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Color-Based Time Synchronization for Future Networks: Advantages, System Architecture, and Potential Use Cases

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***Abstract*—Given its relevance to industrial applications, over-the-air time synchronization (TS) is anticipated to play a crucial role in future communication networks. Thus, we investigate the potential of optical wireless signals for TS in various applications, including high-precision manufacturing and power distribution. More specifically, in this paper, we propose the use of color-based encoded timestamps for TS. In the proposed technique, the master node transmits timestamps to the existing slave nodes encoded in optical signals. To do this, we introduce the implementation of the color-based TS technique and highlight its merits. It is concluded that color-based optical signals can be efficiently used for TS in future networks.**

I. Introduction

As the commercial deployment of 5G networks continues, there is already a focus on planning and researching for future networks. This is driven by the expectation of new use cases that will demand higher quality of service (QoS) standards for wireless communication [1]. For example, smart factories with dense deployments of intelligent mobile robots that require extremely low-latency communication (approximately 10 μs) are being envisioned [2]. In such an environment, low-latency is required for fast adaptability and robustness, especially for the time critical tasks. Therefore, in addition to the introduction of the ultra-reliable low-latency communications (URLLC) services of 5G, further enhancements will be needed.

According to the Architecture Working Group (WG) within the 5GPPP Initiative and several other fora, the key performance indicators (KPIs) for the future networks are identified in Fig. 1 [3]. Compared to the previous generations of wireless communication, the reduction of the effect of jitter draws significant attention as a new KPI in future networks. This indicates that the importance of time synchronization (TS) will increase in the near future. This is because jitter is directly associated with TS. The goal is to attain TS with a jitter level of the order of 1 μs [3], [4]. The concept of TS involves the exchange of timestamps among wireless network nodes that are located at a distance from each other. In most scenarios, a master node is responsible for transmitting timestamps to the respective slave nodes involved in the synchronization process. In many environments, TS is necessary for efficient cooperation among physically interacting machines in a coordinated and non-distractive manner.

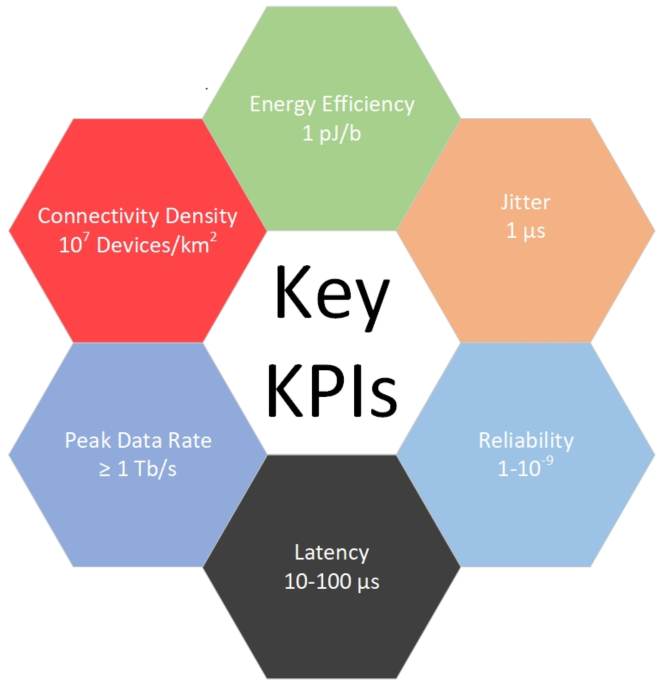

Figure 1: Key performance indicators for the anticipated future networks.

TS has been considered in several standardization organizations such as the 3rd Generation Partnership Project (3GPP) and the Institute of Electrical and Electronics Engineers (IEEE). The 3GPP working group has undertaken studies for the support of time-sensitive networking (TSN) in the Technical Study 23.501 Release-16. Also, timing resiliency systems are defined in the Technical Report (TR) 22.878 Release-18 by 3GPP [4]. Besides, in February 2016, the International Telecommunication Union (ITU) approved a new version of time requirements in the report G.8271. Two different IEEE groups, IEEE 802.1 TSN and IEEE 1588 Precision Time Protocol (PTP), also studied TS.

