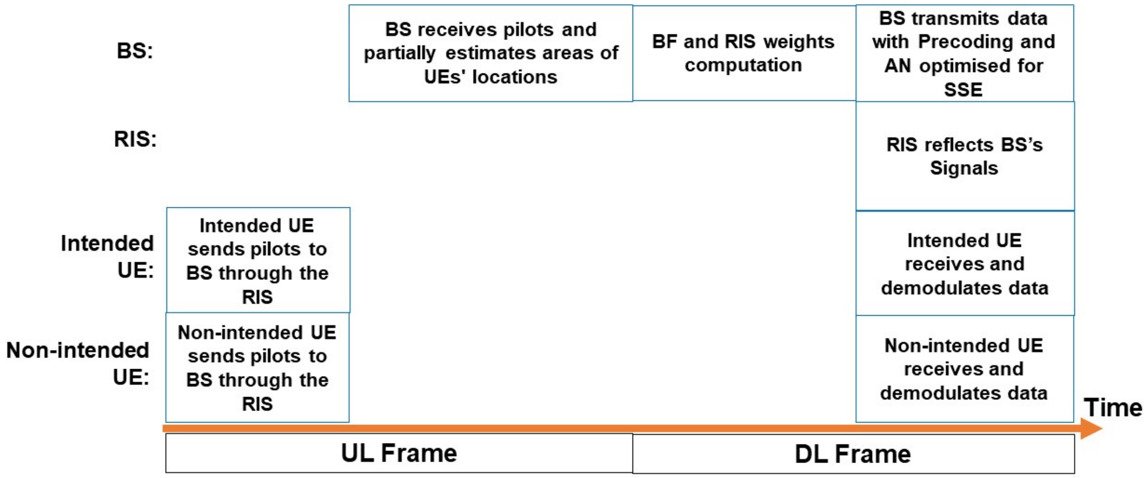


Figure 2-13 Time Diagram for the spatial SSE scheme with partial CSI.

Energy Efficiency

According to the obtained numerical results, we note that the proposed optimisation algorithm can be readily applied to the case where Eve is absent, thus optimizing the spatial energy efficiency with respect to the intended-UE.

3 EMFE Utility RISE networks

In this section, we derive the requirements in terms of network architecture and control signalling to support EMFE Useful schemes proposed in the project. Such EMFE Utility (EMFEU) oriented schemes are presented in Section 3.2 and try to maximise the EMFEU metric, which definition is recalled in Section 3.1.

Note that the detailed description of the schemes and their performance is not in the scope of this deliverable. They will be provided in the upcoming D6.4 deliverable.

3.1 EMFEU metric

The EMFEU metric has been defined in Deliverable [D2.4] Section 2.10. We recall its definition hereafter.

In addition to the DL case, we also consider the UL case.

We first consider as a target service, a DL data communication towards an intended UE. We also consider a non-intended user (or person or object) who is potentially exposed to the EMF generated by this link. For this target service, we propose the following definition of the ***inter EMFEU (I-EMFEU)***:

$$\boldsymbol{EMFEU_{inter} = R^{DL}/X^{NI},}$$

where R^{DL} is data rate that is delivered to the intended UE and X^{NI} is the EMF which the non-intended user (or person or object) is exposed to. In the case we are considering multiple non-intended users (or persons or objects), X^{NI} is the EMF of the most exposed one.

As a target service, we then consider an UL data communication issued by an intended UE. In this case, the intended UE is also the exposed one. For this target service, we propose the following definition of the **self EMFEU (S-EMFEU)**:

$$\boldsymbol{EMFEU_{self} = R^{UL}/X^{I},}$$

where R^{UL} is data rate that is transmitted by the intended UE and X^{I} is the EMF which the intended user (we recall that the intended user "uses" the intended UE) is exposed to. This refers to the user own radiation, which should be a very local phenomenon. A RIS can help boosting the self EMFEU through improving the link's quality, thus, allowing the UE to achieve the same rate with a lower transmit power and a lower self EMFE.

Note that, in these definitions, the waves impinging on non-intended users fall into the category of *undesirable* waves, whereas the waves impinging on intended users can be seen as *desirable*, as defined in Section 1.1.

3.2 EMFE-oriented architecture and control signalling requirements

In this section, we derive the requirements in terms of network architecture and control signalling to support EMFE Useful schemes proposed in the project. For each scheme, like for the SSE-oriented solutions in Section 2, we provide:

- The objective of the scheme and the deployment scenario.
- The Architecture Requirements (which nodes must be connected).
- The Data Flow and Control Signalling Requirements (a protocol description).
- The impact of energy efficiency.

The detailed specification of the proposed schemes and initial performance results are not in the scope of this deliverable; they will be provided in the future D6.4 deliverable.

3.2.1 TC#5: RIS-aided EMF-Aware Downlink BF for sub-6 GHz

This sub-section presents the architecture and control signalling required to support examples of schemes [APV21] [APV+22-1] [APV+22-2] [YIP22-1] [YIP22-2] designed for I-EMFEU improvement, at sub-6 GHz.

Objective & Deployment Scenario

A macro-cell deployment of massive multiple-input multiple-output (MIMO) BSs operating with a sub-6GHz carrier frequency is considered. As illustrated in Figure 3-1, we consider both outdoor-to-outdoor and outdoor-to-indoor environments. The following type of propagation is considered: multiple scatterers, multiple RISs, both line-of-sight (LOS) and non LOS(NLOS). RISs and scatterers are in far field of target UE and BS. Slow moving or steady UEs only are considered. TDD mode is assumed. Channel reciprocity can be exploited to acquire full CSI.
RIS-aided EMF-Aware beamforming schemes [APV21] [APV+22-1] [APV+22-2] [YIP22-1] [YIP22-2] are proposed with the following objectives: to deliver DL data from the BS to the UE with maximum received power at the target UE, whilst complying with the EMFE regulation. [APV21] [APV+22-1] [APV+22-2] are simple algorithms designed for single-user MIMO (SU-MIMO), whereas [YIP22-1] [YIP22-2] are more complex algorithms been designed for MU-MIMO.

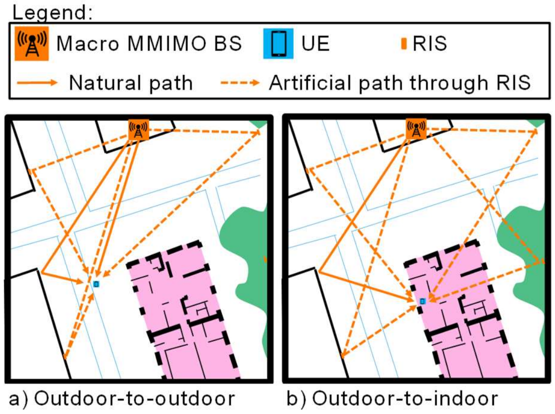


Figure 3-1 Considered deployment scenarios.

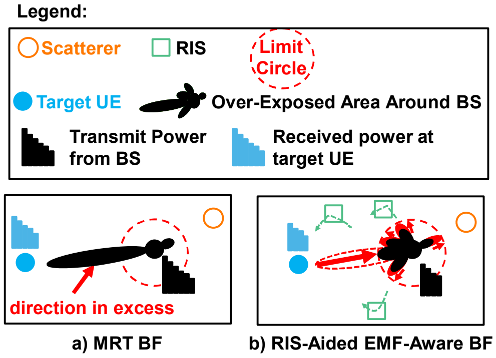


Figure 3-2 RIS aided EMF-Aware BF principle.

The principle of the proposed technical solutions is summarised hereafter. It addresses a drawback of MassiveMIMO (M-MIMO) maximum ratio transmission (MRT) BF (which exploits the channel reciprocity in TDD systems), which yields the creation of undesired high exposure regions (over-exposed area in terms of EMFE) in the vicinity of the antenna, as illustrated in Figure 3-2 a). Such over-exposed area is concentrated in few directions (around the antenna) corresponding to the best propagation paths between the antenna and the receiver. Various novel electromagnetic field aware beamforming schemes are proposed that: (i) spread the beamforming radiation pattern in the angular domain by adding to the 'natural' propagation paths some 'artificial' propagation paths thanks to RISs; (ii) truncate the pattern in strong directions; (iii) boost the pattern in weak directions. Such proposed novel schemes maximise the received power at the target, without violating the exposure constraint.

This scheme therefore boosts the *inter EMFEU* metric. However, as non-intended UEs, persons and objects are *not helping* the network to avoid exposing them, this scheme only reduces the global level of *undesirable* radiations.

Architecture requirements

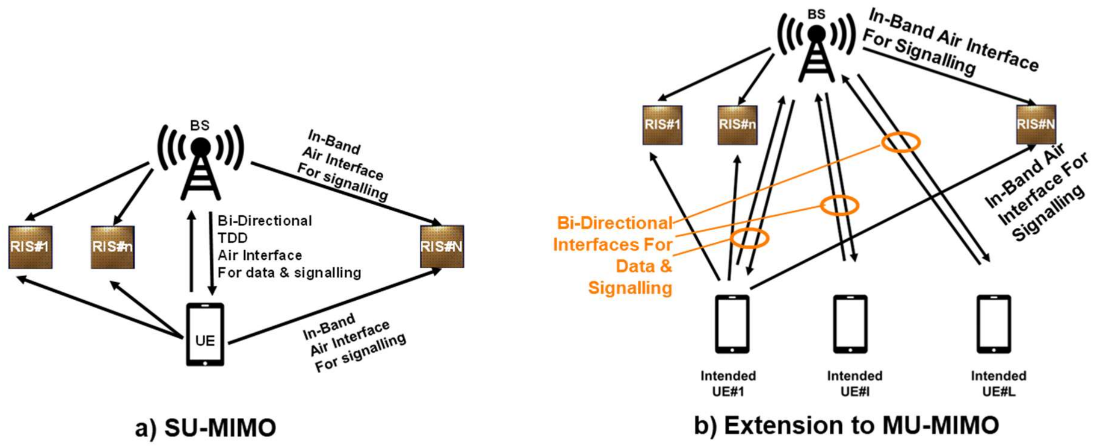


Figure 3-3 Architecture requirements, with RIS #n, n=1 to N, for (a) SU-MIMO, and (b) MU-MIMO (with intended UE#l, l=#l to L).

The proposed schemes for **SU-MIMO** have the following minimum architecture requirements (captured in Figure 3-3-a): a single BS is serving a single UE at a time, through a bi-directional TDD air interface, with the help of one or several RIS nodes. The BS BF weights and RISs reflected BF weights are optimised for a single UE at a time. Although a RIS node is mute, it is connected to the BS and the UE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down.
- it listens to the UE uplink pilots.

