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Localization of the user in beam steered optical wireless communication systems

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In an ever more interconnected world, the pursuit of advanced communication technology with rapid data transmission capabilities has become a focal point of extensive research endeavors. Optical wireless communication systems have found widespread application across various scenarios due to their ability to deliver fast data transmission, robust security measures, and energy-efficient performance. Over a long distance, their performance may be degraded due to atmospheric conditions, but for short-medium ranges, optical systems are very attractive compared to RF systems. OWC systems can be used as an independent system as well as jointly with RF systems.

To cover an entire room or office space, OWC systems with LEDs often use wide beams. Contrary to LEDs, lasers can be modulated at higher bit rates. To provide a high bit rate and to avoid interference, it is better to use a narrow beam as a wide beam prompts high attenuation. The use of a narrow beam requires it to be pointed towards the user or a target receiver, which may require a lengthy user search [1]. Recently, the authors published a solution [2] [3] that quantifies the search performance of a number of search strategies. A summary of these results is in the appendix, which largely follows these papers. Yet, in the current paper the authors elaborate the debate on the consequences of these findings, by interpreting these results.

We made a number of system choices in [2] [3]:

- We avoid systems in which the outgoing and incoming paths are identical. Recently, in satellite communication, systems where outgoing and incoming beams follow the same path, have become quite popular, which also repeat the idea of a compact-disc. Such idea lies in a property that if your transmitter is aligned, then your receiver is also aligned. However, they prove to be complicated and require optics of considerable size. These systems are very effective for FSO but it is yet to be seen such systems to be miniaturized. In fact, these may require bulky optics with movable mirrors and semi-transparent mirrors to split incoming an outcoming beams

- No retroreflector: The use of the retroreflectors is regularly seen in various optical wireless applications. However, not every application can use retroreflectors. Retroreflectors could be detrimental in military applications as they immediately compromise the position of their bearer. Also, due to its nature, there are possibilities of false locks in a case where coverage area may have strong reflectors.

- Future proof by allowing fast searching when mechanical limits are resolved by fast photonic beam steering

Our approach focuses on the optimization of the forward link of the user localization system, with the assumption that the feedback channel through which the user device transmits back that the forward beam has found its target. The feedback channel may have a slower, non-aligned beam as the system is designed not to be sensitive to the latency of the feedback channel. This feedback link may be an RF channel.

Therefore, the choice of the system was made in favor of a high bitrate narrow beam. The feedback channel uses a wide beam as it works independently of the transmitter, as only when the address identifier is received, the feedback channel works (Fig. 1). Thus, it will reach the (primary) central station as it has a slower bit rate, for instance using a wide optical beam or an RF signal.

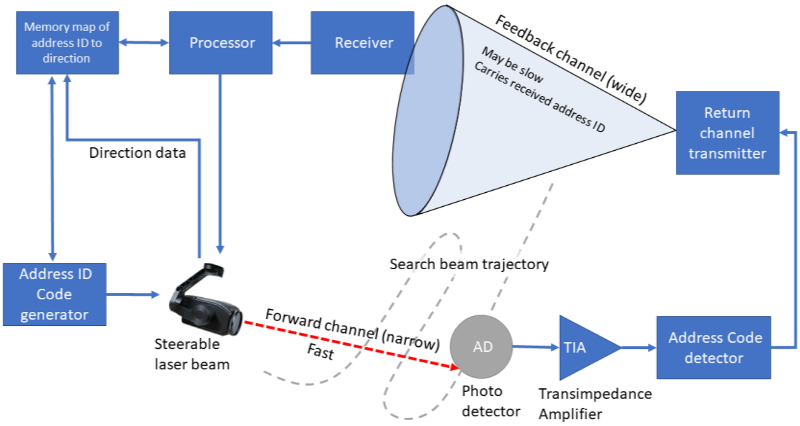

Fig. 1. Functional block diagram of the optical wireless communication link with fast forward search beam and non-critical feedback channel.

The transmitter at the central station sends address identifiers while swiping the laser beam over the coverage area in search of users (target devices) (Fig. 2). Each address identifier corresponds with the angular and directional position of the beam steering device. When the target device receives an identifier, it reports its back via a slower feedback channel. Therefore, the transmitter knows in which position of the beam steering device, the user was found.

