Accurate Carrier Frequency Offset Estimation in Time-Reversal Communications

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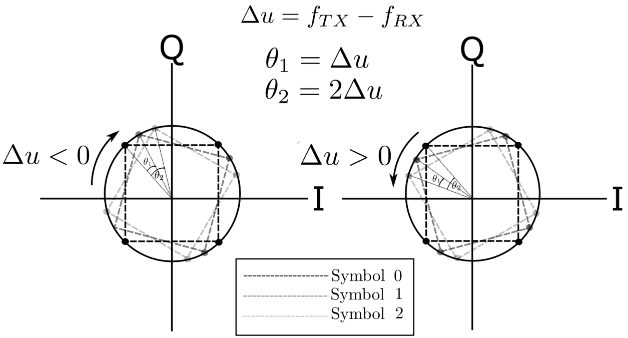
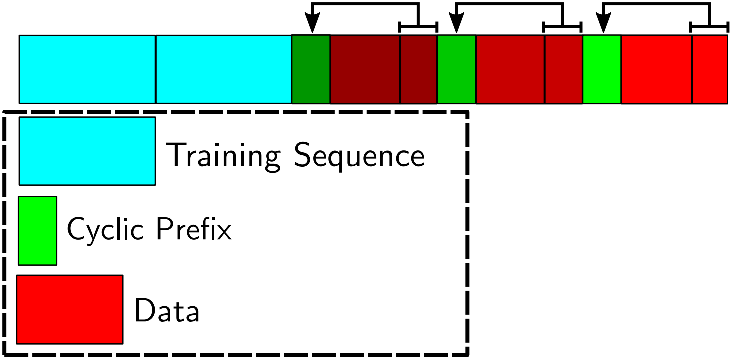
Outline

Introduction to Carrier Frequency Offset (CFO)

- CFO exists due to the misalignment between the oscillators at the transmitter (TX) and receiver (RX) for up-conversion and down-conversion respectively.
- CFO introduces a linear phase shift in proportional to time, which degrades the performance of decoding phase-modulated symbols.

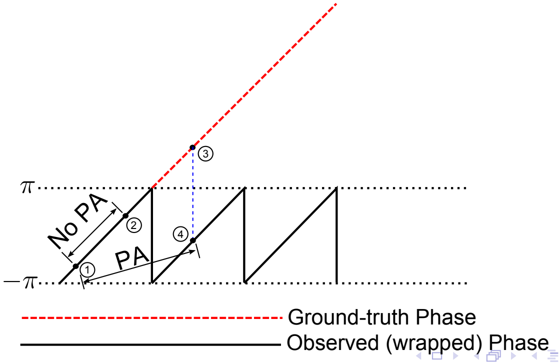


Most methods in literature use (a) cyclic prefix (b) training sequence to obtain an estimated CFO.

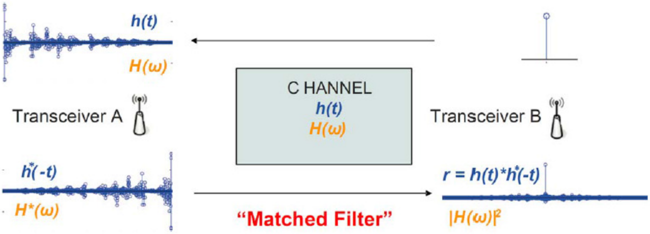


Potential Problems in CFO Estimators

- Training sequence has to be very long for wideband transmissions as it requires highly accurate CFO estimation.
- The performance using cyclic prefix could be not good enough since the cyclic prefix cannot be reused.
- The phase wrapping might occur due to inappropriate choice of parameters



Introduction to Time-Reversal (TR) Communications

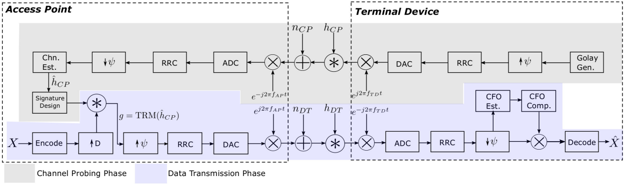


The TR communication is based upon two observations:

Reciprocity The channel impulse response (CIR) between the forward and backward link are highly correlated.

