Discussion on own Works

Channel Estimation of MB-OFDM UWB Systems in Interfering Environments

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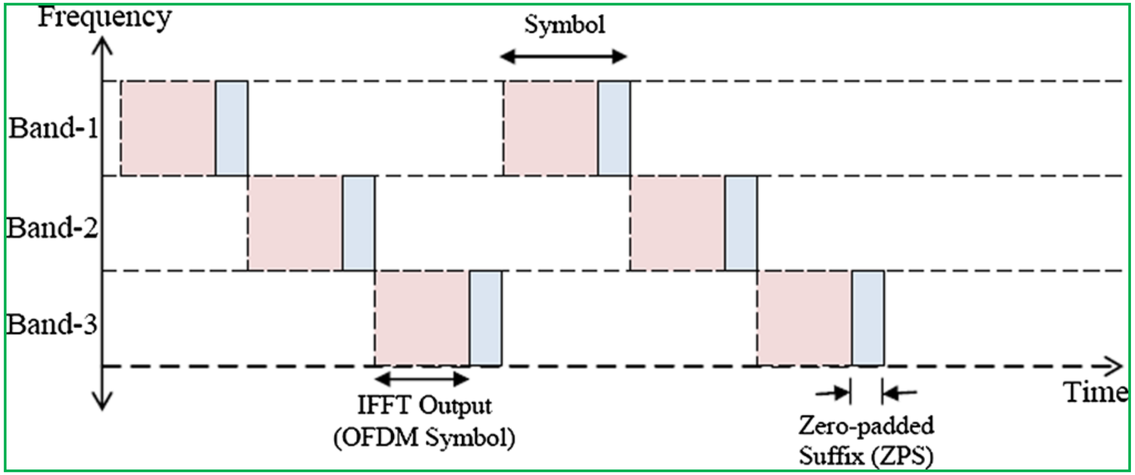
- MB-OFDM PHY in ECMA-368
- Channel estimation in MAI and NBI environments
- Channel estimation with unknown NBI
- Iterative interpolation & weighted channel estimation

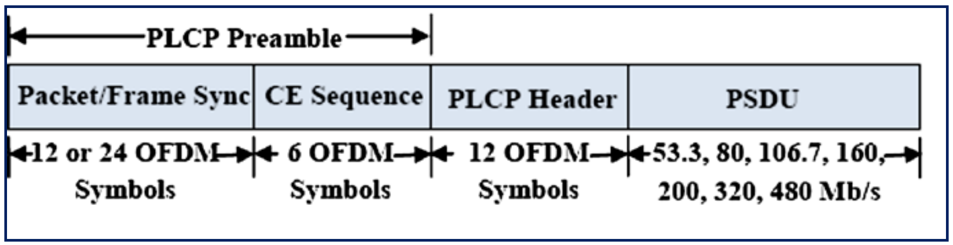
Islam, and Kwak

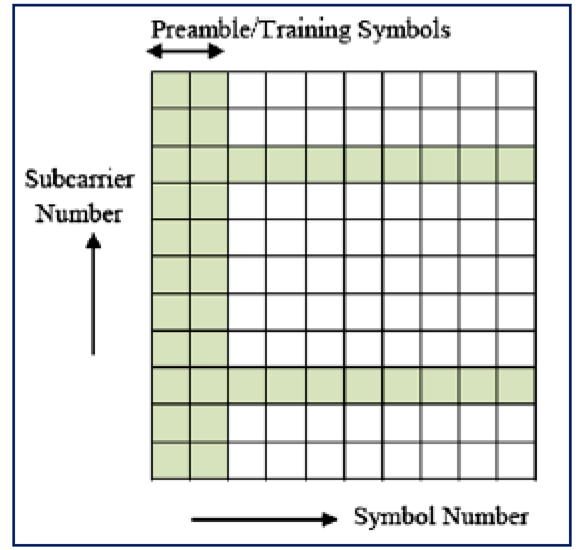
Realization of RF Tx Signal using 3 Bands



MB-OFDM Approch; 14 Sub-Bands; 528 MHz BW; TFC; ZPS

PLCP Packet Data Unit (PPDU)

