Robust Respiration Sensing via Cell-Free Massive MIMO Systems

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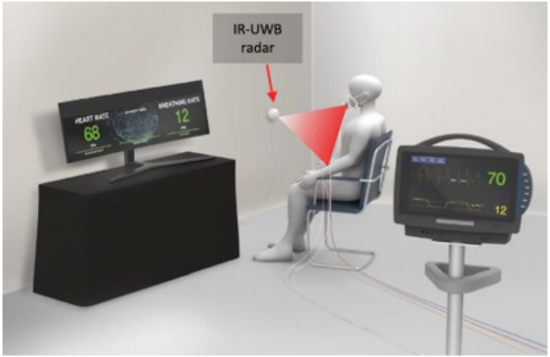
Overview

- Research Background and Use Case
- Bistatic Signal Model
- Signal Processing - Single Antenna
- Signal Processing - Multiple Antenna
- Experimental Setup and Result
- Open Dataset

Research Background

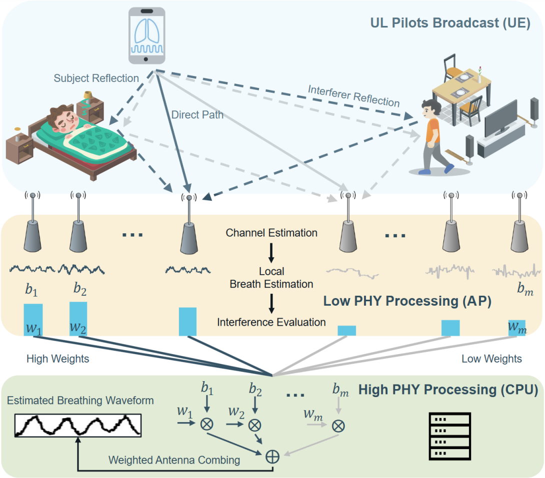
RF vital signs monitoring is non-intrusive, comfortable, and ubiquitous[1, 2]



Research Questions:

- How to achieve accurate sensing under interference from dynamic objects in the environment [3, 4]?
- How to effectively estimate the breathing with massive antennas (co-located massive MIMO and distributed cell-free MIMO) [5, 6, 7]?

Use Case Demo



- A subject is sleeping to be monitored
- An interferer is walking nearby of the subject
- APs determine the CSI using UL pilots

Parameters	Symbol	Value
Central carrier frequency	f_c	3.51 GHz
Wavelength	$\lambda = \frac{c}{f_c}$	8.56 cm
Bandwidth	B	18 MHz
No. subcarriers	K	100
Subcarriers spacing	Δf	180 KHz
No. receiver antennas	M	64
Antenna array spacing	d_s	0.07 m
No. APs	N	8
Sample rate	f_s	1000 Hz
Range resolution	$d_{\text{res}} = \frac{c}{B}$	16.67 m
Maximum unambiguous range	$d_{\text{max}} = \frac{c}{\Delta f}$	1667 m

Table: Parameter table

Evaluation Methods

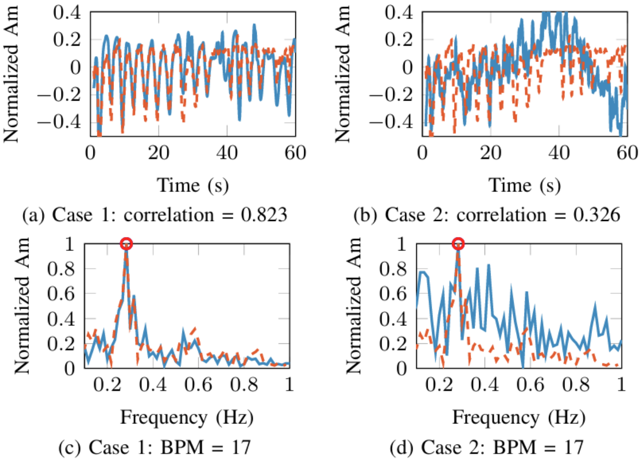
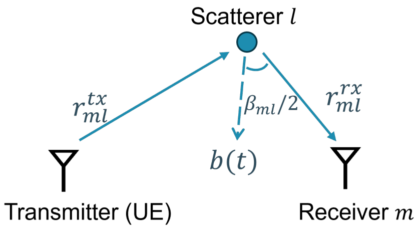


Figure: Comparison of time-domain and frequency-domain evaluation metrics. Correlation is more accurate than BPM.

