IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15.7 Task Group Visible-Light Communication (TG-VLC)
Title	**Color stabilization for CSK by use of visibility frames**
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Abstract	I describe an extension of CSK for duplex links, so that the point of gravity of the CSK constellation diagram can be kept stable in case of changes in the output characteristics of a CSK transmitter. In contrast to document 15-10-0089-02-0007 only the low-frequency dynamics of the transmitter is compensated for. Visibility frames are exploited for inferring the compensation coefficients in the Tx.
Purpose	Contribution of standard-text material for the preparation of IEEE 802.15.7 D2
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1. Nomenclature

1.1. Symbols

Symbol	Declaration
$\square^{(b)}$	Binary representation of $\square$
$\{.\}_{A/D}$	A/D converted value of {.}
$\{.\}_{D/A}$	D/A converted value of {.}
α_l	D/A scaling factor for band *l*
β_l	A/D scaling factor for band *l*
a	One-dimensional quantity
$\boldsymbol{a}$	Column vector
$\boldsymbol{A}$	Matrix
e_{lm}	Sensitivity of photo detector for band *m* when receiving emission in band *l* [A/W]
i	Current [A]
p	Optical power [W]
$\boldsymbol{Q}$	Diagonal matrix proportional to the quantum efficiencies of the LEDs in

	bands *i*, *j*, *k* [W/A]
s	Signal
$\boldsymbol{s}_{\mathrm{Rx}}$	Vector of received signals
$\boldsymbol{s}_{\mathrm{Tx}}$	Vector of transmitted signals
t	Time [s]
t_{lm}	Transmittance from LED *l* to photodetector *m* [unit 1]
$\boldsymbol{T}$	Transmittance matrix [unit 1]
T_{comp}	Time between two color compensations [s]

1.2. Abbreviations

Abbreviation	**Long form**
CSK	Color-shift coding
LED	Light-emitting diode
OOK	On-off keying
PD	Photodetector
PHY	Physical layer (OSI layer 1)
Rx	Receiver
Tx	Transmitter

2. Description of use case

The quantum efficiency of LEDs is dependent on their operation time and age, and also on various environmental conditions. Among those, temperature is generally the most important factor. When using CSK modulation all these factors lead to a change of the center of gravity and a distortion of the CSK constellation diagram of the emitted signal. The standard text for IEEE 802.15.7 provides a mechanism of how to stabilize the center of gravity of the CSK constellation diagram. By so doing one can stabilize the average color of the emitted light. Notice that this compensation scheme only is applicable to duplex links. In this contribution I provide more detail on how the compensation factors mentioned in subclause 8.5.4 of the aforementioned standard text.

3. Control loop

This is a recapitulation of an explanation provided in subclause 8.5.4 of the aforementioned standard text. The control-loop model for the color-stabilization scheme is shown in Figure 1. Visibility patterns are sent from the tri-band Tx of an CSK-PHY to the tri-band Rx. The corresponding received signals is fed back to the LEDs in the tri-band Tx. An optional back link is used to relay these signals back to the tri-band Tx, where they are used to correct the LED driving currents in such a way that the center of gravity of the constellation diagram is moved back to its initial position.

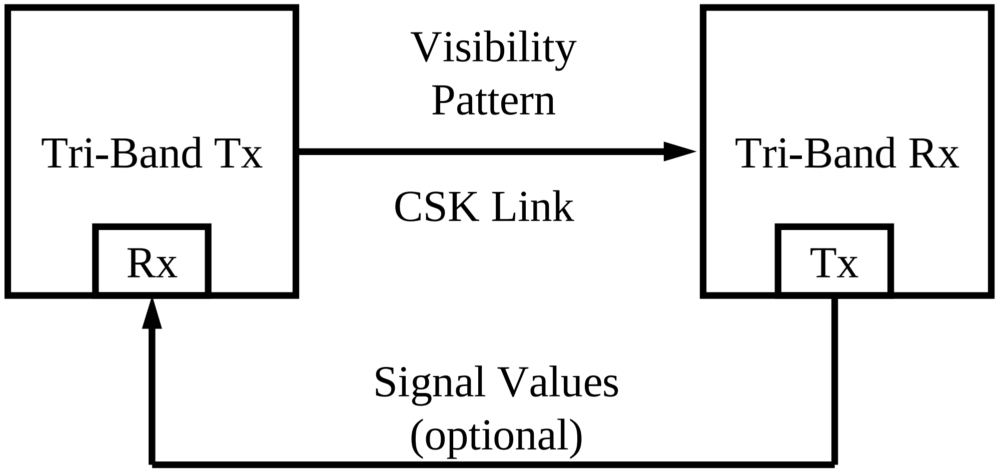


Figure 1 – Control loop for a color-stabilized CSK link. The calibration sequences are discussed in detail in Section 4. The back link used for routing the compensation factors back to the tri-band Tx does not need to be a CSK link.

