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Towards Atomic MIMO Receivers

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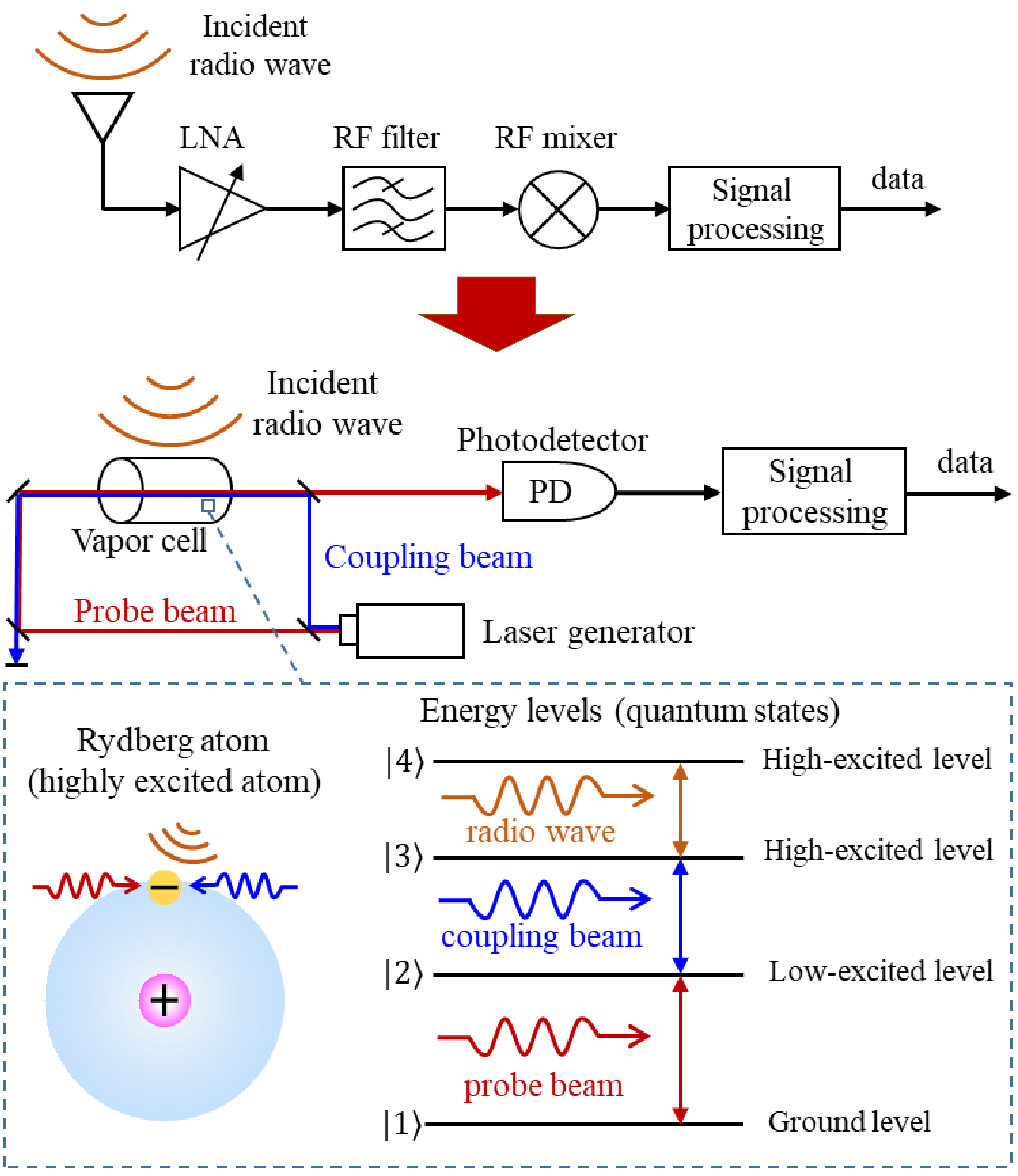
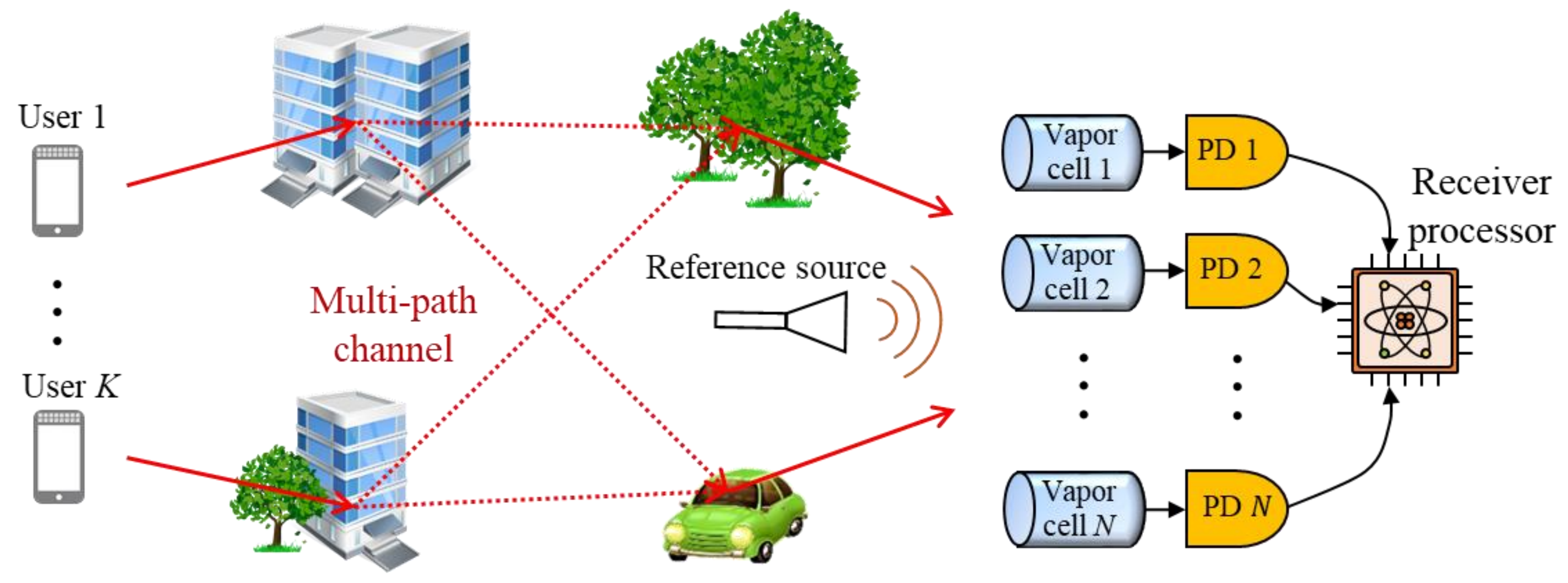
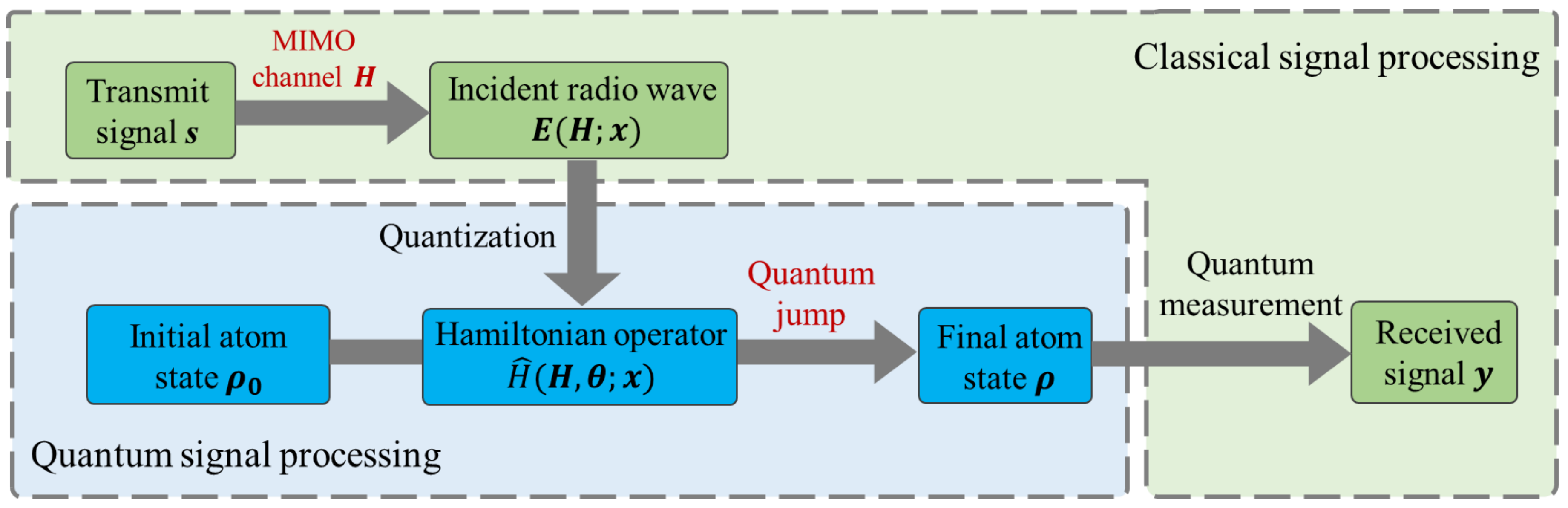
The advancement of Rydberg atoms is driving a paradigm shift from classical receivers to atomic receivers. Capitalizing on the extreme sensitivity of Rydberg atoms to electric field via quantum jump, atomic receivers can measure radio waves more precisely than classical receivers to support high-performance wireless communication. Although the atomic receiver is developing rapidly in quantum-physics domain, its integration with wireless communications is at a nascent stage. In particular, systematic methods to enhance communication performance are largely uncharted.