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

Figure 3-3-b) illustrates the minimum architecture requirements for the **MU-MIMO** schemes, which are extensions of the SU-MIMO schemes. More precisely, a single-BS serves multiple UEs at a time, through bi-directional TDD air interface, with the help of one or several RIS nodes. The RISs weights are optimised only for Intended UE#1 (to boost the propagation channel between the BS and the UE#1, though all RISs). Therefore, the BS therefore operates in a propagation channel that is shaped by RISs for UE#1 only, but that influences the channels of all UEs. Under these conditions, the BS BF weights are optimised for all the multiple UEs at a time. Again, as for SU-MIMO schemes, a RIS listens to the BS synchronisation signals and listens to the UE#1 uplink pilots.

Data Flow and Control Signalling Requirements

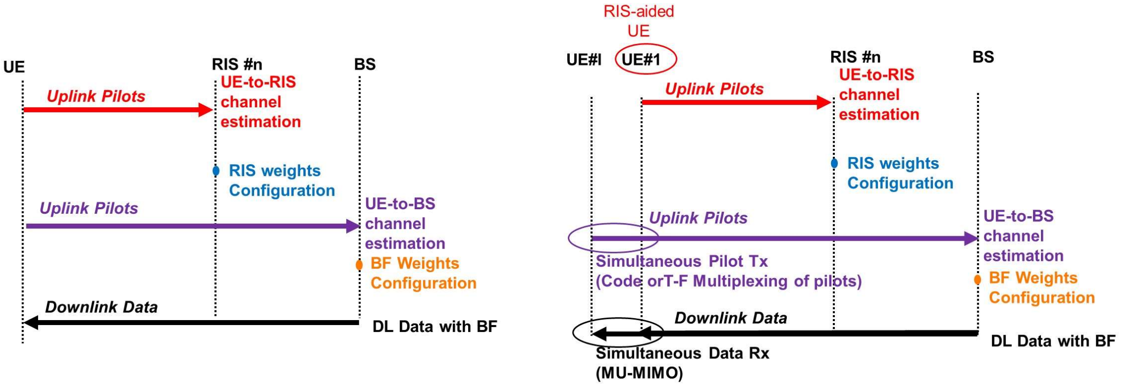
The proposed schemes for **SU-MIMO**, have the following minimum requirements (captured in Figure 3-4-a) and Figure 3-5-a)) in terms of protocol and control signalling:

1. the UE sends pilots in the uplink, each RIS senses the phases of the propagation channel between the UE and its unit cells;
2. then, based on the knowledge of these phases, each RIS computes its weights to “turn itself electronically” towards the target UE, and “freezes”.
3. The UE sends pilots in the uplink again, to allow the BS to sense the UE-to-BS channel under the influence of RISs.
4. Then, based on the knowledge of the channel, the BS computes the BF weights

5. Finally, the BS sends data to the UE, using BF.

Steps 1 to 4 are re-iterated to take into account changes in the propagation environment. However, the UE is supposed to be steady or slowly moving. Moreover, the most frequent occurrence of steps 1 to 3 is once per UL frame (as illustrated in Figure 3-5-a)).

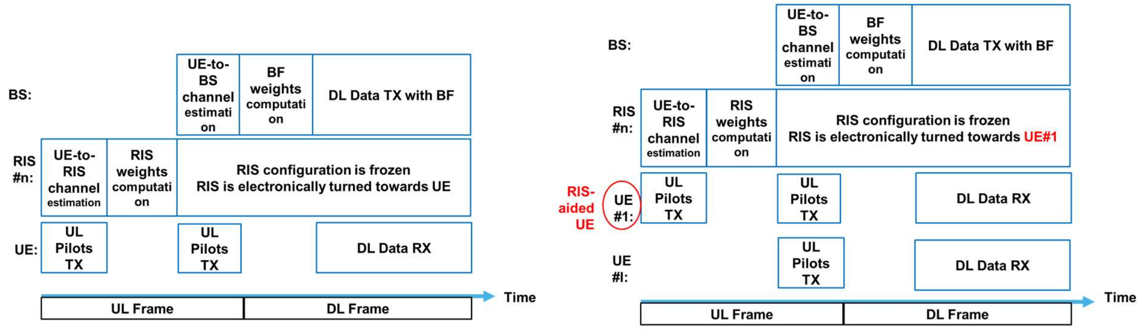
Note that in this scheme, the *non-intended* UE is not helping as it is not participating to the protocol.



a) SU-MIMO

b) Extension to MU-MIMO

Figure 3-4 Data and control flows, for (a) SU-MIMO and (b) MU-MIMO, with following convention: when RISs #n is indicated it means that all RISs #n, with n=1 to N, are doing the same thing simultaneously, when UE #l is indicated, it means that all UEs #l, with l=1 to L, are doing the same thing simultaneously.



a) SU-MIMO

b) Extension to MU-MIMO

Figure 3-5 Time diagram, all RISs #n (n=1 to N) doing the same thing simultaneously.

The proposed schemes for **MU-MIMO**, have the following minimum requirements (captured in Figure 3-4-b) and Figure 3-5-b) in terms of protocol and control signalling:

1. the UE#1 sends pilots in the uplink, each RIS senses the phases of the propagation channel between the UE#1 and its unit cells;
2. then, based on the knowledge of these phases, each RIS computes its weights to “turn itself electronically” towards the target UE#1, and “freezes”.
3. Simultaneously, all the UEs#l, with l=1 to L, send pilots in the uplink (included UE#1 again), to allow the BS to sense each UE-to-BS channel, under the influence of RISs. Standard code or Time-Frequency multiplexing for uplink pilots as already exiting in 5G [3GPP-TS38.201] is applicable.
4. Then, based on the knowledge of the channels, the BS computes the MU-MIMO BF weights

5. Finally, simultaneously, the BS sends data to all the UEs#l, with l=1 to L, using MU-MIMO BF.

Again, steps 1 to 4 are re-iterated to take into account changes in the propagation environment. However, the UEs are supposed to be steady or slowly moving, and to the most frequent occurrence of steps 1 to 3 is once per UL frame (as illustrated in Figure 3-5-b)).

Note that, again, in this scheme, the *non-intended* UE is not helping as it is not participating to the protocol.

Energy Efficiency

For SU-MIMO, [APV21] shows that using truncation only already improves the attained received power at the UE, whilst meeting the EMFE constrain. Hence the EMFE Utility is boosted. [APV+22-1] shows that boosting in addition to truncation, further improves the attained received power at the UE, whilst meeting the EMFE constrain, but at the expense of a large amount of energy spending. Hence, in this case, the EMFE Utility is further boosted, at the expense of an EE degradation. [APV+22-2] is similar to [APV+22-1]. It is therefore up to the network operator to choose the trade-off between EMFEU and EE and select the right technique to attain this trade-off. The extension of the SU-MIMO schemes to MU-MIMO in [YIP22-1] [YIP22-2] do not change the conclusion on this aspect.

3.2.2 TC#6: Energy Efficiency Optimisation of Reconfigurable Intelligent Surfaces with Electromagnetic Field Exposure / Global Reflection / Active element Constraints, at mmWaves

This sub-section presents the architecture and control signalling required to support examples of schemes [ZR22] [FZR22-1] [FZR22-2] designed for S-EMFEU improvement, at mmWaves.

Objective & Deployment Scenario

Energy efficiency (EE) was already considered a key performance indicator of 5G networks, and remains a major aspect of 6G networks, too. While considering EE, other points need to be addressed too:

- At the same time, a relevant issue for future wireless networks is the growing concern for electromagnetic pollution. Although, at present, non-ionizing radio frequency radiations have not been associated to any health condition, the continuous exposure to electromagnetic fields (EMF) raises concerns among end-users and diminishes their acceptance of novel technologies [ZR22].
- While RISs have the potential of drastically improving the EE of wireless networks, due to their very limited hardware power consumption, most research contributions on radio resource allocation for RIS-aided networks have focused on maximizing the system rate or on minimizing the power consumption rather than optimizing the bit-per-Joule EE. Only few contributions have started addressing the issue of radio resource allocation for EE maximisation in RIS-based networks [FZR22-1].
- From an energy perspective, the nearly passive behaviour of RISs has been recognised as a major advantage, but, on the other hand, it also limits the rate performance that a RIS-aided network can ensure, especially when no direct path exists. For this reason, recently, the use of active RIS has started to be investigated, i.e. the RIS is equipped with analogue amplifiers that allow it to increase the amplitude of the incoming signal [FZR22-2].

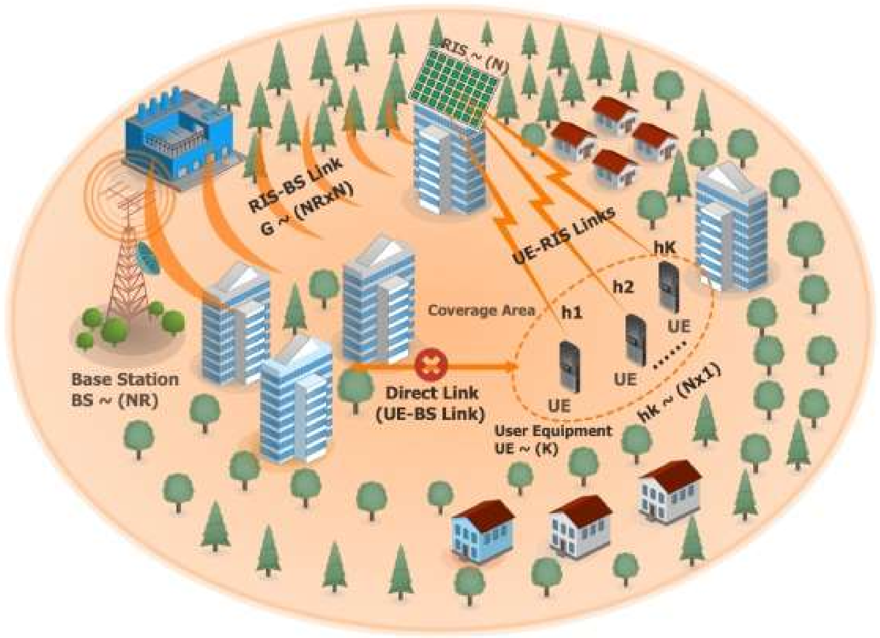


Figure 3-6 Considered deployment scenarios for energy efficiency optimisation.

[ZR22] considers a single-user system in which a transmitter with multiple antennas and a receiver with multiple antennas communicate through an RIS. [FZR22-1] and [FZR22-2] consider the uplink of a multi-user system in which *K* single-antenna mobile terminals communicate with a base station equipped with multiple antennas, through an RIS with *N* reflecting elements (Figure 3-6). For all cases, it is assumed that the direct link between the transmitter and receiver is weak enough to be ignored.

