# Amplitude Modulation by Superposition of Independent Light Sources

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Abstract: Visible light communication (VLC) is a promising alternative to radio waves, when high data rates are required over short distances. Using lighting equipment for communication offers very high receive power values without consuming additional energy than already required for illuminating the environment. The bandwidth restriction of the employed light-emitting diode (LED) light sources is one limiting factor to exploiting the channels potential capacity. In this paper, we propose spatially distributed modulation schemes to increase the data rate by switching the LEDs of the lighting equipment individually. Towards this goal, three different techniques for superposition of independent light sources are compared.



## 1 INTRODUCTION

Since the beginning of wireless communications, signal amplitudes have been used to represent information. In contrast thereto for visible light communication, where typically light-emitting diodes are used as transmitters, modulation shemes with two amplitude levels, like on-off keying (OOK) and pulse-position modulation (PPM), offer specific advantages. For intensity modulation, the non proportional voltage to optical output power dependency of LEDs has to be taken into account and power-efficient amplifier designs are challenging. Another advantage of switched operation is that it is already implemented as pulse-width modulation in many lighting applications to control the brightness level and could be easily adopted for additional communication purposes.

In this publication, we introduce superposition amplitude modulation (SAM), i.e. to use an array of individually switchable LEDs in such a manner that, taking the channel characteristics into account, a unipolar amplitude-shift keying (ASK) constellation is created at the receiver.

In the following, we restrict ourselves to interpret the amplitude coefficients as constellation points of an ASK constellation. Besides this use, the amplitudes can also be interpreted as the quantized representation of a positive and real-valued discrete-time signal enabling the use of other modulation techniques as well.

An alternative to the proposed scenario, where each LED is switched individually, one could suggest to modulate the light intensity (compare (Tsonev et al., 2014; Cossu et al., 2012; Vučić et al., 2010b)). A comparison of SAM to discrete multitone transmission (DMT) is given in Section 6.

There are alternative approaches known from literature to increase $R$ that can be combined with the proposed solution but require additional hardware effort. These methods exploit diversity in space or frequency, e.g. by using multiple LED colors (Cossu et al., 2012).

The remainder of this paper is organized as follows: In Section 2 the physical channel for visible light communication, with a special focus on the superposition of independent LED light sources, is introduced. The main contribution of this work is presented in Section 3, with three different superposition schemes that enable us to create an amplitude-modulated signal at the receiver. In Section 4 the accuracy of the SAM methods is analyzed. Based on these results the achievable data rates are discussed and the section is concluded with the presentation of some promising simulation results on the symbol error rate (SER) and the peak to average power ratio (PAPR). Finally measurement results are presented to justify the assumptions made in Section 3 and the paper is concluded with a comparison to alternative intensity-modulation/direct-detection (IM/DD) VLC modulation methods.

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## 2 FUNDAMENTALS

Without loss of generality, we assume rectangular pulses with equal symbol duration $T$ for all $N$ individually switchable light sources with optical output power $Pt_n$, $0 \leq n \leq N-1$. When using direct-detection the light waves constructively overlap at the photo detector such that the received signal is a linear superposition of all light sources and paths. Consequently, the constituted symbol constellations $\mathcal{A}$ are uni-polar and real-valued. We assume that all LEDs can be switched independently with $s_n \in \{0,1\}$. Hence, the received signal power of the $n$th LED can be written as

$$Pr_n = s_n \int_{\tau_0}^{T+\tau_0} \sum_{l=0}^{L} y_{l,n}(t)\,\mathrm{d}t\,, \qquad (1)$$

where $y_{l,n}(t)$ is the instantaneous receive power amplitude of the $n$'th LED via an $l$-times reflection path. $L$ is the maximum number of reflections to consider and $\tau_0$ is the delay of the shortest path.

Typically, bi-directional communication with a strong asymmetry of up- and downlink can be found in visible light communication systems due to the high brightness level of ceiling lights and restrictive power requirements in mobile devices. For example, a low-speed infrared uplink channel is proposed in (O'brien et al., 2008, IV-B) that could be used to exchange channel coefficient measurements.