Motivated by this observation, we propose to incorporate atomic receivers into multiple-input multiple-output (MIMO) communications to implement atomic MIMO receivers. We establish the framework of atomic-MIMO receivers by exploiting the principle of quantum sensing. Our model reveals that the signal detection of atomic-MIMO systems is inherently a biased phase-retrieval problem, as opposed to the linear model in classical MIMO systems. To perform atomic-MIMO signal detection, an Expectation-Maximization Gerchberg-Saxton algorithm is proposed to iteratively solve the biased phase-retrieval problem iteratively. Experimental results validate that atomic MIMO receiver outperform conventional MIMO systems in sensitivity by **16 dB** and in signal detection accuracy by **13 dB**. Our work serves as an important step towards advanced atomic wireless receivers for next-generation communication systems.



Framework of atomic MIMO receivers





1. Transmit signal of the k-th user: $x_k(t) = Re\{s_k e^{j\omega t}\}$
2. Incident radio wave on the n-th atomic antenna:

$$\boldsymbol{E}_n(t) = Re\{\underbrace{\textstyle\sum_{k=1}^{K}\sum_{l=1}^{L} \boldsymbol{\epsilon}_{nkl} h_{nkl} s_k e^{i\omega t}}_{\text{Radio waves from users}} + \underbrace{\boldsymbol{\epsilon}_{r,n} h_{r,n} e^{i\omega t}}_{\text{Radio wave from reference source}}\}$$

3. Quantization: $\hat{H}(t) = \underbrace{\mathrm{diag}\{\hbar\omega_e, \hbar\omega_g\}}_{\text{Rydberg energy levels}} + \underbrace{\hat{\boldsymbol{\mu}}_n^T \boldsymbol{E}_n(t)}$