Stationarity The CIR remains highly correlated for at least one cycle of TR transmission.

Introduction to TR Communications, Cont.



One cycle of TR transmission consists of **two phases**

Channel Probing (CP) Terminal device (TD) sends a Golay sequence to the access point (AP) to facilitate CIR estimation. AP generates the *TR signature* g.

Data Transmission (DT) AP convolves the transmitted signal with g and sends to the receiver. The receiver detects the correct symbol timing, performs CFO estimation and compensation, then decodes the symbols using a Viterbi decoder.

System Model: CP Phase

Signal model for CP Phase

$$Y_{CP}[k] = (G * h)[k] \exp(j2\pi \Delta f T_s \psi k) + n_{CP}[k], \quad (1)$$

where $\{h[\ell]\}_{\ell=0,1,\cdots,L-1}$ is the CIR between the AP and the TD, $\Delta f = f_{AP} - f_{TD}$ is the CFO, i.e., the difference between the LO frequencies at the TD and that at the AP, T_s is the sampling interval before decimation, ψ is the upsampling ratio, and $n_{CP}[k] \sim \mathcal{CN}(0, \sigma^2)$.

CIR Estimation

$$\begin{aligned}\hat{h}[\ell] &= \frac{1}{L_{GS}} \sum_{\ell'=0}^{L-1} h[\ell'] \sum_{m=0}^{L_{GS}-1} G[m]G[\ell + L_{GS} - 1 - \ell' - m]e^{j2\pi\Delta f T_s \psi(\ell + L_{GS} - 1 - m)} + n'[\ell + L_{GS} - 1] \\ &\approx h[\ell] \exp(j\Delta\omega\psi\ell) \exp(j\theta) + n'[\ell + L_{GS} - 1] \quad (2)\end{aligned}$$

where $n'[k] = \frac{1}{L_{GS}}(G * n)[k]$ is the average of many zero mean Gaussian noises and thus can be ignored. $\Delta\omega = 2\pi\Delta f T_s$ is the normalized CFO, and $\theta = 2\pi\Delta f T_s \psi(L_{GS} - 1)$ is the common phase error in estimating $\hat{h}[\ell]$.

System Model: DT Phase

Signal model for DT Phase

$$Y[k] = S[k]\exp(-j\Delta\omega D\psi k) + n_{DT}[k]$$

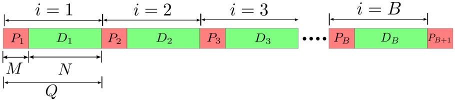
$$S[k] = (h*g)[L-1]\underbrace{X[k-L^\star]}_{\text{intended symbol}} + \sum_{\substack{l=0,\\ l\neq L^\star}}^{(2L-2)/D} (h*g)[Dl]X[k-l] \qquad (3)$$

$$g[k] = \frac{h^*[L-1-k]\exp(-j\Delta\omega(L-1-k)\psi)\exp(-j\theta)}{\sqrt{\sum_{\ell=0}^{L-1}|h[\ell]|^2}}, \qquad (4)$$

where $L^\star = (L-1)/D$, $X[k]$ is the transmitted symbols, D is the backoff rate, $n_{DT}[k]$ is the zero-mean complex Gaussian noise with variance σ^2, and $g[k]$ is the signature. In absence of CFO, $(h*g)(L-1) = \sqrt{\sum_{\ell=0}^{L-1}|h[\ell]|^2}$ which is the *TR focusing gain*.

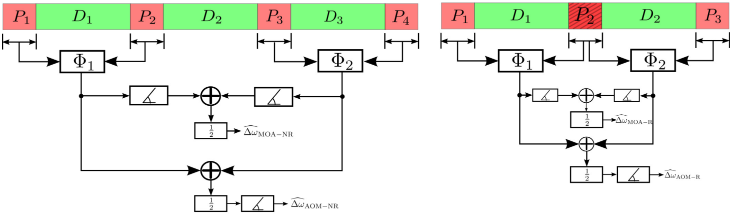
Proposed CFO Estimators

To estimate CFO, we *sandwitch* data blocks D_i between pilot blocks P_i and P_{i+1}.



