On Massive MIMO Cellular Systems Resilience to Radar Interference

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Summary of the paper

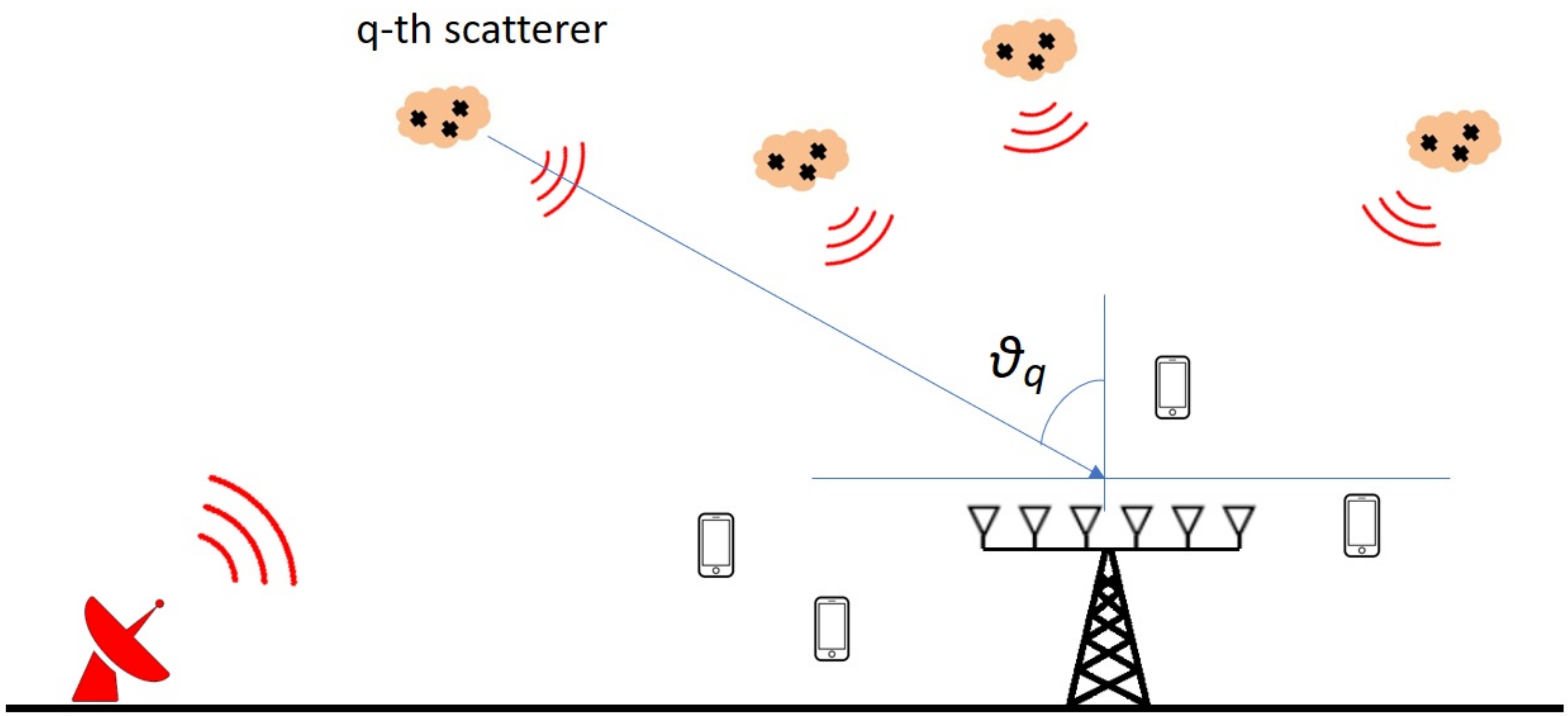
This paper considers a single-cell massive MIMO communication system in uplink coexisting with a radar system using the same frequency band. In particular,

(a) We consider a system model taking into account the clutter produced by the radar system at the massive MIMO receiver

(b) We provide a theoretical analysis, in terms of UL spectral efficiency and in terms of mutual information