4. PHY-layer mechanism

4.1. General approach

Here, we discuss the proposed compensation scheme for the general case of a nonlinear characteristic function (radiant power vs. driving current). However, in light of its high usability, we also briefly discuss the case of a linear characteristic function. Also notice, that we only attempt to apply this scheme for a visibility-pattern line rate that is slow enough to invoke thermal and other low-frequency relaxation effects in the transmitter. Notice though that the scheme is in principle also also applicable to high-frequency modulation.

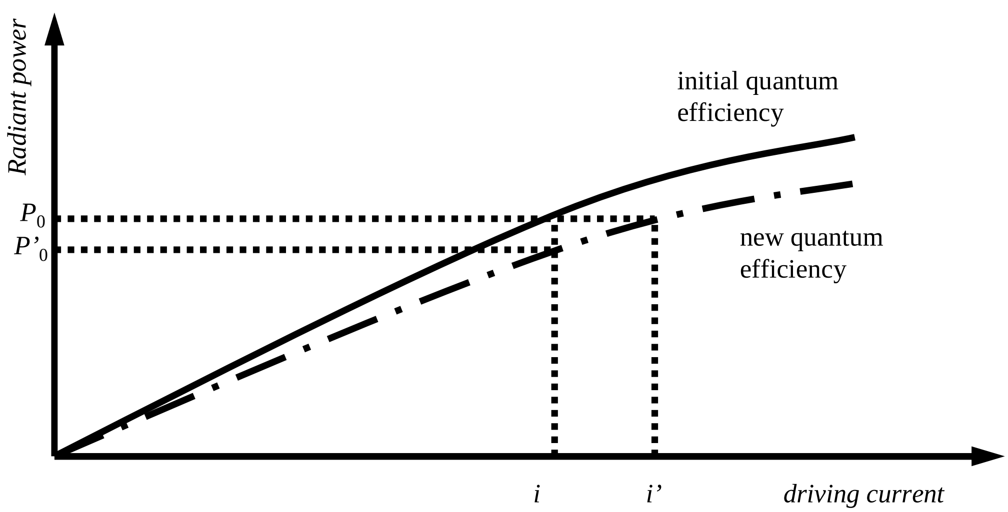


Figure 2 – Characteristic curve of an LED (radiant power as a function of driving current) for two quantum efficiencies and ac driving currents.

Figure 2 displays an example alteration of the transmitter characteristic function due to a change in quantum efficiency. For a driving current *i*, the initial radiant power drops from P_0 to P'_0. In order to regain the original radiant power p_0 the driving current has to be changed to *i*'.

As shown in Figure 3, the signal to be transmitted over a CSK link, viz. $\mathbf{s}_{\mathrm{Tx}}^{(\mathrm{b})}$, is translated into the ac current vector i_{Tx} by aid of D/A convertors. The transmitted radiant power of the transmitter is, according to Figure 4, given by

$$\boldsymbol{p}_{\mathrm{Tx}} = \boldsymbol{f}(\boldsymbol{i}_{\mathrm{Tx}}),$$

where $\boldsymbol{f}$ is a vector function consisting of the characteristic functions for each band. Examples for such vector functions are polynomial fits of the static characteristic function of the LEDs or Volterra-series approximations of the dynamic response of the LEDs [Kamalakis, 2011].

For a simple linear relationship between radiant power and the driving current this Equation can be written as

$$\boldsymbol{p}_{\mathrm{Tx}} = \boldsymbol{Q}\boldsymbol{i}_{\mathrm{Tx}},$$

where $\boldsymbol{Q}$ is a diagonal matrix, whose values are proportional to the (dc) quantum efficiencies of the individual LEDs.

