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Proposed Schemes for Image Sensors Compatibility in IEEE TG7r1 Image Sensor Communications

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ABSTRACT

The IEEE 802.15.7r1 Task Group (TG7r1), known as the revision of the IEEE 802.15.7 Visible Light Communication standard targeting the commercial usage of visible light communication systems which mainly use either image sensors or cameras, is of interest in this paper. The vast challenge in Image Sensor Communications (ISC), as it has been addressed in the Technical Consideration Document (TCD) of the TG7r1, is the Image Sensor Compatibility to support the variety of different commercial cameras available on the market. The on-going ISC standard must adhere to compatible image sensors regulations. This paper brings an inside review of the TG7r1 and an inside look of related works on Image Sensor Communications. The paper analyzes the compatibility features by introducing a revised model of receiver to explain how those features are necessary. One of the most challenging but interesting features is the capability in being compatible to camera frame rates. The variation of camera frame rate is modeled from verified experimental results. Noticeably, three singular approaches to support frame rates compatibility, including temporal approach, spatial approach, and frequency-domain approach, are proposed on the paper along with concise definitions. Those schemes have been presented as valuable proposals on the call-for-proposal meeting series of the TG7r1 recently.

Key Words : Optical Wireless Communications (OWC), Image Sensor Communications (ISC), the IEEE 802.15.7r1 Task Group (TG7r1), TG7r1 review, Image Sensor Compatibility, varying frame rates, frame rate compatibility, temporal scheme, spatial scheme, frenquency domain scheme

Ⅰ. Introduction

It has been witnessed an unprecedented growth in the wireless device technology along with numerous groundbreaking wireless innovations. These innovations have significantly improved wireless communications. In the decade of internet connectivity, however, it remains a challenging to meet the demands on wireless services. The limited spectrum needs to be shared for thousand wireless devices per person/thing causing to a mass of interference that wireless communication using RF has unmitigated limitation remaining. Fortunately, the expansion of RF spectrum towards an unregulated, free and thousand times greater than RF spectrum, light, can circumvent that. Consequently, LED light technology brings massive opportunity that light is illumination now but going to be a service in the future[1], has been becoming a feasible technology since the IEEE standard of VLC technology was first released in 2011[2]. Recently, LiFi is supposedly to be ready to compete with RF

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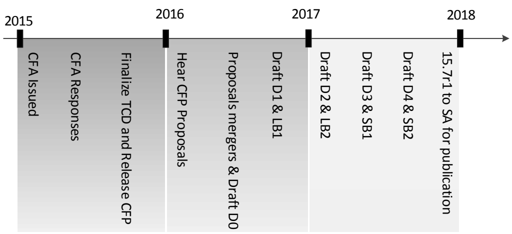


Fig. 1. Architecture of Software Defined Networking.

and it could outshine WiFi in industrial settings in the not-too-distant future[3].

Optical Wireless Communications technologies can be classified according to the types of a receiver, including a Photo Diode (PD) receiver type and an Image Sensor receiver type. Inheriting the massive achievement of the VLC technology, the on-going standardization activities on Optical Wireless Communication in the IEEE 802.15.7r1 Task Group (TG7r1)[4], taking consideration in both PD communications and Image Sensor communications, have been attracted a plenty of international corporations and researchers. Especially, Image Sensor Communication (ISC) sub-section has got a major attraction and a high dense number of researches all around the world till now, as a survey of ISC technology in [5] showed. The TG7r1 is known as the revision of VLC specification because it aims to bring the light closer to commercial services with more feasible applications. Most recently, the final release of the Technical Consideration Document (TCD) in the TG7r1 addressed the guideline of development direction for any technical proposal submitted[6]. Evidently, the feasibility on this revised standard is addressed as to play the key role as well. As a consequence, the compatibility in supporting available cameras is involved.

The variety in image sensors and its global trend on various manufactured/deployed areas were reviewed in the recent-year studies[8,9]. The survey references on the population of cameras manufacture and usage[8,9] showed the variety and population of different camera types with different shutter operations (global shutter or progressive scan; rolling shutter; interlaced; and global reset release); frame rates (overwhelming majority belongs to less than 25fps frame rates group and no larger than 60fps frame rate group; high frame rates are of minor interest but still commercial used for specific purpose); resolutions (however the trend of high-resolution use is increasing); hardware connection interfaces Also, the survey concluded that the market on smart cameras usage is increasing and becoming essentially. The variety on cameras market on image sensors' shutter operations, frame rates, resolutions, and sampling rates has affected to the communications consideration, and led to the prior requirement of image sensor compatibility functionality. In addition to the growing market of cameras, the rapid increasing interests on ISC applications which has been seen. The selection of highlighted papers related to ISC technology from various applicant areas and services using light with ISC, refs[11,12], shows the variety on commercial image sensors and their not-too-far distant ISC services. Thus, the support for sensors compatibility in ISC is not only necessary but also mandatory to ISC.