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Every generation of wireless communication networks has been redefined in terms of its new fundamental technologies, system architecture, and enablers. In light of the stringent TS requirement for future networks, it might be easier for new solutions to achieve the target of more precise TS [4]. For example, in radio frequency (RF) TS, the largest inaccuracy of over-the-air TS (± 100 ns) is caused by the propagation of RF signal [5]. Consequently, achieving future TS targets with RF signals becomes a challenging task. These stricter requirements of future networks motivate the consideration of wireless TS in non-RF bands, i.e. the optical bands. The main strength of TS in the optical band relies on the deterministic nature of optical wireless transmission. Further characteristics that motivate TS in the optical bands are: i) low-cost of implementation; ii) availability of unlicensed spectrum; and iii) potential energy efficiency benefits [6]. Hence, TS within the optical spectrum, specifically in the visible and infrared bands, is a solution that deserves further exploration.

In infrared and visible light spectrum, data can be transmitted by intensity-modulating of the different color components emitted by multi-color Light Emitting Diodes (LEDs). More specifically, an LED acting as a communication transmitter is able to twinkle the intensity of light of each color component very rapidly. At the receiver side, the modulated signals are received by a photodetector, also known as a light sensor or a photodiode, or an image sensor consisting of a matrix of photodiodes. These received signals can then be processed to extract the transmitted data.

A. Time Synchronization in the Optical Bands

In recent years, accurate over-the-air TS has gained significant attention, especially in light of the industrial 4.0 paradigm. However, RF-based TS faces several common challenges, including:

- Both noise and the presence of line-of-sight (LoS) or non-line-of-sight (NLoS) multipath propagation introduce perturbations from the true time of arrival (ToA) [5].
- The extensive bandwidth utilization for TS imposes a large overhead in the network.
- Intentional and unintentional RF jamming can cause disruptions of the network synchronization [7].
- The implementation cost is high due to RF circuitry or due to the need of complex and sophisticated algorithms.

In contrast, TS using optical signals is not susceptible to the previous challenges. Firstly, in many setups, the wireless optical channel exhibits a directional nature, resulting in minimal or negligible multi-path propagation. Also, it does not suffer from small scale fading. TS in the optical band does not create any interference in the RF bands. In addition, the front-end components of both transmitters and receivers are relatively simple. Specifically, these components operate in the baseband, eliminating the need for frequency mixers and complex algorithms to compensate for RF impairments, such as phase noise and IQ imbalance [8]. Thus, the implementation cost of the proposed technique is expected to be lower than conventional RF-based techniques. Furthermore, higher energy efficiency is anticipated due to the use of light components which are energy efficient [9]. Optical bands can also offer security advantages over radio waves due to their inability to penetrate opaque objects. In indoor certain industrial deployments, the absence of windows can make it difficult or even impossible for external jamming to occur. Finally, the proposed color-based TS is easily adaptable to different previously defined standards. This is because of the harmony between domain numbers and their color representation. For example, many IEEE 1588 PTP specifications, such as clockClass and clockAccuracy, are identified in the range of 0 to 255 enumeration [5]. Assuming a sufficiently high SNR, a single color LED can produce at least 256 levels of light intensity with sufficient signal separation. Thus, it is very convenient to match one shade of color to one PTP domain.

II. The System Architecture of Time Synchronization in Optical Bands

The process of TS involves the coordinated maintenance of multiple clocks to ensure they are accurately aligned. In the general case, $K+1$ devices need to be time synchronized. This is achieved with the transmission of the reference time from the master node, t_m, to the k-th slave node, $t_{s,k}$. Usually, the master node acquires the reference time either from the global positioning system (GPS), its internal clock, or another source. In the current state-of-the-art (SotA) TS, the transmission of the reference time t_m is undertaken using RF signals. However, this process is challenging as jitter causes random clock skews and drifts.

Figure 2 depicts the architecture of the color-based TS technique, showcasing the arrangement of a master clock, slave clocks, and a GPS satellite. In this architecture, the PDs are used for the reception of color encoded optical signals and the LEDs are used for the creation of the color encoded optical signals. The proposed architecture uses GPS signals as the source of time reference. Alternatively, the clock of the master node can be used as the source of time reference.

