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***Abstract*—In a communication system with steerable laser beams, the transmitter must find the direction towards the receiver. This requires a feedback loop such that the receiver can signal that the correct direction has been found. However, the receiver may not be able to instantly give high-resolution feedback if the beam hits its detector. At least during the acquisition phase, thus before transmitter and receiver are aligned in both directions, this feedback channel typically has a wider beam and a much lower bandwidth, thus a (possibly random) latency and a lower time resolution. It is often not practical to adaptively widen the optical beam during acquisition, but even if one designs for an adaptive beam width, it is not evident that this accelerates the search as we argue in this paper. The paper also describes a suitable address coding scheme based on maximum-length Linear Feedback Shift Register sequences, that accelerates the search significantly.**

I. Introduction

In optical wireless communications, it is a challenge to ensure that the laser beam covers the target client device. As it requires real-time knowledge of the direction towards the counter station, which may not always be available during the set up of a link. For LED-based communication systems, it is often solved by projecting a wide beam over a coverage area so that every possible position is covered within the light beam. This leads to a relatively weak signal, which limits the achievable bit rate. Lasers create more coherent light than LEDs and give more confined beams. Lasers also have a much broader modulation bandwidth than LED. But working within eye-safety limits for indoor optical communications means that using a relatively high power is prohibitive. Nonetheless, the use of a narrow beam is preferred for high bit rates and low power consumption.

The acquisition system may use a feedback loop such that the client device can transmit back when the beam from the central station found the correct position of the client. This feedback loop may have to use a wider beam, thus use a lower bandwidth, and may have unknown latency and timing offsets caused by creation and scheduling of data packets.

There are examples that report practical implementation of the search systems but that proves to be time-consuming [1], low precision, and power inefficient due to a large beam spot [2]. However, little literature has been devoted to quantified models for the benefits or drawbacks of a narrow beam, for instance in terms of acquisition search time. Also, the use of dedicated training and addressing sequences is yet not heavily researched. The idea of embedding identifiers or address codes was presented earlier, in [3], for the purpose of channel estimation and to identify the relative light contribution from multiple emitters, but not yet for beam steering.

This paper, to our knowledge, is one of the first in literature that models and evaluates the challenge of position acquisition. We propose a novel method of encoding the direction (or target position) of a steerable device using a linear feedback shift register (LFSR) code. This can improve the search time, compared to conventional address labeling.

For the time being, we ignore limitations caused by the mechanical time response of the steering devices. These may have a large impact on overall search time, but we believe that with the development of integrated photonic steering, mechanical effects would become less relevant, even to the point of not being the main limitation. We focus on limitations caused by the required energy per bit that the detector needs to recover an identifier embedded in the beam.

This paper is organized as follows: Section II and III formulate the model that shows that widening a beam may be counterproductive to accelerate beam searching. The choice of the beam width is described in Section IV. Section V proposes the use of an LFSR instead of discrete addresses.

II. System model

A. Considerations for a width of the search beam

Depending on its design, an OWC system with highly directional beams may have to execute a 4-dimensional search for the transmitter and receiver to align. Acceleration may be if the transmitter sends directional identifiers as it sweeps over the coverage area in search of its receiver location. If the receiver sees an identifier, it reports this via a feedback channel. However, this feedback channel is likely to have a lower bit rate and may have an unknown, variable, and possibly large delay.

In a typical communication setting, a received bit needs to have at least a certain minimum electrical energy to allow reliable detection. In an OWC receiver, a photodiode converts an arriving light intensity, that is, an optical *power* into an electrical signal *current* or voltage. The electrical power is proportional to *the square* of the optical power arriving at the detector.

This has an intriguing consequence if one has to send a message to a detector of size A_D, if the detector is located at an unknown location in a coverage area A_C that has N times the area of A_D: $A_C = NA_D$. Sending the message N times sequentially at full power sending a narrow beam $A_B = A_D$ is much faster than sending a message once, simultaneously to all possible locations, with $A_B = A_C$. The latter yields a signal-to-noise ratio (SNR) that is N^2 smaller than in the former strategy. Thus, to obtain the same received energy per bit, the latter system must run at a bit rate that is N^2 slower, but it only needs to send the message once. The former strategy (N times a narrow beam) is N times faster than the latter (one broad beam). The comparison would be different for RF. For RF, the two scenarios would be equally fast. To our knowledge, this effect has not been reported before. However, it implies that the design of an OWC needs to take the specific properties of SNRs into account.