From an inside look of the TG7r1, this paper aims to provide a review about ISC technologies with different proposals for considering image sensor compatibility. The model and analysis of our proposed schemes are going to be given along with comparison to related works. The paper is organized as follows. After this section, a review of related works and a brief classification on methodology are addressed on the section II. Followed by a revised model of image sensor is given on section III along with verification of frame rate variation by testing some of commercial cameras. And the important contribution is on section IV presenting our three approaches which is compatible to image sensor frame rates in a comprehensive way. Finally, discussion and conclusion are to close the paper.

Ⅱ. A Review of Related ISC Works on TGr1

According to an official website of TG7r1 in [14], aapproved in December 2014, the Task Group has been formed by IEEE 802.15 in order to write a revision to IEEE 802.15.7-2011 (shorten name as TG7r1) as that accommodates infrared and near ultraviolet wavelengths, in addition to visible light, and adds options such as:

- **Optical Camera Communications** which enables scalable data rate, positioning/localization, and message broadcasting, etc. using devices such as the flash, display and image sensor as the transmitting and receiving devices.
- **LED-ID** which is wireless light ID (Identification) system using various LEDs.
- **LiFi** which is high-speed, bidirectional, networked and mobile wireless communications using light.

For more information, definitions, current status, schedule, and contact information of the TG7r1 can be found at [14]. Noticeably, the TG7r1 has been calling for proposals from near the end of 2015 till now February 2016, and scheduling to finalize a first draft of the standard for letter balloting near the end of 2016 and finalization of the standard near the end of 2017. The latest updated milestones and schedule can be found at [15].

Until March 2016 meetings, the TG7r1 has been attracting plenty of concerned cooperation, companies and universities researchers from all around the world such as Panasonics (Japan), Intel (USA), China Telecom (China), pureLiFi (USA), Ozyegin Universiy (Turkey), Seoul National University of Science & Technology - SNUST (Korea), California State University Sacramento (USA), Fraunhofer Heinrich Hertz Institute (Germany), Kookmin Universiy (Korea), Istanbul Medipol University (Turkey), National Taiwan University (Taiwan), Fudan University (China), Huawei Technologies (China), LG Electronics (Korea), and so on. Since numerous contributors and proposers are getting interested in, the proposals merging process and the creation process of the first draft of the TG7r1 standards document were agreed. Please refer to the January meeting minutes[16] for more detail.

The ISC technologies are of interest to be discussed on this paper. Evidently, the popularity of rolling shutter cameras is outstanding compared to global shutter cameras. Therefore, taking the consideration, submitted proposals all support at least a PHY mode for rolling shutter receiver. Related proposed rolling shutter modulation schemes include OOK (Kookmin), PWM (Panasonic), Multiple-FSK (NTU and Kookmin), and Offset-VPPM (SNUST). Meanwhile, a hybrid modulation scheme for either global shutter camera or rolling shutter camera or both is proposed by Intel and Kookmin on different way. Specifically, to target high performance on global shutter camera receivers, there are VPPM modulation scheme proposed by Intel and dimmable Spatial-PSK modulation scheme proposed by Kookmin. Last but not least, a high data rate MIMO-OCC PHY mode (up to Mbps) would be continuing updated and merged by concerned proposers.

To compare our proposals to the other ones, Kookmin proposals take a major consideration on frame rate variation and image sensor compatibility. To be compatible to varying frame rate image sensors, we assume that frame rate range of a typical camera may vary on a wide range, for example from 10fps to greater than 30fps. The reason is that our proposals target an application layer solution without any intervention into operating system or firmware or any modifying in hardware. This is suitable for most of devices nowadays. In contrast, the others take consideration on little variation of frame rate cameras in which an action on firmware or hardware solution may be considered for better communications performance. In summarization, the basic review of presented documents is only to give an overview on the activity of the TG recently. Any refer to original documents at [17,18] would be appreciate.

