Enabling Indoor Internet through Visible Light Communications: when Light brings Data

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Outline

- Visible Light Communication (VLC)
  - Metameric Color Shift Keying (CSK)
  - Indoor Localization
  - Optical Multiple-Input Multiple-Output Transmission
  - Space-Time Equalization

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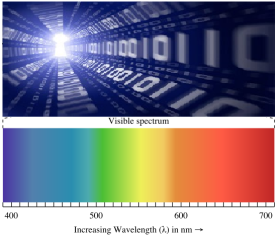
Visible Light Communications

transmitting data by changing the light intensity of ordinary LEDs in a way that is not perceived by the human eye



Pros

- Unlicensed spectrum;
- No Electromagnetic Interference with existing radio system;
- High spectral efficiency per unit area;
- Simple, low-cost, front-end devices;
- Power saving, illumination & communication paradigm;
- Security.

Cons

- Path loss is inversely proportional to the distance raised to the power of four;
- Obstacles can block the light propagation.

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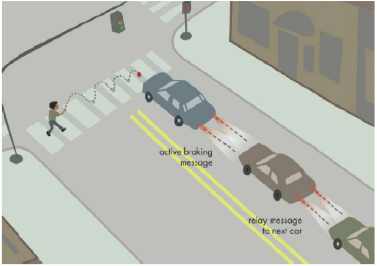
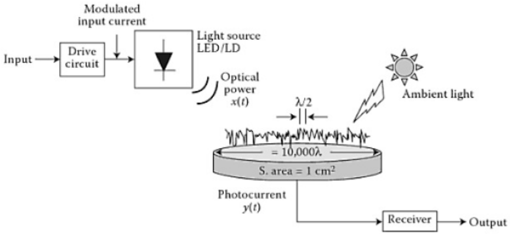
Few Applications



Visible Light Communications

Intensity-Modulated/Direct-Detection (IM/DD) System



$$y(t) = RA_e x(t) * h(t) + n(t)$$

where $x(t)[W]$ is the transmitted optical instantaneous power, R responsivity $[A/W]$, A_e PD effective area, $y(t)[A]$ received current. With constraints:

- $0 \leq x(t) \leq P_{peak}$
- $P_{avg} = \frac{1}{2T} \int_{-T}^{T} x(t)dt \leq I_{max}$

Contribution

A VLC system has to guarantee a high quality illumination capability without compromise the deployment cost and the energy saving characteristics of solid state lighting sources.

- It is tackled the issue of having good color quality perception when the transmitting source is composed by trichromatic LEDs: metameric modulation with CPPM;
- It is presented a hybrid received signal strenght/time difference of arrival technique, which leads to a system that is more resilient to the presence of different impairments. Useful also for LEDs selection in a MIMO transmission;
- Trace orthogonal space-time block coding technique is analyzed and used with PPM, taking into account lighting constraints on the signal transmitted.
- Spatial diversity can lead to spatial intersymbol interference. A novel system architecture for OCC adaptive equalization is presented.

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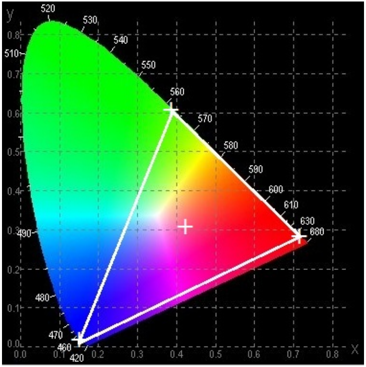
Color Shift Keying

modulation used in IEEE 802.15.7 PHY layer III



- encodes data in the instantaneous output color of the LEDs (RGB).
- based on the x-y colour coordinates defined in CIE 1931 colour space.

Compared to FSK has 3 sub-bands and optical band fixed tied to the LED used.