Bistatic Signal Model: Breath in reflection



- $m = 1, ..., M$ is the rx antenna index
- $l = 1, ..., L$ is the multipath index
- $k = 1, ..., K$ is the subcarrier index
- β_{ml} is the bistatic angle
- $b(t)$ is the breathing at time t

The single-path channel is given by

$$x_{ml}(k,t) = \frac{\kappa}{r_{ml}^{(tx)}(t)\, r_{ml}^{(rx)}(t)} e^{-j2\pi f_k \frac{r_{ml}^{(tx)}(t)+r_{ml}^{(rx)}(t)}{c}}, \tag{1}$$

where $r_{ml}^{(tx)}(t)$ and $r_{ml}^{(rx)}(t)$ are the length of transmit (UE-scatterer) and receive(scatterer-Receiver) paths, respectively [6, 8].

$$r_{ml}^{(\mathrm{tx})}(t) = \underbrace{\breve{r}_{ml}^{(\mathrm{tx})}}_{\text{initial path length}} + \underbrace{b(t)\cos\left(\frac{\beta_{ml}}{2}\right)}_{\text{projected fluctuation}},$$

$$r_{ml}^{(\mathrm{rx})}(t) = \underbrace{\breve{r}_{ml}^{(\mathrm{rx})}}_{\text{initial path length}} + \underbrace{b(t)\cos\left(\frac{\beta_{ml}}{2}\right)}_{\text{projected fluctuation}}, \tag{2}$$

where κ is the antenna gain constant for all transmit-receive pairs, $\cos(\frac{\beta_{ml}}{2})$ is the bistatic projection term of the transmit and receive paths.

Channel Without Interference and Breathing Estimation

The channel consists of two sets of multipath components: multipath from the subject ($\boldsymbol{S}$) and multipath from the static environment, referred to as clutter ($\boldsymbol{C}$). The receiver noise is modeled via η_m. The channel between the UE and the m-th antenna is expressed as,

$$
\begin{aligned}
h_m(k,t) &= h_m^{\boldsymbol{S}}(k,t) + h_m^{\boldsymbol{C}}(k) + \eta_m(k,t) \\
&= \sum_{l \in \boldsymbol{S}}^{\boldsymbol{S}} x_{ml}(k,t) + \sum_{l \in \boldsymbol{C}}^{\boldsymbol{C}} x_{ml}(k) + \eta_m(k,t),
\end{aligned}
\tag{3}
$$

To extract the breathing signal from the channel, we first estimate the range profile via IDFT [9]

$$
h_m^{(d)}(d,t) = \frac{1}{K} \sum_{k=1}^{K} h_m(k,t) e^{j \frac{2\pi \Delta f}{c} kd}, \tag{4}
$$

where d are the range bins. Then we extract the interest range (e.g., the peak value $\hat{d}$) from the estimated range profile d. The estimated breathing signal, $\hat{b}_m(t)$, is found by calculating the phase of the signal at the range of interest as,

$$
\hat{b}_m(t) = \angle\left(h_m(\hat{d},t)\right). \tag{5}
$$

Channel without Interference

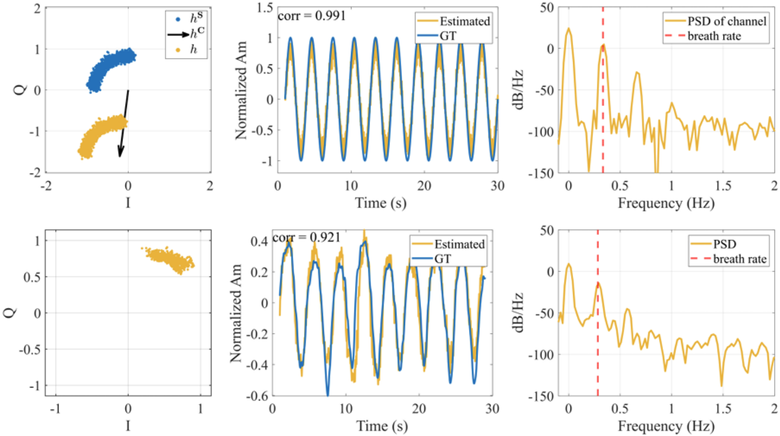


Figure: The PSD analysis of the breathing channel without interference.The Top set [simulated channel], the lower set [measured channel].