Architecture requirements

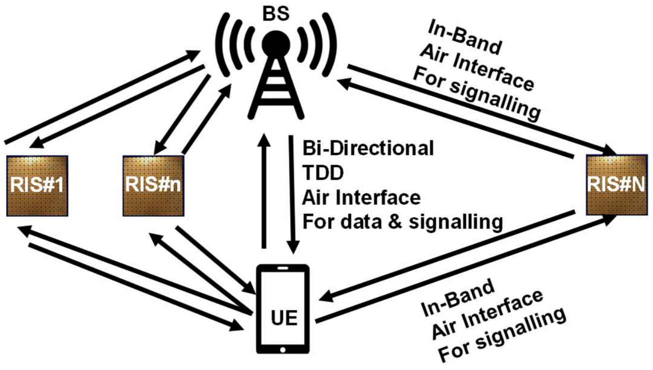


Figure 3-7 Architecture requirements for energy efficiency optimisation

The proposed schemes have the following minimum architecture requirements (captured in Figure 3-7): a single BS is serving a single UE at a time, through a bi-directional TDD air interface, with the help of one or several RIS nodes. The BS BF weights, the UE filter and RISs reflected BF weights are optimised for a single UE at a time.

The RIS node can listen and talk, and it is connected to the BS and the UE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down;

- it sends pilots to the BS;
- it sends pilots the UE;
- it listens to the UE message signaling the RIS weights to be applied.

Hence, the RIS node is assumed to be hybrid: it can switch between a transmission mode, a reception mode and a reflecting mode.

Data Flow and Control Signalling Requirements

The proposed schemes have the following minimum requirements (captured in Figure 3-8 and Figure 3-9) in terms of protocol and control signalling:

1. Each RIS #n (n=1 to N), in sequence, sends pilots to allow the UE and the BS to measure the RIS-to-UE and the RIS-to-BS channels.
2. The BS reports the RIS-to-BS channels, for each RIS, to the UE;
3. The BS sends pilots to the UE to allow the UE to measure the BS-to-UE channel (for this stage, the RIS are assumed to be frozen in a known configuration, so that the UE can withdraw from the BS-to-UE the ‘artificial’ part of the channel with RIS influence, and extract the ‘natural’ part only);
4. Based on all aforementioned channel measurements, the UE computes the UE BF weights, the BS filter weights and the RIS weights;
5. The UE sends to each RIS, its individual weights;
6. Each RIS configures its weights according to the received control message from the UE;
7. The UE sends data with demodulation pilots to the BS
8. The BS measures the channel, equalises it (after having determined the BS filter) and received the data.

Step 1 requires the introduction of a ‘RIS frame’ during which the BS and the UE are mute.
Steps 1 to 8 are re-iterated to take into account changes in the propagation environment. However, the UE is supposed to be steady or slowly moving. Moreover, the most frequent occurrence of steps 1 to 3 is once per overall (RIS, DL and UL) frame (as illustrated in Figure 3-9).

Note that in this scheme, the non-intended UE is helping as it is participating to the protocol.

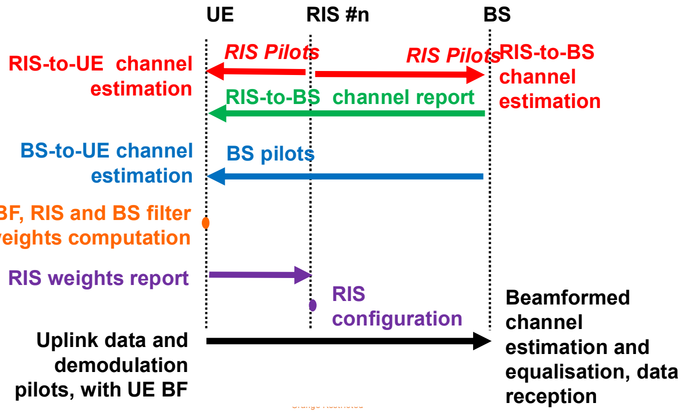


Figure 3-8 Data and control flows for energy efficiency optimisation, with RIS channels estimation, in sequence for RIS #n, n=1 at N.

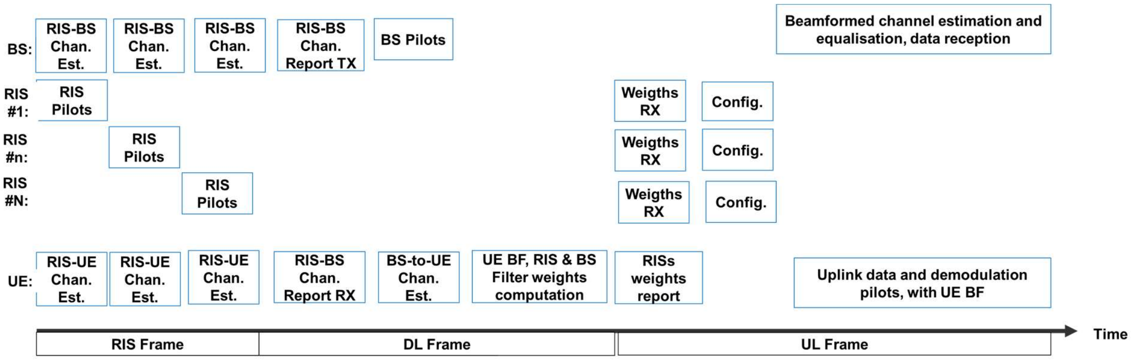


Figure 3-9 Time diagram for energy efficiency optimisation, with RIS channels estimation, in sequence for RIS #n, n=1 at N.

One RIS equipped with multiple passive reflection elements for schemes is used in [ZR22] and [FZR22-1]. One RIS equipped with multiple active and passive reflection elements for schemes is used in [FZR22-2]. The phase shifts on the RIS are assumed to be continuously adjustable.

In [FZR22-1], the optimisation is performed assuming that the RIS is capable of global reflection, i.e. the constraint on the power reflected by the RIS is not applied to each reflecting element individually, but rather to the complete surface.

Energy Efficiency

[ZR22], [FZR22-1], and [ZR22-2] aims at maximizing the EE with their own constraints.

- In [ZR22], Two low-complexity algorithms are developed that jointly optimise the RIS phase shifts, the transmit beamforming, the linear receive filter, and the transmit power. The numerical results in [ZR22] show that RIS-based communications can ensure high energy efficiency while fulfilling users' exposure constraints to radio frequency emissions.

- The work in [FZR22-1] addressed the EE maximisation problem in a multiuser network aided by an RIS endowed with global reflection capabilities. The results indicate that the proposed radio resource optimisation algorithms provide large EE gains compared to heuristic random resource allocations.
- The work in [FZR22-2] has proposed two provably convergent algorithms with polynomial complexity for EE maximisation in a wireless network aided by an active RIS. Numerical results show the merits of the proposed algorithms and highlight a trade-off between the EE of active and passive RISs, in terms of the number of RIS elements and the additional power consumption due to the presence of the active-load hardware.

3.2.3 TC#7: Low sum EMFE of multiple radio access networks in strong visibility, without coordination, at mmwaves

This sub-section presents the architecture and control signalling required to support examples of schemes designed for I-EMFEU improvement, at mmwaves.

Objective & Deployment Scenario

A deployment of small cell BSs or Aps operating with a mmWave carrier frequency is considered. As illustrated in Figure 3-10, we consider indoor-to-indoor environments. We consider the following type of propagation: multiple scatterers, multiple RISs and LOS dominant propagation. RISs and scatterers are in far field of target UE and BS. No constrain on the mobility of UEs is considered. As illustrated in Figure 3-10, at least two operators O1" and "O2" are considered, each with its own RIS, BS, radio access network (RAN) and core network (CN) equipments.

As illustrated in Figure 3-10, a joint RIS and BF EMFE aware scheme is proposed with the following objective: each operator should avoid exposing a common target "low EMFE area" that is in strong visibility of the BSs.

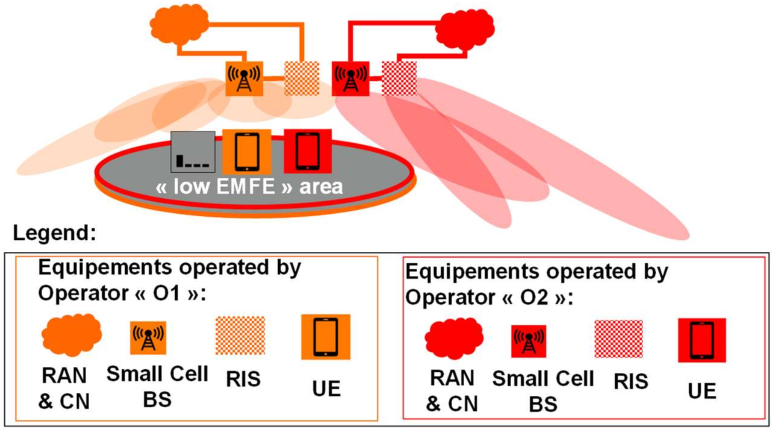


Figure 3-10 Considered deployment scenarios.

The principle of the proposed technical solution requires some field measurements by "O1" and some static optimisation of the BS and the RIS.

More precisely, a measurement UE is used to scan the "low EMFE" area, manually (by an employee of "O1" for instance) while the BS and the RISs of "O1" are performing transmitted beam sweeping, and reflected beam sweeping, respectively. The BS of "O1" determines the list of "forbidden couples of beams and reflected beams" that expose the "low EMFE" area above a pre-defined threshold and stores them. The complementary list of couples of beams and reflected beams therefore gathers the "allowed couples of beams and reflected beams".

Then, when the network is operated it only uses allowed couples of beams and reflected beams.

The same principle applies to operator “O2”.
This is expected to provide a “low EMFE area” without live coordination between operators O1” and “O2”.
However, it is operationally expensive as it requires some field measurements and sub-optimal since it is not dynamically adapted. Some pre-optimisation using ray-tracing simulation tools can reduce the time spent in field measurements.
Note that the detailed description of this scheme and its performance is not in the scope of this deliverable. It will be provided in the upcoming D6.4 deliverable.

This scheme therefore boosts the inter EMFEU metric.

Architecture requirements

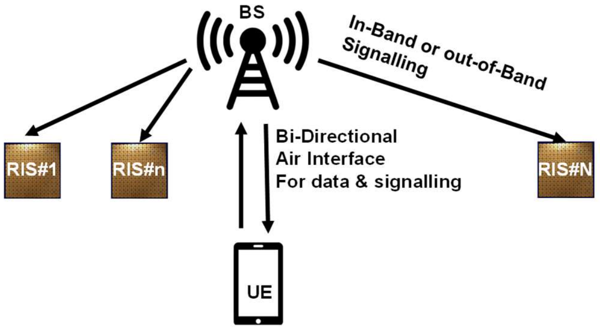


Figure 3-11 Architecture requirements.

The proposed scheme has the following minimum architecture requirements (captured in Figure 3-11) : a single BS is serving a single “measurement UE” at a time, through a bi-directional TDD or frequency division duplex (FDD) air interface, with the help of one or several RIS nodes.
The RIS node can listen to the BS as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down;
- it listens to the BS message signalling the RIS weights to be applied.