Segnale CSK

$$x_k(t) = \sum_{m=1}^{3} \sqrt{\beta_{m,k}} g_{m,k}(t), \quad k = 1, ..., K$$

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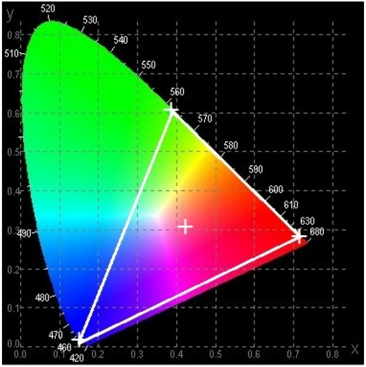

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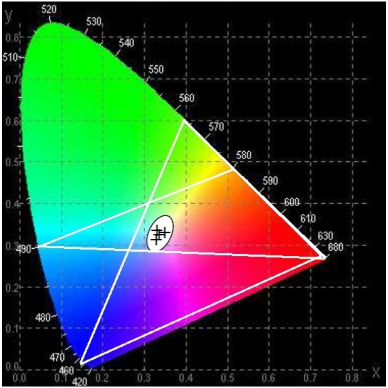
Metamerism



- Colors with different spectral power distributions can appear chromatically identical to the human eye.
- The three colors should evoke the same spectral response, perceived as the $C(\lambda)$ color.

$$\sum_{m=1}^{3} \beta_{m,k} \int_0^{\infty} \Gamma_{m,k}(\lambda) S_i(\lambda) d\lambda =$$

$$= \int_0^{\infty} C(\lambda) S_i(\lambda) d\lambda \; k = 1, ..., K$$

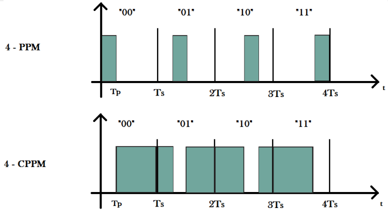
Complementary PPM

To increase transmission rate, K-CSK colors are modulated with a complementary PPM

CPPM signal

$$p_n(t) = \sum_{l=0, l \neq n}^{L-1} u(t - l\Delta_p)$$

The duty cycle of L-CPPM is $(L-1)/L$ rather than $1/L$ of L-PPM.



Segnale CSK-CPPM

$$p_{nk}(t) = \sum_{m=1}^{3} \sqrt{\beta_{m,k}} g_{m,k}(t) p_n(t)$$

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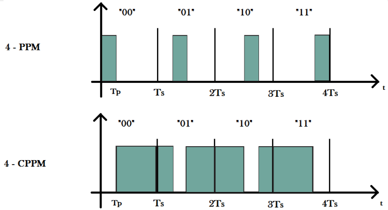
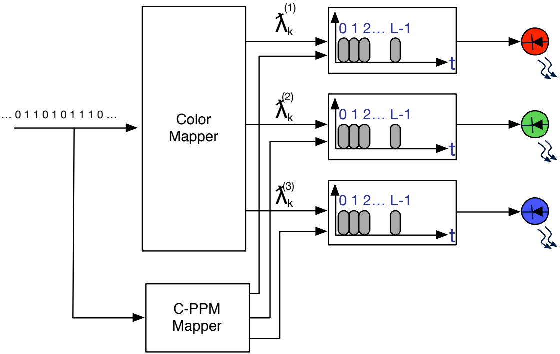


Segnale CSK-CPPM

$$p_{nk}(t) = \sum_{m=1}^{3} \sqrt{\beta_{m,k}} g_{m,k}(t) p_n(t)$$

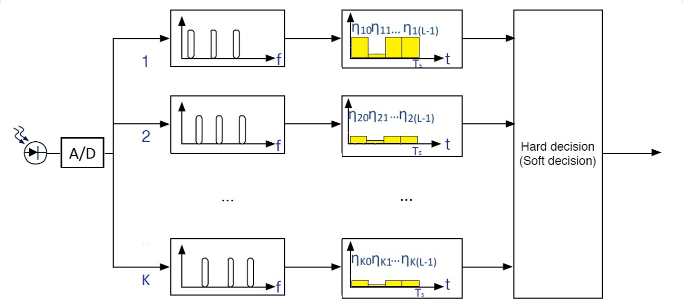
Transmitter

gathering source bits in groups of $\log_2 K + \log_2 L$, leads to use the first $\log_2 K$ bits by K-CSK while the successive $\log_2 L$ are used by L-CPPM.