A transmitter beams an optical power of Φ_T to a target receiver. If a detector captures the arriving photons by means of a detector with effective area A_D and the light intensity is uniform over A_B with $A_D << A_B$, the received optical light intensity, i.e., the optical power is

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

A photodiode converts an incoming photon into a hole electron pair. Hence, the electron current is proportional to the photon density, thus to the electrical power is

$$P_{R,el} = h^2\eta_R^2\Phi_T^2. \tag{2}$$

The responsivity η_R expresses the efficiency of converting photons into electrons (amperes per watt). We defined the pathloss h for an optical system as h_o being the ratio of the optical received light intensity Φ_R over the transmit light intensity Φ_T. In lossless media, the law of conservation of energy implies that the entire light transmit power flows through A_B, thus $h_o = A_D/A_B$. So, the electrical received power relates to $h^2 = A_D^2/A_B^2$. This differs from h_{RF} in radio links where the power gain is inversely proportional to the beam width. For an optical system, the extra square in the received power has large consequences for an optimum system choice for A_B. For comparison, according to expression for RF free space loss, the electrical received power relates to $h_{RF}^2 = A_D/A_B$ if we take for A_D the antenna aperture and A_B the effective beam width.

Already (2) shows that increasing the radius of the beam but keeping to the total optical power constant reduces the energy per bit by the fourth power of the radius. However, for a fixed coverage area A_C, the number of positions that the beam needs to test grows with the square of the beam radius. Therefore, considering that the required energy per bit is a modulation constant, it is apparent that widening the laser beam may be counterproductive as the duration of sending each identifier will be also increased.

Most of the laser beams used in optical communications have, in good approximation, a Gaussian intensity distribution. Getting and keeping the center of the beam aligned with the detector is one of the key challenges for the system. Here, we address an approach for acquisition of the beam direction by a search.

B. Search time and effect of the beam size

The search time T_{scan} can be interpreted as the product of the number of bits per address ID, the number of different directions into which such an ID has to be sent times the bit duration. The beam width has a strong influence on the bit rate that can be used.

Considering a minimum required energy per symbol, the number of symbol levels that can be carried in M-PAM, thus with m bits per symbol can be obtained following [4] or Eq. (9) in [5]

$$M^2 = 2^{2m} = 1 + \frac{h^2\Phi_T^2}{\kappa\Gamma N_0 f_{max}} \tag{3}$$

where Γ is a modulation gap that is derived from bit error rate (BER), N_0 is a noise floor, κ is a noise enhancement that may occur of its parasitic capacitances of the PD needs to be compensated, and the bit rate is $R_b = 2m \cdot f_{max}$. We take $\kappa = 1$. If the detector die has a large size, measures to mitigate the capacitance may lead to a noise enhancement $\kappa > 1$ that grows with f_{max}. This may reduce the bit rate at which a very focused beam can be sent. Evaluation of this effect is outside the scope of this work and will be reported later in detail. To carry M-PAM with m bits per symbol, (3) reveals the need for minimum SNR, with

$$\text{SNR} = \frac{h^2\Phi_T^2}{\kappa N_0 f_{max}} \geq \Gamma(M^2 - 1). \tag{4}$$

If a certain signal power is available at the receiver and if the bandwidth f_{max} is limited beforehand, one may use the highest fitting M. If we restrict M to a power of 2 (integer m), this gives $R_b = 2f_{max}\log_2 M$, thus

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

To simplify beam detection, $m = 1$ (OOK) or even bi-phase (Manchester) encoding may be preferred. To carry OOK, a minimum energy per bit is needed to ensure that in the above expression $\frac{1}{2}\lfloor\log_2(1 + ...)\rfloor \geq 1$ bit per symbol. We can rewrite the equations to express the highest achievable bit rate, by taking the highest possible f_{max} that gives adequate SNR:

$$R_b = 2f_{max} \leq 2h^2\frac{\eta_R^2\Phi_T^2}{\kappa\Gamma N_0}. \tag{6}$$

Via h^2, this is inversely proportional to A_B^2.