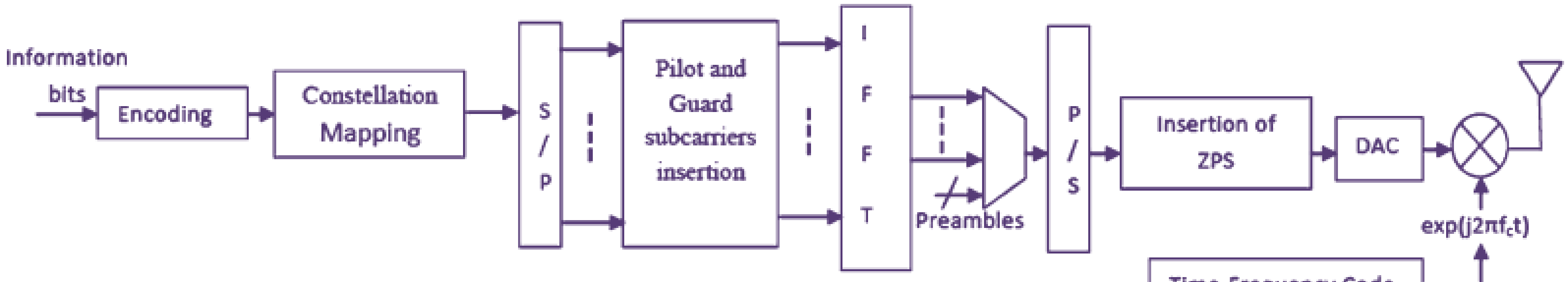




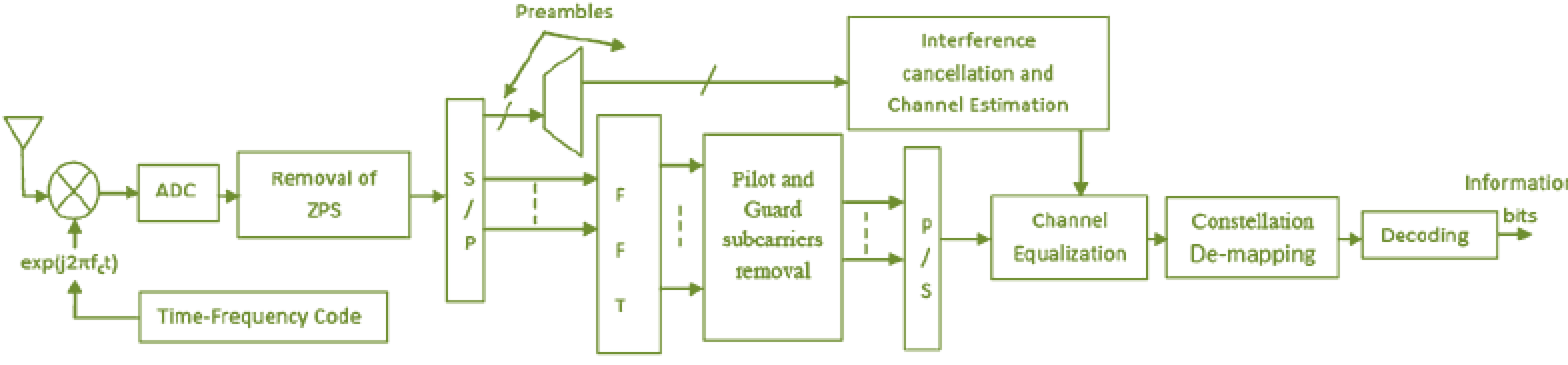
PLCP= Packet Layer Convergence Protocol

PSDU= PLCP Service Data Unit

SISO Architecture



(a) Transmitter



(b) Receiver

DFT Properties

- **Principle:** Subcarrier/Sample Nulling provides TR/FR property

$$x_{even}[n+M] = \frac{1}{2M}\sum_{k'=0}^{M-1} X[2k'] \times e^{\frac{j2\pi(2k')(n+M)}{2M}}$$

$$= \frac{1}{2M}\sum_{k'}^{M-1} X[2k'] \times e^{\frac{j2\pi(2k')(n)}{2M}} \times e^{j2\pi k'}$$