Receiver

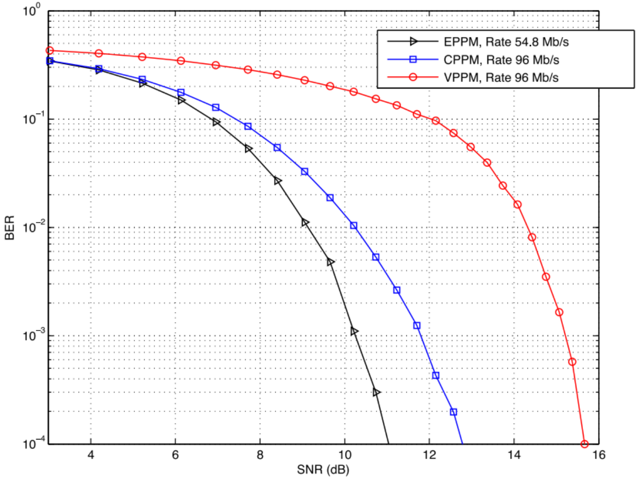
$$z(t) = RA_e p_{nk}(t) * h_{\mathrm{LED}}(t) * h_{\mathrm{ch}}(t) * h_{\mathrm{PH}}(t) + n(t)$$



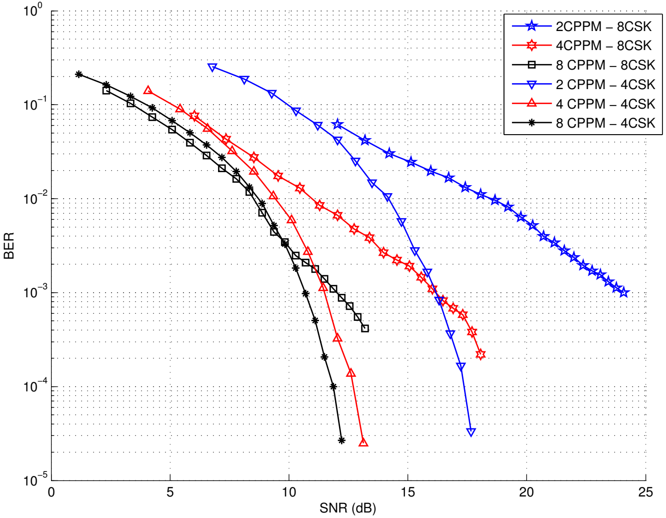
$$\eta_{kl} = \int_{lT_s/L}^{(l+1)T_s/L} z(t) g'_k(t) dt \quad k = 1, \dots, K, \;\; l = 0, \dots, L-1$$

$$g'_k(t) = \sum_{m=1}^{3} \sqrt{\beta_{m,k}} g_{m,k}(t), \quad k = 1, \dots, K$$

PPM Comparison



CSK-CPPM



BER
SNR (dB)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
20
25
2CPPM – 8CSK
4CPPM – 8CSK
8 CPPM – 8CSK
2 CPPM – 4CSK
4 CPPM – 4CSK
8 CPPM – 4CSK

CSK-CPPM Conclusion

- Provide illumination with good color rendering, thanks to metamerism, and without dimming issues when the CPPM cardinality grows;
- Combining CPPM with CSK improves the spectral efficiency;
- Higher transceiver complexity, affordable by VLC technology.

Localization

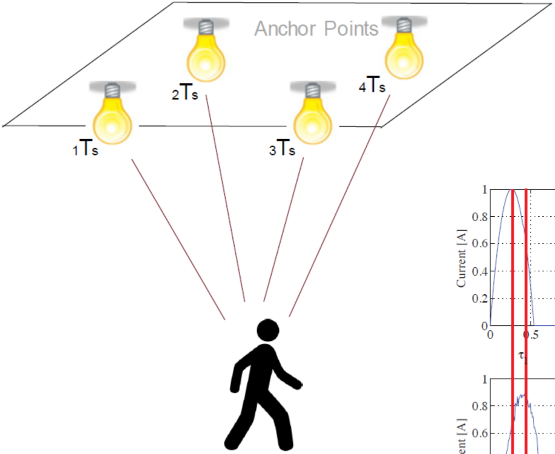
- In the indoor environment GPS is not accurate;
- A very high precise indoor localization procedure leads to: navigation inside buildings and new localization-based services.