C. Address Identifiers

To encode the beam direction from the steering device with a resolution of A_R, we need $N_b = \lceil\log_2(A_C/A_R)\rceil$ bits. One may argue that for a beam spot size A_B and a uniform light level, it would be adequate to use $A_R = A_B$. However, this paper focuses on a pointing accuracy that aims the center of the beam towards the detector, thus $A_R = A_D$.

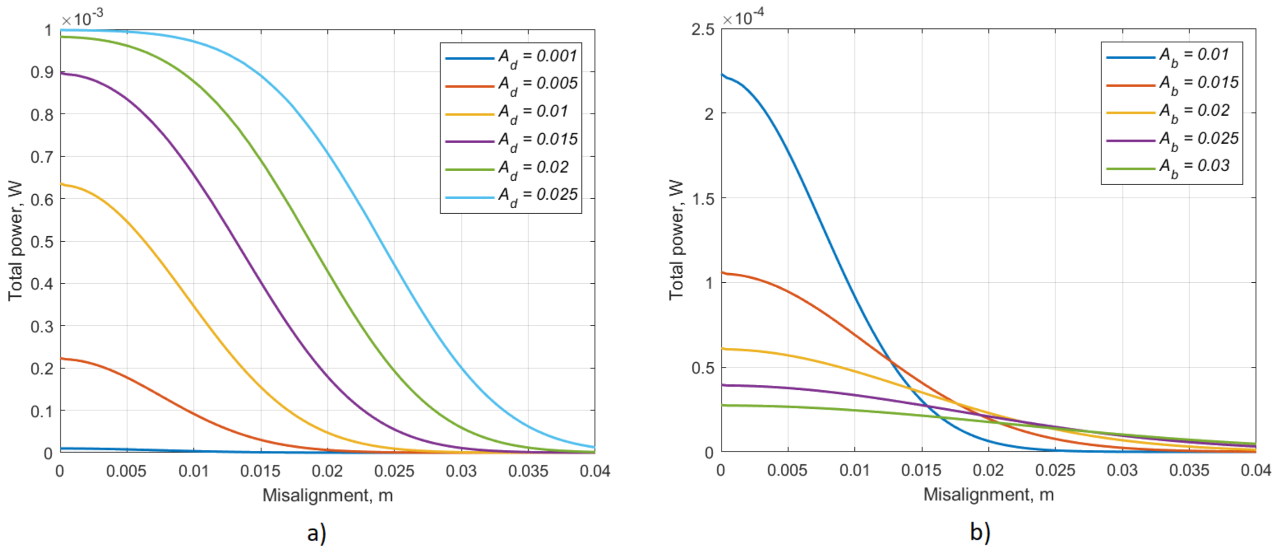

Fig. 1. The influence of the misalignment between the center of a beam with a Gaussian intensity profile and the photodetector. a) for different detector sizes A_D for $\Phi_T = 1$ mW and b) for different beam sizes A_B for $\Phi_T = 2.5$mW.

If the beam has a Gaussian distribution, this gives the highest SNR. We need $N_b = \log_2(A_C/A_D)$ bits. Taking into account N_h header bits, synchronisation bits, and other overhead, the time T_P spent per position follows from

$$T_P = \frac{N_b + N_h}{R_b}. \tag{7}$$

Typically, scanning occurs over N_Y lines, in each of which N_X positions are checked, with $N_b = N_X N_Y$. We do not consider mechanical speed limitations.

The key challenge of the steering mechanism is to align the beam optimally with the detector, therefore the desired resolution of the system is $A_R = A_D$. The number of positions for which an Address ID is needed is the size of the entire coverage area A_C divided by the required resolution A_R: we need $\lceil \log_2 A_C/A_R \rceil$ bits for the addresses. In a typical system, the coverage area may be scanned as N_Y lines of N_X positions on each line. Then $N_Y N_X \approx A_C/A_R$ where the approximation is because it ignores overlaps of A_R footprints to contiguously cover the entire area A_C.