In the following sections, we provide a detailed description of a general color representation system, including a detailed description of the widely recognized red-green-blue (RGB) three color model. This explanation aims to provide a comprehensive understanding of how time encoding can be achieved using color-based optical signals.

A. The General Case

In the proposed TS method, the master node utilizes optical signals of different colors to transmit timestamps to the existing slave nodes. This coding scheme can be implemented in multiple ways, including the use of specific modulation formats such as metameric modulation (MM), color-shift keying (CSK), or optical orthogonal frequency division multiplexing (OFDM) to encode the timestamps [6].

An alternative method involves representing timestamps directly using specific combinations of color shades. This approach utilizes a predefined color codebook where different timestamps are associated with distinct shades of color. The transmitted timestamps are then represented as unique points within a designated color representation scheme. This technique allows for a direct mapping between timestamps and colors, facilitating accurate and efficient representation of time. In particular, for the representation of timestamps, K color components with n bits per color component may be used. In this case, the resolution of each timestamp is $K \times n$ bits. Therefore, the timestamps are able to quantize

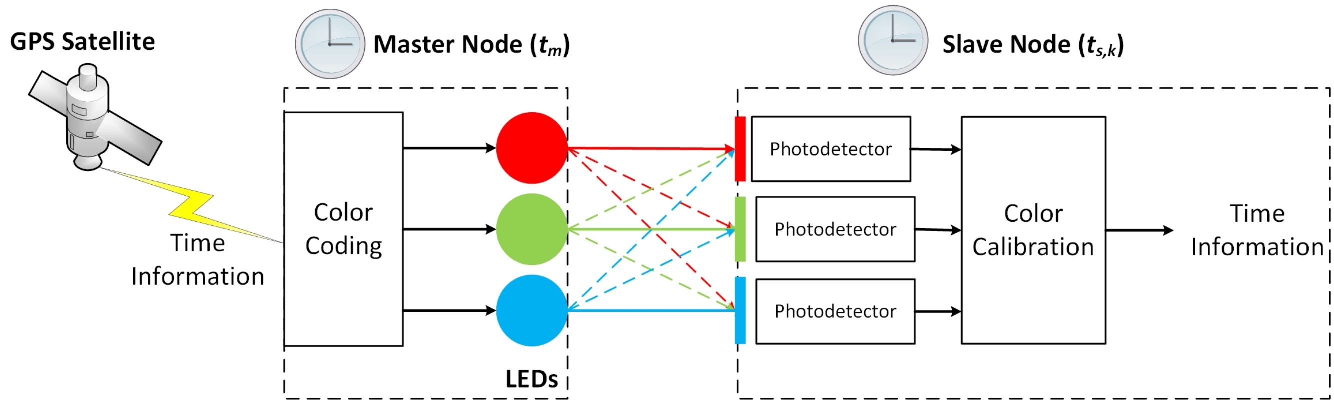


Figure 2: The architecture consists of a master clock, slave clocks, and a GPS satellite serving as the time source for color-based time synchronization distribution.

the time interval of interest with $2^{K\times n}$ points. Note that a resolution of 10 (2^{10} levels) is already demonstrated in [10]. In addition, [11] identifies that a resolution of 12 bits is supported by the existing photo-detector (PD) technology. This suggests that the 10-bit time resolution for TS is attainable with the current LED/PD technology. However, it should be noted that the upper limit of resolution is constrained by the currently available LED/PD technology, rather than the technique itself. Clearly, any technological improvement in the future can further improve the resolution of an optical TS system.

In practice, a trade-off can be made between the color codebook size and its time representation precision. A smaller codebook is more robust against complexity at the expense of lower time precision, and vice versa. However, in some cases, it is not possible to sacrifice time precision. As an example, to ensure smooth and deterministic execution of a machine production cycle, timely coordination among devices/machines has to be accomplished. This may only be possible if the devices/machines are synchronized to a common time reference with a clock disparity of less than $1~\mu$s [12]. The current off-the-shelf LEDs achieve a seamless flickering speed of approximately 1 ns which can be used for accurate TS [6].