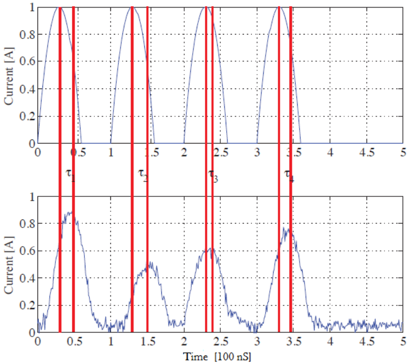
In the VLC literature:

- Several works use RSS, issues when the channel is not ideal;
- Nah et al. TDOA, synchronization issues;
- Rahman et al. AoA, an image sensor is needed.

Localization

LED k-th $X_k(t, \vartheta', \varphi') = P_{[loc]}(t - (k-1)T_s, \vartheta', \varphi')$





n_T

RSS-TDOA

linear combination of received signal strenght (RSS) and time difference of arrival (TDOA)

$$\tilde{d}_{ku} = (1-\rho)\tilde{d}_{ku}^{(RSS)} + \rho\tilde{d}_{ku}^{(TDOA)}$$

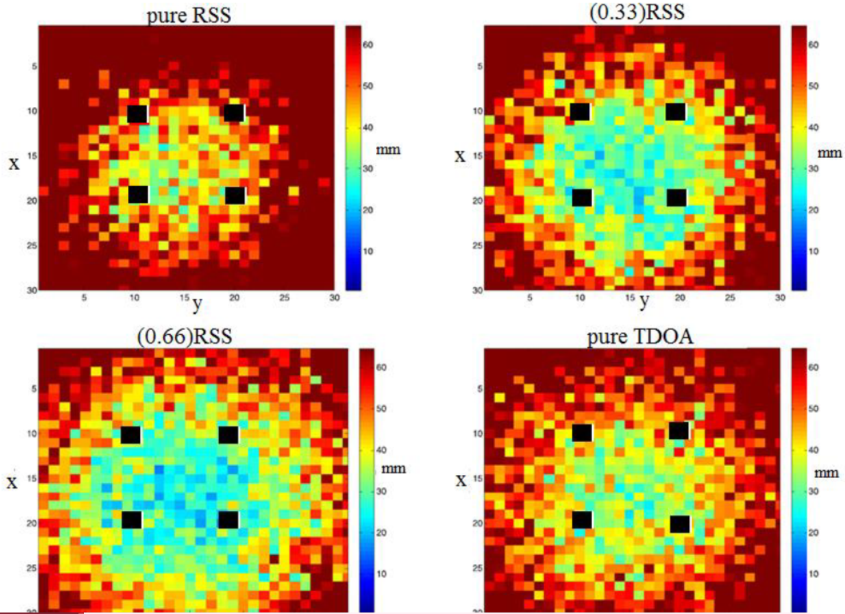
$$\tilde{d}_{ku}^{(RSS)} = \mathcal{A}^{-1}\left(\frac{\max_{(k-1)T_s \le t \le kT_s} Y_{ku}(t,\vartheta,\varphi)}{RA_e(\vartheta,\varphi)P_{[loc]}(t-(k-1)T_s,\vartheta',\varphi')}\right)_\lambda$$

$$\tilde{d}_{ku}^{(TDOA)} = \tau_{ku}^{(TDOA)}/v - (k-1)T_s; \quad \tau_{ku}^{(TDOA)} = \arg\max_{(k-1)T_s \le \tau \le kT_s} Y_{ku}(t)$$