$$= x_{even}[n], \quad n = 0, 1, \ldots, M-1.$$

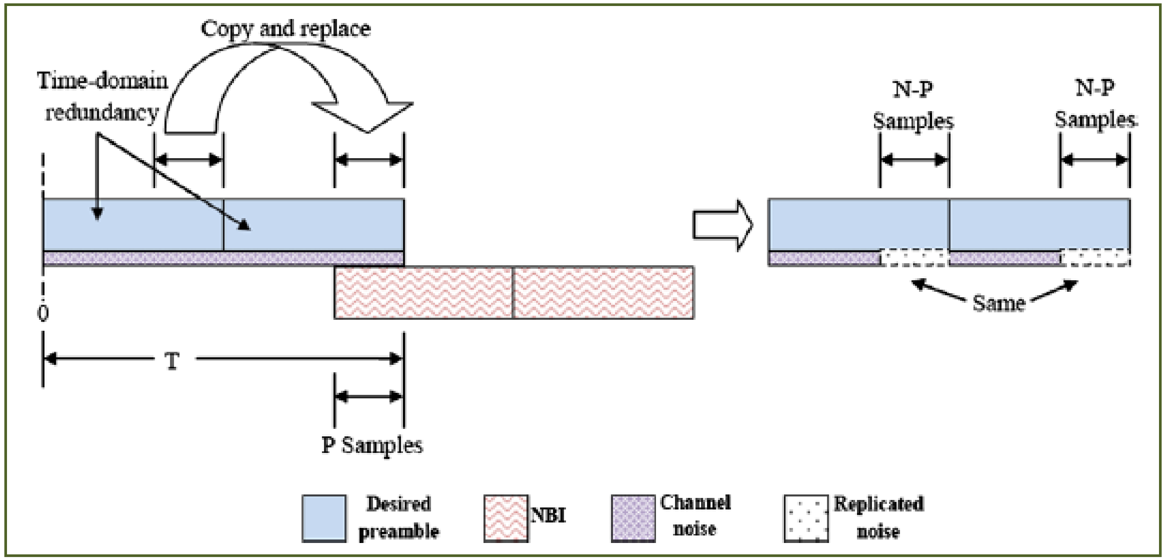
$$X_{even}[k+M] = \sum_{n'=0}^{M-1} x[2n'] \times e^{\frac{j2\pi(2n')(k+M)}{2M}}$$

$$= \sum_{n'}^{M-1} x[2n'] \times e^{\frac{j2\pi(2n')k}{2M}} \times e^{j2\pi n'}$$

$$= X_{even}[k], \quad k = 0,1,\ldots,M-1,$$

MAI Rejection

Multiple Access Interference



Adaptive Select and Replace (ASR) Scheme

NBI Position

$$x[n] = x[n+N], \quad n = 0, \ldots, N_{ZPS} - 1$$

$$y[n] = y[n+N], \quad n = L-1, L, \ldots, N_{ZPS} - 1$$

$$q[n] \triangleq y[n+N] - y[n] = \alpha e^{j\emptyset}\left(e^{j\omega N} - 1\right)e^{j\omega n} + w[n],$$

$$\bar{q}[n] = [\; q[n] \;\; q[n+1] \; \ldots \; q[n+P-1] \;]^T = \alpha e^{j\emptyset_n}\left(e^{j\omega N} - 1\right)\sqrt{P}\bar{s} + \bar{w}[n],$$

$$\boldsymbol{C}_{\bar{q}} \triangleq E\{\bar{q}[n](\bar{q}[n])^H\},$$

$$\boldsymbol{C}_{\bar{q}} = \alpha^2 P\left|e^{j\omega N} - 1\right|^2 \bar{s}\bar{s}^H + \sigma_w^2 \boldsymbol{I},$$

$$\boldsymbol{C}_{\bar{q}} = (\bar{u}_{\bar{s}} \;\; \bar{U}_{\bar{w}}) \begin{pmatrix} \lambda + \sigma_w^2 & 0 & \ldots & 0 \\ 0 & \sigma_w^2 & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \ldots & 0 & \sigma_w^2 \end{pmatrix} \begin{pmatrix} \bar{u}_{\bar{s}}{}^H \\ \bar{U}_{\bar{w}}{}^H \end{pmatrix},$$

$$\widehat{\boldsymbol{C}}_{\bar{q}} = \frac{1}{L_2} \sum_{n=L-1}^{N_{ZPS}-1} \bar{q}[n](\bar{q}[n])^H,$$

