# Achieving Distributed MIMO Performance with Repeater-Assisted Cellular Massive MIMO

Sara Willhammar, Hiroki Iimori, Joao Vieira, Lars Sundström, Fredrik Tufvesson, and Erik G. Larsson

***Abstract*—In what ways could cellular massive MIMO be improved? This technology has already been shown to bring huge performance gains. However, coverage holes and difficulties to transmit multiple streams to multi-antenna users because of insufficient channel rank remain issues. Distributed MIMO, also known as cell-free massive MIMO, might be the ultimate solution. However, while being a powerful technology, it is expensive to install backhaul, and it is a difficult problem to achieve accurate phase alignment for coherent multi-user beamforming on downlink. Another option is reflective intelligent surfaces – but they have large form factors and require a lot of training and control overhead, and probably, in practice, some form of active filtering to make them sufficiently band-selective.**

**We propose a new approach to densification of cellular systems, envisioning *repeater-assisted cellular massive MIMO*, where a large numbers of physically small and cheap wireless repeaters are deployed. They receive and retransmit signals instantaneously, appearing as *active scatterers*. Meaning that they appear as ordinary channel scatterers but with amplification. We elaborate on the requirements of such repeaters, show that the performance of these systems could potentially approach that of distributed MIMO, and outline future research directions.**

## I. Introduction

Massive multiple-input multiple-output (MIMO) has become *the* 5G technology and will continue to be one of the cornerstones in cellular systems. Sub-6 GHz time-division duplex (TDD) multi-user massive MIMO systems with reciprocity-based beamforming can serve many terminals in the same time-frequency resource, also in high mobility scenarios. By phase-coherent combining, an array gain is achieved, which can significantly improve signal quality and link budget.

Despite this, there will be coverage holes. In addition, with multiple antenna terminals, it can be a challenge to offer more than a single (or a few) data streams per terminal if there are not enough independent scatters that bring up the rank of the channel. Distributed MIMO (D-MIMO) has emerged as a promising solution to address this. In D-MIMO, access points (APs) are densely deployed over a large area and due to shorter distances between APs and terminals, the path loss decreases and coverage improves. Such deployment is not to be confused with the D-MIMO deployment currently considered in 3GPP Rel. 19 standardization, which performs coherent joint transmission between several macro base stations. Moreover, with D-MIMO, shadow fading becomes less problematic due to improved macro-diversity, and favorable propagation can be experienced even in line-of-sight (LoS).

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Although the opportunities with D-MIMO systems are many, they impose deployment issues. Many of the current solutions are not standardized and/or not yet sufficient in order to get the envisioned performance gains. Questions, such as how to get the data to the distributed units, where to perform the processing, how to synchronize the APs, and how to distribute the clocks and phase references still need further development. Furthermore, the main concepts in the standards are designed for co-located MIMO (C-MIMO) and going to D-MIMO would be a big step for industry to adopt. There would be a need for radical network architectural changes and a large increase in site and maintenance costs. In industry there can be some reluctance to big changes and smaller steps, each beneficial, would be more likely to be implemented.

To make the transition smoother and challenge the existing views on how densification of current cellular systems could be done in today's sub-6 GHz systems, we envision *repeater-assisted massive MIMO (RA-MIMO)*. A similar vision was presented in [1], but extra delay, increased delay spread and compromised channel reciprocity were identified as obstacles; these issues are solved in our vision. Repeaters have traditionally been deployed to improve coverage. Coverage improvements and capacity scaling in MIMO systems aided by repeaters was studied in LoS environments [2] and full-duplex radio relays were investigated to improve outdoor-to-indoor communication [3]. Today modern massive MIMO base stations enable multi-user MIMO operation. Challenging the current views on how densification could be done; we propose to rethink repeaters, could they be deployed inside the cell to support massive C-MIMO systems to increase macro diversity, acting as active scatterers, i.e. channel scatterers but with amplification, and potentially approach D-MIMO performance?

The use of the terms *relay* and *repeater* in literature is not always consistent. A repeater is here considered to be the same thing as a full-duplex relay, and *instantaneously* amplifies and re-transmits the signal, with a delay of at most a few hundred nanoseconds. However, a repeater is different from a half-duplex relay; the difference lies in the delay introduced. A half-duplex relay receives a signal of substantially longer duration (e.g., half a slot) and then either amplifies and forwards, or decodes and forwards, that signal. Repeaters (full-duplex relays) act as an active scatterer, but half-duplex relays do not.