Interaction of atom and radio wave: $\hat{\boldsymbol{\mu}}_n$ is the dipole moment operator of atom

4. Schrodinger equation: $i\hbar \frac{\partial |\psi(t)\rangle}{\partial t} = \hat{H}(t)|\psi(t)\rangle$
5. The probability of finding the atom at energy level $|4\rangle$: $p = \sin^2\left(\frac{\Omega_n}{2} t\right)$
6. Rabi frequency: $\Omega_n = \left|\sum_{k=1}^{K}\sum_{l=1}^{L} \boldsymbol{\mu}_{eg}^T \boldsymbol{\epsilon}_{nkl} h_{nkl} s_k + b_n\right|$

Electric dipole moment Wireless channel User signal Known reference signal

7. Quantum shot noise results from the randomness of measurement:

$$\sigma^2 = \frac{\hbar^2}{4\pi^2 \|\boldsymbol{\mu}_{eg}\|^2 T_r N_a}$$

- N_a: number of atoms
- T_r: atom relaxation time
- Quantum shot noise is much weaker than thermal noise

8. Transmission model of atomic MIMO receivers:

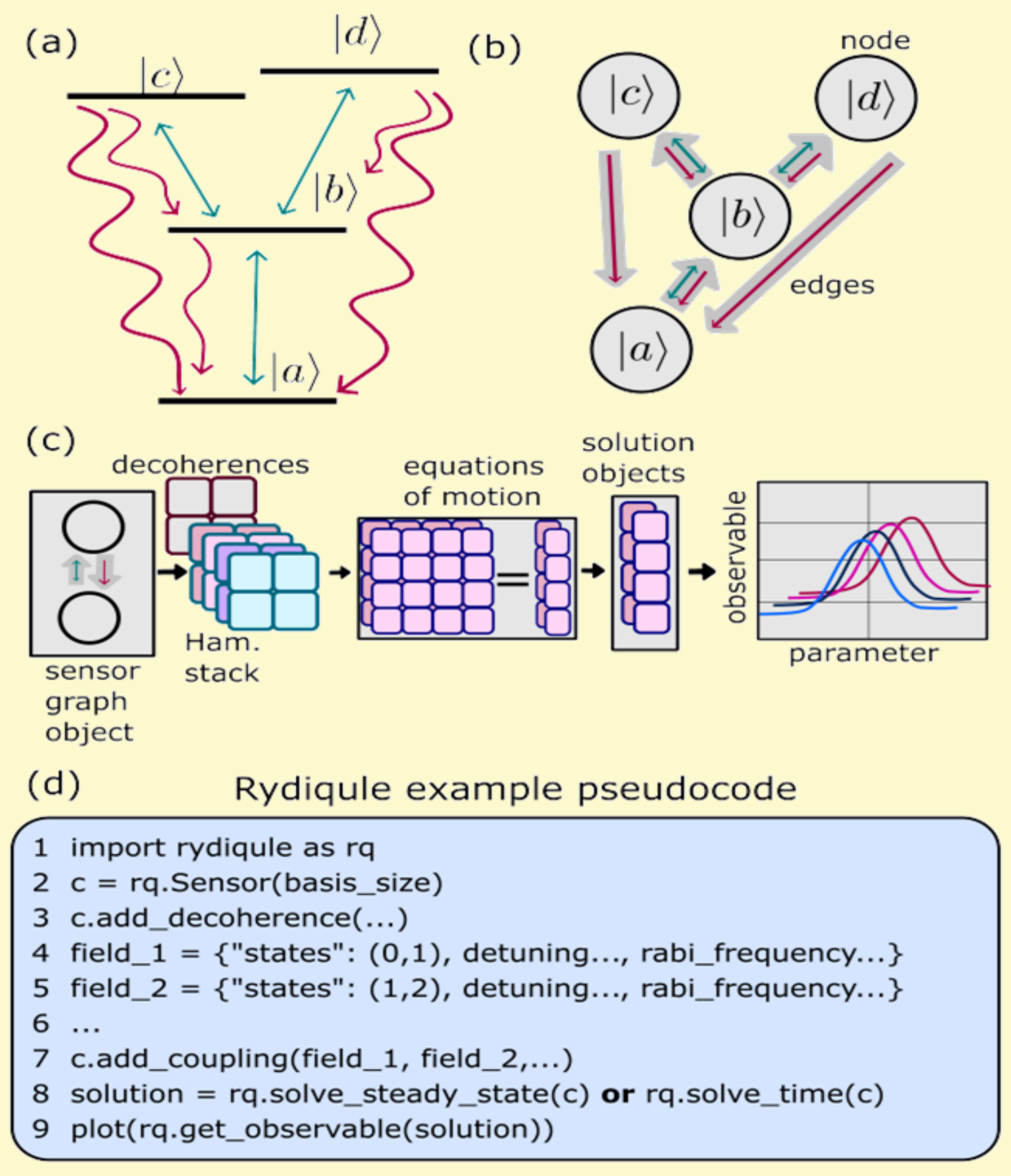
$$y_n = \left|\sum_{k=1}^{K}\sum_{l=1}^{L} \boldsymbol{\mu}_{eg}^T \boldsymbol{\epsilon}_{nkl} h_{nkl} s_k + b_n + w_n\right|$$

