Measurement of Capacity Enhancement with Parasitic Reconfigurable Aperture Antennas in Interference-limited Scenarios

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***Abstract*—The potential of capacity enhancement with a parasitic reconfigurable aperture (RECAP) antenna is investigated through a measurement campaign in line-of-sight (LOS) and non-LOS conditions in an indoor laboratory environment. Measurements are performed using a 5×5 parasitic RECAP for a bandwidth of 70 MHz centered at 2.55 GHz. Both noise-limited as well as interference-limited cases are considered with a varying level of interference under two different realistic power constraints: average receive signal-to-noise ratio (SNR) and fixed total transmit power. For RECAP optimization a simple genetic algorithm (GA) is implemented and its performance is compared with that of a random search. Measurements confirm that a large increase in capacity is possible especially for the case when there is high interference present.**

I. Introduction

Multiple-input multiple-output (MIMO) wireless communications has been the attention of significant research effort, due to the high capacity gain offered by spatial multiplexing in noise-limited multipath channels [1]. MIMO communications in interference-limited networks [2] tends to be less effective, due to high mutual interference of the users, and often using a single stream (simpler beamforming) is preferable for optimal capacity. A possible solution to allow high-rate MIMO communications in interference-limited scenarios is to employ reconfigurable antennas that optimize antenna patterns to avoid and suppress interference as well as enhance useful multipath directions.

The reconfigurable aperture (RECAP) antenna [3] is a dense array of reconfigurable elements (REs), which can be manipulated in order to support many applications like beamforming, interference-suppression, security enhancement and capacity maximization. In our earlier work [4] we have considered a 9×9 parasitic RECAP for capacity enhancement in both noise-limited and interference-limited scenarios assuming different channel models and under different power constraints. It was shown that a large gain in capacity is possible using RECAPs as compared to a non-RECAP antenna, especially for the case when a high degree of interference is present. However, this previous study was based solely on simulations.

In this work, we extend the idea presented in [4] by performing actual channel measurements with a prototype RECAP. For this purpose the receiver (Rx) node is equipped

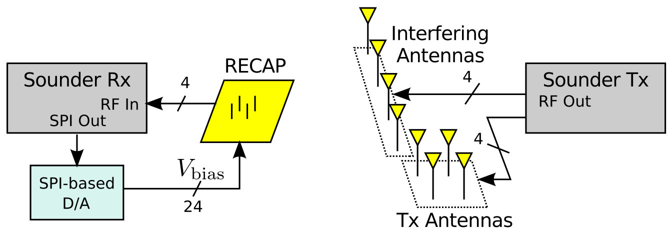

Fig. 1. Channel-sounder-based setup for MIMO-RECAP measurements

with a 5×5 square parasitic RECAP array confined to an area of $1\lambda\times1\lambda$. Measurements are performed for both line-of-sight (LOS) and non-LOS scenarios for 2×2 and 4×4 MIMO systems for the case of a finite bandwidth (BW) as well as a single frequency. A simple genetic algorithm (GA) is implemented for the optimization of the RECAP and its performance with respect to a random search is presented for MIMO capacity maximization. MIMO capacity results are compared with the case when a usual (non-RECAP) array is present at Rx, verifying the capacity enhancement possible using RECAPs.

The remainder of the paper is organized as follows: Section II covers the experimental setup and gives details regarding the transmit and receive node used for these measurements. Section III presents the computation of MIMO channel capacity for different power constraints for both noise-limited and interference-limited scenarios. Section IV characterizes the capacity improvement for this environment using the prototype RECAP antenna. Finally, Section V concludes the paper.

II. MEASUREMENT CONFIGURATION

This section covers the details regarding relative transmit (Tx) and receive node locations for LOS and non-LOS measurements, the experimental setup which was used for channel acquisitions, and the prototype RECAP used in this study.