(c) We show that for large number of antennas at the BS the radar clutter effects can be suppressed

System model (Part I)



References

[1] S. Buzzi, M. Lops, C. D'Andrea, and C. D'Elia, "Co-existence between a radar system and a massive MIMO wireless cellular system," in *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2018, pp. 1–5

System model (Part II)

- We denote by
  - N the number of subcarriers of the SC-FDMA system
  - M the number of elements of the ULA at the BS
  - C the number of consecutive subcarriers where the channel is constant
  - K the number of users of the cellular system

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- The radar system transmits every T_{PRT} a coded waveform whose baseband equivalent is

$$s_R(t) = \sqrt{P_T} \sum_{\ell=0}^{L-1} c_\ell \psi(t - \ell T_s)$$

Signal model (Part I)

- **UL data transmission**: The observable corresponding to the N subcarriers for the ℓ-th data packet is the $(M \times N)$-dimensional matrix

$$\mathbf{Y}(\ell) = \sum_{k=1}^{K} \sqrt{p_k} \left(\left[\mathbf{h}_k^{(1)} \ldots \mathbf{h}_k^{(Q)} \right] \otimes \mathbf{1}_{1 \times C} \right) \text{diag}(\mathbf{X}_k(\ell)) + \mathbf{W}(\ell) + \mathbf{C}(\ell) \ ,$$

with $Q = N/C$.

Signal model (Part II)

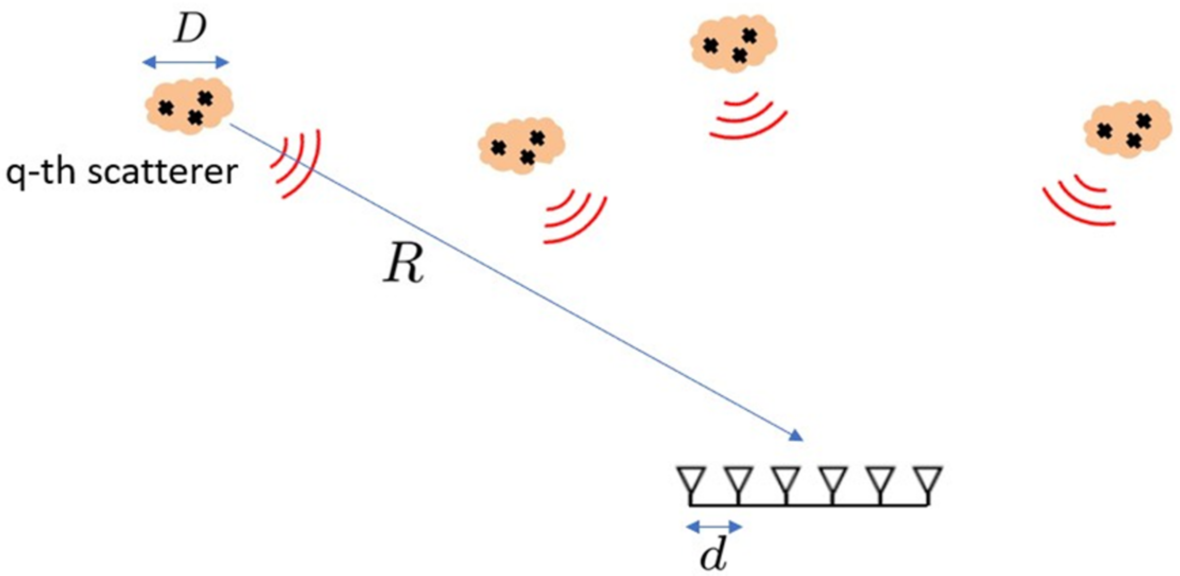
- **UL training**: Let T denote the number of consecutive packets devoted to training, and let $\mathbf{p}_k(1), \ldots, \mathbf{p}_k(T)$ denote N-dimensional vectors containing the k-th MS pilots.
  Assuming that the M-dimensional channel vectors $\mathbf{h}_k^{(q)}$, $\forall k = 0, \ldots, K-1$, are to be estimated we focus on the observable

$$\mathcal{Y}_q = \sum_{k=1}^{K} \sqrt{p_{\mathrm{p,k}}} \mathbf{h}_k^{(q)} \mathbf{P}_k^{(q)\ T} + \mathcal{W}_q + \mathcal{C}_q \ ,$$

  where $\mathbf{P_k}^{(q)}$ is a (TC)-dimensional vector containing FFT samples of the k-th MS pilots