## 3 IDENTIFICATION OF THE CONSTELLATION AMPLITUDES

Next the three methods USAM, EQSAM and GEOSAM are introduced that generate the constellation

$$\mathcal{A} = \{a_0, \ldots, a_{M-1}\} \qquad (2)$$

at the receiver by selectively switching the transmitter light sources and exploiting information about the physical channel, such as measured channel coefficients and geometric considerations. For each modulation scheme, the cardinality $M$ is given as a function of $N$, the number of LEDs available. Also the PAPR is derived for each schema as the mean ratio of LEDs available to the number of LEDs switched on. In the following we assume equal probable constellation points.

### 3.1 USAM: Universal Approach, Taking Different Path Coefficients and LED Brightness Levels into Account

In the general case, we assume that the $N$ light sources are spatially distributed, e.g. at the ceiling of a room, and exploit the diverseness of the channel coefficients to create an universal SAM (USAM) constellation. The coefficients can be found for example in a training phase where all LEDs are sequentially switched on for one symbol duration and, by measuring the received power, separated into signal part and intersymbol interference (ISI) part. These channel estimates are then communicated to the transmitter in a second step and have to be updated if the environment changes, e.g. the receiver position is changed.

With the assumption of unique channel coefficients, the number of possible constellation points can be derived as

$$M^{\mathrm{USAM}^*} = 2^N. \qquad (3)$$

Instead of employing an exhaustive search to select $M$ constellation points closest to the intended ASK constellation from the $M^{\mathrm{USAM}^*}$ possible amplitude values we reduce the complexity by using the following suboptimal algorithm:

1. Save receive powers $Pr_n$ in set $\mathbf{C}$. Variants:
   (a) in descending order
   (b) in random order
2. The constellation's extreme values are given as

$$a_0^{\mathrm{USAM}} = 0 \qquad (4)$$

$$a_{M-1}^{\mathrm{USAM}} = \sum_{n=0}^{N-1} Pr_n\,. \qquad (5)$$

3. Derive $a_m^{\mathrm{USAM}}$ for $m = 1, \ldots, M^{\mathrm{USAM}} - 2$.
   The desired amplitude ASK constellation amplitudes $d_m$ are given with

$$d_m = \frac{a_{M-1}^{\mathrm{USAM}}}{M^{\mathrm{USAM}} - 1} m\,. \qquad (6)$$

   The approximated USAM constellation points can be found as follows:

$a_m^{\mathrm{USAM}} = 0$
**foreach** $c$ *in* $\mathbf{C}$ **do**
  **if** $a_m^{USAM} + c \leq d_m$ **then**
    $a_m^{\mathrm{USAM}} = a_m^{\mathrm{USAM}} + c$
  **end**
**end**

This search method reduces the number of possible combinations to

$$M^{\text{USAM}} = \frac{N(N+1)}{2} + 1\,. \tag{7}$$

This simple procedure is close to the optimal solution, if $M^{\text{USAM}} \ll M^{\text{USAM}^*}$ and a uniform distribution of the combinatoric combinations can be assumed, which is valid in most cases.

The PAPR is two, if random ordering is applied and can be derived to three for the case of descending order as follows:
If we assume uniformly distributed amplitudes, the PAPR is given as

$$\text{PAPR} = \lim_{M\to\infty} \frac{M}{\sum_{m=0}^{M-1} \int_{x=0}^{\frac{m}{M-1}} (1-x)\,dx} \tag{8}$$

$$= \lim_{M\to\infty} \frac{12\,(M-1)}{4M-5} \tag{9}$$

$$= 3 \tag{10}$$

Furthermore, it is possible to include additional optimization constraints like accounting for non-linear detectors or reducing the ISI power by preferring the light sources with a high signal power to ISI power ratio.

### 3.2 EQSAM: Simplification by Assuming Equal Receive Power for All LEDs

Given the special case that all receive power amplitudes can be assumed to be approximately the same, there are

$$M^{\text{EQSAM}} = N + 1 \tag{11}$$

possible constellation points and in contrast to USAM no uplink channel is necessary to communicate the varying receive power values. This assumption is typically valid if all LEDs are operated with the same transmit power $P_{t_n}$ and are geometrically close together compared to their distance to the detector. The constellation points then are

$$a_m^{\text{EQSAM}} = \begin{cases} 0 & m = 0 \\ \sum_{n=0}^{m-1} P_{r_n} & m = 1 \ldots M-1 \end{cases} \tag{12}$$

where $m$ can be interpreted as the number of arbitrarily chosen LEDs that are switched on at a time. This leads to an PAPR of two, since in the mean half of the LEDs are switched on.