D. Signal strength-limited systems

For any M-PAM, a minimum energy per bit E_b is needed, but OOK ($M = 2$) is the most power efficient. If excess power is available, we use that to make the symbol duration shorter (thus allowing very high f_{max}) rather than to increase M. For OOK, we find a scan time that equals the number of bits per address times the number of addresses times the duration of transmitting one bit:

$$T_{scan} = 2\left(\log_2 \frac{A_C}{A_R} + N_h\right) \frac{A_C}{A_R} \frac{\kappa \Gamma N_0}{h^2 \eta_R^2 \Phi_T^2}. \tag{8}$$

If we insert $h = A_D/A_B$, the counterproductive effect of increasing beam width becomes evident, as it reduces the received power and leads to $T_{scan} \propto A_B^2$:

$$T_{scan} = 2\left(\log_2 \frac{A_C}{A_R} + N_h\right) \frac{A_C}{A_R} \frac{A_B^2}{A_D^2} \frac{\kappa \Gamma N_0}{\eta_R^2 \Phi_T^2}. \tag{9}$$

We will compare the system performance as a function of Φ_T^2/N_0, thus for the same transmit power Φ_T and the same link budget. That implies that the SNR differs per system, depending on A_B and on the bandwidth f_{max} that the system can use. We explicitly note that comparing systems for the same SNR would be misleading. For Manchester encoded signals, a similar expression is found, considering rate 1/2 but it tolerates a lower signal power.

III. Comparison of Scan Times

The scanning strategy needs to send A_C/A_R address IDs and that a wider beam implies that a client device receives A_B/A_R such addresses and picks the one that is received at the highest strength. However, that is not the fastest strategy. Accelerated scans may need to change the beam width in successive scan steps to zoom-in after initially finding a position hit at limited A_B resolution. We leave that for further optimization.

Changing the beam size does not show linear dependencies of the scan time, as it also influences the SNR, thus the feasible bit rate. Increasing the beam size A_B also increases the time scan T_{scan} thus resulting in a slower acquisition 2. Therefore, it urges to use the smallest possible beam size A_B to minimize T_{scan}. Ideally, $A_B = A_D$. From Figs. 2 and 3 is it evident that for the proposed model, making the beam size larger does not result in a more effective scan. In later work, we will elaborate on this relation, and on appropriate

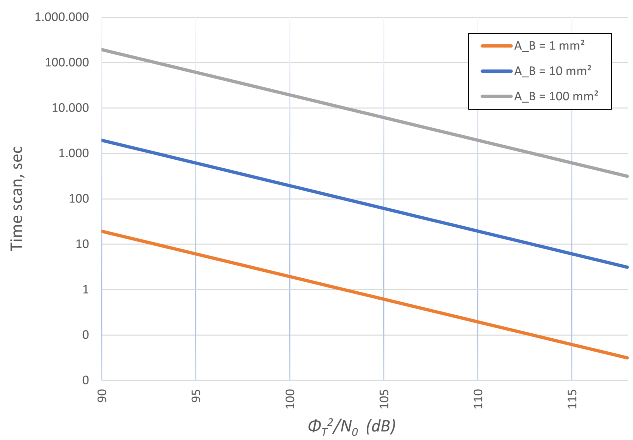

Fig. 2. The influence of Φ_T^2/N_0 over scan time for system with different widths of the beam.

choices for A_B. In fact, we see that A_B preferably is kept small.

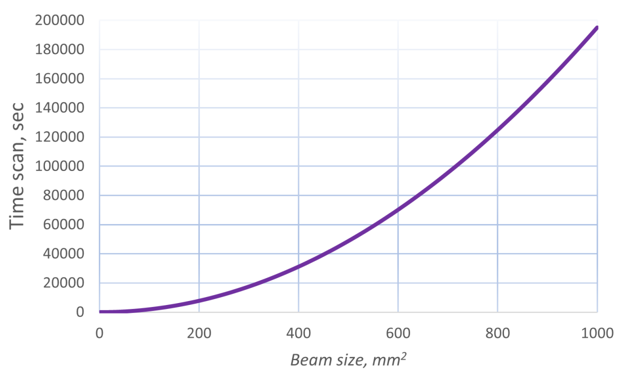

Fig. 3. Time to acquisition versus the size of the beam for the system with transmit power $\Phi_T = 1$ mW, detector size $A_D = 1$ mm^2, and a noise floor $N_0 = 10^{-14}$ W/Hz.