Clutter modeling (Part I)

- Given the BS array dimension, it is reasonable to assume that these scatterers are seen by the BS as "**colocated**", i.e. $d \ll R\frac{\lambda}{D}$



References

[2] J. Li and P. Stoica, "MIMO radar with colocated antennas," *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 106–114, 2007

Clutter modeling (Part II)

- The radar-to-BS channel can be modeled as a LTI channel

$$\mathbf{h}(t) = \sum_{q=0}^{N_s-1} \sum_{m=0}^{Q-1} \beta_{q,m} \mathbf{b}(\theta_q) \delta(t - \tau_q - m/W)$$

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- Let $\mathcal{S}(\ell)$ denote the set of the scatterers corrupting the reception of the ℓ-th data packet; the clutter $(M \times N)$-dimensional matrix is

$$\mathbf{C}(\ell) = \sum_{q \in \mathcal{S}(\ell)} \sum_{m=0}^{Q-1} \sum_{p=0}^{L-1} \sqrt{P_T} \beta_{q,m} c_p \mathbf{b}(\theta_q) \mathbf{r}_{q,p,m}^T(\ell) \mathbf{W}_{N,FFT}$$

Receiver processing

- **UL channel estimation**
  - Pilot matched (PM)
  - Minimum-mean-square-error (MMSE)

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- **UL channel estimation**
  - Pilot matched (PM)
  - Minimum-mean-square-error (MMSE)
- **UL data detection**
  - Channel-matched (CM)
  - Zero-forced clutter (ZF)
  - Linear minimum mean square (LMMSE)
  - Full zero-forcing (FZF)

References

[1] S. Buzzi, M. Lops, C. D'Andrea, and C. D'Elia, "Co-existence between a radar system and a massive MIMO wireless cellular system," in *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2018, pp. 1–5

Uplink spectral efficiency derivation

- We derive closed-form expressions for a LB to the UL SE under the hypothesis of CM detection and both PM and MMSE channel estimation strategies with the **UatF** bounding technique
- The UatF bound exploits the channel estimates only for computing the receive combining vectors, while this information is not exploited in the signal detection phase
- This assumption is reasonable when there is substantial **channel hardening**

$$\mathsf{SE}_k^{(n)} \geq \frac{N_{\mathrm{pkt}} - T}{N_{\mathrm{pkt}}} \log_2\left(1 + \mathsf{SINR}_k^{(n)}\right) \ [\mathsf{bit/s/Hz}]\,,$$

References

[3] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO*. Cambridge University Press, 2016

Information Theoretic Analysis

- The clutter contribution has no effect on the single-user mutual information

$$I\left(\boldsymbol{y};\boldsymbol{X}^{(0)},\boldsymbol{X}^{(1)},\ldots,\boldsymbol{X}^{(Q-1)}\middle|\,\boldsymbol{h}^{(0)},\ldots,\boldsymbol{h}^{(Q-1)}\right)=\log\left|\boldsymbol{I}_{NM}+\boldsymbol{K}'\left(N_0\boldsymbol{I}_{NM}+\boldsymbol{K}_{\mathrm{c}}\right)^{-1}\right|$$

- We show that, in the **large number of antennas regime**, the product $\left[\boldsymbol{K}'^{\dagger}\boldsymbol{K}_{\mathrm{c}}\right]$ vanish **almost surely**
- The radar clutter effect at the BS is suppressed and single-user capacity is restored

References

[4] W. F. Stout, *Almost sure convergence*. Academic Press, 1974
[5] P. Billingsley, *Convergence of probability measures*, 2nd ed. Wiley, 1999

Simulation Setup[1]