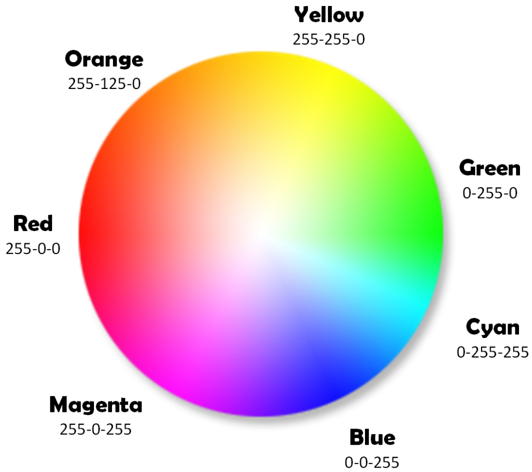
A K multicolor optical TS system can be implemented with luminaries of K LEDs of different colors and photodiodes. Any inter-color interference can be avoided with simple optical filtering and thus each color component is distorted only by additive noise. As the noise in each color component may be different, the detected signal-to-noise ratio (SNR) in each color component may be different as well. This may motivate the allocation of more time representation bits to the color components that have a higher SNR.

B. The RGB Case

A multi-color LED is a device that uses electroluminescence and semiconductors in order to generate light of different colors. This can be achieved by combining red, green, and blue color outputs. In the RGB color representation scheme, a color is described by indicating the numerical value that represents how much of the red, green and blue portion is to be included in the combination. Such color may be expressed as an RGB triplet $(\mathrm{R},\mathrm{G},\mathrm{B})$, where each component varies from 0 to a defined maximum value. Usually, the color component values are stored as integer numbers in the range from 0 to 255 (i.e., the range a single byte (8-bit) can offer). As an example, Figure 3 illustrates shades of color obtained by different RGB LEDs values. In the given example, the range is between 0 and 255, resulting in 256 values for each of the red, green, blue color components. The resulting total number of available shades of color for such an RGB scheme is $256\times256\times256$ colors.

Figure 3 serves as an illustrative example, demonstrating a color coding scheme that assigns specific color codes to units of time. It is crucial to note that the color coding resolution level, whether in the nanosecond or picosecond range, can be tailored to meet the specific requirements of the system. In the right-hand portion of the figure, the precision of the time units is given, showcasing a picosecond resolution level (ps) as an example. Since 1 second corresponds to 10^{12} ps, the figure shows a mapping of $256 \times 256 \times 256$ ps to $256\times256\times256$ different RGB triplets, starting from $(0,0,0)$ and increasing by 1 for each ps. Thus, the color combinations offer $256\times256\times256$ distinct codewords for any color coding utilization. However, alternative mapping methods for color codebook mappings between RGB colors and timestamps/time units are generally conceivable. Besides, dedicated RGB triplets can be defined (or "reserved") as time markers. For example, some special RGB triplet options may be defined in the color codebook for the determination of the start of new time units. Since such time markers are known by both the master node and slave node, they are used to re-establish synchronization rapidly, even if synchronization was lost previously. If needed to create more robustness in the detection of color-coded timestamps, larger gaps may be defined between color codes adjacent in the color codebook.

*1) **Time Protocol**:* The signalling diagram of the proposed solution is shown in Figure 4. Any time protocol can be converted to the proposed method. This shows that the proposed optical TS approach is technology-neutral. This is because it only depends on light as an information bearer. However, in Figure 4, PTP messaging is used for illustration purposes between the master clock and the master node. As shown in Figure 4, the master clock prepares a SYNC message and writes the actual timestamp into the SYNC message at that time. Due to the processing time,



1 second = 10^{12} picoseconds

RED	GREEN	BLUE	Picoseconds (ps)
0	0	0	1
0	0	1	2
0	0	2	3
0	0	3	4
0	0	4	5
.	.	.	...
.	.	.	...
255	255	252	16,777,213
255	255	253	16,777,214
255	255	254	16,777,215
255	255	255	16,777,216

Figure 3: The change of the red, green, and blue colors with the different code numbers from 0 to 255 (on the left) and color coding in picoseconds (on the right).

medium access, and propagation delay, the transmission of a timestamp introduces inaccuracies. To mitigate this issue, a FOLLOW_UP message is sent. A FOLLOW_UP message contains the exact transmission time as recorded by the hardware. As an example, in Figure 4, one master node calculates its offset to one master clock. Yet, there is an error because of the propagation delay, which has to be subtracted in order to get the correct value. To determine the propagation delay, the master node sends a DELAY_REQUEST message to the master clock for measuring the delay. That is then answered by the master clock by timestamping and sending back a DELAY_REPLY message. Consequently, the transmitted timing alignment protocols are represented as unique points within a designated color representation scheme. Color mapping technique allows for a direct mapping between timestamps and colors, enabling accurate and efficient representation of the protocol.