A. Node Locations

Figure 1 shows the basic measurement setup used in this study, consisting of a Tx node which uses a usual (non-RECAP) array as well as interfering antennas. The Rx node

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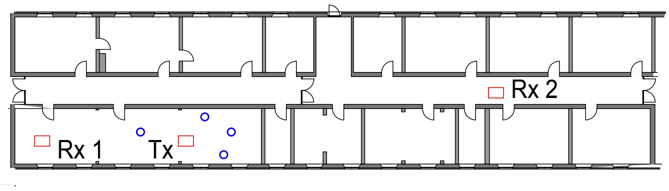

Fig. 2. Location of the Tx and Rx node for LOS (Rx1) and non-LOS (Rx2) measurements, where blue circles mark the location of interfering antennas

has a RECAP with multiple feeds, where the number of feeds depends on whether the 2×2 or 4×4 MIMO system is considered. For LOS measurements, both the Tx and Rx node are placed in the same room separated by 10 m as shown in Figure 2. Red rectangles mark the location of the Tx and Rx node while blue circles mark the location of possible interferers. For the non-LOS measurement, the Tx node location stays the same while the Rx node is moved to the hallway (at label Rx2).

B. Experimental Setup

A MIMO channel sounder similar to the one presented in [5] was used for the measurement campaign, where the Tx and Rx arrays are connected to the Tx and Rx MIMO channel sounder nodes. An SPI-based digital-to-analog (D/A) conversion unit is implemented at the receiver to control the bias voltage V_{bias} on the reconfigurable elements. The measurement setup is depicted with a block diagram in Figure 1. The FPGA-based SPI implementation is integrated with the channel sounder, allowing random RECAP states to be be streamed in a synchronized fashion to SPI-based D/A converters, providing automatic pairing of the channel snapshots and RECAP states.

C. Transmit Node

The transmit node consists of an array of 8 monopole antennas with a ground plane below them, which is partitioned in two parts: a usual (non-RECAP) array that represents the transmitter (squares) radiating desired signals, and the remaining 4 elements that represent interfering antennas (filled circles) as shown in Figure 3. For analysis of 2×2 or 4×4 MIMO systems, blue squares alone or blue and black squares, respectively, are used for the active transmit elements. The feeds of the transmit node are located at the corners of an area of $1\lambda \times 1\lambda$.

The signal transmitted by the Tx node consists of eight frequency tones separated by 10 MHz with a center frequency of 2.55 GHz. The total transmit power is 23 dBm. For the analysis of results we have used a signal-to-noise ratio (SNR) of 10 dB, while the achieved SNR in the actual measurements was approximately 60 dB for LOS channels and 20 dB for non-LOS channels.

D. Receive Node (RECAP Antenna and RE Design)

In our study, the Rx node has a RECAP consisting of a 5×5 square parasitic array of monopole antennas confined to an area of $1\lambda \times 1\lambda$. The RECAP uses either 2 or 4 active

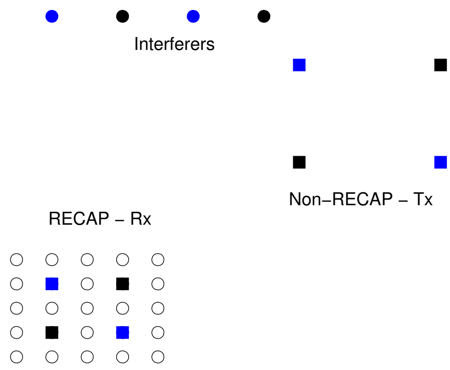

Fig. 3. Top view of the antenna configurations used for the MIMO-RECAP measurements

feeds for MIMO communications, indicated by blue squares alone or blue and black squares, respectively. Empty circles denote the positions of parasitic monopoles that are terminated with reconfigurable elements as shown in Figure 3. In order to compare the results with a reference non-RECAP case, a receive array identical to the transmit array was used at the receiver (i.e. the REs are all removed and the feed configuration is identical to Tx).

Figure 4 shows the current design of the reconfigurable element based on a single SMV1232 varactor diode, providing a tunable capacitance from 1.05 pF to 4.15 pF for a reverse bias range from 0 to 5 Volts. In order to enhance the phase shift given by the varactor diode in this reversed biased region, a 1.2 nH inductor is used in parallel, resulting in almost 200° phase shift corresponding to 0 to 5 volts at 2.54 GHz. In the measurements, the useful bias range of 1 to 5 volts was uniformly divided into 16 possible reconfigurable states.