Channel with Interference

The channel contains three sets of multipath: multipath from the subject ($\boldsymbol{S}$), multipath from the interference ($\boldsymbol{I}$), and multipath from the static environment ($\boldsymbol{C}$) (including the LoS)

$$
\begin{aligned}
h_m(k,t) &= h_m^{\boldsymbol{S}}(k,t) + h_m^{\boldsymbol{I}}(k,t) + h_m^{\boldsymbol{C}}(k) + \eta_m(k,t) \\
&= \sum_{l \in \boldsymbol{S}}^{\boldsymbol{S}} x_{ml}(k,t) + \sum_{l \in \boldsymbol{I}}^{\boldsymbol{I}} x_{ml}(k,t) + \sum_{l \in \boldsymbol{C}}^{\boldsymbol{C}} x_{ml}(k) + \eta_m(k,t),
\end{aligned} \tag{6}
$$

How to enable reliable respiration sensing in practical deployments?

Near-range Domination Effect: When the sensing subject is close to the UE or AP, their breathing motion strongly modulates the channel, suppressing distant interference [4].

Channel with Interference

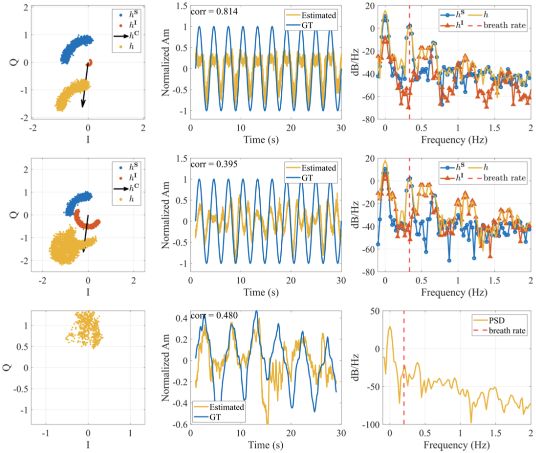


Figure: Top: interference close to the transceivers at 0.6m; Middle: interference far from the transceivers at 2m; Bottom: measured channel with strong interference.

Sensing-Signal-to-Interference Ratio (SSIR)

To quantify the impact of interference, we propose SSIR

$$\mathrm{SSIR} = 10\log_{10}\frac{E_{\mathrm{subj}}}{E_{\mathrm{interf}}}, \tag{7}$$

with

$$E_{\mathrm{subj}} = \int_{f\in F_{\mathrm{subj}}} S(f)df, \quad E_{\mathrm{interf}} = \int_{f\in F_{\mathrm{interf}}} S(f)df, \tag{8}$$

where $S(f)$ is the PSD of the channel, F_{subj} and F_{interf} represent the frequency bands of interest for the subject's respiration and the interference, respectively. The normal respiratory rate for an adult at rest is 10 to 30 BPM, i.e., 0.16 Hz - 0.5 Hz in the frequency domain. Based on this, we set the $F_{\mathrm{subj}} \in [0.02, 0.5]$ Hz, capturing low-frequency components associated with breathing, while the interference band is defined as $F_{\mathrm{interf}} \in [0.5, f_s/2]$

WAC: Multiple Antenna Signal Processing

We have estimated the breathing signal at each antenna $\hat{b}_m(t)$ separately. The M preprocessed estimates $\hat{b}_m(t)$ have the same underlying breathing signal $b(t)$.

$$\hat{\mathbf{b}}(t) = [\hat{b}_1(t)\, \hat{b}_2(t)\, \dots\, \hat{b}_M(t)]^T, \tag{9}$$