After this process, the aforementioned method for time synchronization between the master node and the slave node begins. For the long-range distances, the propagation delay between the master node and the slave node may become perceivable. Therefore, a delay offset which aims to compensate for the previous delay needs to be calculated. To resolve the delay problem, a preliminary synchronization process may be performed. During the synchronization process, the master node encodes a timestamp, t_1, which represents the current clock time of the master node using the color-based coding scheme. The timestamp is received by the slave at time t_2, based on its own clock. The difference between t_1 and t_2 is the delay offset including any propagation delay between the master and slave nodes. The time difference between t_2 and t_3 represents the processing duration in the slave node. Once this processing is completed, the slave node transmits a timestamp t_3 representing its current clock time, which is then received by the master at time t_4. Based on these timestamps, the master device calculates the delay offset as $[(t_4 - t_3) + (t_2 - t_1)]/2$. The value of the counter is divided by 2 in order to account for the two propagation delays.

*2) **Performance Comparison**:* In TS, the most important parameter is time-of-arrival (ToA) which measures the propagation delay between nodes. The measurement of the ToA includes an inaccuracy, which is a function of the signal bandwidth and signal-to-noise ratio (SNR) [5]. In order to observe the main relations between the signal bandwidth and the theoretical limits for ToA estimation, the Cramer-Rao Lower Bounds (CRB) of ToA is derived in equation (1), based on [13] and [14]. By following the same steps as the previous papers, the ToA is estimated. Here, ideal conditions were considered. Also, we use a non-negative smooth window which has a finite mean-square frequency deviation. Based on Parseval's law, the derivative of the window function is square-integrable [13]. Thus, an estimate of the ToA is obtained from (1). The CRB, in general, can be defined as the theoretical lower bound on the variance of any unbiased estimator of an unknown parameter. The CRB for color-based ToA can be given as [13]:

$$\sqrt{\mathrm{var}(\tau)} \geq \frac{\sqrt{3}}{2\sqrt{2}\pi\alpha R_P \sqrt{SNR} f_c}, \qquad (1)$$

where $\alpha = (m+1)S/2\pi d^2$ is the attenuation of the optical channel, $m = 1$ is Lambertian index, $S = 1\ \mathrm{cm}^2$ is area of the photodiode and $d = 5\ \mathrm{m}$ is the distance between transmitter and receiver. $\tau = d/c$ is the time taken for the signal to travel from the transmitter to the receiver in the line-of-sight way with c being the speed of light. The responsivity R_P is the conversion factor from the optical to the electrical domain. It is a function of the wavelength of the received light. The typical value of the responsivity is in the range of $0.2\ \mathrm{mA/mW}$ at $400\ \mathrm{nm}$ up to $0.6\ \mathrm{mA/mW}$ at the peak. For illustration purposes, the responsivity is taken at the central optical frequency of operation with $R_P = 0.4\ \mathrm{mA/mW}$ [13]. The modulation bandwidths are chosen as $f_c = \{1, 2\}$ MHz. In Figure 5, the evaluation of CRB of the color-based and RF-based ToA estimation (as given in [14]) is presented. The modulation bandwidths of the RF-based ToA estimation are also chosen as $f_c = \{1, 2\}$ MHz. Also, the distance between the master and slave node is considered to be $d = 5\ \mathrm{m}$. Furthermore,