Matrix form

$$\boxed{\boldsymbol{y} = |\boldsymbol{A}\boldsymbol{s} + \boldsymbol{b} + \boldsymbol{w}|}$$

- Biased phase-retrieval as opposed to classical linear MIMO model
- Solvable using EM algorithm

Simulation Results



Rydiqule example pseudocode

```
import rydiqule as rq
c = rq.Sensor(basis_size)
c.add_decoherence(...)
field_1 = {"states": (0,1), detuning..., rabi_frequency...}
field_2 = {"states": (1,2), detuning..., rabi_frequency...}
...
c.add_coupling(field_1, field_2,...)
solution = rq.solve_steady_state(c) or rq.solve_time(c)
plot(rq.get_observable(solution))
```

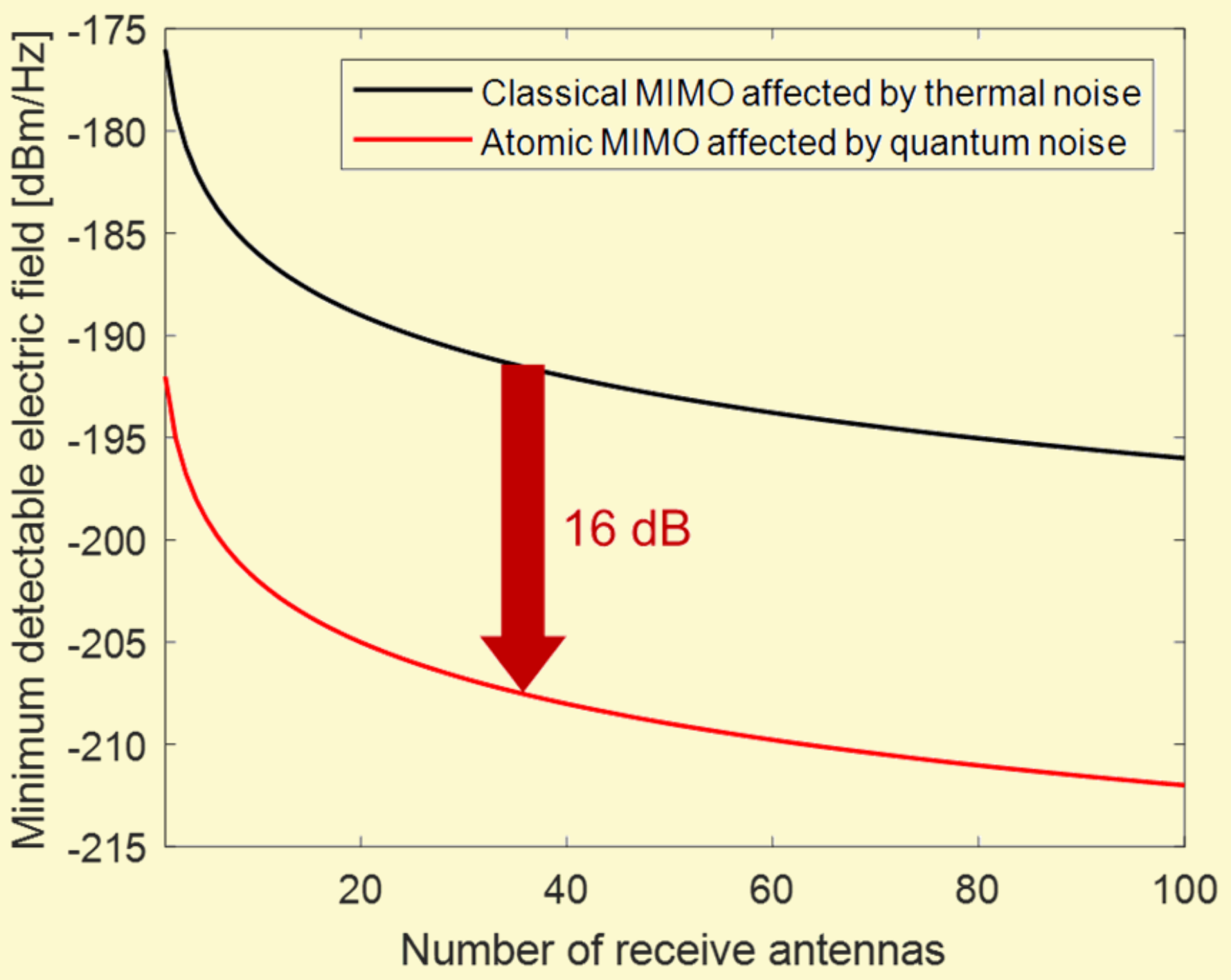
RydIQule: Graph-based numerical computing platform for atomic physics

Simulation parameters	Values
Number of clusters	23
Number of paths per cluster	20
Path gains	$\mathcal{CN}(0,1)$
Incident angles	$\mathcal{U}(-90^\circ, 90^\circ)$
Maximum angle spread per cluster	$\mathcal{U}(-5^\circ, 5^\circ)$
Maximum delay spread	$\mathcal{U}(0\ \mathrm{ns}, 30\ \mathrm{ns})$
Number of users	1,4
Number of transmit antennas	1-100, 36
Modulation	16 QAM
Energy levels	$52D_{5/2}, 53P_{3/2}$
Transition frequency	5 GHz
Electric dipole moment*	$1785.916qa_0$
Number of participating atoms	10^5