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

Data Flow and Control Signalling Requirements

The proposed schemes have the following minimum requirements (captured in Figure 3-12 and Figure 3-13) in terms of protocol and control signalling:

1. the BS choses a configuration (a reflected beam ID for each RIS, and a beam ID for the BS itself).
2. The BS signals the configuration to all RISs;
3. Each RIS configures its reflected beam according to the signalled configuration;
4. The BS configures its beam according to the chosen configuration;
5. The BS sends pilots using the chosen beam and the UE measures the BS-to-UE channel for the given configuration;
6. The UE feeds back to the BS the received power;
7. The BS classifies the tested configuration as “forbidden” or “allowed” depending on whether it exceeds or not a given threshold.

Steps 1 to 7 are iterated for all configurations. If the BS does not receive any feedback during step 6, it considers that the propagation is so poor that the configuration can be classified as “allowed”.

Note that in this scheme, the non-intended UE is not helping as it is not participating to the protocol. However, a testing UE is *helping* before the network is used by the non-intended user.

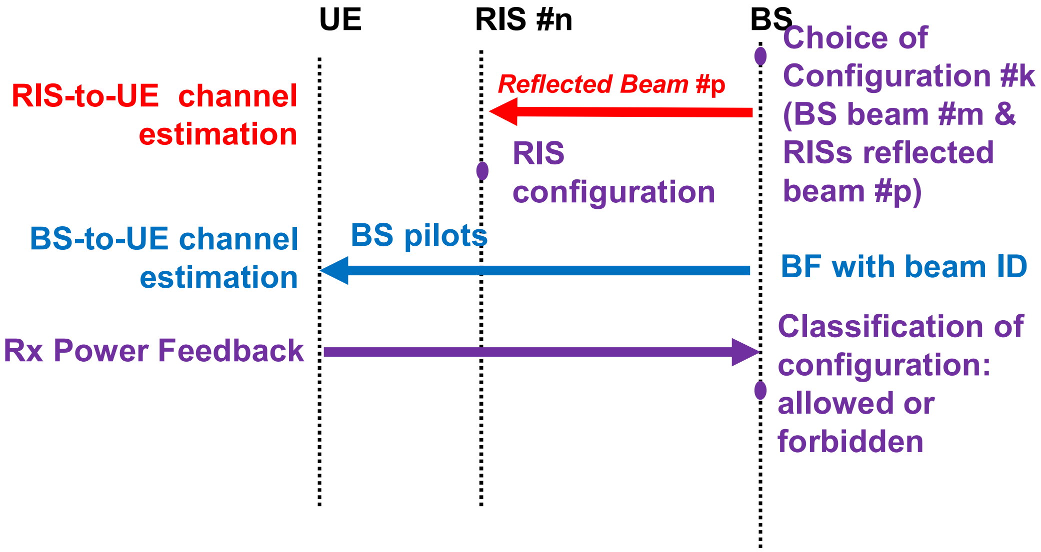


Figure 3-12 Data and control flows, with all RISs #n=1 to N, doing the same thing simultaneously.

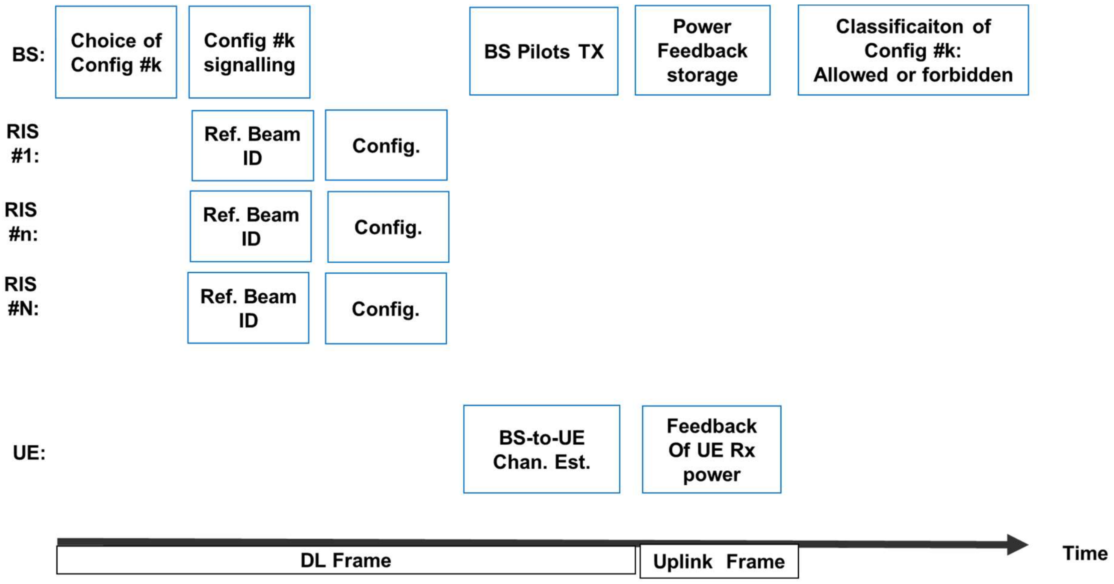


Figure 3-13 Time diagram, with all RISs #n=1 to N, doing the same thing simultaneously.

Energy Efficiency

Such scheme is sub-optimum as it is based on field measurements and then the use of a static list of allowed and forbidden beams. The energy efficiency is expected to be very degraded compared to a scheme without this static list constraint.

3.2.4 TC#8: EMFE Avoidance thanks to Non-Intended User Equipment and RIS-aided BF, at mmwaves

This sub-section presents the architecture and control signalling required to support examples of schemes [GPS22] designed for I-EMFEU improvement, at mmwaves.

Objectives and deployment scenarios

We consider a small cell outdoor BS/AP operating with mmWave carrier frequencies [GPS22]. As illustrated in Figure 3-14, the following type of propagation is considered: geometry-based channel with multiple scatterers and one RISs. RISs and scatterers are assumed to be in the far field of intended user equipment (IUE) and the BS. TDD mode is assumed, where full channel state information can be obtained from channel reciprocity.

As illustrated in Figure 3-14, we jointly optimise the RIS and the BS BF for the IUE, given that a non-intended user (NIU) is potentially between the BS to the IUE, and it has some EMF constraints. Targeting on minimizing the transmit power at the BS to satisfy the SNR requirement of the intended user, we propose a closed-loop scheme with the direct link being considered, in order to fully explore the potential of RIS-assisted systems with EMF constraints.

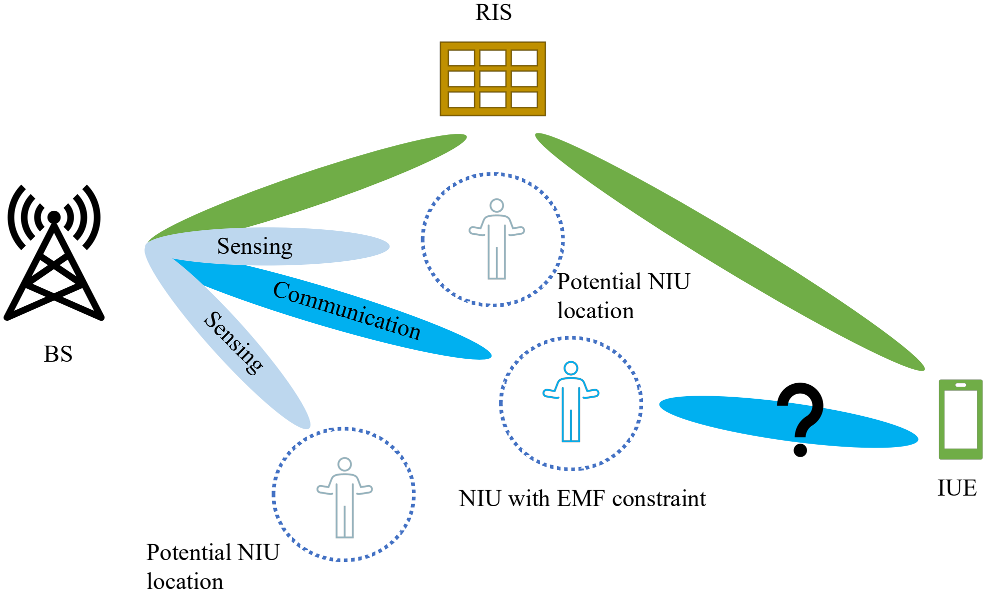


Figure 3-14 Considered deployment scenarios with NIU having location uncertainties.

The principle and objective of the proposed technical solution is summarised here after:
We jointly optimise the BF weights for BS and RIS in a DL transmit system, targeting on minimizing the transmit power at the BS. Here, the direct link between the BS to the IU is potentially "blocked" by a NIU with EMF constraints. With, e.g., different level of EMF requirements, channel statistics, user's location uncertainties, there are potentials to utilise the direct link to further reduce the transmit power at the BS based on the EMF exposure level feedback from the NIU. This scheme is therefore boosting the inter EMFEU metric. Compared to the studies in [D6.1] and [D6.2] [GPS22], in this work, we consider a more general case where the NIU is not actively helping the network and the BS needs to sense the location of NIU in advance to guarantee the EMF requirement. An RIS-assisted joint sensing and communication setup with EMF constraint is studied and various design options are evaluated.

Note that the detailed description of this scheme and its performance is not in the scope of this deliverable. It will be provided in the upcoming D6.4 deliverable.

Architecture requirements

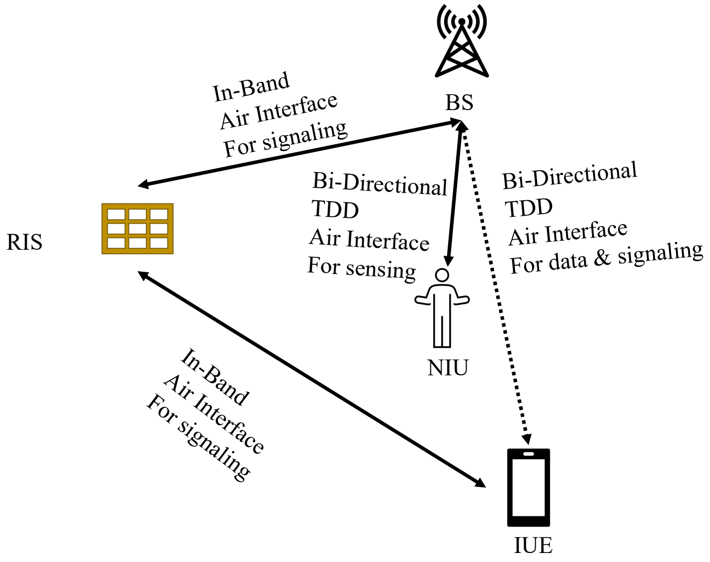


Figure 3-15 Architecture requirements with non-collaborative NIU.