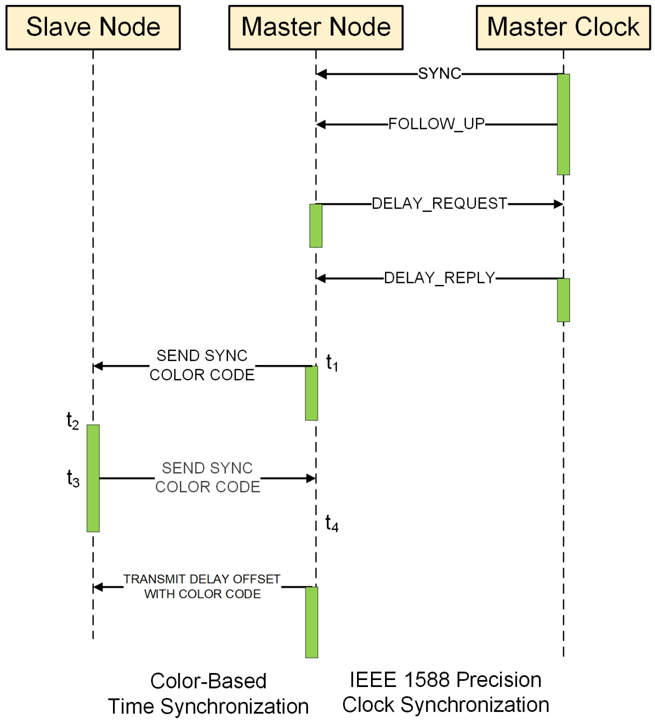


Figure 4: The signalling diagram of the proposed solution.

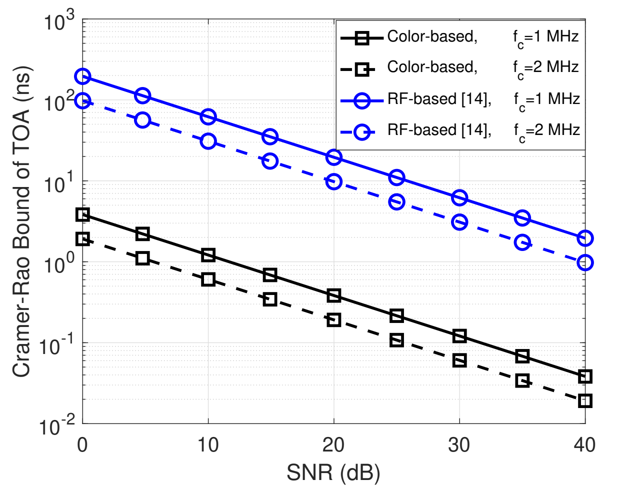


Figure 5: The comparison of ToA performance for proposed color-based and conventional RF-based technique [14].

there is a LoS between these nodes. In Figure 5, we compare the permanence of the ToA estimation for different SNR values, as obtained using the proposed technique and RF transmission. In order to make this comparison fair, the received optical power for the optical TS transmission and the received electrical power for the RF transmission are both normalized by their noise power. Figure 5 shows that the CRB of ToA becomes more precise with the increase of the SNR and signal bandwidth values for both cases. Furthermore, the same figure demonstrates that the CRB of the ToA achieved by the proposed color-based technique exhibits superior precision in comparison to the conventional RF-based technique. The enhanced precision can be attributed to the deterministic nature of the optical channel.

*3) **Challenges**:* In optical networks, two types of optical noise can be identified: (i) sunlight and artificial light noise originating from illumination fixtures, and (ii) light noise from other optically communicating transmitters. In the case of sunlight and light noise from illumination fixtures, their impact on the optical network results is (i) the introduction of a near DC component to the received optical signal, and (ii) a negligible increase in ambient noise levels. Therefore, the effect of this type of light noise can be easily treated. One approach to dealing with this kind of background noise involves the use of optical filters that can selectively block or transmit certain wavelengths of light. This can effectively reduce the impact of ambient light sources, such as sunlight, on the optical signal. Additionally, the use of directional or focused light sources can minimize the interference caused by ambient light sources. By combining these techniques, the impact of ambient noise on color-based TS technique in outdoor environments can be significantly reduced, thereby improving its overall performance and reliability. On the other hand, thermal noise is inherent to any communication system and arises from the random thermal motion of electrons. It cannot be completely eliminated but can be minimized through various techniques, such as optimizing system design. Additionally, it is important to highlight that optical TS is primarily suitable for controlled indoor industrial applications. As a result, it can be safely concluded that light noise coming from sun or illumination fixtures is absolutely negligible.