How to optimally combine the estimations $\hat{b}_m(t)$ from diverse APs to enhance the resilience to the interference? We proposed Weighted Antenna Combining (WAC). The antenna selection is given by

$$\mathcal{A}_\gamma = \begin{cases} \{m \mid \mathrm{SSIR}_m \geq \gamma\}, & \text{if } \exists m : \mathrm{SSIR}_m \geq \gamma, \\ \{m \mid \mathrm{SSIR}_m \in \text{top-}K\%\}, & \text{otherwise}, \end{cases} \tag{10}$$

where $\mathcal{A}_\gamma$ denotes the selected antenna subset, and K serving as a tunable parameter ($K = 5$ in our implementation). The weighting is defined as

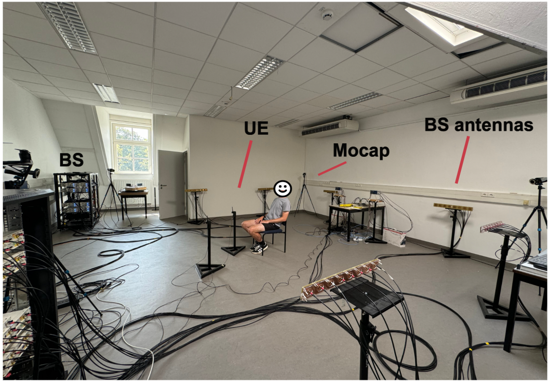
$$w_m = \begin{cases} \dfrac{\mathrm{SSIR}_m}{\sum_{j \in \mathcal{A}_\gamma} \mathrm{SSIR}_j}, & m \in \mathcal{A}_\gamma, \\ 0, & m \notin \mathcal{A}_\gamma. \end{cases} \tag{11}$$

The final respiration estimate is then expressed as

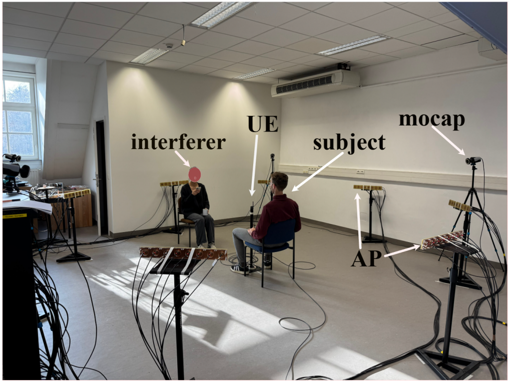
$$\hat{b}(t) = \sum_{m=1}^{M} w_m \, \hat{b}_m(t). \tag{12}$$

Experimental Setup

without interferer

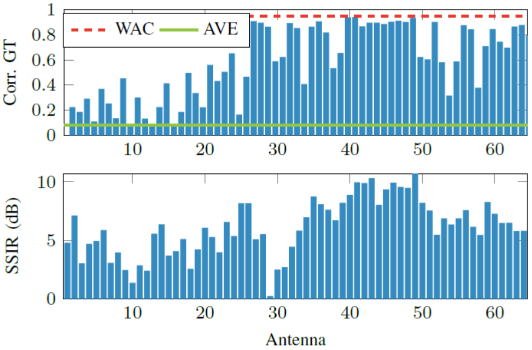


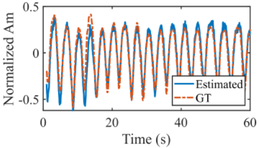
with interferer



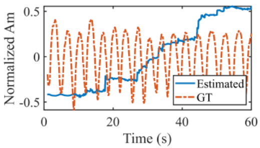
Example Result 1

Interference is close to the array 2 (antenna 9-16)

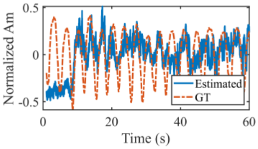




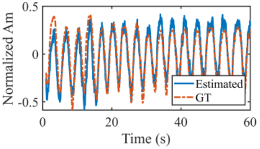
(b) WAC combining, corr = 0.948.



(c) AVE combining, corr = 0.079.



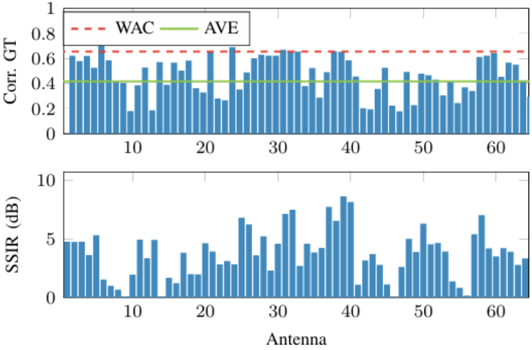
(d) The 1st antenna: corr = 0.223.