The proposed scheme has the following minimum architecture requirements (captured in Figure 3-15) : A single BS is serving a single IUE at a time, through a bi-directional TDD air interface, with the help of one RIS node and potentially the direct link. The BS BF weights and RISs reflected BF weights are optimised for the IUE at a time. Channel reciprocity can be exploited to acquire full CSI. Here, the exact location of NIU is unknown, as a result, the BS needs to allocate resources to sense the NIU and make sure the EMF requirement is fulfilled.

The RIS node can listen and talk, and it is connected to the BS and the IUE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down;
- it sends pilots to the BS;
- it sends pilots to the IUE;
- it listens to the IUE message signalling the RIS weights to be applied.

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

Data Flow and Control Signalling Requirements

The proposed schemes have the following minimum requirements (captured in Figure 3-16 and Figure 3-17) in terms of protocol and control signalling:

1. NIU does not send EMF-related information, e.g., location, object size, to the BS. Hence, BS needs to sense the detailed information with additional resources.
2. The RIS sends pilots to allow the IUE and the BS to measure the RIS-to-IUE and the RIS-to-BS channels.
3. The IUE reports the RIS-to-IUE channels to the BS.

4. The IUE sends pilots to the BS to allow the BS to measure the IUE-to-BS channel (for this stage, the RIS are assumed to be frozen in a known configuration, so that the BS can withdraw from the BS-to-IUE the 'artificial' part of the channel with RIS influence, and extract the 'natural' part only).
5. Based on all aforementioned channel measurements, the BS computes the BS BF weights and the RIS weights.
6. The BS sends to the RIS with its weights.
7. The RIS configures its weights according to the received control message from the BS.
8. The BS sends data with demodulation pilots to the IUE.
9. The IUE measures the channel, equalises it (after having determined the BS filter) and received the data.

Step 2 requires the introduction of an 'RIS frame' during which the BS and the IUE are on mute. Steps 2 to 6 are re-iterated to take into account changes in the propagation environment.

Note that in this scheme, the NIU is *not helping* as it is not participating to the protocol.

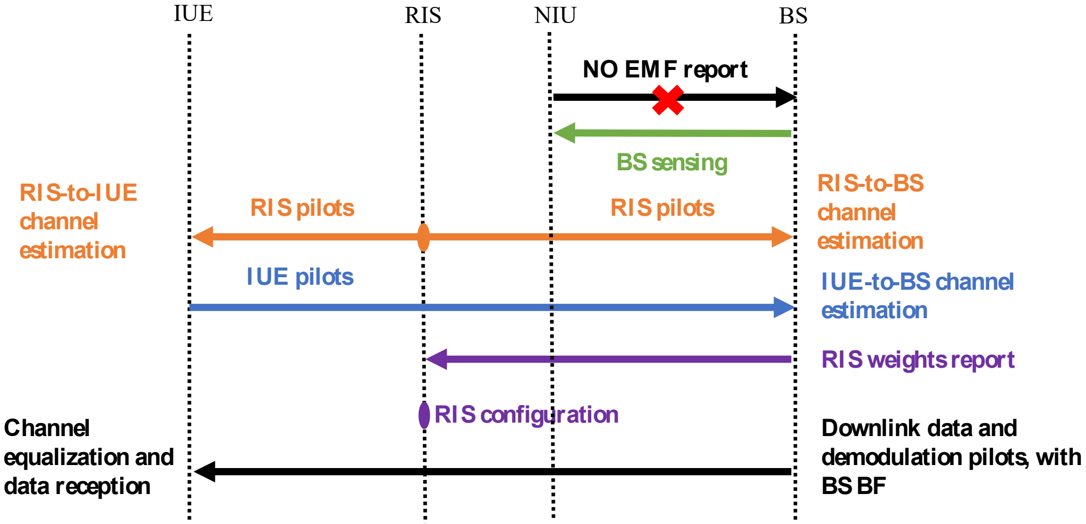


Figure 3-16 Data and control flows with non-collaborative NIU. BS sensing is needed to guarantee EMF.

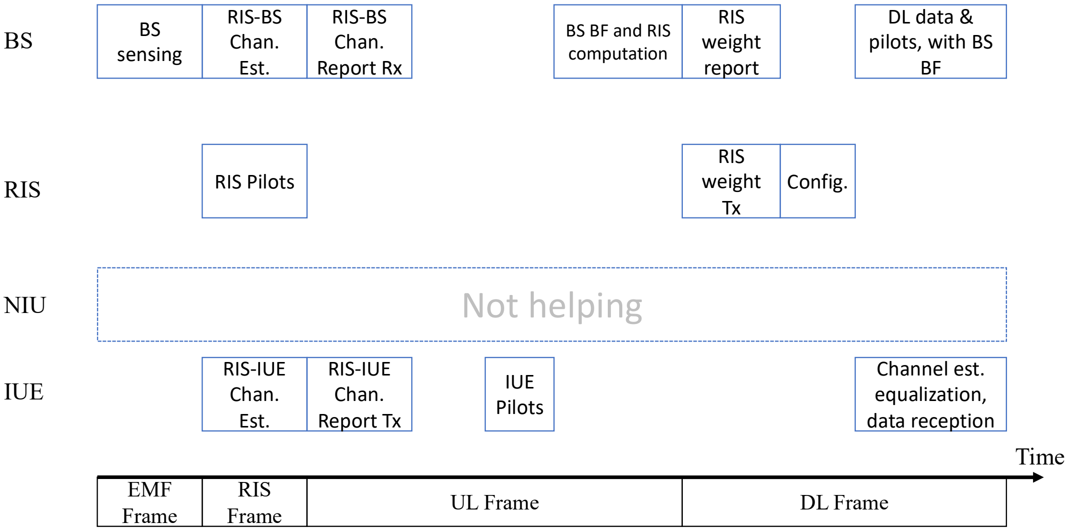


Figure 3-17 Time diagram with non-collaborative NIU.

Energy Efficiency

The proposed RIS-assisted beamforming scheme targets on better energy efficiency when serving the intended user, while satisfying the EMF requirements for the non-intended user.

3.2.5 TC#9: Creating and Operating Areas With a reduced S-EMFE Thanks to RIS-aided received BF

This sub-section presents the architecture and control signalling required to support schemes [PBH+22] designed for S-EMFEU improvement, at sub-6 GHz.

Objective & Deployment Scenario

A macro-cell deployment of massive MIMO BSs operating with a sub-6GHz carrier frequency is considered. As illustrated in Figure 3-18, we consider an outdoor-to-indoor environment. The following type of propagation is considered: multiple walls, one single RIS, and NLOS. The RIS and walls are close to the target UE and far from the BS. Slow moving or steady UEs only are considered. TDD mode is assumed, such that channel reciprocity can be exploited to acquire full CSI.
RIS-aided Self-EMFE-Aware beamforming scheme [PBH+22] together with UL closed loop power control is proposed with the following objectives: to deliver an UL voice call with a target quality of service (QoS) from the UE to the BS with minimum transmit power from the target UE, and minimum self-exposure of the customer using the target UE.

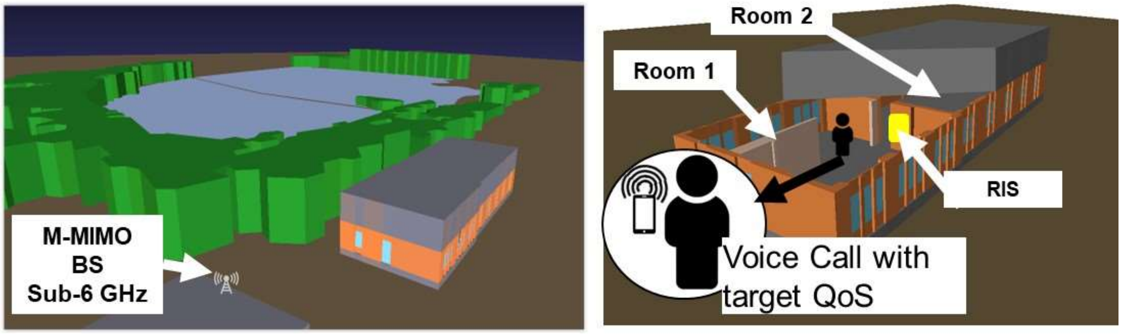


Figure 3-18 Considered deployment scenario.

Architecture requirements

The proposed schemes have the following minimum architecture requirements (captured in Figure 3-19): a single BS is serving a single UE at a time, through a bi-directional TDD air interface, with the help of a single RIS node. The BS BF weights and RISs reflected BF weights are optimised for a single UE at a time. Although a RIS node is mute, it is connected to the BS and the UE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down.
- it listens to the UE uplink pilots.

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

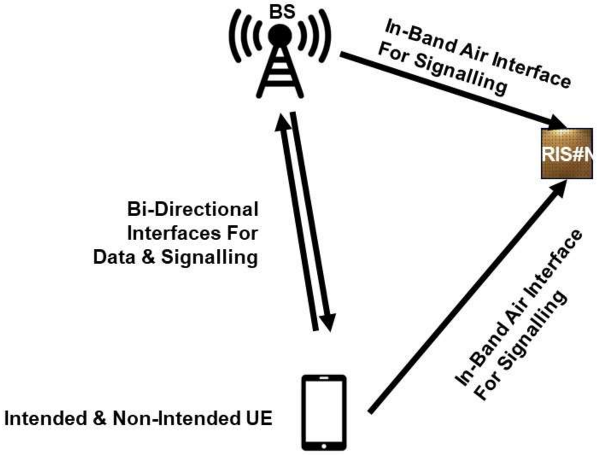


Figure 3-19 Architecture requirements.

Data Flow and Control Signalling Requirements

The proposed schemes have the following minimum requirements (captured in Figure 3-20 and Figure 3-21) in terms of protocol and control signalling:

1. the UE sends pilots in the uplink, the RIS senses the phases of the propagation channel between the UE and its unit cells;
2. then, based on the knowledge of these phases, the RIS computes its weights to “turn itself electronically” towards the target UE, and “freezes”, i.e., kept fixed, until next reconfiguration.
3. The UE sends data and pilots in the uplink again, to allow the BS to sense the UE-to-BS channel under the influence of RISs. The BS performs channel equalisation and data reception. The BS compares the received SINR with the target SINR for a voice call and generates a Transmit Power Control command.
4. Then, the BS sends a Transmit Power Command to the UE
5. Finally, the UE transmits data again, after having applied the Transmit Power Command.

Step 1 requires the introduction of a ‘RIS frame’ during which the BS and the UE are mute.
Steps 1 to 5 are re-iterated to take into account changes in the propagation environment. However, the UE is supposed to be steady or slowly moving, hence the most frequent occurrence of steps 1 and step 3 is once every two UL frames (as illustrated in Figure 3-21).

Note that in this scheme, the non-intended UE is helping as it is participating to the protocol.