Due to the critical nature of TS, in order to avoid optical interference from neighbouring optically communicating transmitters, the operation of TS is totally separated from communication. This separation can be temporal or in the frequency domain. The best example of this kind of separation is the GPS where its bandwidth is not used for communication. Building upon the established concept of a separate TS channel, the proposed color-based TS technique aims to extend its applicability by incorporating several crucial enhancements. These include the integration of cost-effective and simple circuitry; harnessing the deterministic nature of optical channels; achieving higher energy efficiency; and implementing enhanced security measures.

*4) **Solutions**:* In uncontrolled scenarios, the blocking of the propagation path between a master and slave node is an important issue that needs to be resolved. The most common solution for the case of temporal blocking is the storage of the system's internal clock (holdover time). In this way, whenever a blockage occurs the slave node can retrieve the system's internal clock from its memory [4]. TS does not require constant modulation as opposed to continuous data transmission. An intermittent time synchronization process can keep the system in accurate working mode. However, there are more sophisticated techniques that can be used for addressing the NLoS issues in optical time stamping. For high-precision manufacturing applications, one potential approach is to utilize reflective surfaces to redirect optical signals around obstacles, thereby overcoming potential line-of-sight (LoS) challenges. This technique is similar to the use of mirrors for redirecting light in a room and to the use of reflective intelligence surfaces (RIS) in optical bands. An