Figure 5 plots the magnitude and phase of S_{11} of the reconfigurable element at 2.54 GHz using a vector network analyzer. Although it can be seen that phase variation is very low from 0 to 1 volts, biases from 1 to 5 volts produce nearly linear phase variation with increasing reverse bias. The variation in the magnitude of S_{11} indicates that our simple RE circuit exhibits loss, which results mainly from the 1.2Ω series resistance of the varactor diode. Since we feel that phase tunability is more important in this initial study than the absolute antenna efficiency, we have chosen to use the simple design in this research.

III. MIMO Channel Capacity

This section briefly summarizes the results from [4] that are required to compute capacity for noise and interference-limited scenarios. MIMO channel capacity is computed as

$$C = \log_2(\det[\mathbf{I} + \mathbf{H}\mathbf{R}_{\text{x}}\mathbf{H}^H]), \qquad (1)$$

where $\mathbf{H}$ is the channel matrix between Tx and Rx. For equal power allocation $\mathbf{R}_{\text{x}} = \frac{P_{\text{T}}}{N_{\text{F}}}\mathbf{I}$, where P_{T} is the total Tx power, and N_{F} is the number of Tx feeds (antennas). The capacity improvement by employing RECAPs is assessed using three different cases as explained below.

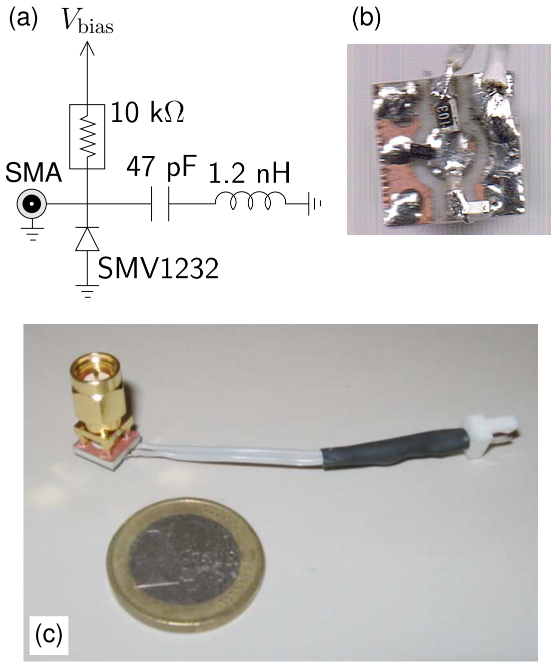

Fig. 4. Reconfigurable element circuit: (a) schematic, (b) printed-circuit board with components, (c) completed RE with SMA connector

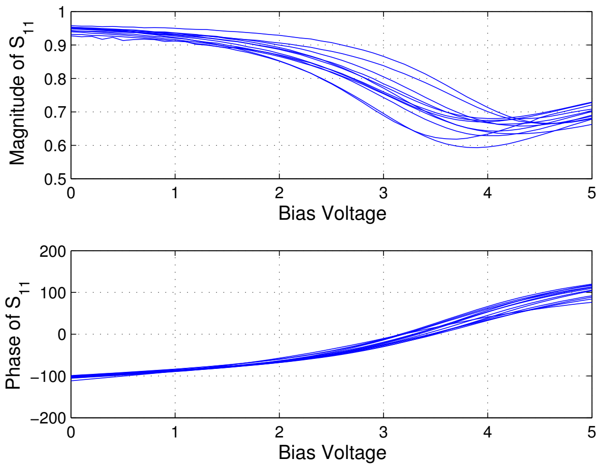

Fig. 5. Phase tunability and loss of REs with respect to bias voltage

First, the non-RECAP case (Case 1) will be considered the reference that indicates the base performance possible with a normal MIMO system. Here, both Tx and Rx are equipped with non-RECAP arrays and the channel matrix is normalized with

$$\underline{\mathbf{H}}_{\mathrm{REF}} = \frac{\sqrt{N_{\mathrm{F}} N_{\mathrm{F}}'}}{\|\mathbf{H}_{\mathrm{REF}}\|_F} \mathbf{H}_{\mathrm{REF}} \quad (2)$$

where $\|.\|_{\mathrm{F}}$ is Frobenius norm, N_{F}' is the number of feeds (antennas) at Rx, and $\mathbf{H}_{\mathrm{REF}}$ is the non-RECAP channel.