$$\hat{\sigma}_w^2 = \frac{1}{P-1} \sum_{i=1}^{P-1} \rho_i$$

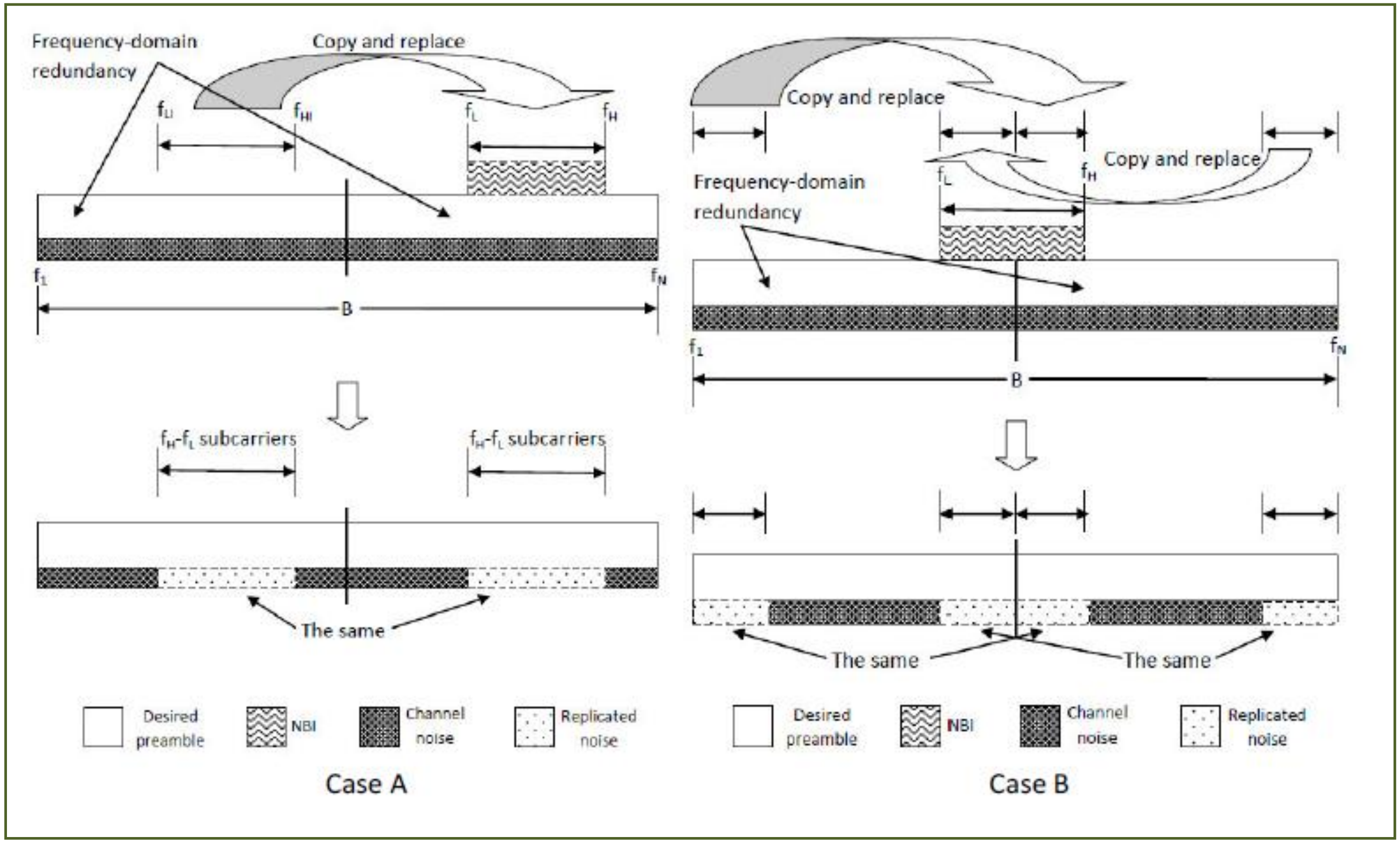
$$\hat{\bar{s}} = [\hat{s}_0 \quad \hat{s}_1 \quad \ldots \quad \hat{s}_{P-1}]^T,$$

$$\hat{\omega} = \frac{1}{P-1} \sum_{n=0}^{P-2} Im\left\{ln\left(\frac{\hat{s}_{n+1}}{\hat{s}_n}\right)\right\},$$

NBI Rejection

Narrowband Interference

Adaptive Band Select and Replace (ABSR) Scheme



Channel Filtering and Windowing

Power Delay profile

$$P_z = \sum_{i=1}^{2} \left| \sum_{j=z}^{z+N} y_{i,j} \times x_{i,j-z} \right|^2$$

Profile Vector

$$g_z = \begin{cases} 1, & P_z \geq \frac{1}{K} \max\{P_z\}_0^{Z-1} \\ 0, & P_z < \frac{1}{K} \max\{P_z\}_0^{Z-1} \end{cases}$$