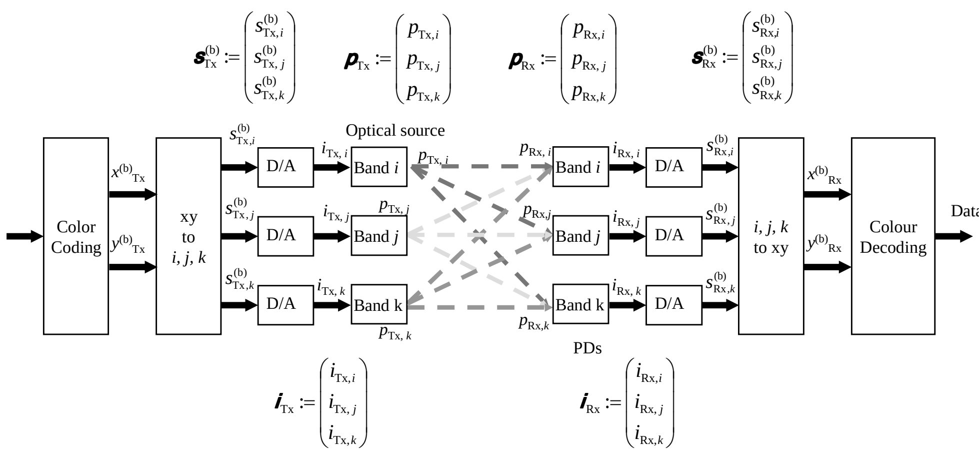


Figure 3 – Definition of system vectors and matrices for a CSK link.

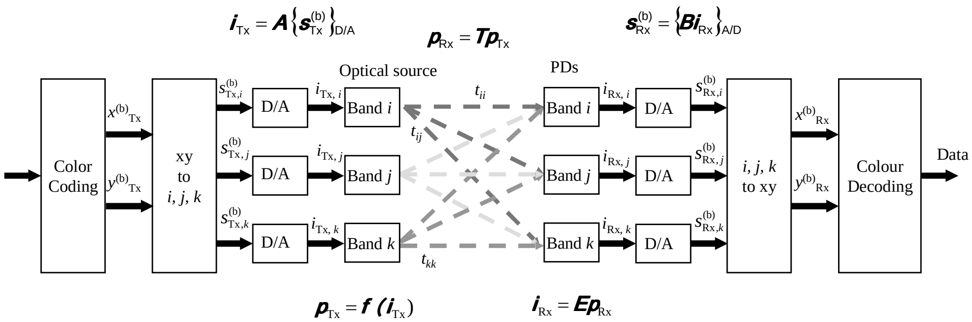
According to Figure 3 and Figure 4**,** the received radiant power is

$$\boldsymbol{p}_{\mathrm{Rx}} = \boldsymbol{T}\boldsymbol{p}_{\mathrm{Tx}},$$

where $\boldsymbol{T}$ is the transmission matrix. The pertinent current output of the photodetectors is

$$\boldsymbol{i}_{\mathrm{Rx}} = \boldsymbol{E}\boldsymbol{p}_{\mathrm{Rx}},$$

where $\boldsymbol{E}$ represents the spectral sensitivity of the photodetectors. The photodetector currents are translated into digital representations, viz. $\boldsymbol{s}_{\mathrm{Rx}}^{(\mathrm{b})}$, by aid of D/A convertors.



$$\boldsymbol{A} := \begin{pmatrix} \alpha_{\mathrm{r}} & 0 & 0 \\ 0 & \alpha_{\mathrm{g}} & 0 \\ 0 & 0 & \alpha_{\mathrm{b}} \end{pmatrix} \qquad \boldsymbol{T} := \begin{pmatrix} t_{ii} & t_{ij} & t_{ik} \\ t_{ji} & t_{jj} & t_{jk} \\ t_{ki} & t_{kj} & t_{kk} \end{pmatrix} \qquad \boldsymbol{E} := \begin{pmatrix} e_{\mathrm{rr}} & e_{\mathrm{rg}} & e_{\mathrm{rb}} \\ e_{\mathrm{gr}} & e_{\mathrm{gg}} & e_{\mathrm{gb}} \\ e_{\mathrm{br}} & e_{\mathrm{bg}} & e_{\mathrm{bb}} \end{pmatrix}$$

Figure 4 – Definition of further transfer matrices for a CSK link.