Name	Value	Description
f_c	3 GHz	carrier frequency
M	16, 64, 128	number of antennas at the BS
d	$\frac{\lambda}{2}$	antenna spacing
K	1,10	number of users in the cellular system uniformly distributed in the range [20,500] m
p_k	100 mW	MSs transmit power in training and data transmission phases
N	4096	number of subcarriers
Δ_f	30 kHz	subcarrier spacing
C	16	number of consecutive subcarriers where the channel is considered constant
Q	$\frac{N}{C} = 256$	number of scalar coefficients representing the amount of channel state information for each user and for each BS antennas
N_s	100	number of total scatterers in the system uniformly distributed in the range [1,150] km
N_{CP}	288	discrete length of the cyclic-prefix
T_{PRT}	1 ms	radar pulse repetition time
N_{pkt}	14	number of packets into a 0.5 ms timeslot
T_s	8.146 ns	symbol time
T	7	number of packets used for the channel estimation
L	32	discrete length of the radar coded waveform
F	3 dB	noise figure at the receiver
$\mathcal{N}_0$	-174 dBm/Hz	power spectral density of the noise

[1] These numbers are inspired by the December 2017 3GPP first realease of the 5G New Radio standard.

Numerical Results: SINR versus CNR

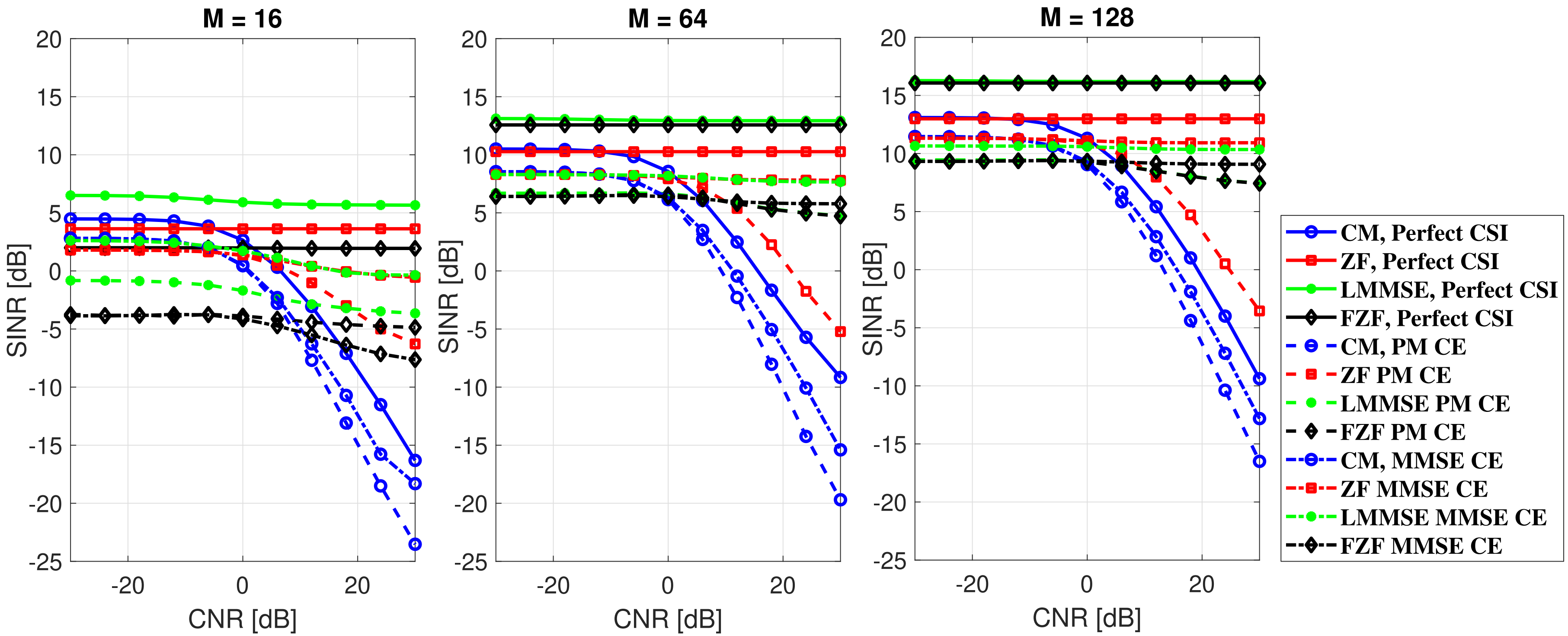

Figure: SINR versus CNR of four detection strategies in the cases of perfect CSI, PM CE and MMSE CE, with $K = 10$ and different values of M.