Other ways to enhance performance in sub-6 GHz systems, without creating extra cells, are to add extra APs or, use reflective intelligent surfaces (RISs). Table I presents a comparison between these three options; these technologies are of different maturity in terms of practical implementations. A RIS could

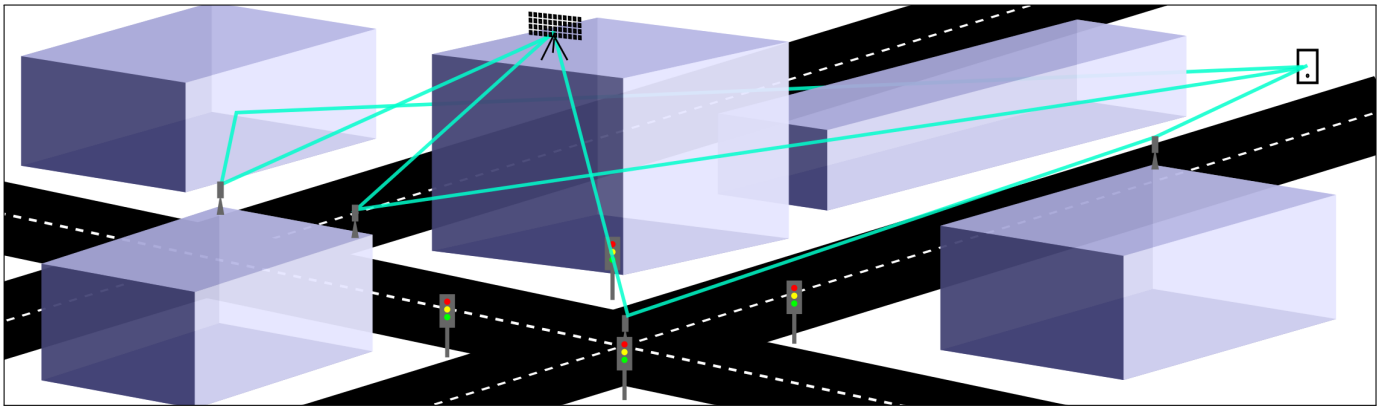


Fig. 1: Envisioning repeater-assisted cellular massive MIMO: a massive MIMO base station is installed on the rooftop, and assisted by multiple repeaters.

perform the work of a repeater while bringing benefits stemming from the many unit cells. Network-controlled repeaters (NCRs) are a part of Release 18 [4], [5], while RISs has been decided to not become a study-item; several challenges need to be addressed before they can be used in practice [5].

Due to the different maturity of the technologies and the various possibilities to implement them, the power consumption numbers given are merely indicative. While sub-6 GHz low-power cellular repeater products on the market (not network-controlled) may consume as little as 10 W, an AP will consume significantly more due to the required processing capabilities and backhaul interface. The low power consumption potential of RIS yields a number at least an order of magnitude less than that of repeaters and APs. With radio frequency (RF) switch-based RIS elements, the power consumption will be dominated by the RIS control and switch driver circuitry [6], which may be further optimized and tailored for the application.

The advantages of deploying repeaters or RISs, compared to extra APs, are that neither phase synchronization nor backhaul is needed. While having these benefits in common, RISs have however drawbacks in comparison repeaters: it has a much larger form factor, requires significant control signaling, and incurs significant training and configuration overhead. Furthermore, a passive, or semi-passive RIS would not be nearly as band-selective as a repeater, which can be frequency-selective down to the level of a single channel. An active RIS, which could amplify signals, could act similar as a repeater but due to regulatory requirements it would likely require a large number of expensive components to filter the signal. As a first-order approximation, to achieve the same signal amplification as a repeater, a [passive] RIS would require a number of unit cells equal to the square root of the repeater (power) gain. To replace a 60-dB gain repeater, a RIS would need in the order of $31 \times 31 \sim 1000$ unit cells (for simplicity, we ignore the directivity of the patch antenna patterns here). Furthermore, to obtain the macro diversity, one would need many distributed units, which appears challenging with RISs. Challenges with incorporating RISs into cellular networks were discussed in [5], including a simulated comparison to NCRs, showing a performance gain in terms of spectral efficiency to the latter.