Filtered

$$\hat{\hat{H}}_{Filtered} = G_z \otimes \hat{\hat{H}},$$

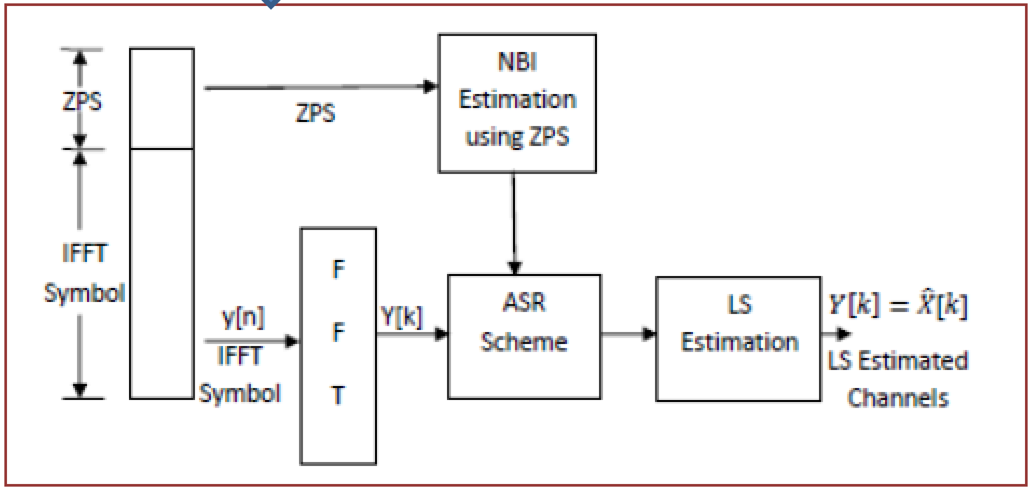
M-point IDFT

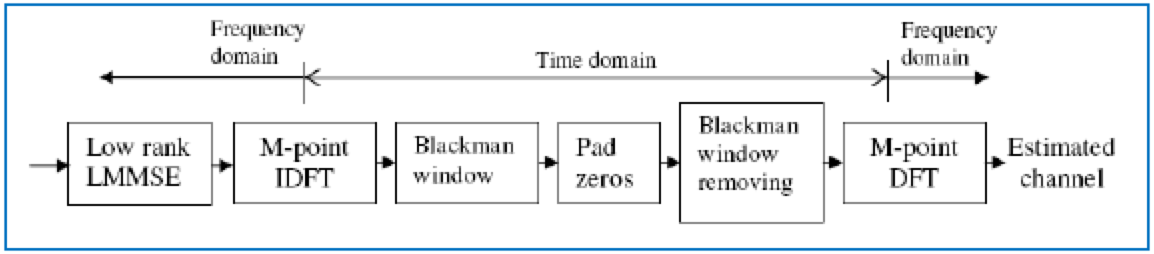
$$h_{lrLMMSE}(i) = \frac{1}{M} \sum_{k=0}^{M-1} \hat{H}_{lrLMMSE}(k) e^{j2\pi \frac{ki}{M}}$$

Blackman Windowing

$$d(i) = 0.42 - 0.5 \cos\left(\frac{2\pi i}{M-1}\right) + 0.08 cos\left(\frac{4\pi i}{M-1}\right), \quad i = 0, 1, \dots, M-1$$

Refined Channel and Blackman Windowing





System and Signal Model

- **Principle:** the interference power on each subcarrier is treated as a nuisance parameter which is averaged out from the corresponding likelihood function

$$H(n) = \sum_{l=1}^{L} h(l) e^{-j2\pi n(l-1)/N} \qquad -N_\alpha \le n \le N_\alpha$$

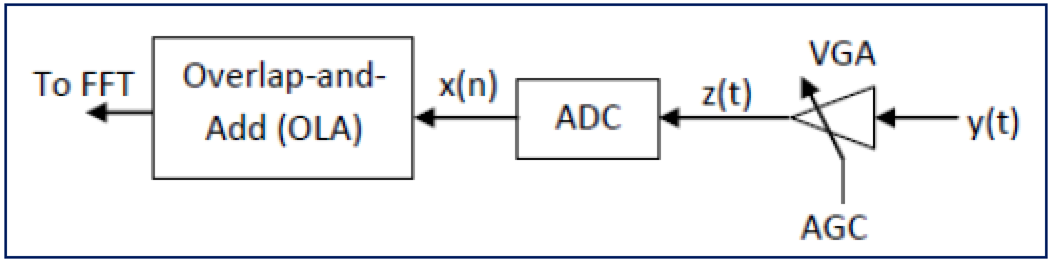
$$Y(n,k) = s(n,k)H(n) + w(n,k) \qquad -N_\alpha \le n \le N_\alpha$$

$$\boldsymbol{Y}(k) = \boldsymbol{S}(k)\boldsymbol{F}\boldsymbol{h} + \boldsymbol{w}(k) \quad \rightarrow \quad \sigma^2(n) = \sigma_w^2 + \sigma_I^2(n)$$

$$\boldsymbol{S}(k) = diag\{s(n,k); 1 \le n \le N\}$$

$$\boldsymbol{H} = \boldsymbol{F}\boldsymbol{h} \quad \Rightarrow \quad \widehat{\boldsymbol{H}} = \boldsymbol{F}\widehat{\boldsymbol{h}}$$