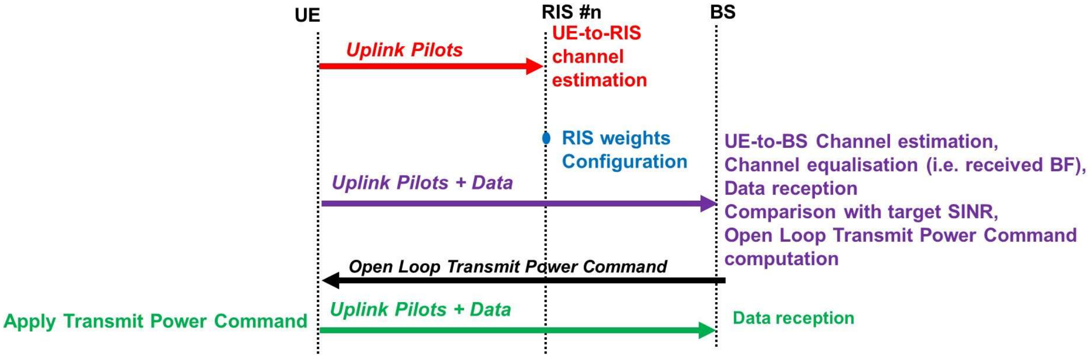


Figure 3-20 Data flow and control signalling

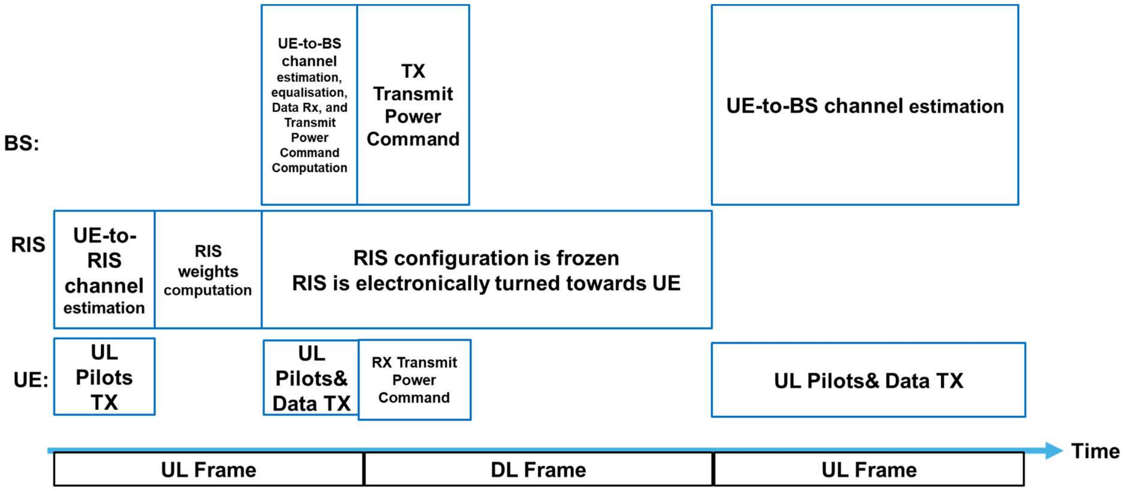


Figure 3-21 Time Diagram

Energy Efficiency

By minimizing the transmit power of the UE to meet a given target QoS (and also to minimise the S-EMFE of the customer using the UE), the proposed scheme also automatically improves the EE of the UE.

3.2.6 TC#10: EMF Exposure Mitigation in RIS-Assisted Multi-Beam Communications

This sub-section presents the architecture and control signalling required to support schemes [SVK+23] designed for I-EMFEU improvement, at mmWaves.

Objective & Deployment Scenario

We consider a mmWave TDD MIMO system where a BS equipped with M antennas communicates in DL with a single-antenna UE aided by an RIS composed of N reflective elements. Along with the active UE, there is a set of NUEs that are not communicating with the BS and should not be exposed to excessive EMF. The example scenario is shown in Figure 3-22.

We consider the Rayleigh channel model with the channel coefficients described as a factor of the path-loss (PL), specifically mmMAGIC urban LOS model, and small-scale fading accounting for multi-path propagation. The PL is dependent on the three-dimensional (3D) Euclidean distance, the carrier frequency, and stochastic shadow fading.

The objective of the proposed technique is twofold. We would like to increase, or at least maintain the QoS for the active UE, while limiting the EMFE at points/areas where the NUEs are located. We provide an evolutionary heuristic solution based on Genetic Algorithm for power equalisation and multi-beam selection of a codebook at the BS.

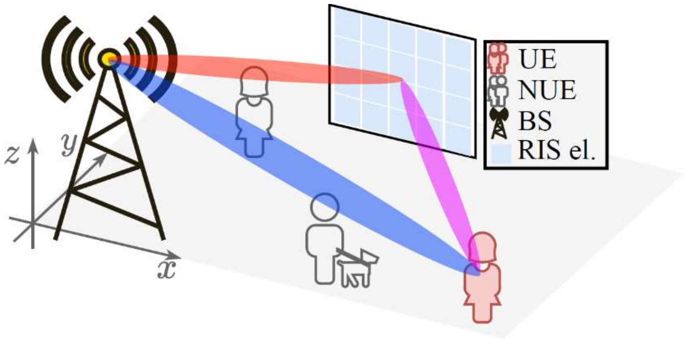


Figure 3-22 Considered deployment scenario.

Architecture requirements

The proposed scheme has the following minimum architecture requirements (captured in Figure 3-23): A single BS is serving a single intended UE at a time (while it is possible to extend to multiple UEs), through a bi-directional TDD air interface, with the help of one RIS node and the direct link. The BS BF weights, the UE equaliser and the RIS's reflected BF weights are optimised for the intended UE at a time. There are two approaches considered: a) with full CSI, and b) with knowledge of the UE/NUEs positions only. In the former, channel reciprocity can be exploited to acquire full CSI. Note that since the CSI or positions information of the NUEs is required, the latter also need to be connected (the same way as the intended UE).

In the approach a) with full CSI, the RIS node must be able to receive and transmit over the air interface, and it is connected to the BS and the UE as follows:

- it listens to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down;
- it sends pilots to the BS;
- it sends pilots to the UE;
- it listens to the UE message signalling the RIS weights to be applied.

In the approach b) which requires only the knowledge of the positions of the UEs/NUEs the RIS needs to:

- listen to the BS synchronisation signals to remain synchronised with the BS, to be aware of the frame structure, and be able to apply the protocol described further down;
- listen to the BS message signalling the RIS weights to be applied.
- In case the localisation algorithm is run locally at the RIS, it needs to be able to forward those estimates to the BS (preferably over a wired, out-of-band connection)

Hence, the RIS node is assumed to be hybrid: it can switch between a reception mode and a reflecting mode.

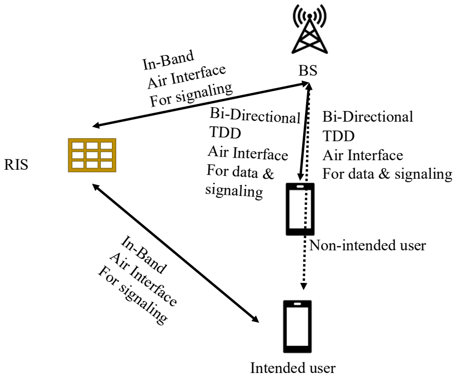


Figure 3-23 Architecture requirements (same as Figure 3-15).

Data Flow and Control Signalling Requirements

The variant a) of the proposed scheme (with full CSI) have the same minimum requirements in terms of protocol, data flows and control signalling as technique described in section 3.2.4 shown earlier.

For the variant b) an example of the data flow and control signalling is presented in Figure 3-24. Note that this is an example which relies on a specific implementation of the localisation procedure shown in Deliverable 5.3, Contribution C#10 [VRK+22]. The NUE is not shown on the diagram as it is not actively participating in the communication (its position is determined based on the scattered signals transmitted by others).

The procedure involves the following steps:

1. While the localisation is based on the arbitrary uplink signals transmitted by the active UE, the communication is typically initiated by the BS/AP. This preceding DL signal could be the access grant, scheduling information or explicit "localisation start" instruction sent to the UE.

2. Upon receiving the relevant signal from the BS/AP, the UE starts transmitting its own uplink signal in response. The transmission could be simply the payload, pilots or a dedicated sensing signal.
3. The UL signal transmitted by the UE is received by the sensing (hybrid) RIS (after being subject to scattering from passive elements and users). This signal is processed locally at the RIS to
    a. Estimate the position of the active (transmitting) UEs
    b. Create a negative mask based on the positions of the active UEs and fixed scatterers
    c. Apply the negative mask to the received signal to determine the positions of the remaining passive (not-transmitting, non-intended) users
4. The RIS forwards the estimated active and passive UE positions to the BS/AP for further processing.
5. Using the gathered measurements, the BS computes the BS BF weights, the UE filter weights and the RIS weights.
6. The BS informs the RIS about the configuration.
7. The RIS configures its weights according to the received control message from the BS.
8. The BS sends data with demodulation pilots to the UE.
9. The UE measures the channel, equalises it (after having determined the BS filter) and decodes the data.