Ⅲ. The Need of Compatibility Support

3.1 System model and analysis

According to [13], an image sensor can be modeled as a two dimentional lightwave-to-digital converter. In this revised-model, all possible parameteres which control image sensors/ cameras are considered as shown in Figure 2. Frame rate, exposure, sampling rate and resolution have not the same values in different image sensors, but they together operate and then explain the presence of variation in each output parameter, leading to the need of image sensor compatibility

The input signal at the pixel photo detector is

$$x(t) = \sin(\omega_{OOK} t + \theta_{OOK}) \quad (1)$$

where ω_{OOK} and θ_{OOK} are the OOK frequency and phase.

The discrete sampling operation in imaging causes to the evidence that we have access to information signal $x(t)$ only at discrete time instances (actually at discrete time durations, but let assume it samples as a simplified model of sampling)

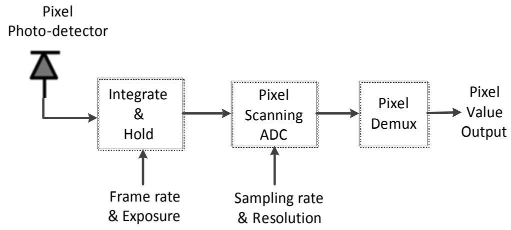
$0 = t_0 < t_1 < ... < t_k < ...,\ with \lim_{k \to \infty} t_k = \infty$

and a simplified model of sampling using the Fourier series presentation of the Direc comb sampling function can be introduced as

$$\sum_k \delta(t - t_k) \quad (2)$$

where t_k = kT +△T is the varing time instance of k-th sampling. T and △T are the mean and max deriviation value of the varying sampling-interval.

Notice that the sampling interval is not constant.



1 Frame rate & Exposure are setup for Integrate&Hold functional block. This block defines the limited bandwidth for communications
2 Sampling rate & Resolution (or Region of Interest mode) are setup for Pixel Scanning ADC functional block. The digital output signal which contains the information is re-defined in here.

Fig. 2. A revised model of image sensor

And due to the long exposure, the Intergrate & Hold takes a rule as the Low Pass Filter. That is the reason why the sampling rates of image sensors are up to tens of kHz but the practial cut-off frequencies of cameras are less than ten of kHz. Consequently, the bandwidth is limited due to the long exposure.

To shortly explain, the exposure time and frame rate are to control Integrate&Hold to output single frames of image. Those parameters may vary for brightness adjustment. Followed by PixelScanning ADC, which is controlled by sampling rate (or rows scanning rate in rolling shutter image sensor) and resolution parameter. An image sensor has a constant sampling rate but an adjustable resolution. Different image sensors have different sampling rates and different avalibale options of resolution.

For the communications performance along with compatibility of sensors, we have to identify those paremeters which are constant or varying, those

Table 1. Classification and Comparison of Frame-rate Compatibility Approaches

	Fixed frame-rate Mode	Varying frame-rate Mode
Cameras Compatibility	- Applied for controllable camera that the frame rate can be fixed[13]	- Applied for all types of cameras[12]
Communications Assumption	- Camera is setup at a know frame rate. - The variation of frame rate is allowed in within a small range at which the error correction is required additionally[17].	- Assume camera has varying frame-rate inherently. - The variation is allowed in within a wide range, from 10fps to any frame rate above for example[12].
Implement complexity and video quality consideration	- Hacking existing camera firmware to fix frame rate, or controlling camera without being through an Operating System. - The video quality should be considered while the auto brightness adjustment mode is off[12].	- Software programming (application layer) based on existing camera firmware[11]. - The data reception mode is operated along with video recording mode. Thus video quality is maintained while integrating ISC into video (e.g. Augmented reality).

bring limitation. Frame rate, is considered as varying because it is naturally for brightness adjustment. Long exposure and sampling rate, which define the limited bandwidth for communications (the cut-off frequency of image sensor response) are considered as constant, or can be setup constantly in an image sensor, however, noticeably, different image sensors have different values. Therefore the bandwidth of communications should be limited for image sensors compatibility. Finally, resolutions are easily controlled in an image sensor, but let considere the minimum resolution can be occur in a low-cost camera for a common situation. The variety in parameters and corresponding challenges are analyzed more detail in each of below sections.

3.2 Frame rate variation analysis

To verify the variation in frame rate for a mathematical model of image sensor frame rate, an experimental result is presented in figure 3. Two types of commercial camera are chosen which operate on the Window OS, a 30fps USB camera and 60fps USB camera respectively. A software application interface allows user to setup the operating frame rate of camera acquisition. The difference between setup value and recorded varying frame rate is of interest.