TABLE I: Repeaters versus RISs versus extra APs for performance enhancement.

| ***Required* \ *Assisted by*** | **Repeater** | **RIS** | **Extra AP** |
|---|---|---|---|
| Form factor | Small | Large | Small |
| Power consumption | ~10 W | ~1 W | ~20 W |
| Instantaneous CSI | No | Yes | Yes |
| Extra training | Little | Large | Little |
| Phase synchronization | No | No | Yes |
| Backhaul | No | No | Yes |
| Active radiated power | Yes | No | Yes |
| Noise source | Yes | No | Yes |
| Array gain | Some | High | Some |
| Control overhead | Low | High | None |
| Deployment cost | Low | Medium | High |
| Deployment flexibility | High | Low | Medium |
| Band-selectivity | Yes | Little | Yes |

## II. Envisioning Repeater-Assisted Massive MIMO

Within a cell covered by a massive MIMO base station, the deployment of multiple repeaters could be simple and inexpensive: they have a small form factor and only require a power supply. The massive MIMO base station will remain in control of all multi-antenna signal processing, enabling full backward compatibility and requiring no major system upgrades. The base station will control the repeaters and configure their parameters (see [7] for possible configurations) via, e.g., a control channel. No significant control signaling is required and the NCR 3GPP framework could be sufficient for the purpose, with the addition of power control. Fig. 1 shows a deployment example. The massive MIMO array is placed on the rooftop and the terminal is a handheld device. Four repeaters are deployed: three on rooftops and one on a traffic light. Repeaters could be deployed in a wide variety of ways: on separate masts, on building facades or rooftops, on lamp posts and traffic lights, to mention some possibilities. An advantage is that the deployment does not need to be too carefully planned; repeaters can be installed in a "plug-and-play" fashion. The coverage zones of different repeaters can overlap and they can pick up signals from each other, as long as positive feedback effects are under control [8].

The signal received at the base station or the terminal will be a superposition of signals traveling via direct paths,

including LoS and/or multipath reflections, and signals going via repeater(s). This means that the channels between a terminal and the base station is a result of several components: 1) the direct path between the terminal and base station, 2) paths between a terminal and a repeater, 3) paths between a repeater and a scatterer, 4) paths between repeaters, 5) paths between a repeater and the base station, and 6) paths between a scatterer and the base station. As this is only concatenations of linear time-invariant (LTI) systems, the result is also an LTI system. Its response is (in principle) the same in uplink and downlink, enabling reciprocity-based multi-user beamforming. Repeaters should act as active scatterers in the environment, i.e. similar to ordinary channel scatterers, but with higher gain. The repeaters will naturally introduce a delay, i.e. a frequency-dependent phase shift, which is typically not a problem as it is comparable to the frequency response of a far-away scatterer.

## III. Repeaters as active channel scatterers

### A. Requirements on the repeater

To support the vision of RA-MIMO systems, the key aspect is that it must be possible to realize repeaters that have the same properties as channel scatterers present in the propagation environment. With the same properties, they would be a transparent part from both the base station and terminal perspective. To act as a channel scatterer, the repeater must satisfy the following requirements:

1) The repeater should ***have an LTI response*** and hence not introduce non-linearities and out-of-band radiation. It should not have an automatic gain control circuit that introduces fast time-variations of the amplification gain.
2) For reciprocity-based transmission, the contribution of the repeater should be the same in uplink and downlink, i.e. the repeater should ***be reciprocal***. The forward gain of the repeater should, for each subcarrier, be equal to its reverse gain.
3) The excess delay of the channel collectively comprised by the ordinary channel scatterers and the repeaters must be smaller than the duration of the cyclic prefix. Hence, each repeater may only ***introduce*** **a much smaller** ***delay than the duration of the cyclic prefix***, which requires an almost instantaneous processing and amplification.
4) The repeater should ***be band-selective***, i.e., only amplify signals within the desired band. This requires the use of sharp filters, which have long impulse responses – but whose length still fits within the duration of the cyclic prefix.
5) Noise is unavoidable and stems from multiple sources: foremost thermal noise and phase noise. There is a limit on how noisy a repeater can be in order to ***not act as a limiting noise source***.
6) Repeaters can be categorized into single-antenna and dual-antenna repeaters; for the latter, the repeater implementation should ***align with the TDD pattern***.