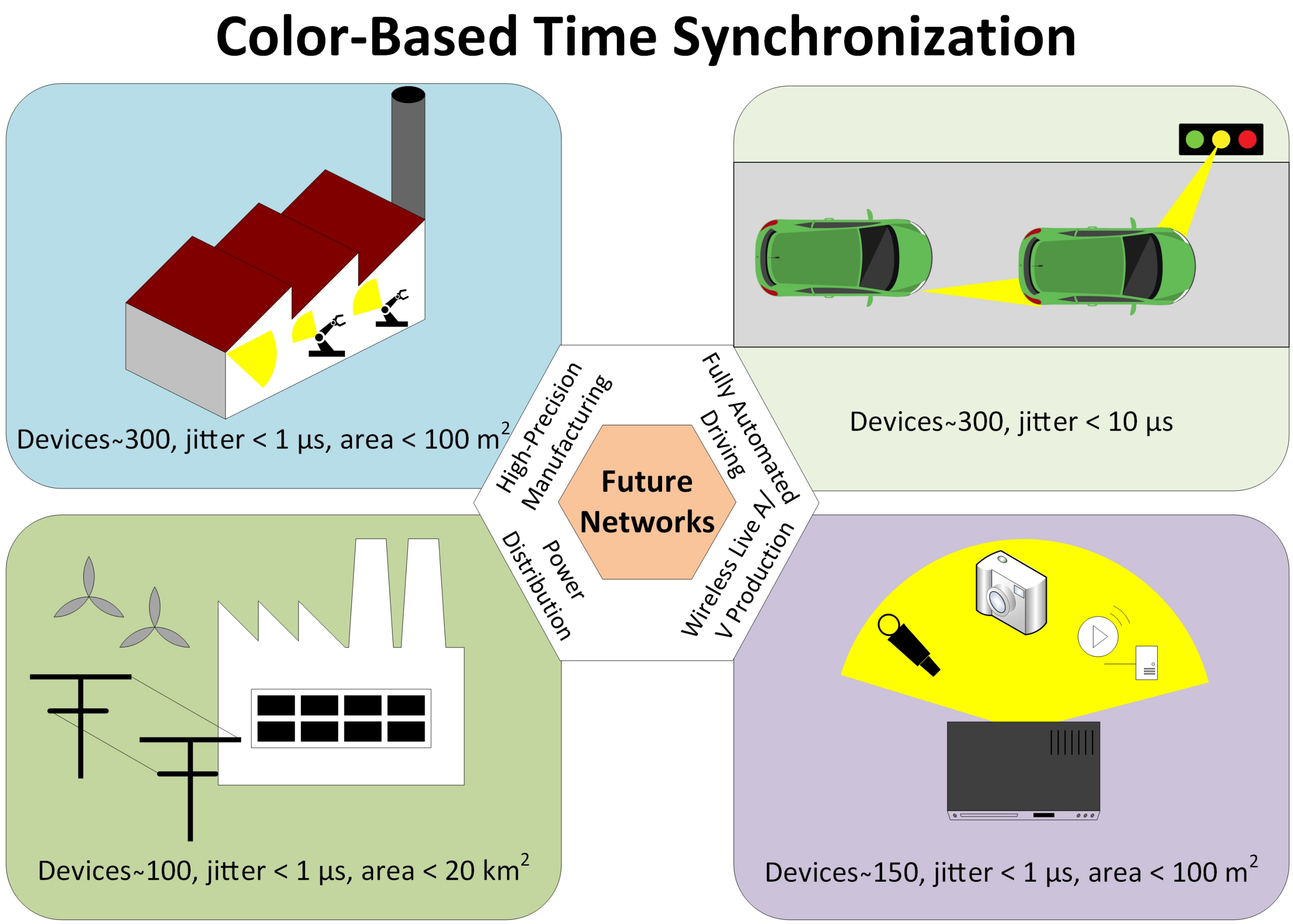


Figure 6: Use cases of color-based time synchronization as a potential enabling technique for future networks.

alternative method for wireless live audio/video production involves the utilization of multiple optical transceivers to establish a mesh network. This network configuration enables signals to be routed through multiple paths, circumventing obstacles and ensuring reliable communication. Additionally, an airy beam can be used, which is a propagation-invariant wave whose main intensity lobe propagates along a curved parabolic trajectory while being resilient to perturbations [6].

III. Use Cases for Color-Based Time Synchronization Technique

In the section, we present potential use cases for the proposed TS, these are shown in Figure 6. The synchronization requirements on the figure are based on the 3GPP Technical Study 22.104 Release-18.

1) ***High-precision Manufacturing****:* It is anticipated that intelligent robots will be a part of high-precision manufacturing. In particular, machines need to execute real-time tasks isochronously such as packaging, printing, and symmetrical welding/polishing. Coordination among intelligent machines and network slicing for industrial internet-of-things (IoTs) are not possible without stringent TS. Given that optical bands primarily rely on LoS propagation and offer wide bandwidth, the utilization of color-based TS emerges as a highly effective solution for industrial environments where the environment is controlled and carefully designed.

2) ***Fully Automated Driving****:* The most widely known and studied use cases for optical wireless networks are vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication. These use cases are appropriate for optical networks because the headlights and taillights on automobiles can act as a transmitter and a receiver to provide reliable communication between vehicles as long as the LoS path is not blocked. The advent of fully automated driving has placed significant importance on guaranteeing the prompt and resilient transmission of safety-related messages which is linked to precise TS. For example, a car broadcasts its real-time speed and clock information to other cars to minimizing the chances of collisions. Thus, a color-based system can provide the requirement of these critical operations when the LoS propagation path is not blocked.

3) ***Power Distribution****:* Power plants are highly sensitive environments when it comes to RF interference, making optical networks a proposed solution to ensure reliable and secure operations. Furthermore, precise TS is crucial in power plants for various purposes such as fault location, control, optimization, monitoring, and diagnostics. Thus, a color-based system can be useful for coordinating the operation of a power plant. Based on fine-grained information obtained from measured electrical values of the power source, real-time control of power supply and demand is implemented to ensure compliance with voltage and frequency regulations. Thus, adjusting the voltage and frequency requirements needs precise TS.

*4) **Wireless Live Audio/Video Production**:* With the increasing demand for personalized entertainment technologies, wireless audio/video (A/V) productions have become a major component of the entertainment and creative industries. Wireless cameras and microphones, in-ear monitors, and conference systems are integral parts of an A/V production. In professional media production, the synchronization of samples across multiple devices at precisely the same moment is essential. Hence, failure to create synchronized content is unacceptable as it would ruin the production [15]. Given the low latency and jitter nature of optical wireless communication, the utilization of color-based TS will be a potential solution for wireless A/V production.

IV. Conclusion

This paper presents the concept of color-based TS that can be employed either independently in specific environments or in conjunction with existing RF TS solutions in a broader setting. The proposed technique involves the master node transmitting timestamps to existing slave nodes using optical signals that encode time on the hue of the optical signal. The implementation of the color-based TS technique is described along with its merits when compared with existing TS approaches. To illustrate, a generalised colour coding scheme that uses RGB LEDs has been presented. Finally, potential use cases are provided to illustrate the applicability of the proposed technique in different scenarios.

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