Impacts of NBI on Channel Estimation



The ADC output is given by

$$x(n) = G\left(\sum_{l=0}^{L-1} s(n-l)h(l) + w(n)\right) + q(n)$$

$$SINR = \frac{\bar{\sigma}_c^2}{(\bar{\sigma}_c^2 + \sigma^2(n))/\gamma_q + \sigma^2(n)}$$

$$\begin{aligned} \boldsymbol{J}_{hh} &= E_{\boldsymbol{Y}(k)|\boldsymbol{h}}\left(\frac{\partial \ln p(\boldsymbol{Y}(k)|\boldsymbol{h})}{\partial \boldsymbol{h}^*}\right)\left(\frac{\partial \ln p(\boldsymbol{Y}(k)|\boldsymbol{h})}{\partial \boldsymbol{h}^*}\right)^H \\ &= \frac{1}{\boldsymbol{\sigma}^4} E_{\boldsymbol{Y}(k)|\boldsymbol{h}}\left[\frac{\partial}{\partial h^*}(\boldsymbol{Y}(k)-\boldsymbol{B}\boldsymbol{h})^{\boldsymbol{H}}(\boldsymbol{Y}(k)-\boldsymbol{B}\boldsymbol{h})\right]\left[\frac{\partial}{\partial h^*}(\boldsymbol{Y}(k)-\boldsymbol{B}\boldsymbol{h})^{\boldsymbol{H}}(\boldsymbol{Y}(k)-\boldsymbol{B}\boldsymbol{h})\right]^H \\ &= \frac{1}{\boldsymbol{\sigma}^2}\boldsymbol{B}^H\boldsymbol{B} \end{aligned} \quad (13)$$

Impacts of NBI on Channel Estimation

Thus, using (10), the variance of the estimator is bounded as

$$E\left[\|\hat{\boldsymbol{h}} - E(\hat{\boldsymbol{h}})\|^2\right] = E\left[\|\hat{\boldsymbol{h}} - h\|^2\right]$$

$$= tr[\boldsymbol{R}_{\tilde{h}}] \geq \frac{\boldsymbol{\sigma}^2}{\sigma_s^2}[tr\{(\boldsymbol{F}^H\boldsymbol{S}(k)^H\boldsymbol{S}(k)\boldsymbol{F})^{-1}\}]$$

$$\geq \frac{1}{SINR}[tr\{(\boldsymbol{F}^H\boldsymbol{S}(k)^H\boldsymbol{S}(k)\boldsymbol{F})^{-1}\}]$$

$$= \frac{(\bar{\sigma}_c^2 + \sigma^2(n))/\gamma_q + \sigma^2(n)}{\bar{\sigma}_c^2}[tr\{(\boldsymbol{F}^H\boldsymbol{S}(k)^H\boldsymbol{S}(k)\boldsymbol{F})^{-1}\}]$$

$$= \frac{(\bar{\sigma}_c^2 + \sigma_w^2 + \sigma_I^2(n))/\gamma_q + \sigma_w^2 + \sigma_I^2(n)}{\bar{\sigma}_c^2}[tr\{(\boldsymbol{F}^H\boldsymbol{S}(k)^H\boldsymbol{S}(k)\boldsymbol{F})^{-1}\}] \quad (15)$$

- it is evident that as the NBI power increases, the variance of the estimator increases and thus the estimator performance gets worse

ML Channel Estimation

Given the unknown parameters $(\boldsymbol{h}, \boldsymbol{\sigma}^2)$, vectors $\{\boldsymbol{Y}(k)\}$ in (4) are statistically independent and Gaussian distributed with mean $\boldsymbol{S}(k)\boldsymbol{F}\boldsymbol{h}$ and covariance matrix $\boldsymbol{C}$. Therefore, their joint pdf gets the form

$$p(\boldsymbol{Y}|\breve{\boldsymbol{h}}, \breve{\boldsymbol{\sigma}}^2) = \prod_{n=1}^{N} \frac{1}{[\pi\breve{\boldsymbol{\sigma}}^2(n)]^2} exp\left\{-\frac{1}{\breve{\boldsymbol{\sigma}}^2(n)} \sum_{k=1}^{2} \left|Z_k(n, \breve{\boldsymbol{h}})\right|^2\right\} \quad (16)$$

where

$$Z_k(n, \breve{\boldsymbol{h}}) = Y(n,k) - s(n,k) \sum_{l=1}^{L} \breve{h}(l) e^{\frac{j2\pi n(l-1)}{N}} \quad (17)$$

$$p(\sigma^2; \alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} (\sigma^2)^{-\alpha-1} \exp\left(-\frac{\beta}{\sigma^2}\right) \quad (18)$$

Taking the value of shape parameter $\alpha = 1$, (18) becomes

$$p(\sigma^2) = \frac{\beta}{\sigma^4} \exp\left(-\frac{\beta}{\sigma^2}\right) \quad (19)$$

where the scale parameter β is thought as a suitable design parameter.