### B. Single-antenna repeaters

Repeaters only amplify the received signals, without performing any processing. In a *single-antenna repeater*, the same antenna is used simultaneously for reception and transmission and is shared between the input and output of the amplifier chain; see 1) in Fig. 2. This antenna is connected to an antenna-interface circuit (AIC) that forwards the received signal to a low-noise amplifier (LNA), which in turn forwards the signal to a power amplifier (PA) that generates the transmit signal. The AIC also forwards the PA output to the antenna. Note that the physical implementation of the antenna is not restricted to a single *physical* antenna, it could be an antenna array with beamforming capabilities.

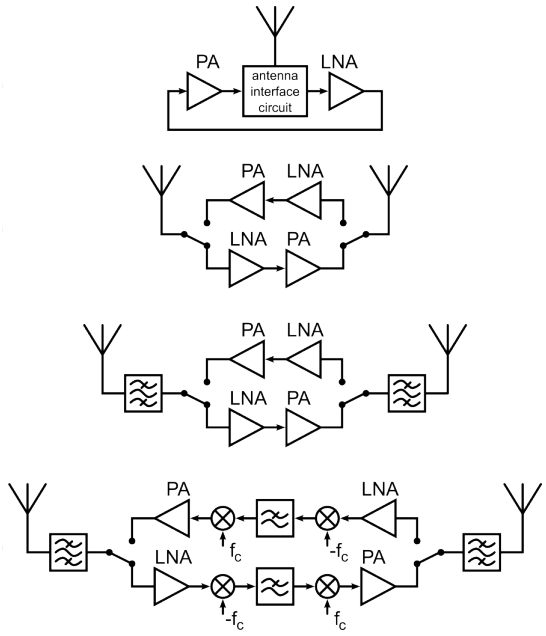



Fig. 2: Principle of 1) single-antenna and 2) dual-antenna repeater architectures, 3) with RF filters, and 4) with up- and down-conversion for baseband filtering.

Important AIC parameters are the level of PA-to-antenna and antenna-to-LNA losses, and the PA-to-LNA isolation. The latter dictates the maximum gain of the repeater: the gain must be lower than the isolation to avoid self-oscillation. The antenna-to-LNA loss adds to the repeater's noise figure (NF) and the PA-to-antenna loss reduces the transmit power.

The AIC may be implemented as a circulator or as an electrical-balance duplexer. PA-to-LNA isolations of 20–50 dB have been reported, with the highest levels only achieved with a relative bandwidth of up to 10% [9]. Assuming a 50 dB isolation, the single-antenna repeater may only allow for a gain up to some 40 dB (assuming a 10 dB margin to avoid self-oscillation). The PA-to-antenna loss introduced by the AIC is in most cases within 2–4 dB for the sub-6 GHz range and the NF contribution is within 2.5–6 dB [9].

While having a limited gain potential, the single-antenna repeater intrinsically supports reciprocity-based communication.

### C. Dual-antenna repeaters

The repeater architecture considered in recent standardization efforts on NCR [10] is the dual-antenna repeater. Dual-antenna repeaters are substantially more robust than

single-antenna repeaters, and much more resilient to self-oscillation. One antenna is assigned for the base station side and another for the terminal side, see 2) in Fig. 2, with one amplification path for the uplink and another for the downlink. A switch selects the transmission direction. Dual-antenna repeaters naturally provide high isolation between the PA output and the LNA, as the two antennas can be physically designed and placed to provide a low inter-antenna gain. Therefore, dual-antennas repeaters allow for substantially higher gains, compared to single-antenna repeaters. Furthermore, design compromises associated with the AIC in single-antenna repeaters are avoided. In particular, a dual-antenna repeater has a lower NF and a higher output power capability.

The dual-antenna repeater does however not support reciprocity-based communication unless the uplink and downlink signal paths have matching transfer functions across the band. Even with the signal paths *designed* to be identical, when temperature changes, their relative gains and phases will change. This calls for periodic reciprocity calibration [11].

Existing repeater requirements [4] include metrics such as error vector magnitude (EVM), adjacent channel leakage ratio (ACLR), and emission limits. No maximum gain is specified for the passband of the repeater, but there are requirements on the maximum allowed gain outside the passband, 60 dB up to 1 MHz from the passband edge, dropping to 35 dB at 10 MHz offset. Also, the ratio between the passband gain and the adjacent channel gain must exceed 33 dB or 45 dB, depending on repeater class and carrier frequency.