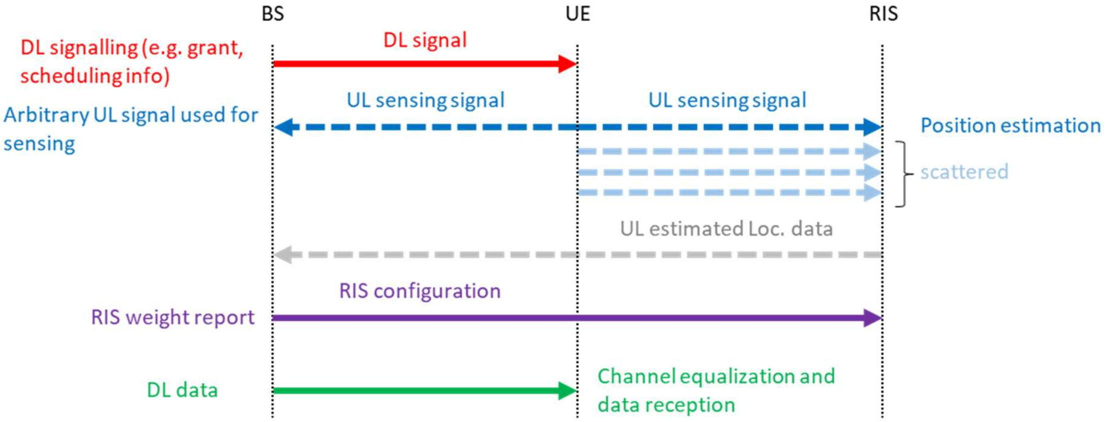


Figure 3-24 Data flow and control signalling

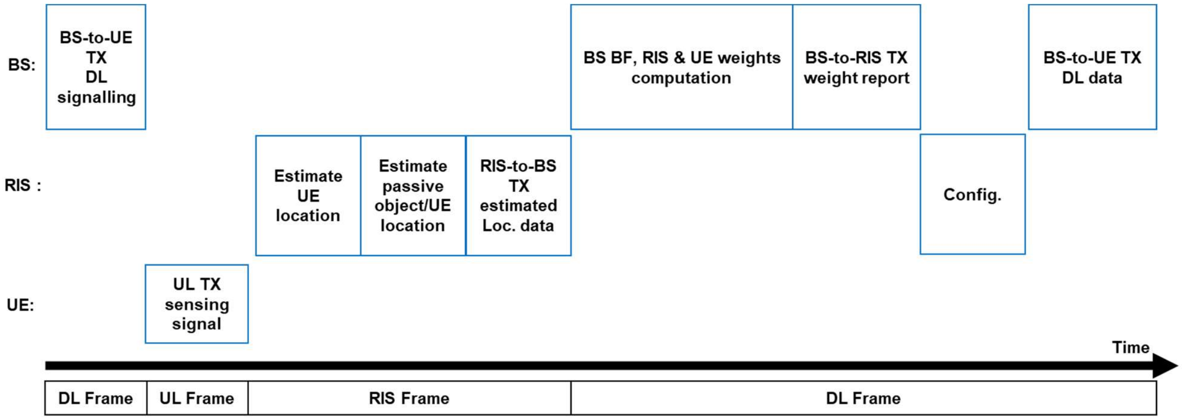


Figure 3-25 Time Diagram

Energy Efficiency

Our results reveal that with the proposed technique it is possible to exploit multiple propagation paths to improve the QoS and reduce EMFE. Specifically, assuming perfect CSI, it is possible to achieve both goals simultaneously, at a cost of increased complexity and computation overhead at the BS. Meanwhile, by relying on localisation information only, it is possible to decrease the exposure significantly (up to 2 orders of magnitude) at a cost of slightly reduced spectral efficiency. Importantly, this approach also allows to avoid having an extensive CSI acquisition phase.

4 EE RISE Networks

Most proposed schemes in RISE-6G project improve other metrics (such as SE, localisation accuracy metrics, EMFEU, SSE metrics etc.), in addition to the EE metric.

However, there are few examples of schemes that strictly focus on the EE metric alone. Here is an example.

4.1 EE metric

The EE metric for a DL data communication from a BS to a UE is given as follows [D2.4]:

$$\boldsymbol{EE} = \boldsymbol{R}/\boldsymbol{P},$$

where R is the sum data *spectral efficiency* (accounting for *overhead* as in [ZDR+21-1][ZDR+21-2]) in bit/s/Hz and P is the total power consumption in watts for providing the target service, as in [HZA+19].

4.2 EE-oriented architecture and control signalling requirements

4.2.1 TC#11: Energy efficiency maximisation of MMIMO communications with dynamic metasurface antennas

This sub-section presents the architecture and control signalling required to support schemes in [YXA+21-1] and [YXA+21-2] designed for EE improvement, at mmWaves.

Objective & Deployment Scenario

The considered system, illustrated in Figure 4-1, comprising a multi-element dynamic metasurface antenna (DMA) as the receiving antennas at the BS, and U multi-antenna UEs communicating with the BS in the uplink direction. It is assumed that the BS simultaneously receives signals from the UEs. The EE optimisation of such a single-cell system is investigated, by optimizing the transmit precoding of each UE and the DMAs' weights. The CSI in DMA-based wireless communications can be obtained based on existing channel estimation methods for hybrid A/D communications [AV20].

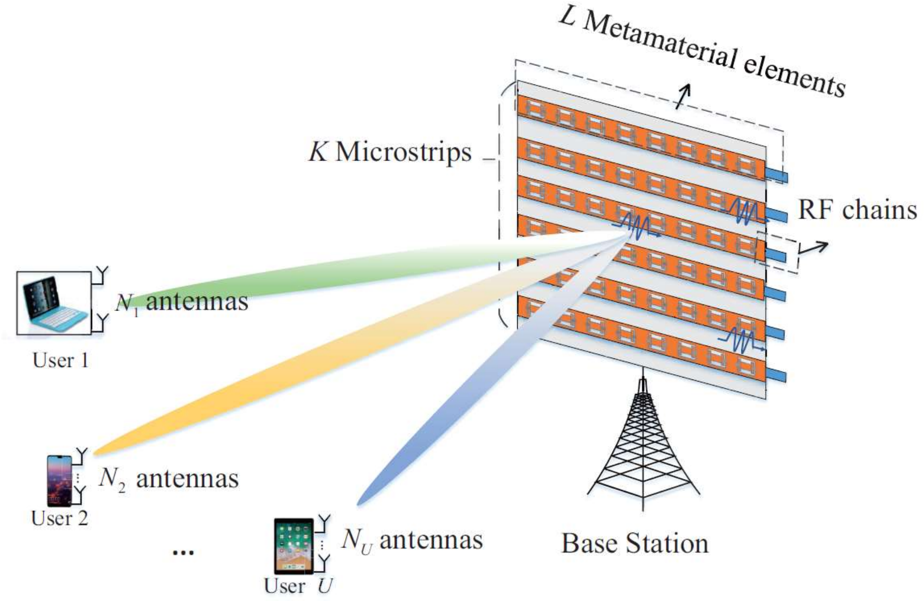


Figure 4-1 Considered deployment scenario for the DMA-based energy efficiency of MMIMO.

Architecture requirements

For the considered system model, the following architecture requirements are assumed: we consider full CSI knowledge, which is needed to design each UE's transmit precoding and the DMA weights. In addition, the BS is equipped with a planar array consisting of M metamaterial elements. Specifically, the planar array consists of K microstrips and each microstrip consists of L metamaterial elements, that is, $M = KL$. Moreover, each UE has a uniform linear array comprising N_u conventional antennas interconnected in a fully digital beamforming architecture.

Data Flow and Control Signalling Requirements

For the described scheme above, the necessary protocol requirements for control signalling are summarised next:

1. The (U) users send pilots in the uplink and the BS estimates the required channel matrices, from each user to the BS.
2. Then, the BS computes the DMA weights (denoted as $\boldsymbol{Q}$) and the transmit precoding matrices.
3. The DMA configures each element's response according to the computed weights.
4. The BS sends pilots and the transmit precoding matrices to each user.
5. Each user sends data to the BS.

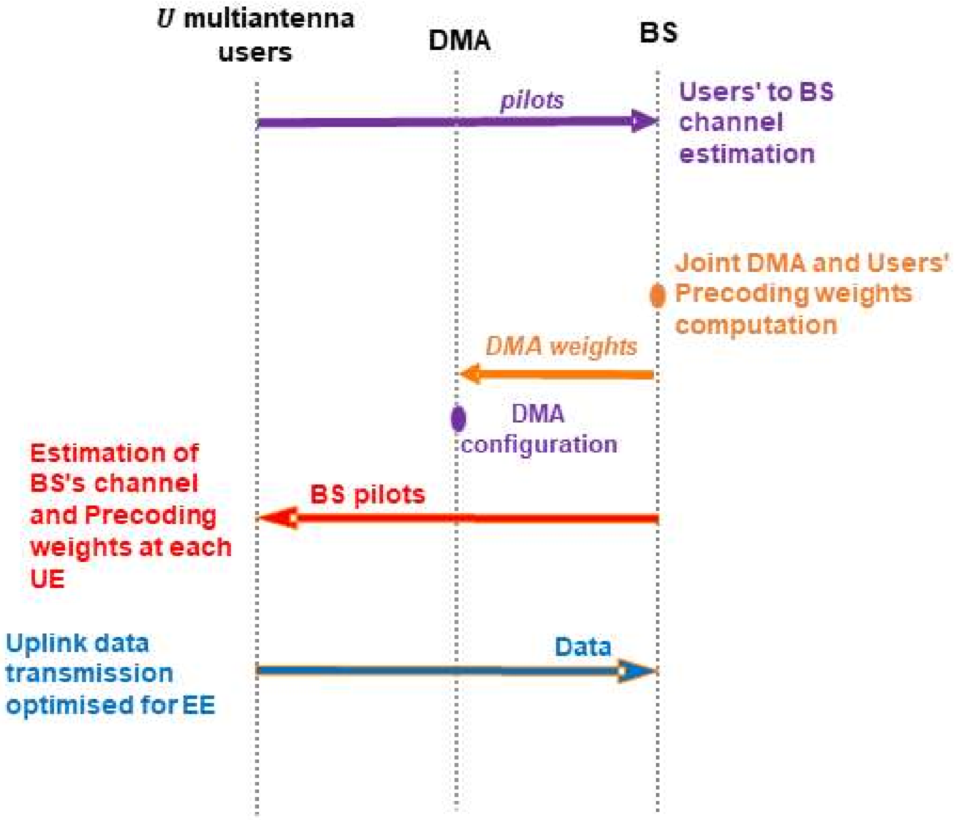


Figure 4-2 Data flow and control signalling for the energy efficiency scheme with perfect CSI.

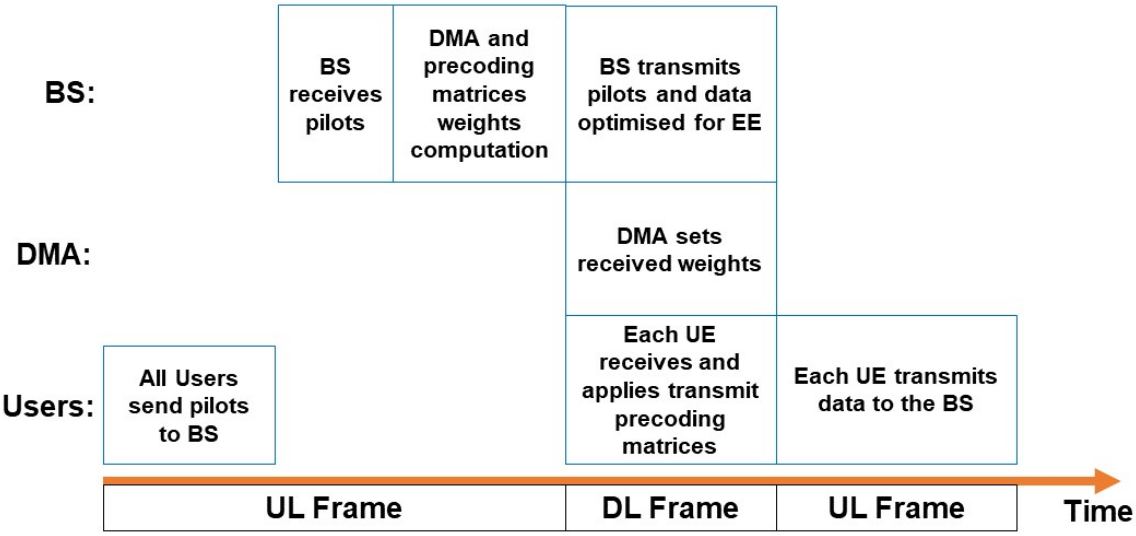
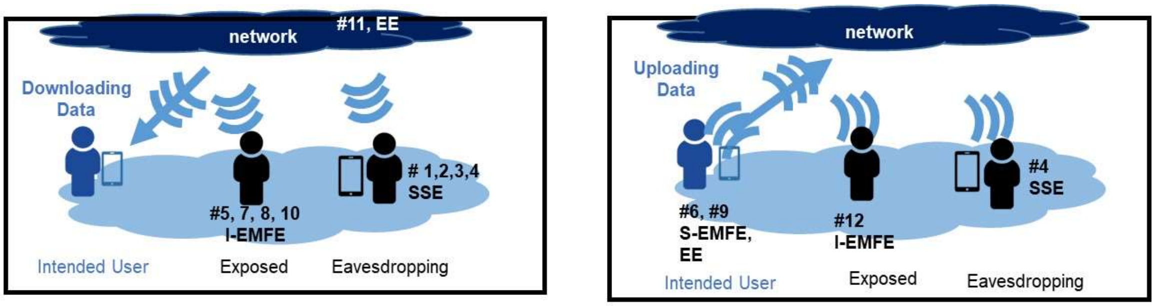


Figure 4-3 Time Diagram for the DMA-based energy efficiency scheme.