The cardinality of the constellation alphabet can be reduced by grouping the LEDs. With $G$ LEDs per group, one can construct a constellation of cardinality

$$M^{\text{EQSAM,grouped}} = \left\lfloor \frac{N}{G} \right\rfloor + 1. \tag{13}$$

### 3.3 GEOSAM: LED Amplitudes in Geometric Series

We consider a third case (compare (Li et al., 2013)) where the transmit powers of the LEDs are adjusted in a geometric series. With the assumption of equal channel characteristics for all LEDs (similar to EQSAM) the receive values are structured as follows:

$$\mathbf{P_r} = \left[\frac{P_{r_0}}{2^0}, \frac{P_{r_0}}{2^1}, \frac{P_{r_0}}{2^2}, \ldots, \frac{P_{r_0}}{2^{N-1}}\right]. \tag{14}$$

For this special setup the number of possible constellation points is

$$M^{\text{GEOSAM}} = 2^N. \tag{15}$$

The constellation amplitudes can be calculated as:

$$\mathbf{a}^{\text{GEOSAM}} = \mathbf{S} \cdot \mathbf{P_r}^T \tag{16}$$

with a binary counting switching matrix

$$\mathbf{S} = \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ \vdots \\ 2^N - 1 \end{bmatrix}_{10} = \begin{bmatrix} 0 & \ldots & 0 & 0 \\ 0 & \ldots & 0 & 1 \\ 0 & \ldots & 1 & 0 \\ 0 & \ldots & 1 & 1 \\ \vdots & \ddots & \vdots & \vdots \\ 1 & \ldots & 1 & 1 \end{bmatrix}. \tag{17}$$

The PAPR is two, since half of the entries in $\mathbf{S}$ are one and each element of $\mathbf{a}^{\text{GEOSAM}}$ is even likely to be chosen.

The adjustment of the transmit power levels of light sources can be achieved with different methods, among others to use different LED types, to adjust the driving circuit, to use pulse-width modulation or to attenuate the optical path. A promising method is to combine multiple LEDs to one light source, such that the optical power levels emerge as proposed in geometric series. This method does not require an uplink channel.

## 4 SIMULATION RESULTS

### 4.1 Environment and Parameters

To allow a comparison of SAM to known results, the lighting scenario including the electrical parameters and the geometric composition was taken from (Komine et al., 2009), and used to generate all simulation results:

- Room of size $5\,\text{m} \times 5\,\text{m}$ and $3\,\text{m}$ height. All simulations were performed using a grid with $0.125\,\text{m}$ spacing. The refraction indices of the room boundaries are $p_{\text{ceiling}} = 0.8$, $p_{\text{wall}} = 0.5$ and $p_{\text{floor}} = 0.2$.

- Photo detector with a surface area of $1\,\text{cm}^2$ and conversion efficiency of $0.54\,\text{A/W}$ is located at a $0.85\,\text{m}$ high desk and looking upwards.
- Receive amplifier parameters: $I_{bg} = 5100\,\mu\text{A}$, $I_2 = 0.562$, $I_3 = 0.0868$, $T_k = 298\,\text{K}$, $G = 10$, $g_m = 30\,\text{mS}$, $\Gamma = 1.5$ and $\eta = 112\,\text{pF/cm}^2$.
- The USAM simulation results are generated with four lamps that are mounted on the ceiling at the coordinates $(1\,\text{m}, 1\,\text{m})$, $(4\,\text{m}, 1\,\text{m})$, $(1\,\text{m}, 4\,\text{m})$ and $(4\,\text{m}, 4\,\text{m})$. Each is equipped with $10 \times 10$ LEDs with $4\,\text{cm}$ spacing next to each other. The LEDs are of type LXHL-LW6C with a semi-half angle of $80\,°$, the electrical transmit output power is given with $0.452\,\text{W}$.
- For EQSAM and GEOSAM seven LEDs where placed on a circle with a radius of $5\,\text{cm}$ at the center of the ceiling.