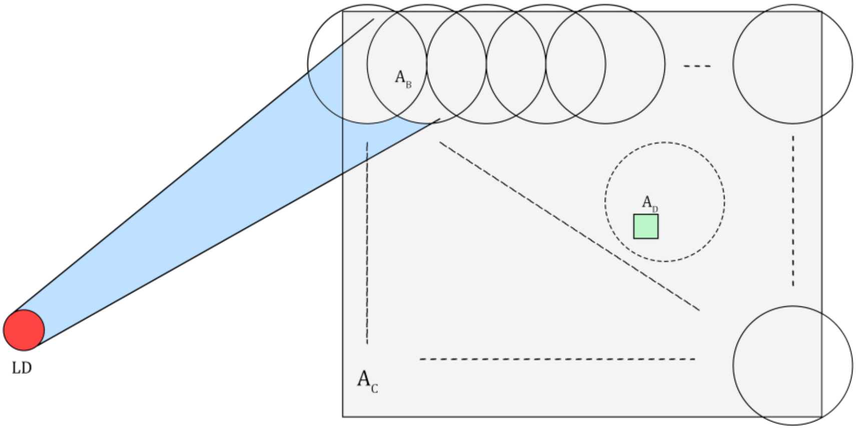

Fig. 2. Example of the laser beam with width A_B scan system that search over the coverage area $A_C$with resolution $A_R = A_B$. Simplified for step wise motion of the scanning beam.

Continuous scanning introduces an interesting effect to the acquisition process that we observe on the receiver side. As the beam swipes across the detector, the signal strength does not remain constant, but it has a rather Gaussian distribution. Fig. 3 shows an experiment that we conducted, where we manually swiped the beam across the coverage area with the detector inside. The experiment shows how misalignment between the transmitter and the receiver affects the signal-noise ratio during packet reception. Manchester-encoded signals can effectively handle such rapid variations, thus avoiding the need for accommodating an address data packet during a period when the signal is constant in strength.

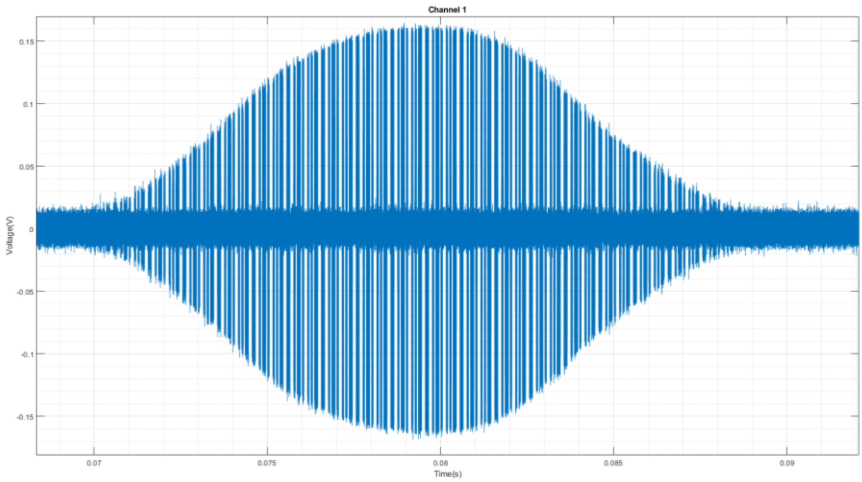

Fig. 3. Example of the laser beam swiping across the detector transmitting one or more address identifiers.

We start with evaluating a system that transmits directional addresses as a data packet with a header, sync word, and error correction bits. A research question is how wide the beam should be. Wider beams cover more area but contain less power per unit of detector area. Hence the bit rate needs to be reduced.

As an acceleration, we introduced the concept of coded-beam searching [2], [3] that uses a linear feedback shift register (LFSR) sequence. It is a type of shift register that is particularly known for its simplicity and efficiency in generating pseudorandom sequences of bits. The key characteristic of an LFSR is its feedback mechanism, which involves using XOR (exclusive OR) for certain bits in the shift register and then feeding the result back to the input. This feedback loop is responsible for generating the pseudorandom sequence [4]. Using the properties of pseudorandom binary sequence (PRBS), we can effectively reduce the number of transmitted bits.

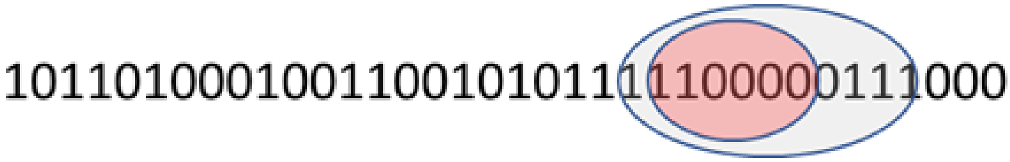

Fig. 4. LFSR sequence emitted during search. Red effective subset sufficient for location recover, blue: additional reduction symbols that allow error correction

As every N bits of the LFSR sequence with a period $2^N - 1$ are unique, it is possible to map the whole sequence onto the space where the user is located, which also means that bits correspond to the angular and directional position of the beam steering device. The bigger the sequence, the higher the precision. In that case, if the detector receives N bits and transmits them back to the central station, it is possible to find the exact location of these N bits in the sequence and, therefore, the exact location of the user.