RF band filters can be used, see 3) in Fig. 2, to attenuate out-of-band signals before the LNA, and to comply with out-of-band emission requirements. However, such filters may not be sufficient to fulfill gain requirements outside the repeater passband. Better selectivity can be achieved by baseband filtering, as shown in 4) in Fig. 2: the received signal is then down-converted to baseband, filtered, and up-converted using the same local oscillator (LO).

Baseband filtering may also be carried out in the digital domain, enabling the use of sharper and more flexible filters. This comes at increased cost and complexity, due to the digital processing itself, and to the addition of analog-to-digital and digital-to-analog converters.

### *D. Hardware performance and impairments*

*1) Additive noise:* In the architecture in 3) in Fig. 2, both the RF band filter and the antenna-to-LNA switch introduce losses and thus an increase in the repeater's NF. The filter loss varies greatly depending on the type of filter technology and the target band. A typical terminal band filter at sub-6 GHz frequencies has a loss of around 2 dB while the switch loss is only a fraction of a dB.

The NF for the remaining part of the signal chain is dominated by the LNA. CMOS LNAs operating in the sub-6 GHz range have a NF of 2–3 dB [12]. Adding a 2 dB filter loss yields a total NF of up to 5 dB.

*2) Amplification, distortion, and power:* The LNA may provide a gain of some 20–30 dB for sub-6 GHz frequencies. With additional amplifiers prior to the final PA, a total gain of 60 dB and beyond can be achieved. As the amplification level increases, so does the non-linear distortion generated by the amplifiers. The overall distortion should be dominated by the PA as there is most to gain in power consumption by optimizing the PA efficiency.

A fully analog repeater can not use digital linearization techniques to reduce the PA distortion. However, limited improvements may be achieved using analog linearization techniques. Backing off the output power reduces distortion, but comes at the expense of decreased efficiency. The required backoff depends on both the targeted ACLR level and the PA's non-linearity characteristics. An estimate may be calculated assuming a third-order polynomial PA model and an OFDM input signal. The output power for a desired ACLR is then proportional to the PA's 1-dB gain compression point, and inversely proportional to the square root of the ACLR [13].

The PA's power capability depends on both semiconductor technology and frequency [14]. For low-cost repeaters, targeting "local area class" specifications and operating in the sub-6 GHz range, it is reasonable to use terminal-grade components. Therefore, the output power target should be in the 20 dBm regime (comparable to cellular and WiFi terminals). Repeaters with higher output power are subject to "wide area class" specifications and must fulfill more stringent emission requirements. The ACLR requirements for wide-area and local-area repeaters are 45 dB and 31 dB, respectively [10].

*3) Phase noise:* Repeaters with baseband filtering use an LO signal for up- and down-conversion, and this LO signal exhibits phase noise. In conventional transceivers, phase noise leads to EVM degradation and increased emissions close to the transmitted carrier. However, in baseband-filtering repeaters, the same LO signal may be used for both up- and down-conversion. This significantly reduces the impact of the phase noise as the phase noise introduced in the down-conversion will be canceled in the up-conversion. However, the level of cancellation depends on the delay of the signal introduced between the up- and down-conversion [15]. This delay is dominated by the group delay of the baseband filter, and with filters having substantially larger bandwidth than the phase noise spectrum of the LO, the impact of phase noise will be low. Similarly, LO phase noise will not cause any phase drift of the repeater.

*4) I/Q impairments:* To down-convert a signal to baseband (and back to RF), quadrature mixers are used to generate complex baseband equivalents of the RF signal. Quadrature mixers also have impairments, namely I/Q gain and phase mismatch as well as DC offset. If left uncorrected, an I/Q mismatch will degrade the EVM and a DC offset will lead to a transmitted signal with LO signal leakage. In sub-6 GHz bands, I/Q gain and phase errors around 1% and 1 degree, respectively, are typically achieved without correction. The same errors in both the up- and down-conversion result in an EVM contribution of 2%.