ML Channel Estimation

The marginal log-likelihood function (LLF) is thus given by

$$ln[p(\boldsymbol{Y}|\breve{\boldsymbol{h}})] = Nln\left(\beta\frac{2}{\pi^2}\right) - 3\sum_{n=1}^{N} ln\left[\beta + \sum_{k=1}^{2}\left|Z_k(n,\breve{\boldsymbol{h}})\right|^2\right] \qquad (22)$$

$$\Phi(\breve{\boldsymbol{h}}) = -\sum_{n=1}^{N} ln\left[\beta + \sum_{k=1}^{2}\left|Z_k(n,\breve{\boldsymbol{h}})\right|^2\right]$$

Letting $\psi(\breve{\boldsymbol{h}}) = -\Phi(\breve{\boldsymbol{h}})$, results in

$$\psi(\breve{\boldsymbol{h}}) = \sum_{n=1}^{N} ln\left[\beta + \sum_{k=1}^{2}\left|Z_k(n,\breve{\boldsymbol{h}})\right|^2\right]$$

$$\widehat{\boldsymbol{h}}_{MLE} = arg\min_{\boldsymbol{h}}\{\psi(\breve{\boldsymbol{h}})\}$$

ML Channel Estimation

- As indicated by (26), the channel estimation problem becomes a minimization problem. However, it requires a complete search over the multidimensional domain spanned by . Accordingly, optimization algorithm should be simple enough to produce fast convergence with low computational complexity. Quasi-Newton methods, like steepest descent, require only the gradient of objective function to be supplied at each iterate

$$\widehat{\boldsymbol{h}}_{i+1} = \widehat{\boldsymbol{h}}_i + \Delta\widehat{\boldsymbol{h}}_i$$

where the Newton step $\Delta\widehat{\boldsymbol{h}}_i$ is provided as

$$\Delta\widehat{\boldsymbol{h}}_i = -\alpha_i \boldsymbol{B}_i^{-1} \nabla\psi(\widetilde{\boldsymbol{h}})\big|_{\widehat{\boldsymbol{h}}_i}$$

ML Channel Estimation

$$B_{i+1} = B_i + \frac{\Theta_i \Theta_i^T}{\Theta_i^T \Delta\hat{h}_i} - \frac{B_i \Delta\hat{h}_i (B_i \Delta\hat{h}_i)^T}{\Delta\hat{h}_i^T B_k \Delta\hat{h}_i} \tag{29}$$

where Θ_i represents the change in gradient of $\psi(\breve{h})$ expressed as

$$\Theta_i = \nabla\psi(\breve{h})|_{\hat{h}_{i+1}} - \nabla\psi(\breve{h})|_{\hat{h}_i} \tag{30}$$

As required in (28), B_{i+1}^{-1} takes the form

$$B_{i+1}^{-1} = \left(I - \frac{\Theta_i \Delta\hat{h}_i^T}{\Theta_i^T \Delta\hat{h}_i}\right)^T B_i^{-1} \left(I - \frac{\Theta_i \Delta\hat{h}_i^T}{\Theta_i^T \Delta\hat{h}_i}\right) + \frac{\Delta\hat{h}_i \Delta\hat{h}_i^T}{\Theta_i^T \Delta\hat{h}_i} \tag{31}$$

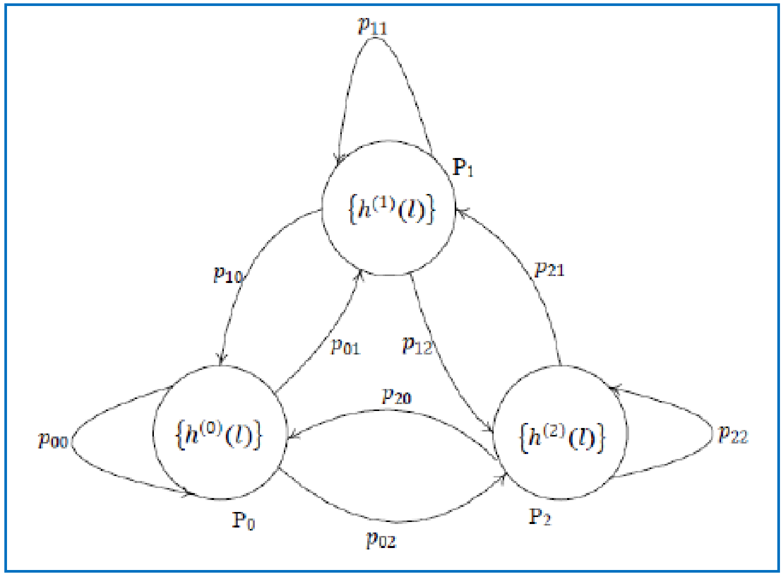
Thus, collecting (27) to (31) leads to the following quasi-Newton based channel estimation (QNCE)

$$\hat{h}_{i+1} = \hat{h}_i - \alpha_i B_i^{-1} \nabla\psi(\breve{h})|_{\hat{h}_i} \tag{32}$$