In Case 2 (Avg Rx SNR Constraint), the Rx is equipped with a RECAP structure while Tx has a non-RECAP. The channel is normalized using

$$\underline{\mathbf{H}} = \frac{\sqrt{N_{\mathrm{F}} N_{\mathrm{F}}'}}{\|\mathbf{H}\|_F} \mathbf{H} \quad (3)$$

where $\mathbf{H}$ corresponds to the RECAP channel. This normalization ensures that the RECAP and non-RECAP cases have the same receive power, thus restricting capacity improvement due to SNR enhancement with beamforming. Capacity improvement is only possible by removing interference or making channels more orthogonal.

In Case 3 (Fixed total transmit power), the normalization is

$$\underline{\mathbf{H}} = \frac{\sqrt{N_{\mathrm{F}} N_{\mathrm{F}}'}}{\|\mathbf{H}_{\mathrm{REF}}\|_F} \mathbf{H}, \quad (4)$$

which represents a fixed transmit power constraint, allowing the RECAP to have increased power through beamforming.

In our analysis, we have considered both noise-limited as well as interference-limited cases. For the noise-limited case, the channel capacity is computed as

$$C = \log_2(\det[\mathbf{I} + \frac{\rho}{N_{\mathrm{F}}} \underline{\mathbf{H}}\ \underline{\mathbf{H}}^H]), \quad (5)$$

where ρ is the signal-to-noise ratio (SNR). For the interference-limited case, the channel capacity is computed as

$$C = \log_2(\det[\mathbf{I} + \frac{\rho}{N_{\mathrm{F}}} (\mathbf{I} + \widehat{\rho} \widehat{\underline{\mathbf{H}}}\ \widehat{\underline{\mathbf{H}}}^H)^{-1} \underline{\mathbf{H}}\ \underline{\mathbf{H}}^H]), \quad (6)$$

where $\widehat{\rho}$ is the per interferer interference-to-noise ratio and $\widehat{\underline{\mathbf{H}}}$ is the normalized channel between interferers and Rx. Note in this study, we always have assumed that the number of interferers is the same as the number of transmitters.

A. RECAP Optimization for Capacity Enhancement

The RECAP used at the receiver has 23 REs, where each RE can have 16 possible states leading to 5×10^{27} possible combinations, making an exhaustive measurement of all states impossible. One possible option is to randomly pick N sets of RE states lying uniformly over the possible domain, compute capacity corresponding to them, and choose the one which gives the best performance. A random search with $N = 20{,}000$ random RE states was initially tried in this study. Note, however, that random searches tend to be inefficient, and a more directed search is desired for our application.

To obtain higher performance than the random search, a genetic algorithm similar to the one presented in [6] was implemented on the receive channel sounder. We should note that the implementation has not yet been fully optimized and tuned, and more optimized algorithms are to be presented in future work. The current GA starts with a random population of 10,000 RE configurations, followed by 40 iterations, where each iteration evaluates 1000 RE configurations composed of cross-overs and mutations of the best population vectors from the previous iteration.

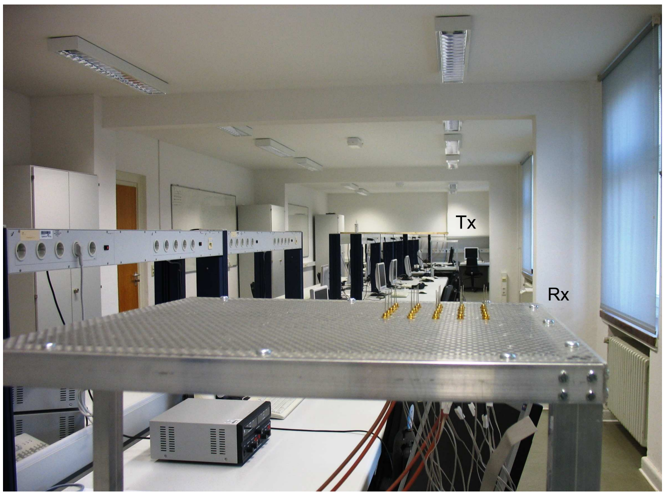

Fig. 6. Photo showing the LOS environment where measurements were taken and the relative positions of the Tx and Rx nodes

IV. Measurement Results

Figure 6 shows the channel measurement setup for LOS case, marking the relative positions of the transmit and receive nodes. All of the measured capacity results are depicted in Figure 7, where the top half is for 2×2 measurements and the bottom half is for 4×4 measurements. The left plot in each group is for random search (solid lines) and the right plot is for the GA (dashed lines).