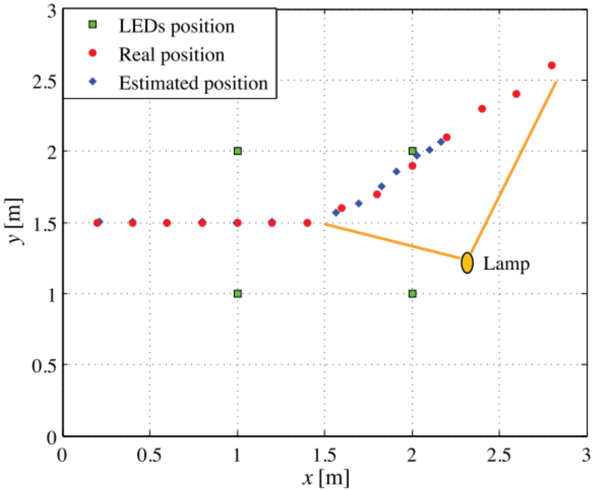
when the n_T distances are available, the mobile user coordinates are obtained through multilateration

$$\begin{bmatrix} (x_1-\tilde{x}_u)^2 + (y_1-\tilde{y}_u)^2 + (z_1-\tilde{z}_u)^2 \\ (x_2-\tilde{x}_u)^2 + (y_2-\tilde{y}_u)^2 + (z_2-\tilde{z}_u)^2 \\ \vdots \\ (x_{n_T}-\tilde{x}_u)^2 + (y_{n_T}-\tilde{y}_u)^2 + (z_{n_T}-\tilde{z}_u)^2 \end{bmatrix} = \begin{bmatrix} \tilde{d}_{1u}^2 \\ \tilde{d}_{2u}^2 \\ \vdots \\ \tilde{d}_{n_T u}^2 \end{bmatrix}$$

RSS-TDOA


pure RSS
(0.33)RSS
(0.66)RSS
pure TDOA
x
y
mm
5
10
15
20
25
30
10
20
30
40
50
60

RSS-TDOA

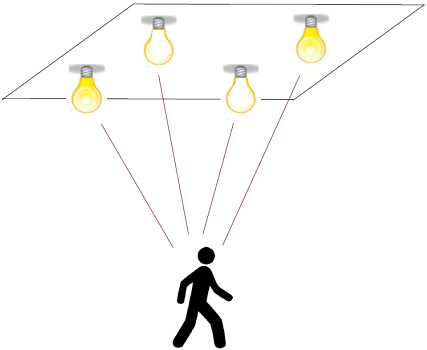

LEDs position
Real position
Estimated position
Lamp
y [m]
x [m]
0
0.5
1
1.5
2
2.5
3

Localization Conclusion

- Indoor localization through VLC is promising;
- RSS and TDOA combination leads to diminish the estimation error and simplify the synchronization procedure;
- Due to the high directivity of the light beam, with the knowledge of the mobile user position it is possible to chose those LEDs that will give the best service to the user in a MIMO scenario.

Optical MIMO related works

- Safari, PAM-based modulation, Repetition Coding;
- Ntogary, Alamouti-type space time block coding, with QAM;
- Poopola, Spatial Pulse Position Modulation;
- C.Abou Rjeily, PPM orthogonal space time block coding, UWB systems.

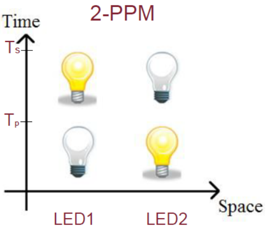


PPM Trace-Orthogonal STBC

$$y_j(t) = \frac{1}{\sqrt{n_T}} \sum_{i=1}^{n_T} h_{ij}(t) * x^{(i)}(t) + w_j(t)$$

$$\mathbf{Y} = \mathbf{XH} + \mathbf{W}$$

$\mathbf{X}$ of size $[Lxn_T]$ is the STBC matrix, which satisfies trace orthogonality.