The relation between the transmitted and received signal is thus given by

$$\mathbf{s}^{(\mathrm{b})}_{\mathrm{Rx}} = \left\{\mathbf{BETf}\left(\mathbf{A}\left\{\mathbf{s}^{(\mathrm{b})}_{\mathrm{Tx}}\right\}_{\mathrm{D/A}}\right)\right\}_{\mathrm{A/D}}.$$

A change in the quantum efficiency of an LED in any of the three bands results in the change of $\boldsymbol{f}$ to $\boldsymbol{f}'$. If the transmitter has access to $\boldsymbol{s}^{(\mathrm{b})}_{\mathrm{Rx}}$, the new vector-characteristic function can be calculated from

$$\boldsymbol{f}'\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right) = \boldsymbol{f}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)\boldsymbol{f}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)^{\mathrm{T}}\left\{\boldsymbol{s}_{\mathrm{Rx}}\boldsymbol{f}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)^{\mathrm{T}}\right\}^{-1}\boldsymbol{s}'_{\mathrm{Rx}},$$

where $\boldsymbol{s}_{\mathrm{Rx}}$ and $\boldsymbol{s}'_{\mathrm{Rx}}$ are the receiver signals before and after the change in the transmitter efficiency, respectively.

The overall goal of this compensation strategy is to achieve a stabilization of the CSK color center of gravity by transforming the transmitted signals with a compensation function $\boldsymbol{c}$ so that

$$\boldsymbol{s}^{(\mathrm{b})}_{\mathrm{Rx}} = \left\{\boldsymbol{BETf}'\left(\boldsymbol{A}\left\{\boldsymbol{c}\left(\boldsymbol{s}^{(\mathrm{b})}_{\mathrm{Tx}}\right)\right\}_{\mathrm{D/A}}\right)\right\},$$

or, in a briefer version

$$\boldsymbol{f}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right) = \boldsymbol{f}'\left(\boldsymbol{A}\boldsymbol{c}\left[\boldsymbol{s}_{\mathrm{Tx}}\right]\right).$$

In general, this is a rather complex inverse problem, but there exist at least two practical cases, for which this problem can readily be solved in a closed form. In both cases one can write

$$\boldsymbol{c}\left(\boldsymbol{s}_{\mathrm{Tx}}\right) = \boldsymbol{C}\boldsymbol{s}_{\mathrm{Tx}},$$

where $\boldsymbol{C}$ is a diagonal matrix.

First, if only the magnitude of the characteristic curves change but not their shape (as is the case in Figure 2), the vector characteristic function can be written as

$$\boldsymbol{f}(\boldsymbol{i}_{\mathrm{Tx}}) = \tilde{\boldsymbol{Q}}\boldsymbol{g}\left(\boldsymbol{i}_{\mathrm{Tx}}\right),$$

where $\tilde{\boldsymbol{Q}}$ is a diagonal matrix that can be understood as a generalized quantum efficiency. In contrast, the vector function $\boldsymbol{g}$ is independent of the transmitter efficiency. The compensation factors for this case can be calculated with

$$\boldsymbol{C} = \boldsymbol{A}^{-1}\boldsymbol{g}^{-1}\left(\boldsymbol{g}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)\boldsymbol{g}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)^{\mathrm{T}}\left\{\boldsymbol{s}'_{\mathrm{Rx}}\boldsymbol{g}\left(\boldsymbol{A}\boldsymbol{s}_{\mathrm{Tx}}\right)^{\mathrm{T}}\right\}^{-1}\boldsymbol{s}_{\mathrm{Rx}}\right)\left\{\boldsymbol{s}_{\mathrm{Tx}}\boldsymbol{s}^{\mathrm{T}}_{\mathrm{Tx}}\right\}^{-1}.$$

Second, for the purely linear case [$\boldsymbol{g}(\boldsymbol{i}) \sim \boldsymbol{i}$] the calculation of the compensation matrix $\boldsymbol{C}$ simplifies to

$$\boldsymbol{C} = \boldsymbol{s}_{\mathrm{Tx}}\boldsymbol{s}^{\mathrm{T}}_{\mathrm{Tx}}\left\{\boldsymbol{s}'_{\mathrm{Rx}}\boldsymbol{s}^{\mathrm{T}}_{\mathrm{Tx}}\right\}^{-1}\boldsymbol{s}_{\mathrm{Rx}}\boldsymbol{s}^{\mathrm{T}}_{\mathrm{Tx}}\left\{\boldsymbol{s}_{\mathrm{Tx}}\boldsymbol{s}^{\mathrm{T}}_{\mathrm{Tx}}\right\}^{-1}.$$

In the following we will only consider schemes relying on the compensation matrix $\boldsymbol{C}$.