## 4.2 Receive Amplitude Accuracy

The key advantage of the proposed SAM methods is the ability to create receive power values in the range

$$0 \le P_r \le \sum_{n=0}^{N-1} P_{r_n} \tag{18}$$

without the need of analog amplifier circuits. The accuracy of these amplitudes is discussed in the following.

In case of USAM we are able to cover the complete value range with a modest amount of individually switchable light sources. This is possible due to the LED's receive amplitude diversity, caused by their individual orientation and distance to the photo detector. Assuming perfect channel knowledge, it can be shown that the discrepancy between the generated receive power values $a_m$ and the intended $d_m$ ones is very small. The proportional amplitude error is depicted in Figure 1 for both variants of the algorithm. In the random case, the error is smaller than 1 % for 97 % of the full scale value range and by sorting a further improvement can be achieved. Since the amplitude error is a-priori known at the transmitter and, as shown, very small for a typical office room scenario, it can be neglected in most cases.

To create EQSAM with receive power values close to an ASK constellation, it is essential to place the LEDs close together and in sufficient distance from the receiver, such that their angles and distances to the detector are virtually equal. To evaluate the amplitude accuracy, the probability distribution of an $8-$EQSAM constellation is exemplarily shown in

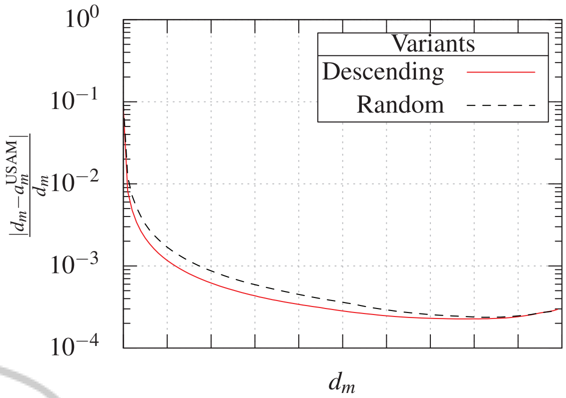


Figure 1: Proportional error of the constellation constructed with USAM in reference to the desired ASK constellation. The error is an average of all positions in the room at desk height. The number of reflections is limited to one.

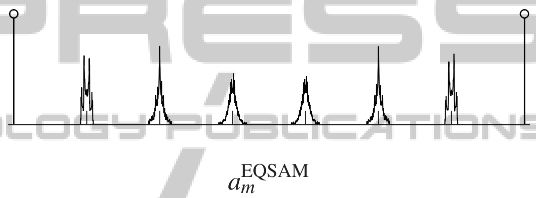


Figure 2: Probability distribution of the EQSAM constellation at desk height.

Figure 2. It can be observed that the preciseness is sufficient, when compared to the other relevant noise sources. Changes in the environment, such as persons moving in the room, are of similar influence on all LED light paths and in consequence scale the constellation, but are of negligible influence on the individual constellation points.

Since the contribution of GEOSAM compared to EQSAM lies in reducing the amount of required switching elements while maintaining the geometric LED arrangement, similar results concerning the constellation accuracy can be expected.

## 4.3 Error Rate Performance

Assuming error free constellation amplitudes, justified in the last section, one can generate arbitrary positive and real-valued waveforms at the receiver. However, for a simple performance evaluation we will restrict ourselves in the following to generate ASK constellations and calculate the SER for this special case.

Comparing the different noise sources in Figure 3, one can identify ISI to be the dominating noise source. Consequently, increasing the number of constellation points, while keeping the data rate unchanged greatly reduces the SER, as shown in Figure 4. E.g. for a SER of $10^{-4}$ the data rate can be

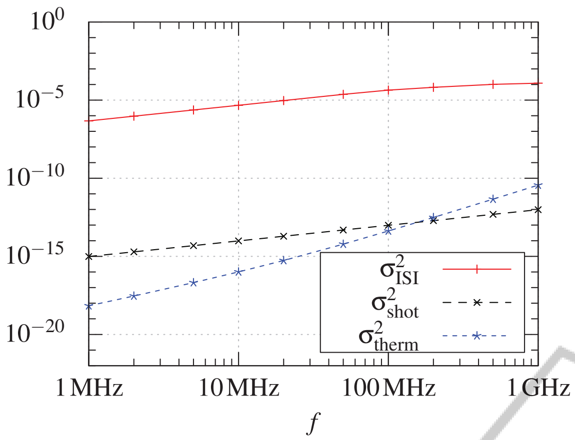


Figure 3: Noise sources at different symbol rates using OOK at detector position $(0.3\,\mathrm{m}, 2.1\,\mathrm{m})$.