After J iterations, the channel frequency response is eventually obtained from (6) in the form

$$\hat{H}_{QNCE} = F\hat{h}_J \tag{33}$$

Channel Model



$$h_{RF}^{(0)}(t) = X \sum_{l=0}^{L_h} \sum_{r=0}^{R} \alpha_{r,l}\delta(t - T_l - \tau_{r,l})$$

$$h_{RF}^{(1)}(t) = X \sum_{l=0}^{L_h} \sum_{r=0}^{R} \alpha_{r,l}\delta(t - T_l - \tau_{r,l}) - X \left[\sum_{r=r_0}^{r_0+J-1} \alpha_{r,l}\delta(t - T_l - \tau_{r,l}) \right]_{l=L_c}$$

$$h_{RF}^{(1)}(t) = X \sum_{l=0}^{L_h} \sum_{r=0}^{R} \alpha_{r,l}\delta(t - T_l - \tau_{r,l}) + X \left[\sum_{r=r_0}^{r_0+J-1} \alpha_{r,l}\delta(t - T_l - \tau_{r,l}) \right]_{l=L_c}$$

Iterative Interpolation & Weighted Channel

- One possible solution consists of shifting the positions of pilot subcarriers in PSDU and estimating the channels at pilot subcarriers using (33) or other proven algorithm.

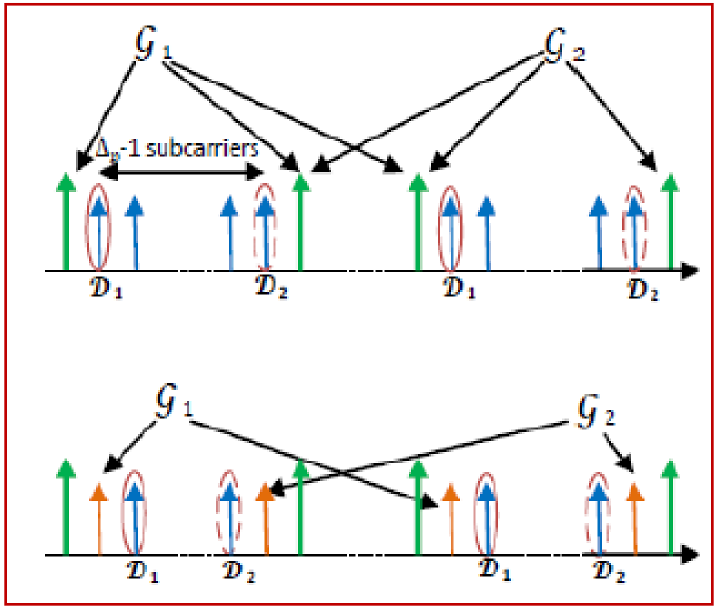
$$\hat{H}_{wgt}^{ref}(n) = \gamma \hat{H}_{QNCE}^{old}(n) + \lambda \hat{H}_{QNCE}^{new}(n)$$

- However, positions of pilot subcarriers are fixed in each OFDM symbol, according to ECMA-368 standard. This leads us to propose an alternate solution, where channels at pilot subcarriers are calculated by above Eq and channels at data subcarriers are estimated through iterative interpolation.

Iterative Interpolation & Weighted Channel

For the nth subcarrier of group $\mathcal{D}_1$, the estimated channel is calculated as

$$\widehat{H}_{\mathcal{D}_1}(n) = \widehat{H}_{\mathcal{G}_1}(n) + \frac{\widehat{H}_{\mathcal{G}_2}(n) - \widehat{H}_{\mathcal{G}_1}(n)}{\Delta_p - 2(i-1)}$$



$$\widehat{H}_{\mathcal{D}_2}(n) = \widehat{H}_{\mathcal{G}_1}(n) + \frac{(\Delta_p - 2i + 1)\left(\widehat{H}_{\mathcal{G}_2}(n) - \widehat{H}_{\mathcal{G}_1}(n)\right)}{\Delta_p - 2(i-1)}$$

$$\widehat{H}_{wgt}^{ref}(n) = \gamma \widehat{H}_{QNCE}^{old}(n) + \lambda \widehat{H}_{D}(n)$$

We Find

- Improved channel estimation with Time-domain redundancy and frequency-domain redundancy based multi-access and narrowband interference rejection.

- Further improvement using PDP-based channel filtering and Blackman windowing

- ML channel estimation with unknown NBI environment optimizing the likelihood function in iterative fashion using quasi-Newton algorithm.

- Iterative interpolation and weighted channel estimation approach for time-varying channel capturing occasional sudden channel change.

Thank you for your suggestions!