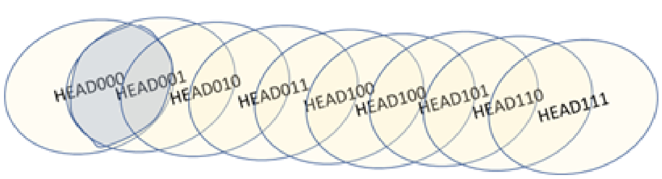

Fig. 4. Packetized address ID, similar to System 1 and 2. Yellow circles: beam are A_B. Grey: the area in which the first packet can be received fully. In this example, packets contain a header and three address bits. The resolution $A_R \approx A_B$.

IV. Beam width Choice

It is possible to use two different laser beams for communication and detector acquisition. But as we saw earlier, it is better to have a high bit rate channel for the searching part as well, as it directly affects the scan time. Therefore, it is reasonable to use one laser beam for both scanning and communication as it also simplifies the system. Then a switch is needed to go from the searching phase into communication.

During a search, there are different approaches to encode direction addresses to identify the position of the steering device as a modulation into the beam data. For the comparison of suggested systems, we keep key parameters constant. The responsivity of the photodetector $\eta = 0.7$ A/W, size of the detector is $A_D = 1$ mm^2, noise floor $N_0 = 10^{-14}$ W/Hz and coverage area $A_C = 16.8$ m^2. For BER $= 10^{-4}$, modulation gap $\Gamma = 4$. Number of the bits for the header $N_h = 64$. Transmit power Φ_T has been chosen in a way to guarantee eye-safe communication for all systems considered.

1) System 1: One, seemingly attractive option is to start with a beam that is artificially made very wide to have fewer steps for each scan line and to send a full address to each step-position which is how we modelled System 1. But this approach has several downsides. Firstly, beams usually have a Gaussian profile. If the system is not aligned perfectly, we can spot drastic losses in received power (Fig. 1). This leads a lower than ideal energy per bit, a lower signal-to-noise ratio and a higher BER.

Having a wide and uniform laser beam that is also used during communication, $A_R = A_B$ may be adequate, similar to Fig. 4 as we only need to illuminate each position once. This would mean that the number of scan steps can be lower than for the same system with a smaller laser beam. However, we benchmark for $A_R = A_D$. In Gaussian beams, the irradiance gradually decreases from the center towards the edges. If the system is not perfectly aligned, the received power drops so it becomes challenging to satisfy the minimum energy per bit requirement. Also, even for uniform beams, it is preferred to align the detector with the center of the beam to avoid potential imbalances in the system. For example, if the laser beam vibrates due to device motions, it is best to place the detector in the middle, to minimize the chance that it falls out of the beam. Secondly, for this case, for every point (thus for every step in the scanning) we need to send a full address packet including overhead such as a synchronisation header and error correction. Fig. 5 shows that to ensure adequate received energy per bit, a wide beam requires a dramatic reduction in modulation speeds that counter-productively reduces scan speed. It outweighs the number of bits per position, therefore System 1 is slower than System 2.

2) System 2: The second approach makes the beam size smaller (ideally to $A_B = A_D$), which would boost the energy per bit. For System 2, with the same resolution ($A_R = A_D$), we have the same problem as for discrete search, we have to use full addresses with a sync header. During a continuous scan, the receiver sees packet boundaries that are random with respect to the time interval during which the detector is illuminated. Every location needs at least two full packet intervals to ensure that it can always receive at least one complete packet (Eqn. 10). Therefore, the number of bits that are sent per position is greater than in System 1. We plot