In absence of noise, we have

$$\Phi[k, k+Q] = Y[k]Y^*[k+Q] \propto \exp(\Delta\omega D\psi Q) \tag{5}$$



(a) (b)

Proposed CFO Estimators

The proposed estimators are summarized into

$$\widehat{\Delta\omega} = \begin{cases} \frac{\measuredangle\left[\frac{1}{MB}\sum_{i\in\mathbb{B}}\sum_{k\in\mathbb{P}}\Phi[2Qi-2Q+k,2Qi-Q+k]\right]}{Q\psi D}, & \text{AOM-NR} \\ \frac{\sum_{i\in\mathbb{B}}\measuredangle\left[\frac{1}{M}\sum_{k\in\mathbb{P}}\Phi[2Qi-2Q+k,2Qi-Q+k]\right]}{BQ\psi D}, & \text{MOA-NR} \\ \frac{\measuredangle\left[\frac{1}{MB}\sum_{i\in\mathbb{B}'}\sum_{k\in\mathbb{P}}\Phi[Qi-Q+k,Qi+k]\right]}{Q\psi D}, & \text{AOM-R} \\ \frac{\sum_{i\in\mathbb{B}'}\measuredangle\left[\frac{1}{M}\sum_{k\in\mathbb{P}}\Phi[Qi-Q+k,Qi+k]\right]}{BQ\psi D}, & \text{MOA-R} \end{cases} \quad (6)$$

where $\mathbb{B}$ stands for the set $[1, 2, \ldots, B]$, $\mathbb{B}'$ for $[1, 2, \ldots, B+1]$, **AOM** for Angle-of-Mean, **MOA** for Mean-of-Angle, **R** for reusing, and **NR** for non-reusing. They differ in (i) whether they reuse the same pilot block for estimation (ii) whether they formulate angles then take average, or average Φ then take angle.

Avoiding Phase Wrapping

To avoid phase wrapping, Q should be chosen carefully according to

$$Q < \lambda Q^{+} = \frac{\lambda \pi}{|\Delta\omega| D\psi}, \lambda \in (0, 1] \tag{7}$$

where $\lambda \in (0, 1)$.

Performance Analysis: No Phase Wrapping

$$\mathrm{Bias}(\widehat{\Delta\omega}) \approx 0, \tag{8}$$

and the MSE performances are given by

$$\mathrm{MSE}(\widehat{\Delta\omega}) = \begin{cases} F\left(\frac{1}{MB}\left[\sigma^2 + \frac{\sigma^4}{2}\right]\right), & \text{AOM-NR} \\ F\left(\frac{1}{M}\left[\sigma^2 + \frac{\sigma^4}{2}\right]\right)/B, & \text{MOA-NR} \\ F\left(\frac{1}{MB}\left[\frac{\sigma^2}{B} + \frac{\sigma^4}{2}\right]\right), & \text{AOM-R} \\ V(M, \sigma^2), & \text{MOA-R} \end{cases} \tag{9}$$

where $F(x)$, $V(x,y)$, $U(x,y)$ are shown as

$$F(x) = \frac{\int_0^{\frac{\pi}{2}} \frac{2y^2}{\sqrt{2\pi x}} \exp\left(-\frac{\tan^2(y)}{2x}\right) \frac{1}{\cos^2(y)} dy}{Q^2\psi^2 D^2}, \tag{10}$$

$$V(x,y) = \frac{F(y)}{B} + \frac{2(B-1)}{B^2 Q^2 \psi^2 D^2} U(x,y), \tag{11}$$

$$U(x,y) = \int_{u=-\infty}^{\infty}\int_{v=-\infty}^{\infty} \arctan(u)\arctan(v) \frac{x}{2\pi\left(y+\frac{y^2}{2}\right)\sqrt{1-\frac{1}{(2+y)^2}}} \exp\left(-\frac{\left[\frac{x\left(u^2+v^2+\frac{2uv}{2+y}\right)}{y+\frac{y^2}{2}}\right]}{2\left(1-\frac{1}{(2+y)^2}\right)}\right) dudv. \tag{12}$$

Performance Analysis: When Phase Wrapping Occurs

$$\mathrm{Bias}(\widehat{\Delta\omega}) = \pm\frac{2k\pi}{Q\psi D}, k \in \mathbb{Z}, k \neq 0, \tag{13}$$

$$\mathrm{MSE}(\widehat{\Delta\omega}) = \mathrm{MSE}(\widehat{\Delta\omega}) + \frac{4k^2\pi^2}{Q^2\psi^2 D^2}, k \in \mathbb{Z}, k \neq 0, \tag{14}$$

where $\widehat{\Delta\omega}$ is the estimated CFO with phase wrapping, and $\mathbb{Z}$ stands for the set of integers.