A. 2×2 *MIMO System*

Figure 7(a) presents the result for the LOS channel corresponding to three cases and varying interference-to-noise ratio ($\hat{\rho}$) per interferer over a bandwidth of 70 MHz. It is observed that although the GA is not fully optimized, it still provides much better capacity than a random search. Both non-RECAP and RECAP capacity drop with increasing $\hat{\rho}$. However a relative comparison shows that for high interference the performance advantage using RECAP increases (reaching to 200%) for $\hat{\rho}$=20 dB.

Figure 7(b) considers the same cases, except that only a single frequency bin is optimized (narrowband system). The increased capacity of the single-frequency optimization is expected, since it is well known that nulling at a single frequency is much simpler than wideband nulling. Interestingly it is observed that the RECAP gives approximately the same capacity for $\hat{\rho}$=20 dB as the non-RECAP gives when no interference is present. Also, fixed transmit power performs better than fixed SNR, indicating that for the single-frequency case, beamforming can provide a significant advantage.

Figure 7(c) and (d) show the same configurations as (a) and (b), except that the non-LOS (hallway) environment is considered. The trends for the 2×2 non-LOS case are similar to the LOS case, except that beamforming advantage for fixed transmit power appears to be higher, even for wide bandwidth.

B. 4×4 *MIMO System*

Figure 7(e) and (f) present channel capacity corresponding to a 4×4 MIMO system for the LOS environment for wide bandwidth and single frequency. Similar to the 2×2 system, the GA is able to find much better solutions than the random search, especially for large $\hat{\rho}$. For the results corresponding to the 4×4 system, it seems that fixed SNR in general performs the same or better than fixed transmit power. This is likely due to the increased difficulty of the optimization problem, since for the same aperture we have more feeds (fewer REs and more paths to enhance) and more interfering antennas need to be nulled out, meaning fewer degrees of freedom are left over for beamforming. Figure 7(g) and (h) show similar trends as for the non-LOS environment. The main new observation is that even the genetic algorithm is unable to provide very large capacity improvement for the wideband non-LOS case.

V. Conclusion

This work has characterized the MIMO capacity enhancement that is possible in a LOS and non-LOS indoor environment when a parasitic reconfigurable aperture (RECAP) antenna is used at the receiver. Measured capacity was presented for both 2×2 and 4×4 MIMO systems for two different constraints (average Rx SNR, fixed total transmit power) in both wide band and narrow band optimization scenarios. It has been observed that RECAP antennas can significantly enhance the capacity in the presence of high interference and narrow bandwidth operation. Also, this work highlights the need of an efficient optimization algorithm, as it is not possible to find a good solution by a random search. In future work, the prototype RECAP system will be used to characterize possible gains in a more comprehensive set of environments. Additionally, effort will concentrate on developing efficient optimization algorithms that can find the RECAP states providing near-peak capacity with minimum possible optimization time.

References

[1] I. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. Telecomm.*, vol. 10, pp. 585–595, Nov./Dec. 1999.

[2] R. S. Blum, "MIMO capacity with interference," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 5, pp. 793–801, 2003.

[3] L. N. Pringle, P. H. Harms, S. P. Blalock, G. N. Kiesel, E. J. Kuster, P. G. Friederich, R. J. Prado, J. M. Morris, and G. S. Smith, "A reconfigurable aperture antenna based on switched links between electrically small metallic patches," *IEEE Trans. Antennas Propag.*, vol. 52, pp. 1434–1445, June 2004.

[4] R. Mehmood and J. W. Wallace, "MIMO capacity enhancement using parasitic reconfigurable aperture antennas (RECAPs)," *IEEE Transactions on Antennas and Propagation*, vol. 2, Feb. 2012, to appear.

[5] B. T. Maharaj, J. W. Wallace, M. A. Jensen, and L. P. Linde, "A low-cost open-hardware wideband multiple-input–multiple-output (MIMO) wireless channel sounder," *IEEE Transactions on Instrumentation and Measurement*, vol. 57, no. 10, pp. 2283–2289, 2008.