*5) Delay:* A repeater introduces delay to the signal. Both the RF and baseband filters, and the amplifiers, contribute to this delay. A representative example is an analog 5th-order lowpass Butterworth filter with 10 MHz bandwidth that has a

group delay of some 50 ns, scaling inversely proportionally to the filter bandwidth. For digital filtering and associated conversion between analog and digital domains, the processing delay may reach 100's of ns. That is only a small fraction of the cyclic prefix and therefore insignificant.

## IV. Performance of Repeater-Assisted Cellular Massive MIMO

After elaborating on how to implement repeaters to act as active scatterers we here aim to show the potential of RA-MIMO, comparing it to massive C-MIMO, small cells, and densely deployed D-MIMO, which serves as a benchmark for ideal performance, e.g. assuming no synchronization issues or other impairments. We consider multi-user MIMO transmission, where either a massive MIMO array located at the base station (first two cases) or distributed APs (last two cases) receive uplink data from multiple terminals, whereas the repeaters in RA-MIMO are located at the same positions as the APs in the last two cases. For simplicity, the results disregard interactions between repeaters, however, the maximum amplification gain is chosen such that the system becomes stable without positive feedback (using the criteria in [8]). The signal-to-interference-plus-noise ratio (SINR) after the uplink combiner is used as performance metric, with conventional minimum mean square error (MMSE) combining and perfect channel state information (CSI) assumed unless otherwise stated. Cumulative distribution functions (CDFs) based on both channel distributions and user locations are generated, using 100,000 realizations. The terminals are randomly positioned in each realization. For the AP selection in the small cell scenario, a greedy strategy leveraging the Hungarian algorithm to optimize total signal strength across all terminals is used.

The simulation is conducted in an outdoor square area with 400 m sides. At the center, the base station with a 64-antenna uniform circular array is located at a 20 m height. The carrier frequency is 3.6 GHz with 20 MHz bandwidth. The noise temperature is 290 Kelvin and the NF is 5 dB. Path loss and LoS probability models stem from 3GPP UMi TS 36.814. The fading is Ricean with a 10 dB K-factor if LoS exists, otherwise it is Rayleigh. The 64 single-antenna repeaters/APs are distributed on a uniform grid at a 10 m height above the terminals. The terminals and repeaters have maximum 20 dBm output power. In addition, the repeaters are regulated by a maximum 70 dB amplification gain. The actual gain used at each repeater is determined as the maximum allowable amplification gain under these two constraints. To demonstrate the potential performance of RA-MIMO, it is assumed that the repeater-base station channels follow Rician fading with a LoS component. In practice, this can not always be guaranteed but is still likely with some deployment considerations.

Considering the additive noise at the base station and the repeaters, we note that the combination of 1) received signal power variations across repeaters with 2) additive noise power at the repeaters may result in low-quality repeated signals that may deteriorate system performance (i.e., some repeaters act as noise sources). We address these challenges with a modified MMSE combiner to incorporate the amplified repeater noise

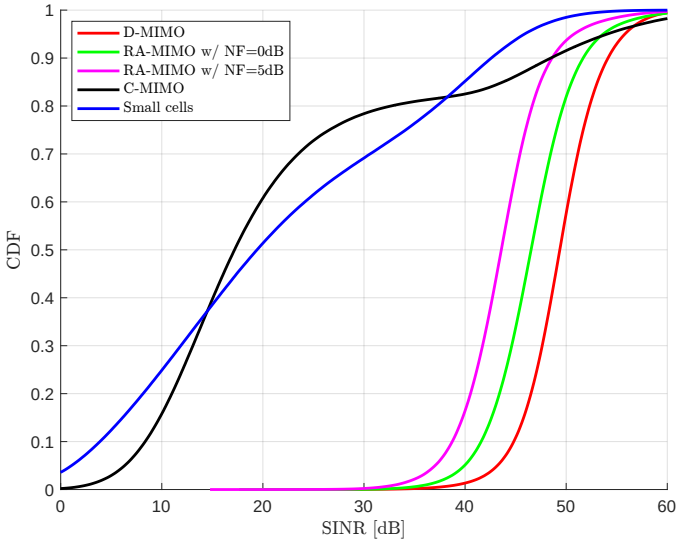



Fig. 3: Simulated SINR distributions for all terminals, for D-MIMO, C-MIMO, ideal-hardware RA-MIMO (0 dB NF), realistic RA-MIMO (5 dB NF), and small cells.