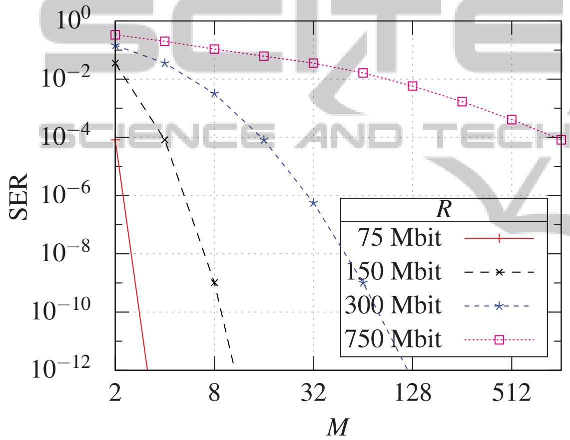


Figure 4: SER of EQSAM for an detector at position $(0.3\,\mathrm{m}, 2.1\,\mathrm{m})$.

increased by the factor of 10 using 1024 – EQSAM instead of OOK. Likewise the thermal noise and the shot noise occurring in the receive amplifier circuitry depend on the switching speed. This can be explained by the increased bandwidth requirements on the receive amplifier.

### 4.4 Peak to Average Power Ratio

When applying the SAM switching schema on an LED cluster, it is favorable, in terms of operating efficiency, to fully exploit the LEDs maximal luminous output power. This is ensured, if the modulation method's PAPR does not exceed the LED's peak to average current limit.

With equal distributed input sequences, the PAPR is two for GEOSAM and EQSAM. While an homogeneous distribution of the switching pattern for the individual LEDs is inherently given when using GEOSAM, it has to be ensured for EQSAM, e.g. by rotating the LED assignment for every send symbol.

The PAPR of USAM using the sorting variant of the algorithm is converging to three for the given simulation setup, e.g. the remaining error is smaller than 6 % for $M^{\mathrm{USAM}} = 8$, but some LEDs are switched on more frequently.

An uniform distribution of the LED usage evolves, if the algorithm's randomized variant is applied for each modulation symbol independently. This variant has a PAPR of approximately two.

## 5 MEASUREMENTS RESULTS

To justify the assumption of quasi-equal channel coefficients in the case of EQSAM and random distribution in the case of USAM we have measured the receive power values for seven LEDs positioned on a ring of 5 cm radius, similar to the simulation setup for EQSAM and GEOSAM. The distance between the light sources and the receiver was set to 20 cm and 100 cm respectively. For a distance of 20 cm the receive values are

$$[0.392, 0.468, 0.521, 0.476, 0.421, 0.370, 0.360]$$

and

$$[0.0570, 0.0581, 0.0553, 0.0550, 0.0559, 0.0513, 0.0520]$$

for a distance of 100 cm.

It can be observed that the normalized receive value variance is decreasing from 0.019 to 0.0021 with the distance increasing from 20 cm to 100 cm, that is why we can assume quasi-equal receive values for a typical indoor VLC ceiling light. On the other hand, USAM can be used favorably in cases with varying receive values, e.g. the light sources are distributed on the ceiling of a room. Figure 5 displays the influence of the measured receive power values on the BER of EQSAM, assuming a pure additive white Gaussian noise channel model. The results show a marginal loss of about 0.1 dB for 1 m distance between the receiver and the LED light sources at a BER of $10^{-5}$.

## 6 COMPARISON OF SAM TO ALTERNATIVE INTENSITY-MODULATION TECHNIQUES

An alternative to switching the LEDs completely off is to modulate the binary OOK signal on a DC carrier. Such data transmission systems are proposed in

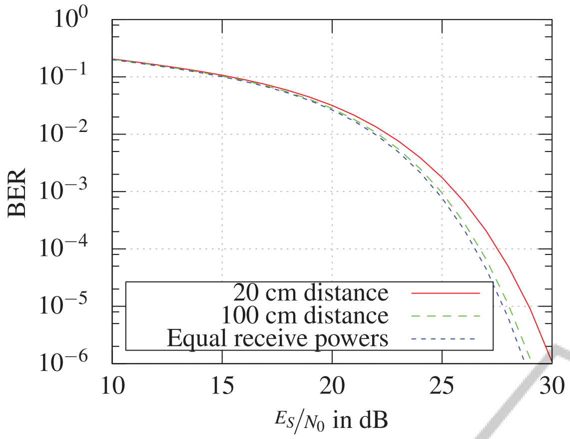


Figure 5: BER of EQSAM with measured receive power values.