The variation in frame rate through an operating system is to adjust light brightness of image. Giving a model of camera frame rate variation mathematically, let $R_{frame}(t)$ denote the varying frame-rate value at the specific moment t. Let E $[R_{frame}]$ denote the mean value of frame rate, and

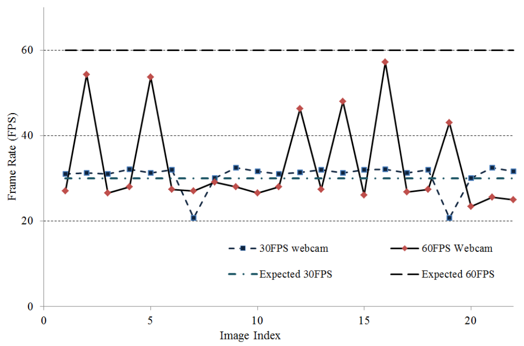


Fig. 3. An experiment in variation of camera frame rates

$\triangle R_{frame}$ be the maximum deviation of frame rate. The varying frame-rate value at the moment t is considered as a function of time as follow.

$$R_{frame}(t) = E[R_{frame}] + \delta(t)(\triangle R_{frame}) \quad (3)$$

where $\delta(t)$ denotes how much frame deviation with time is. ($-1<\delta(t)<1$)

Ⅳ. Proposed System Architecture

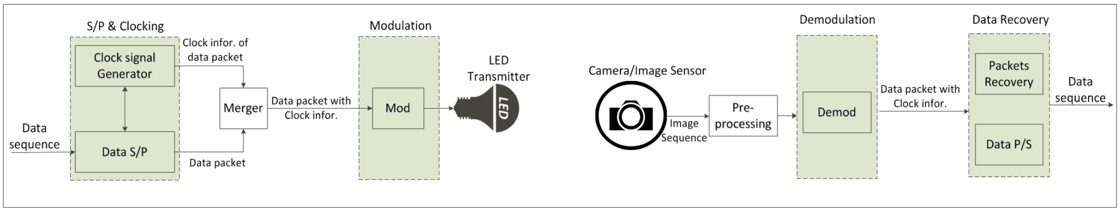
4.1 Problem and Statement

Since the compatibility to image sensors are indispensable for an ISC technology, a number of technical features are considered including: (i) compatibility support to varying frame rates; (ii) compatibility support to different sampling rates and different shutter speeds; (iii) compatibility support to global and rolling shutter camera receivers; and (iv) compatibility support to different resolutions.

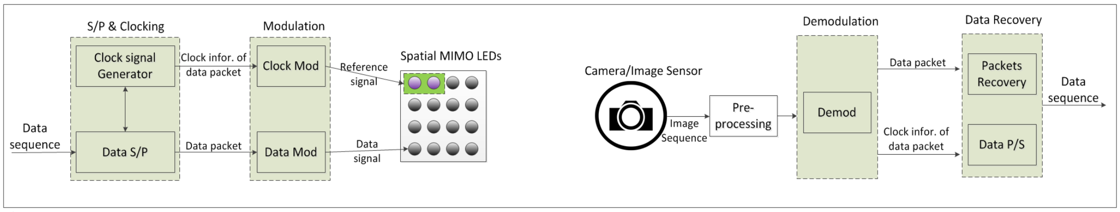
As being explained, one of the most critical technical considerations is the presence of frame rate variation in order to support various types of available image sensors. Consequently, the unidirectional communications between LED transmitter and camera receiver requires a prototype to allow a varying-frame-rate camera can decode data in an efficient way. A novel idea is that the clock information of a data packet, which can be understood as an index of the packet in an easy way, is encoded along with data before transmission in order to tell the receiver how to decode and recover a sequence of packets even if the frame rate of camera is unpredictable. However, instead of a long index, the clock information on our approaches is a form of a single bit only to minimize overhead. And the delicate way the lock information is encoded along with data being a novel idea.

4.2 Proposed Approaches

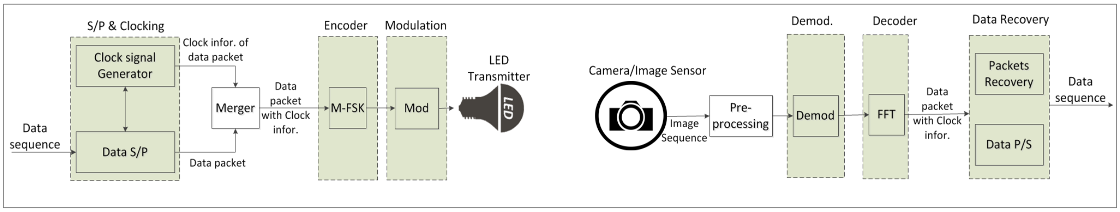
Figure 4 presents three approaches for transmitting clock information in allowing a varying frame rate camera receiver operating. Those approaches are temporal scheme, spatial scheme and frequency domain scheme respectively. In principle, those are different forms of encoding the mount data along with its clock information into a packet for