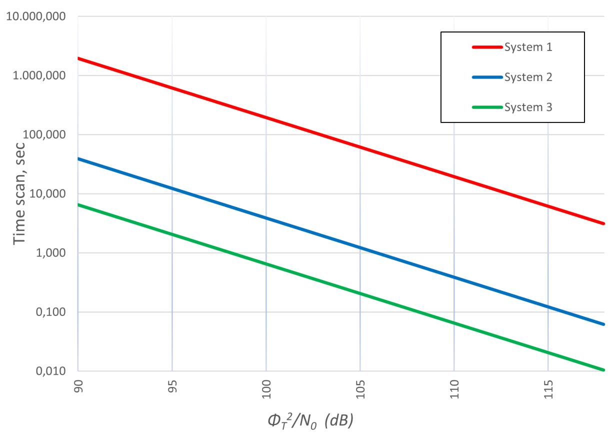

Fig. 5. Performance of 2 packetized addressing systems for beam searching versus Φ_T^2/N_0 using OOK, compared to LFSR addressing.

$$T_{scan} = 2\left(2\left(\log_2 \frac{A_C}{A_R} + N_h\right)\right) \frac{A_C}{A_R} \frac{A_B^2}{A_D^2} \frac{\kappa \Gamma N_0}{\eta_R^2 \Phi_T^2}. \quad (10)$$

Fig. 5 shows that smaller beam size has more impact because of the differences in the bit rate between the two approaches. Hence, System 2 is faster than System 1. There are also variants of System 1 and System 2 that improve search time significantly. The idea lies in the ability of the system to zoom. In fact, if only a single counter station is known to be present, further optimization of System 1 and 2 can be done by gradually zooming in on the target. For instance, in a two-step approach, the first step can be rough, i.e., a wide beam search to locate the approximate position, while the second step localizes the detector with high precision. Such a zooming system is beyond the scope of this paper but will be described in our later work.

V. Address coding by LFSR

Systems 1 and 2 use discrete addresses, as in Fig. 4, which need a sync header and some cyclic redundancy checks (CRC) or other error correction code which would further increase search time.

As an alternative System 3, we propose a coding scheme to embed direction addresses that is more efficient than creating data packets. The idea is to emit a pseudo-random sequence and to omit headers and sync words.

Linear-feedback shift registers (LFSRs) are characterized by the feature that by knowing a small portion of the sequence, namely the number of bits that equals the length L of the LFSR, uniquely identifies the position as it shown in Fig. 6. For this case, an LFSR of length L has a period of $2^L - 1$, thus it can address a little less than 2^L positions in L bits [6]. Any L bits in the sequence, e.g. bits at positions $l, l+1, ..., l+L-1$, form one address and when shifting over one position to $l+1, l+2, ..., l+L$, these L bits form the next address, while as many as $L-1$ bits overlap with the previous address. Thus, instead of having to transmit $\log_2(A_C/A_R) + N_h$ extra bits for one more address, LFSR–coded addresses only need a single bit extra for every next address. Fig. 7 shows that for such encoding scheme, the size of the beam should be L^2 bigger than the size of the detector. Then beam can move forward after sending 1 bit. The other way is that the beam can move forward to the next position after sending L bits. Thus, in (10) instead of the full address, we only need to send L bits as we can retrieve its position in the sequence.

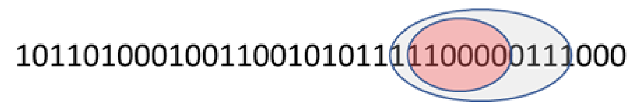

Fig. 6. Addressing by taking a snippet from an LFSR sequence, as considered in System 3. Red: minimum required number of bits for unique ID. (6 in this example) Green: example of a fault tolerant capture of an address

Evidently, the transmitter and the receiver must share the knowledge of the LFSR polynomial. Error correction comes for free: if more than L 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. 7 further explains the area in which a unique address is found, while a beam is being swiped at high speed across the coverage area. System 3 uses this option and is seen to scan much faster than previously considered systems.