4.2. Choice of data sent over the CSK channel

Typical thermal response times of LEDs lie in the µs range. The standard proposes thus to send the same OOK symbol (‘1’) in a CVD frame for so many repetitions that the transmitters have thermally stabilized. The received signal of relevance for the afore-discussed signal vector $\boldsymbol{s}_{\mathrm{Rx}}$ is then only acquired for the last sent repetitive symbol, or an average over a suitable number of last samples. For typical LEDs and the line rates stated in the standard text, this translates to more than 100 repetitions.
Since changes in the quantum efficiency of the LEDs occurs on a rather long time scale (seconds, minutes, hours), it is not necessary to send back $\boldsymbol{s}_{\mathrm{Rx}}$ after each suitable set of visibility frames.

4.3. General guidelines for estimation of the compensation factors

In order for the proposed compensation scheme to function, reference received signal values are needed. They are relayed back to the CSK transmitter via an optional back channel (see Figure 5). In the following these reference values are referred to as $\boldsymbol{s}_{\mathrm{Rx,0}}$ and stored on the transmitter side. Recurring measurements of the received signals (for the same sent signal) results in the vectors $\boldsymbol{s}_{\mathrm{Rx,s}}$ for time t_s. If the elements of $\boldsymbol{S}_{\mathrm{Rx,s}}$ differ significantly from those of the diagonal elements of $\boldsymbol{S}_{\mathrm{Rx,0}}$, the driving currents fed to the band emitters are corrected with the diagonal elements of $\boldsymbol{C}$. A decision about whether an update is necessary can be made by aid of the value of the diagonal elements of $\boldsymbol{C}$ itself. If these values differ significantly from 1, an update of the current compensation factors is made. Whether this difference is significant can either be decided by a preset value (e.g., 5% difference), or the decision threshold can be estimated from the data itself. One example is to acquire a histogram of the diagonal values of $\boldsymbol{C}$. A significant value can then be defined as lying outside a pre-defined confidence interval, e.g. the 95% confidence interval.
In order to avoid damage or saturation of the LEDs or a bit-level saturation of the A/D and D/A convertors, one can introduce a-priori maximum levels for the three values in $s_{\mathrm{Tx}}^{(\mathrm{b})}$.

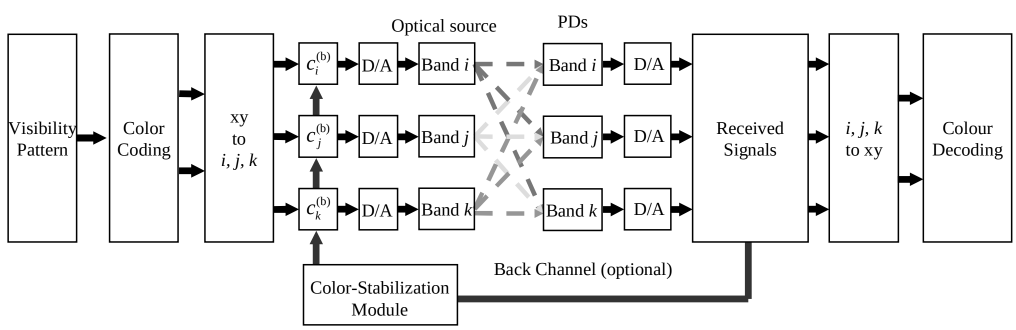


Figure 5 – Detailed implementation of a color-stabilized CSK link. The received signals are relayed back to the transmitter, and the CSK receiver a channel-estimation module in the receiver estimates compensation factors and sends them back to the CSK transmitter via an additional channel.

Changes that affect all channels similarly, e.g. a change in the link length, can be identified by comparing all diagonal values of $\boldsymbol{C}$. If all elements experience the same

relative change, the compensation factors for the Tx driving currents shall not be updated.
If the off-diagonal elements of $\boldsymbol{C}$ significantly differ from zero this indicates other impairments of the CSK-modulated link than those hither discussed. An example for such impairment is the blocking of only one of the photodiodes against cross talk. For instance., photodiode *i* still receives light emitted from LED *i*, but not longer from the other bands. In such a case the Tx driving current shall not be compensated for. Instead one can use this information for, e.g., error messages created by the CSK Tx, the CSK Rx, or both. Another option is to update $\boldsymbol{S}_{\mathrm{Rx},0}$ and to use the update for further compensation.

References

T. Kamalakis, J. W. Walewski, G. Ntogari, and G. Mileounis, “Empirical Volterra-Kernel Modeling of Commercial Light-Emitting Diodes”, submitted to J. Lightwave Comm., 2011