Experiment Results: Setups

We use a pair of TR boards to evaluate the performances of the proposed CFO estimator. We perform two tests: (a) over the cable transmission (b) over the air transmission.

Parameter	Notation	Value
Pilot Block Length	M	32
Transmission Block Length	Q	$[288, 608, 1248, 1888, 2528]$
# of Frames	B	$[39, 19, 9, 4, 1]$
Backoff Rate	D	4
Decimation Ratio	ψ	4
Baseband Sampling Frequency	f_b	125MHz
Baseband Sampling Interval	T_b	8ns
Carrier Frequency	f_c	5.8GHz
# of Trials	U	500

Table: Configuration of Parameters in Experiment

Experiment Results

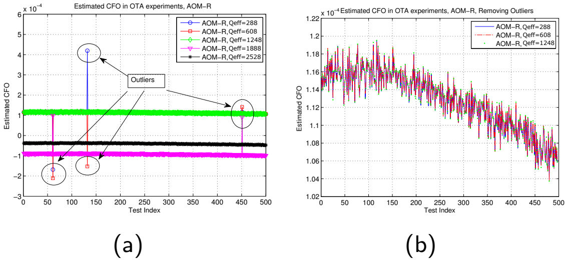


Figure: Experimental Results of AOM-R estimator, OTA Test, Basic Signature: (a) with Outliers (b) Without Outliers.

Experiment Results

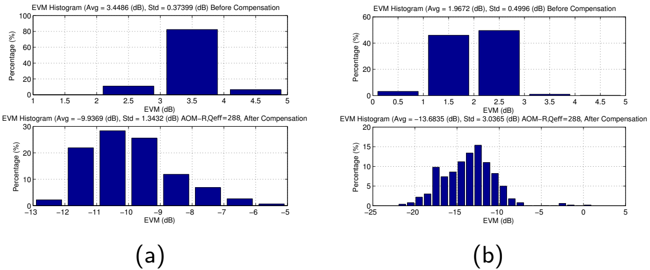


Figure: Effect of CFO Compensation on EVM: (a) OTA (b) OTC.

Experiment Results

Q_{eff}	B_{eff}	AOM-R (dB)	AOM-NR (dB)	$\Delta(\text{AOM})(dB)$
288	39	-9.94	-9.72	0.22
608	19	-9.95	-9.56	0.39
1248	9	-9.95	-9.89	0.06
Q_{eff}	B_{eff}	MOA-R	MOA-NR	$\Delta(\text{MOA})$
288	39	-9.94	-9.72	0.22
608	19	-9.97	-9.59	0.38
1248	9	-9.97	-9.92	0.05

Table: EVM Performance of OTA

Q_{eff}	B_{eff}	AOM-R (dB)	AOM-NR (dB)	$\Delta(\text{AOM})(dB)$
288	39	-13.68	-13.31	0.37
608	19	-13.70	-13.25	0.45
1248	9	-13.71	-13.66	0.05
Q_{eff}	B_{eff}	MOA-R	MOA-NR	$\Delta(\text{MOA})$
288	39	-13.72	-13.35	0.37
608	19	-13.72	-13.27	0.45
1248	9	-13.72	-13.68	0.04

Table: EVM Performance of OTC

Conclusion

- We analyze the effect of CFO for both the channel probing and data transmission phases.
- We propose four highly accurate schemes to estimate the tiny CFO for time-reversal systems with assistance from time-domain pilot.
- Theoretical analyses are rigorously derived together with the conditions to avoid phase wrapping.
- Extensive experimental results in real environment validate the superiority of the proposed schemes.

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Thanks