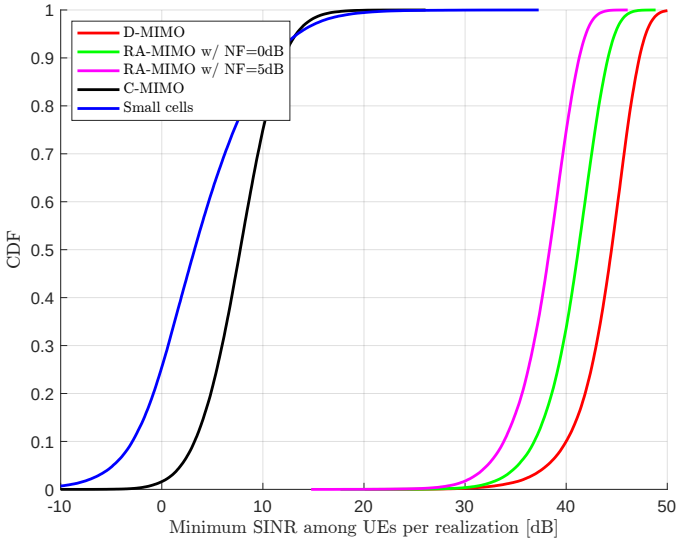



Fig. 4: Simulated distributions of the worst SINR among all terminals per realization, for the same systems as in Fig. 3.

stemming from repeater-base station channels into the matrix inversion of the linear MMSE filtering, in case of RA-MIMO.

Fig. 3 compares simulated CDFs of the SINR for different systems, where the two MIMO architectures are compared to RA-MIMO systems with a 70 dB maximum amplification gain at each repeater. The performance of RA-MIMO systems with a 0 dB NF at each repeater is included as reference to depict an optimistic scenario with ideal-hardware repeaters. This enhancement in SINR signifies that RA-MIMO brings diversity and richer communication channels, thereby improving the low-performing terminals and bridging the performance gap between C-MIMO and D-MIMO systems. RA-MIMO systems can offer substantial benefits, but certain operational considerations must be taken into account. For instance, there is a risk for positive feedback loops between repeaters due to over-amplification if the amplificaiton control is not carefully

designed, which can introduce instability in the system [8]. Additionally, the amplification process may also amplify noise, affecting the signal quality. These factors should be carefully managed in practice to fully realize the advantages of RA-MIMO.

Shifting our focus to the worst-case SINR performance among terminals for each realization, this analysis provides insights into the robustness and reliability of the MIMO configurations under challenging conditions. Fig. 4 presents the CDFs of the worst SINR among terminals for the different architectures. As depicted, RA-MIMO systems exhibit significant improvements over C-MIMO systems in terms of the worst communication performance, approaching the performance levels of D-MIMO. Together with the findings in Fig. 3, these results indicate that RA-MIMO systems have the potential to achieve a level of SINR performance uniformity that is comparable to that of D-MIMO.

## V. Open questions and future work

**System design and adaptions:** Although being an easy-to-deploy solution, some minor adaptions of the network operation might be needed for further performance improvements. Inter-cell interference is, e.g., not considered here.

**Repeater design:** Many of the performance metrics associated with repeaters are common with both base stations and terminals, such as linearity, noise, delays, energy consumption and frequency selectivity, which are all important research topics. One important research question regarding repeaters is how well a repeater can be made reciprocal by design and by means of calibration. Further, the best choice of antennas and antenna patterns is also a research opportunity.

**Multi-antenna repeaters and beamforming:** Performance gains are possible with more antennas. For RA-MIMO, this opens up questions such as how to beamform in presence of repeater impairments and how to compute the beamforming weights with minimal signaling overhead.

**Repeater deployment strategies:** One benefit of repeater deployments is that it does not need to be carefully planned, although optimizations are possible. Aspects to consider are the distribution of repeaters, areas in the cell in need of improved coverage, and areas with few scatterers. Channel analyses would be beneficial in this regard.

**Repeater configuration:** Some configuration of the repeaters is required and configuration strategies need to be assessed. Questions include how to jointly optimize repeater amplification and activation settings.

**Frequency-division duplex:** The focus here has been on TDD-based systems but the solution could potentially be used in frequency-division duplex-based systems. Opportunities and challenges regarding that are left as an open problem.

## VI. Acknowledgements

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