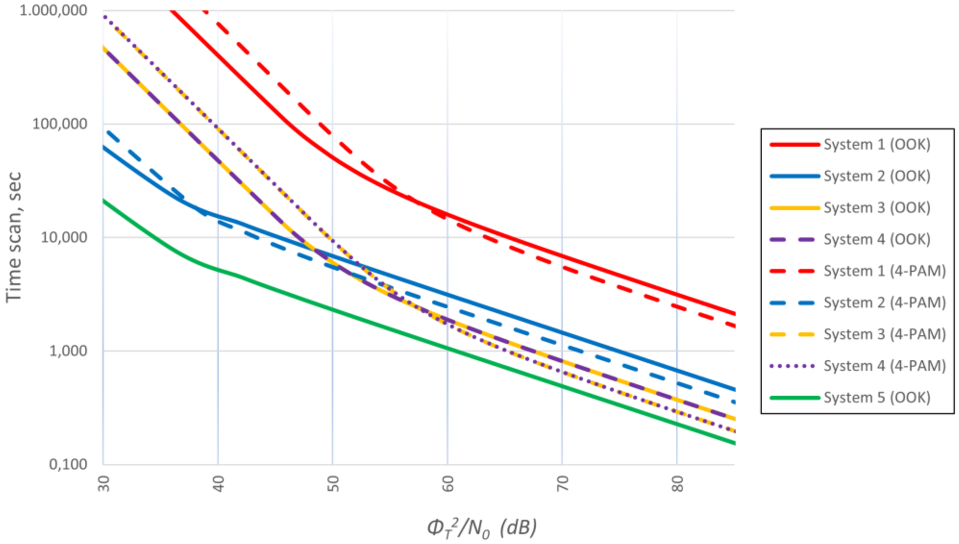

Fig. 5 [2]. Acquisition time for Systems 1-5 with different modulation schemes when $\boldsymbol{A_D} = \mathbf{1}$ mm², $\boldsymbol{N_0} = \mathbf{10^{-14}}$ Hz/W, $\boldsymbol{A_B} = \mathbf{10}\boldsymbol{A_D}$, $\boldsymbol{C_S} = \mathbf{6.47}$ pF, $\boldsymbol{R_F} = \mathbf{1}$ k$\boldsymbol{\Omega}$. Comparison between 4-PAM systems and the OOK-LFSR system. System description: see Appendix. System 1 and 3 use wide beams. System 5 uses a LFSR

We considered 5 system designs (see Appendix for details) and assumed that the shape of the beam does not change regardless of the angle of arrival. In particular, we found that

- Widening the beam during the search process (System 1 and 3) is seemingly a faster way to find a counter station. However, an idealized IM-DD system with emitters and detectors of infinite bandwidth may work counterproductively. If we model the acquisition of a lock by assuming that a minimum electrical energy is needed at the detector, a rapidly scanning, but narrow beam is advantageous: In fact, a large optical power can be deposited on the detector in a short time. The electrical power is proportional to the square of the current from the photo diode, thus to the square of the optical power. Widening the beam by a factor *N* in radius reduces the area covered by the beam by a factor N^2 reduces the optical power by a factor N^2, and reduces the electrical power by a factor N^4. Hence the beam needs to touch every possible detector location N^4 times longer, thus the beam can only move on N^4 times slower.

- For this reason, IM-DD is fundamentally different from searching with a radio beam for which the received electrical power would reduce N^2 times for an increase of the beam radius by *N*. In such cases, a reference beam and a widened beam find the target equally fast. Also, for an OWC system limited by a minimally required number of photons at the detector per detection, increasing the beam radius by *N*, reduces the effective number of photons at the detector by N^{2}. Also in this case, a reference narrow beam and a widened beam find the target equally fast. The observation that IM-DD fundamentally differs, justifies further research and paves the way for further work.

- While the advantage of using a narrow beam for IM-DD seems large, a closer modelling of the effects of photo diode response and of the noise generated in a typical transimpedance amplifier reveals that these conclusions need to be treated with caution. There are limits to effectively useful bandwidth during scanning. These effects were ignored in [2] but quantified in [3]. These are seen as a knee in Figure 5. It also shows that wide-beam System 3 can be fairly fast, particularly for very strong signals.