Classical and atomic simulation parameters

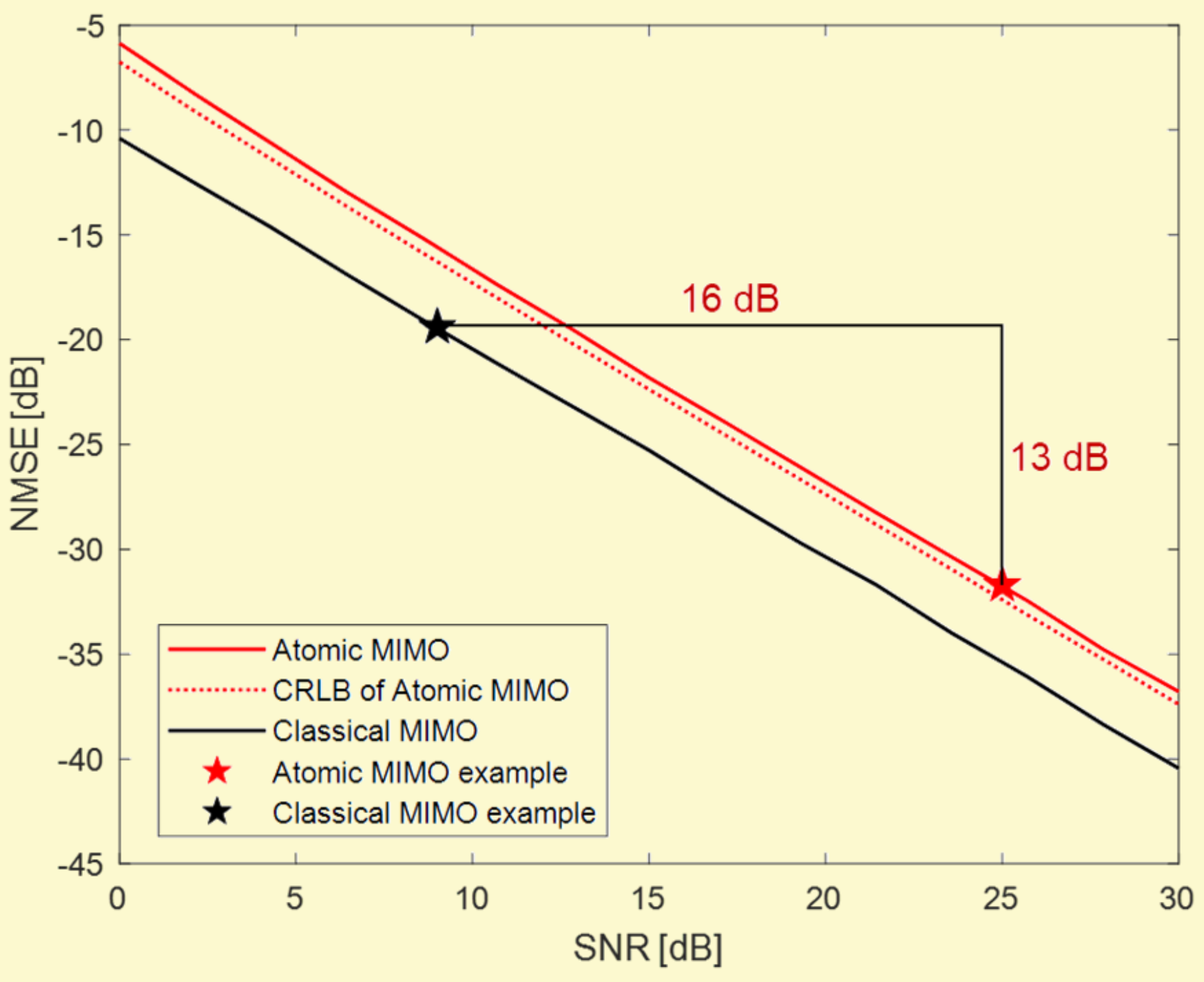
*$q = 1.6 \times 10^{-19}$ C: unit charge

*$a_0 = 5.3 \times 10^{-11}$ m: Bohr distance



Sensitivity (power of Minimum detectable electric field) vs. the number of receive antennas

- 16 dB improvement in sensitivity than classical MIMO
- 20 dB improvement in sensitivity than atomic SISO [Ref.1]



Normalized mean square error (NMSE)

- 13 dB improvement in NMSE realized by the 16 dB higher sensitivity

[Ref. 1] C. T. Fancher, D. R. Scherer, M. C. S. John, and B. L. S. Marlow,"Rydberg atom electric field sensors for communications and sensing," *IEEE Trans. Quantum Eng.*, vol. 2, no. 3501313, pp. 1–13, Mar. 2021.
[Journal] M. Cui, Q. Zeng, and K. Huang, "Towards atomic MIMO receivers", major revision in *IEEE J. Sel. Areas Commun.*, 2024.
[Full version] M. Cui, Q. Zeng, and K. Huang, "Towards atomic MIMO receivers", arXiv preprint, *[Online] https://arxiv.org/abs/2404.04864*, 2024.

Acknowledgment

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