find STBC

offline tool

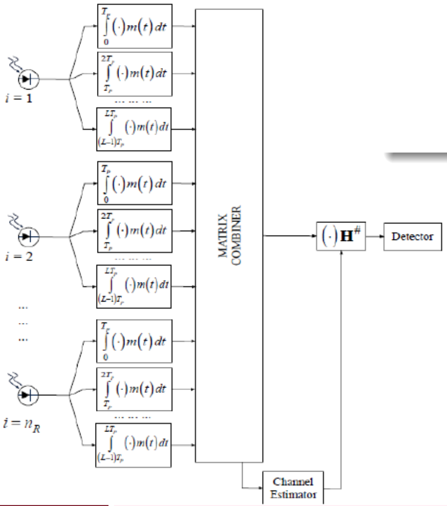
$$\text{s.t.} \sum_{i=1}^{L} \sum_{j=1}^{n_T} c_{ij}^{(l)} c_{ij}^{(m)} = 0, \quad l \neq m, \; l, m \in \mathfrak{M}, \; |\mathfrak{M}| = M,$$

$$M \geq 2^{\frac{\mathcal{R}^{\star} L T_s (N_d + N_e)}{N_d}},$$

$$\sum_{i=1}^{L} c_{ij}^{(l)} = 1, \quad \text{and} \quad c_{ij}^{(l)} \in \{0, 1\},$$

$$\Pr\{e\} \leq \Pr\{e\}^{\star}.$$

Receiver



Spatial Zero Forcing

$$\mathbf{Z} = \mathbf{Y}\mathbf{H}^{\sharp} = \mathbf{X} + \mathbf{W}\mathbf{H}^{\sharp}$$

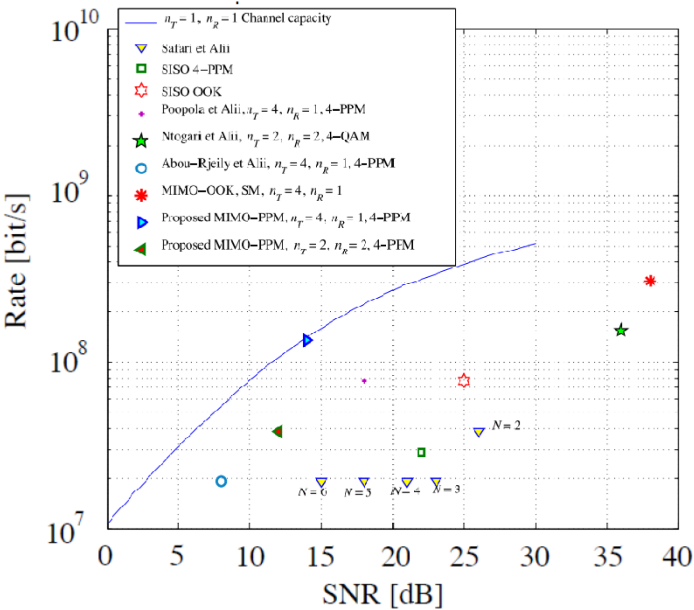
$$\hat{\mathbf{C}} = \arg\max_{i} \mathrm{Tr}\{\mathbf{C}_i^T \mathbf{Z}\}$$

$$\mathrm{Tr}\{\mathbf{C}_j^T \mathbf{C}_i\} = \begin{cases} 0 & j \neq i \\ n_T & j = i \end{cases}$$

Every second, training sequence:

$$\mathbf{X} = \mathbf{I}; \quad \mathbf{Y} = \mathbf{H} + \mathbf{W}$$

Optical MIMO

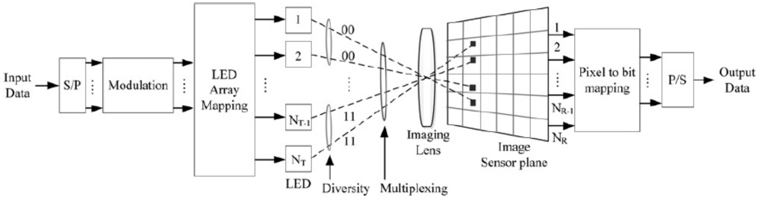


BER 10^-5

MIMO Conclusion

- PPM is known to be a bandwidth inefficient modulation, this drawback is counterbalanced with a multiplexing gain;
- By relaxing the orthogonality constraint, it is possible to have more transmitted matrices;
- Good trade-off between SNR gain and higher data rate.