- A coarse-fine approach showed good results and should be further explored with various beam sizes, as it performs similarly to the approach based on the LFSR sequence.

- The transmitter needs to send “address IDs” to the receiver, which can be used as a reference to the transmit angle during the transmission of the signal that reaches the receiver. The overhead in creating addresses typically is large. Firstly, the non-synchronized receiver must see the beam at least during two full successive packet durations. Sync words, headers, and error correction may be needed. These reduced the search speed.

- An addressing scheme based on a LFSR sequence can lead to substantial gains in avoiding overhead.

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Appendix A

As each station has to direct the x and y (or azimuth and altitude) direction for both the receiver and the transmitter, finding the direction may require an 8-dimensional search. Several solutions have been proposed to reduce the dimensionality. One approach is to build an optical transceiver in which the outgoing and the incoming beam follow the same path, actuated in a direction by the same movable mirror. This reduces the search to 4D, but the size of the common optics typically is relatively large and etendue issues may prohibit the miniaturization of such an approach to sizes that fit on a smartphone or IoT device. There is also a use case for retroreflectors as in [5], [6]. Nonetheless, such a method of feedback channel may falsely lock to a naturally strong reflector. In applications that are connected to the military, the use of retroreflectors may compromise its carrier, making it easy to spot and trace.

We study a system where the transmitter sends a signal with an optical power Φ_T over the detector with an effective area A_D, upon arrival the size of the beam is A_B. Thus, the received optical power Φ_R can be calculated as

$$\Phi_R = \frac{A_D}{A_B}\Phi_T. \tag{1}$$

Non-avalanche photodetectors generate about one charge carrier for each photon received. Therefore, the electrical current is proportional to the optical power

$$\mathrm{P}_{R,el} = \left(\frac{A_D}{A_B}\right)^2 \eta_R^2 \Phi_T^2, \tag{2}$$

where $h = A_D/A_B$, η_R is the responsivity of the detector. Eqn. 2 shows that enlarging the beam size is counterproductive to the received power, thus the bitrate, as it comes at a cost of energy per bit that is the *fourth* power of the radius. In that case, the duration of sending each address identifier will also be increased.

To encode the position of the steering device with a resolution A_R, $N_a = \left\lceil \log_2(\frac{A_C}{A_R}) \right\rceil$ bits are needed. For discrete addressing, N_h bits are needed for the header of each position. At the receiver side, the noise spectral density increases above the 3 dB limit at f_c, according to [7]

$$f_c = \frac{1}{2\pi R_F C_S}. \tag{3}$$

Where R_F is the feedback resistor and C_S is the capacitance of the photodetector. When we optimize the system by letting $f_{max} > f_c$, the noise enhancement penalty $\kappa = 1 + \frac{4}{3}\pi^2 R_F^2 C_S^2 f_{max}^2$ appears. To reduce power dissipation and use lower bandwidth, one may choose On-Off Keying (OOK) or Manchester encoding. Thus, the bit rate

$$R_b = f_{max} \leq \sqrt[3]{\frac{h^2 \eta_R^2 R_F^2 \Phi_T^2}{\frac{4}{3}\pi^2 \mathrm{C}_\mathrm{S}^2 \Gamma N_0}}. \tag{4}$$

To improve energy efficiency, one may use the highest possible M that matches the signal-to-noise ratio (SNR). It may use $f_{max} > f_c$ until the SNR is satisfied. Thus, the maximum achievable bitrate is

$$R_b = f_{max} \left\lfloor \log_2 \left(1 + \frac{A_D^2 \eta_R^2 R_F^2 \Phi_T^2}{A_B^2 \kappa \Gamma N_0 f_{max}} \right) \right\rfloor. \tag{5}$$

From that point, it is easy to express the time spent on the search of the user within the coverage area A_C. The scan time equals the number of bits per position/address, times the number of addresses, A_C/A_R, and time the duration of transmitting one bit. For OOK, the time scan is

$$T_{scan} = 2 \left\lceil \log_2 \frac{A_C}{A\_R} + N\_h \right\rceil \frac{A_C}{A_R} \frac{\kappa \Gamma N_0}{h^2 \eta_R^2 R_F^2 \Phi_T^2}. \tag{6}$$

And for M-PAM systems, it can be expressed as

$$T_{scan} = \frac{2 \left\lceil \log_2 \frac{A_C}{A_R} + N_h \right\rceil \frac{A_C}{A_R}}{f_{max} \left\lfloor \log_2 (1 + \frac{A_D^2 \eta_R^2 R_F^2 \Phi_T^2}{A_B^2 \kappa \Gamma N_0 f_{max}} \right\rfloor}. \tag{7}$$