5 Architecture and control signalling recommendations

In this section, we provide some recommendations regarding architecture and control signalling based on the analysis in Sections 2, 3 and 4. Table 1 and Figure 5-1 below list all the TCs.

Note that TC#12 is not reported in current D6.3 as it will be studied in D6.4. However, it is listed to show that I-EMFEU in the UL is also considered in the project.



a) Downlink **b) Uplink**

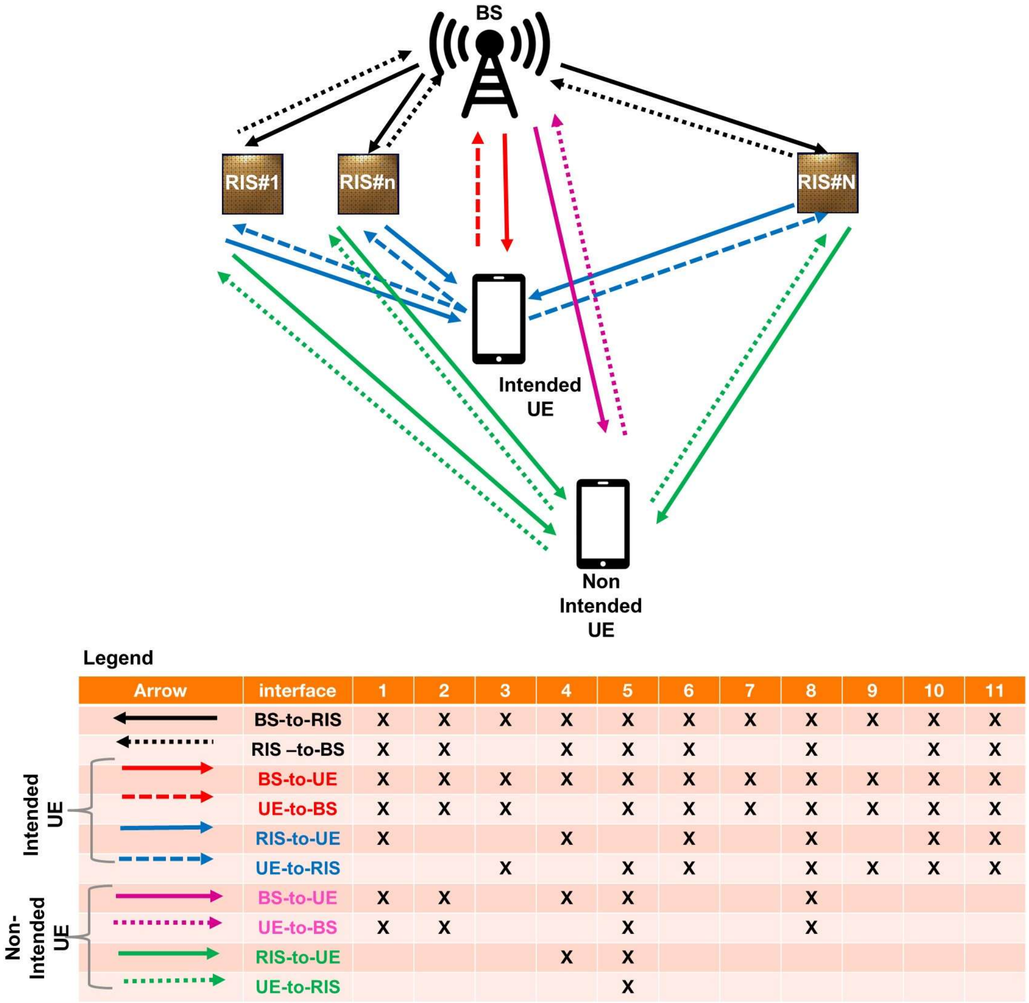
Figure 5-1 All studied TCs in a glimpse.

Table 1 Considered schemes with corresponding objectives and deployment scenarios.

TC#	Name	section	Objective	Frequency
1	SSE with Full CSI knowledge	2.2.1	SSE, EE	Agnostic
2	SSE with Partial CSI knowledge	2.2.2	SSE, EE	Agnostic
3	On Maximizing the Sum Secret Key Rate for Reconfigurable Intelligent Surface-Assisted Multiuser Systems	2.2.3	SSE, EE	Agnostic
4	Spatial SSE	2.2.4	SSE, EE	Agnostic
5	RIS-aided EMF-Aware Downlink BF for sub-6 GHz	3.2.1	I-EMFEU, EE	Sub-6 GHz.
6	Energy Efficiency Optimisation of Reconfigurable Intelligent Surfaces with Electromagnetic Field Exposure / Global Reflection / Active element Constraints, at mmWaves	3.2.2	S-EMFEU, EE	mmWaves
7	Low sum EMFE of multiple radio access networks in strong visibility, without coordination, at mmWaves	3.2.3	I-EMFEU, EE	mmWaves
8	EMFE Avoidance thanks to Non-Intended User Equipment and RIS-aided BF, at mmWaves	3.2.4	I-EMFEU, EE	mmWaves
9	Creating and Operating Areas With a reduced S-EMFE Thanks to RIS-aided received BF	3.2.5	S-EMFEU, EE	Sub-6 GHz.
10	EMF Exposure Mitigation in RIS-Assisted Multi-Beam Communications	3.2.6	I-EMFEU, EE	mmWaves

11	Energy efficiency maximisation of MMIMO communications with dynamic metasurface antennas	4.2.1	EE	mmWaves
12	Blue Communications for Edge Computing: the Reconfigurable Intelligent Surfaces Opportunity [ACS22]	Not studied in D6.3	S-EMFEU	mmWaves

The figure below summarises the architecture requirements for each scheme in terms of over-the-air in-band interfaces needed for control signalling.



	Arrow	interface	1	2	3	4	5	6	7	8	9	10	11
	←——	BS-to-RIS	X	X	X	X	X	X	X	X	X	X	X
	←······	RIS –to-BS	X	X		X	X	X		X		X	X
Intended UE	——→	BS-to-UE	X	X	X	X	X	X	X	X	X	X	X
	- - -→	UE-to-BS	X	X	X		X	X	X	X	X	X	X
	——→	RIS-to-UE	X			X		X		X		X	X
	- - -→	UE-to-RIS			X		X	X		X	X	X	X
Non-Intended UE	——→	BS-to-UE	X	X		X	X			X			
	······→	UE-to-BS	X	X			X			X			
	——→	RIS-to-UE				X	X						
	······→	UE-to-RIS					X						

Figure 5-2 Architecture Requirements for all SSE and EMFEU oriented schemes, in terms of control signalling.

Time diagrams and flowcharts for the considered schemes for SSE and EMFEU improvements show that the full protocol (including control signalling and data transmission) is designed to be preferably performed within the channel coherence time. Therefore, in most cases, the proposed schemes apply to low mobility or steady UEs.

All proposed schemes rely on hybrid RIS which can switch between different modes including at last a reflecting mode and a receiving mode and, for some schemes, a transmitting mode and a transparent mode.

Based on our analysis of the various proposed schemes, we recommend an architecture, where RIS(s) are slave nodes of a BS, and act as UL or DL relay nodes between the BS and the intended UE. Such relay nodes already exist in current standards [TS123501]. Compared to a standard relay node, in all TCs (apart from TC#11) the RIS has the following new property: it can reflect the BS waves or UE waves transporting their data. Regarding the other exiting properties of relay nodes, the RIS may potentially be less sophisticated (with less computing and signal processing capabilities).

All these requirements are illustrated and summarised in the Figure 5-3 below.

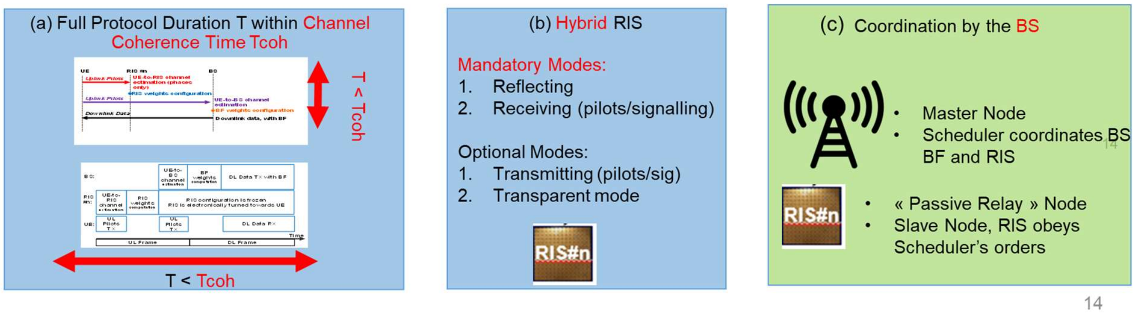


Figure 5-3 Architecture Requirements for all SSE and EMFEU oriented schemes, in terms of control signalling.

6 Conclusions

This document provides the final results from WP6 network architectures & deployment strategies with RIS to boost the EE, EMFEU and SSE metrics defined in Deliverable D2.4, for the use cases listed in D2.3. The deliverable lists several architectural options, RIS control strategies, as well as related data flows and control signalling, all derived from various technical contributions and innovations proposed within WP6.

Time diagrams and flowcharts for the considered schemes for SSE and EMFEU improvements show that the full protocol (including control signalling and data transmission) should be designed to be preferably performed within the channel coherence time. Therefore, in most cases, the proposed schemes apply to low mobility or steady UEs.

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