Optical Camera Communication



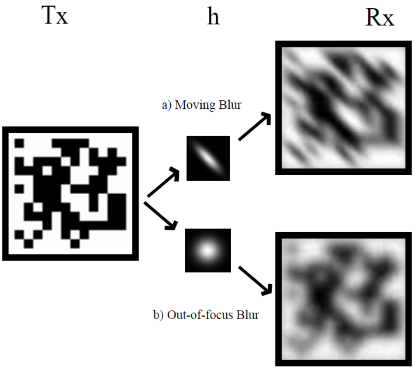
- Image sensors have a very high number of pixels, very high resolution at the receiver;
- Nowadays smartphones have slow frame rate, typically 30fps;
- Massive MIMO to improve the transmission rate;
- The transmitter can be a display or an array of LEDs.

Spatial Intersymbol Interference Issue

- Fractionally spaced equalization can be exploited thanks to the receiver high resolution.

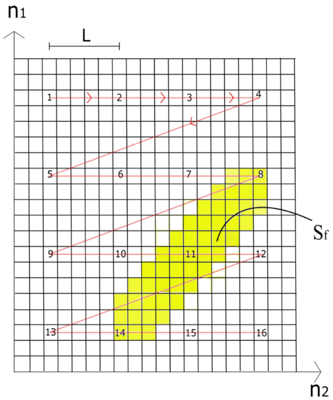
Semiblind Equalization

- Fractionally-spaced equalizer;
- Semiblindness with cornice of white (active) symbols, needed also for image detection and alignment;
- Minimum Mean Square Error (MMSE) symbol (OOK) estimation;



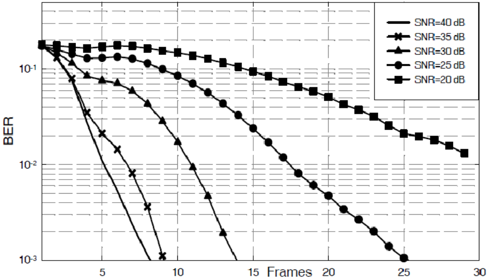
Space-Time Adaptive RLS

- Separation between once-per-frame filtering and intraframe filter coefficients updating. Specifically, the once-per-frame filtering is postponed at the end of the symbol lexicographic scanning;
- Flexible equalizer support choice, well suited to the blur shape and capable to both reduce computational complexity as well as improve estimation accuracy.

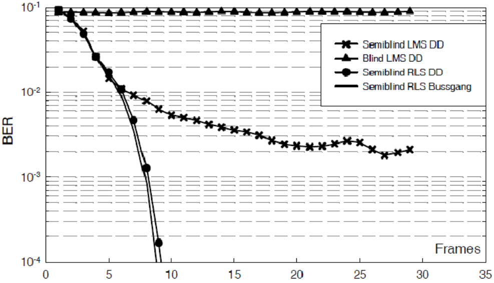


Numerical Results

- SNR comparison



- Other schemes comparison



Equalization Conclusion

- In order to directly equalize the blur introduced by the optical channel, the intrinsic fractionally sampled nature of OCC images has been exploited;
- An adaptive space-time RLS algorithm with postponed filtering has been introduced;
- Symbols used for image detection and alignment have been exploited for driving the convergence of the algorithm (semiblindness).

Conclusion

VLC is a promising complementary technology to RF. In order to enable indoor Internet through VLC the following aspect has been presented:

- A CSK-CPPM modulation in order to improve color rendering and data rate;
- An hybrid RSS-TDOA localization scheme, which is more resilient to the presence of different impairments, such as multipath effect, or amplitude fluctuations;
- An optical MIMO STBC technique with PPM and lighting constraints;
- Spatial Intersymbol Interference suppression through a semiblind fractionally spaced equalizer.