Numerical Results: Spectral efficiency lower bounds

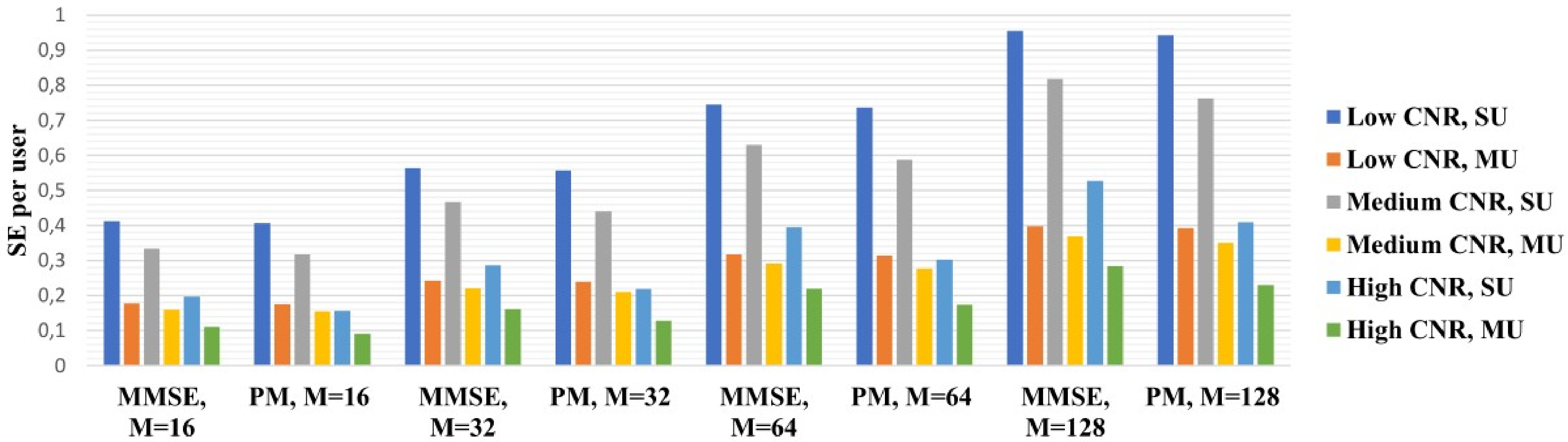

Figure: SE per user lower bounds with CM beamforming, in SU and MU scenarios, for increasing values of M, for CNR $= -20$ dB (Low CNR), for CNR $= 0$ dB (Medium CNR), for CNR $= 10$ dB (High CNR), and with PM and MMSE CE techniques.

Numerical Results: Key insights

- Performance steadily improves increasing the number of BS antennas
- CM beamforming is the most vulnerable combining scheme to interference, while other strategies exhibit much better performance
- Ascending performance order: CM, ZF, FZF, LMMSE
- If *clutter second order statistics* are known at the BS, several strategies exist to tackle the interference from the co-existing radar system, with better and better performance increasing the number of BS antennas

Conclusions

- This paper has been focused on an uplink massive MIMO communication system which co-exists with a radar system using the same frequency band
- We derived spectral efficiency lower bound expressions for the considered scenario
- We showed that in the large number of antennas regime the clutter contribution has no effect on the single-user mutual information
- The results confirmed that increasing the number of antennas at the BS provides increased robustness against the clutter disturbance originating from the radar system

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Thank you for listening!

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S. Buzzi, M. Lops, C. D'Andrea, and C. D'Elia, "Co-existence between a radar system and a massive MIMO wireless cellular system," in *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2018, pp. 1–5.

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