[6] R. Mehmood and J. W. Wallace, "Diminishing returns with increasing complexity in reconfigurable aperture antennas," *IEEE Antennas Wireless Propag. Lett.*, pp. 299–302, 2010.

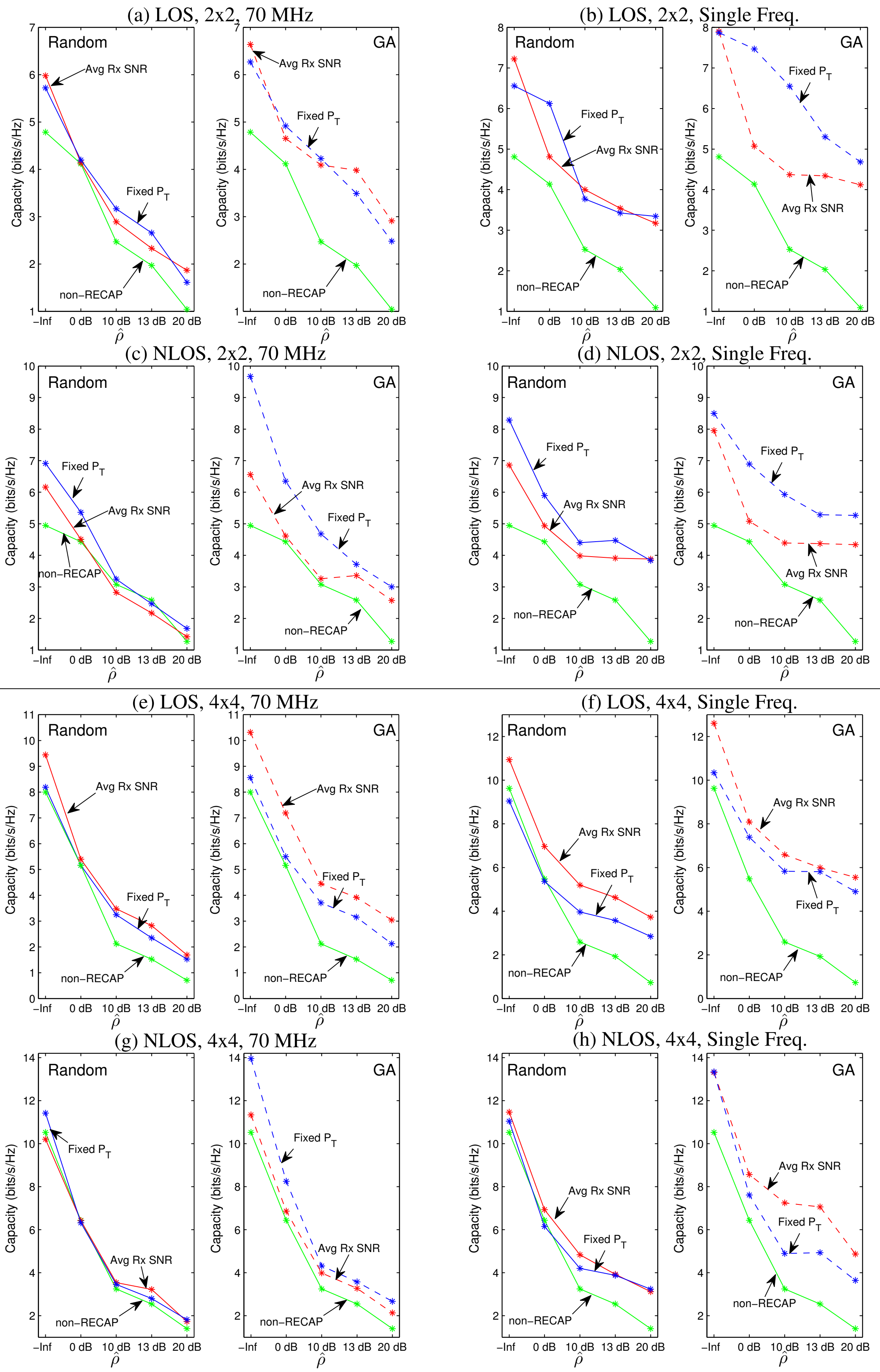

Fig. 7. Peak measured capacity. Random search is on the left and GA on the right of each subplot.