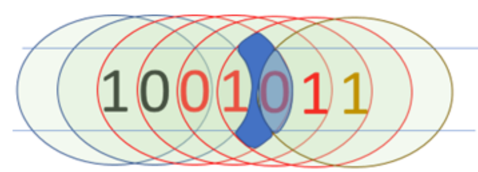

Fig. 7. Swiping beam progressing along the X-axis (position). The circles indicate the beam area at the start of the corresponding symbol. Address symbols are indicated in the center of each circle. A detector positioned in the light-blue area receives the red colored symbols 0101. Both 010 and 101 are unique addresses in the long LFSR sequence. A detector in the dark blue area receives 010, which still gives a unique position in the sequence.

Fig. 8 shows that it is possible to scan two orders of magnitude faster by using an LFSR code than with the use of discrete addresses. Of course this gain highly depends on the number of bits per discrete address and on the effectiveness of the header, and on how the resolution is handled in two dimensions. Nonetheless, it is anyhow significantly faster than System 2. This is particularly attractive if high bandwidths can be supported by the detector circuit. The LFSR addressing is also particularly effective if the desired resolution is smaller than the beam width.

As we rely on the binary properties of LFSRs, as we need synchronisation from the data itself, and as we want to avoid the need to track signal level variations, we use Manchester encoded data that has a rate 1/2.

VI. Further system considerations

After the laser beam from the transmitter hits the receiver, it reports the signal back by means of a lower–rate feedback

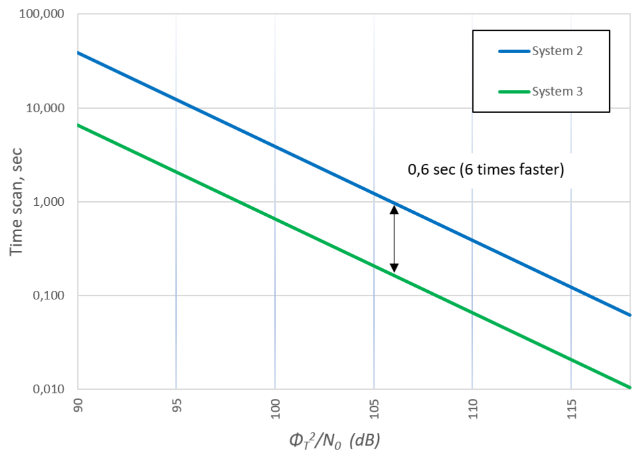

Fig. 8. Scan time for systems with a narrow beam as a function of Φ_T^2/N_0. Comparison of using a LFSR code for scan searching compared to using discrete addresses in data packets.

channel. As there is no prior information on the position of either transmitter or the receiver, it is preferable to use a wide beam for the feedback channel to cover all possible positions of the transmitter. Therefore, we can use both LEDs or lasers for this as it is not required to have a high bit rate to transmit an address back. The lack of information on the location of the transmitter means that a wide beam can come from any angle. Thus the detector on the transmitter side also needs to have a wide field of view (FoV). In photodetector designs, there are two trade-off that plays an important role in the design of the optical receiver: area versus bandwidth and gain versus FoV [7]. There are a couple of proposals in the literature to increase the FoV of the detector. In [8] it was proposed to use a two-dimensional matrix of photodetectors to increase the FoV without compensating for the bandwidth as there is an area-bandwidth trade-off. Such system proved to be capable of supporting > 1 Gb/s transmission, however, the penalty in signal strength was not reported. In [9] authors have proposed a design of a high-speed angle diversity receiver (ADR) that tackles the optimization of configuration of the receiver bandwidth and FoV. The noise versus signal-gain is evaluated in [10]. It appeared that matrix circuit layout may be advantageous for bandwidth but at the cost of sensitivity. Moreover, the size of the detector may be optimized, as in [11].

VII. Conclusions

In optical wireless communication, widening the search beam does not necessarily accelerate the scan time as it disproportionately reduces the energy per bit. The electrical energy per bit is proportional to the symbol duration and to the square of the optical power that falls on the detector. Thus, increasing beam size reduces the received signal strength to a much larger extent than radio communication. We learn from the law of conservation of energy that in free space the received optical or electromagnetic power reduces proportionally with the beam area.

We investigate this by considering systems that are also limited by Additive White Gaussian Noise in the receiver. In fact, in optical systems with a photodiode, the received signal strength declines proportionally to the square of the beam area. This paper studied the impact on the search time.

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.

VIII. Acknowledgment

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