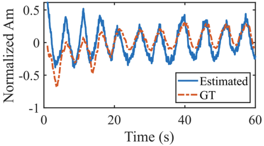


(e) The 26th antenna, corr = 0.910.

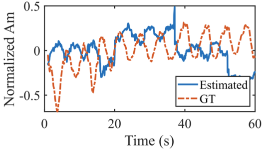
Example Result 2

Interference is close to the array 6 (antenna 41-48)

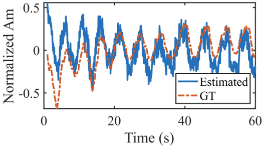




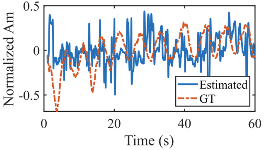
(b) WAC combining, corr = 0.655.



(c) AVE combining, corr = 0.417.

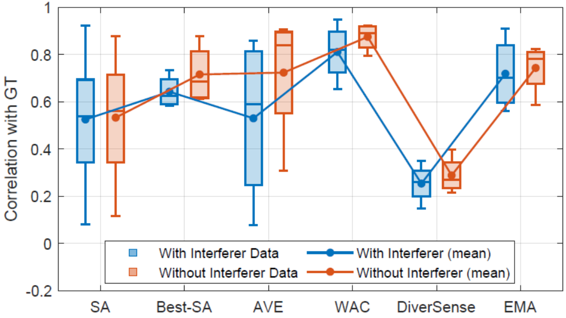


(d) The 28th antenna, corr = 0.621.



(e) The 42th antenna, corr = 0.194.

Benchmark Result



Method	Mean (w)	Mean (wo)	Std (w)	Std (wo)
SA	0.53	0.53	0.21	0.21
Best-SA	0.64	0.72	**0.07**	0.13
AVE	0.53	0.72	0.36	0.28
WAC	**0.81**	**0.88**	0.12	**0.06**
DiverSense [5]	0.25	0.29	0.08	0.08
EMA [7]	0.72	0.74	0.15	0.11

Co-Located Massive MIMO vs. Cell-Free Massive MIMO

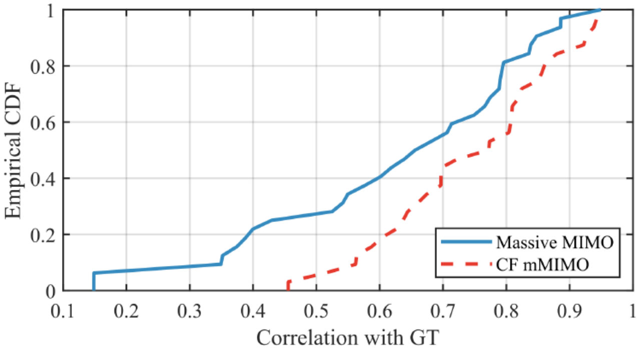
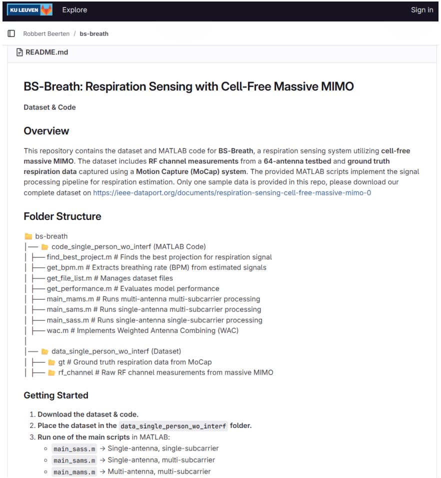


Figure: Empirical CDF of the correlation between the estimated and ground-truth respiration signals using the WAC method under co-located Massive MIMO and distributed CF-mMIMO architectures. 80% of CF-mMIMO estimations achieve correlation above 0.6, compared to only 60% for the co-located mMIMO setup.

Open Dataset for Data-driven RF Sensing



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References

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Thank you! Questions?