We developed a novel and efficient method for encoding the angular direction for the steering device to ensure a fast and error-free search for establishing a connection for laser-based optical wireless communication systems. The idea lies in the use of a pseudo-random binary sequence generated by linear feedback shift register (LFSR) with the length L and a period $2^L - 1$. The prominent feature of such a sequence is that every L bits are unique and can be identified in its position within the full sequence, which makes it possible to use in encoding. The transmitter and the receiver must share the knowledge of the LFSR sequence. In that case, the sequence is mapped to a coverage area A_C in a way that the detector can receive a full period (or more) of the sequence. When the detector receives bits and sends them back to the transmitter, it is possible to identify the position of the steering device that is aligned with the detector.

In some cases, two different beams are used for acquisition and communication. It is also possible to change the beam size between the two procedures. However, using the same beam drastically simplifies the system and as we saw earlier, a narrow beam can perform better than a wider beam system. For comparison, we suggest 5 systems and evaluate their performance. We keep certain parameters constant. The responsivity of the photodetector $\eta = 0.7$ A/W, the size of the detector is $A_D = 1$ mm^2, noise floor $N_0 = 10^{-14}$ W/Hz, coverage area $A_C = 16.8$ m^2. For BER=10^{-4}, modulation gap $\Gamma = 4$. Transmit power Φ_T has been chosen in a way to guarantee eye-safe communication for all systems considered.

1) System 1 (wide beam): On the surface, one may consider wide beam as an attractive option for acquisition, which is what we based our System 1 on. Such a system uses wide beam $A_B > A_D$, therefore fewer steps and send full discrete address for each position. However, this approach has several downsides. Most laser beams have Gaussian distribution profile, and if the beam and detector is not perfectly aligned at the point of detection, the system can not facilitate high bitrate, due to irradiance being decreased towards the edges of the beam. Therefore, instead of resolution $A_R = A_B$, we opt to $A_R = A_D$ to avoid imbalances in the system.

2) System 2 (narrow beam): The system proposed here has all the same parameters as System 1, except the beam size. In this system, we use narrow beam $A_B = A_D$, which enhances the energy per bit. However, during continuous scan, the user might see random packet boundaries and to ensure that the receiver can receive one complete packet at every position, the transmitter needs to send at least two full addresses. Therefore, the number of bits sent per position is greater than in System 1.

3) System 3 (wide-wide beam): System 3 uses a coarse-fine approach based on System 1 ($A_B > A_D$). Its first step is to conduct a coarse search over the coverage area A_C with the resolution $A_R = A_B$ as we only need one hit on the detector. In such case, it is not necessary to align detector to the center of the laser beam. After identifying the approximate position of the user, the system conducts fine search within the small area with the resolution $A_R = A_D$. As Systems 1 and 2, System 3 uses full discrete addresses. The number of steps is smaller than in Systems 1 and 2, which make this approach faster.

4) System 4 (wide-narrow beam): System 4 practically replicates System 3, except the second step. During the second step, System 4 uses a narrow beam to conduct a fine search $A_B = A_D$. However, it drastically complicates the system as it requires additional optics or a second laser.

5) System 5 (LFSR encoding): System 5 uses a narrow beam and performs encoding by using the LFSR sequence. Evidently, the transmitter and the receiver must share the knowledge of the LFSR polynomial. Error correction comes for free: if more than N bits are received, it is possible to use the excess bits for error correction because these extra bits have to adhere to the feedback polynomial of the LFSR. This system can use a continuous scanning swipe.

Fig. 5 shows the comparison between earlier described systems. System 1 proves to be the slowest for both choices of modulation. It is clear that the difference between System 3 and 4 regardless of the choice of modulation is minimal. System 3 and 4 can be used if there is another limit to modulation bandwidth (e.g., use of LEDs). It is also seen that increasing the number of levels can speed up the search process. Nonetheless, System 5 outperforms other systems in all suggested scenarios.

In OWC system, it is counterproductive to widen the search beam as the reduction of the number of positions are disproportionately reduces energy per bit. We developed a novel and efficient method for encoding the angular direction of the steering device to ensure a fast and error-free search for establishing a connection for laser-based optical wireless communication systems. For our example, the use of an LFSR speeds up scan time up by an order of magnitude compared to methods that require sending discrete addresses. As the receiver knows the polynomial of the LFSR sequence, additionally received bits outside the main address data can be used for error correction which saves even more time compared to approaches using packet-based addressing.