(Minh et al., 2009) for a data rate of 100 MBit/s with a modulation depth 0.6 and in (Vučić et al., 2010a) for 230 MBit/s data rate with a modulation depth of 0.03/0.06. With this method the data rates can be increased significantly, at the same time reducing the SNR by introducing a carrier signal. This method can be combined with SAM, resulting in an ASK modulated signal plus constant offset at the receiver.

Another alternative for high speed VLC communication is intensity-modulated DMT signaling, likewise requiring an DC bias. Examples are (Vučić et al., 2010b) with a data rate of 513 MBit/s and a modulation depth of 0.13, (Cossu et al., 2012) with a data rate of 1.5 GBit/s per LED color and (Tsonev et al., 2014) with a data rate of 3 GBit/s. In the following these alternatives are compared to the proposed SAM schemes regarding the hardware effort, the calculation complexity as well as concerning the achievable data rates.

### 6.1 Hardware Effort

**Transmitter.** For implementing the SAM transmitter one can replicate a low-complexity OOK transmit circuit for a number of LED lighting elements. In our setup, we used two mosfets of type IRML2030, one ISL55111 gate driver and six passive components to construct a low-cost switching element that can be operated with 40MHz switching speed in conjunction with an Osram Ostar LED of type LE B Q8WP. For higher switching speeds an additional DC-biasing is often employed.

In contrast, the use of intensity-modulation techniques like DMT typically require a high-speed digital-to-analog converter, an linear amplifier circuit and a DC-bias for driving the transmit LEDs. Thus, the circuit complexity of SAM is significantly lower than for intensity-modulated schemes like DMT.

**Receiver.** The typical receiver consists of a photodetector, a transimpedance-amplifier and an analog-to-digital converter. In contrast to DMT systems, ASK demodulation like used for SAM, can alternatively be implemented using analog components for detection.

### 6.2 Computational Complexity

The computational effort of SAM is low, since only a mapping of the serial datastream to the transmit units is required. Additionally, in case of USAM, the mapping rule is updated if the channel coefficient change.

For intensity modulation, compensation of the LED characteristics (compare (Elgala et al., 2010)) is required, whereby the SAM method inherently superimposes the amplitudes to an intensity-modulated signal without introducing distortions.

### 6.3 Achievable Data Rates

Using SAM, the data rates increase with the number of individually switchable lighting elements. For example, the 230 MBit/s OOK setup in (Vučić et al., 2010a) could be combined with an 32-SAM approach to obtain a data rate of 1150 MBit/s. This would require the use of 5 (GEOSAM), 8 (USAM) or 31 (EQSAM) LEDs. Comparable rates can be obtained with DMT, for example using a single intensity-modulated LED.

## 7 CONCLUSION AND OUTLOOK

We introduced a novel method for generating arbitrary receive waveforms by digitally switching individual LEDs, dubbed SAM. With this method the data rate of OOK VLC systems can be increased without the need for intensity-modulation of individual LEDs. In particular, this allows to generate an amplitude modulated LED light source with a modulation depth of one.

Increasing the data rate while maintaining the LED switching speed is one possibility for the development of high speed VLC systems offered by SAM. One reason is the junction capacity of the LEDs as limiting physical parameter. The advantages of using SAM are even more significant, when phosphoric materials or organic LEDs are used, that further limit the possible signal bandwidth.

On the other hand, given a data rate requirement, we are able to reduce the symbol rate and therewith ISI. This leads not only to increased SNR values, but also the employed equalization algorithms can be, if not removed completely, at least reduced in complexity.

One open question is the implication on the constellation accuracy in time-varying environments. A next step could also be to use the new SAM methods in combination with modulation schemes like DMT.

The channel coefficients, obtained by the receiver can be used additionally for positioning and localization purposes.

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