1 Temporal Scheme using proposed Data Frame Structure along with Clock information



2 Spatial Scheme using proposed Spatial MIMO LEDs transmitter with reference LEDs to transmit clock information



3 Frequency-Domain Scheme using Data Frame Structure along with Clock information modulated in frequency domain

Fig. 4. Proposed Solutions for Varying-Frame-Rate Compatibility Feature in Image Sensor Communications System

transmission. Table 2 indicates a brief comparison between those three.

Table 2. Proposed Schemes for frame rate compatibility

Proposed Approach	Operation principle
Temporal Scheme	Data along with its clock information are transmitted as one packet.
Spatial Scheme	Clock information is also encoded spatially with data. We call those LEDs which transmit reference signal (clock information of a data symbol) are reference-LEDs. The other LEDs which transmit data are called data-LEDs.
Frequency Domain Scheme	Data along with its clock information are transmitted as one symbol. But before transmission, the packet is encoded in frequency domain.

4.2.1 Temporal scheme

The communications scheme is to solve the problem of frame-rate variation in the receiver by transmitting data along with its clock information together as one packet.

On a time domain transmission, a single LED or a LED panel is being used as a transmitter, and a rolling shutter camera is being used as a receiver. The optical clock rate at several kHz is to avoid any flicker and being suitable for a shutter speed of a commercial rolling shutter image sensor on the market. For a detail in technology, please refer to Kookmin proposal number 16-0240-00 available on the IEEE mentor website[17]. Note that asynchronous bits being used as a form of clock information encoding on the time domain. Additionally, the decoding procedure on the receiver side consists of "forward decoding" and "backward decoding" to achieve high performance in data reception. A "data fusion" technique, which is a process in asynchronous decoding to group data parts (forward and backward parts) those belong to one packet, is a novel idea to be noticed. There are two types of data fusion that happens according to the value of asynchronous bits, including inter-frame fusion and intra-frame fusion:

- "inter-frame fusion" is to group data parts from different images
- "intra-frame fusion" is to group data parts from an image.

4.2.2 Temporal scheme

The communications scheme is to solve the problem of frame-rate variation in the receiver by transmitting data along with its clock information spatially. A spatial-MIMO transmitter is used in this scheme.

To employ data transmission spatially, a set of multiple LEDs is being used as a transmitter. For a detail in technology, please refer to Kookmin

Table 3. Proposed definitions in our schemes for frame rates compatibility

optical clock rate	The frequency at which the data is clocked out to the optical source.
symbol rate	The number of different symbols across the transmission medium per time. It shows how fast the data symbol is clocked out (e.g. 10 symbol/sec). Note that a symbol definition is up to the modulation scheme.
clock information	(of a data packet/symbol) The information represents the state of a symbol clocked out. The clock information is transmitted along with a symbol to help a receiver identifying an arrival state of new symbol under presence of frame rate variation.
frame rate variation	This term is applied for a typical camera when a fixed frame rate video mode is not supported or an auto-frame rate mode is selected by a software application. The frame rate variation is limited by the range of frame rate (frame rate range)
frame rate range	The range observed of frame rate in a selected video mode which is lower limited by the minimum practical frame rate and upper limited by the maximum practical frame rate during the recording time.
varying shutter speed	Shutter speed stands for the length of time a camera shutter is open to expose light into the image sensor. Auto-exposure in video mode causes the variation in shutter speed, hence the available bandwidth is varying.
sampling rate	The number of rows are sequentially obtained per time in a rolling shutter image sensor (also known as row-scanning rate). However, in a global shutter image sensor, the frame rate is equal to the sampling rate.
rolling sampling rate	the practical sampling rate observed from the selected resolution mode of an output image. By using a output image to extract data, the practical sampling rate is less than the sampling rate in an image sensor because the output image resolution is reduced.
reference LEDs	In the spatial scheme, the reference-LEDs do not transmit any data but a reference signal (a specific form of clock information) to help a varying frame-rate receiver decoding data.
data LEDs	The LEDs which transmit data in the spatial scheme.
asynchronous bit	A form of clock information in the temporal scheme to solve frame rate variation problem.
majority symbol voting	When the frame rate of a camera receiver is much less than the symbol rate of a transmitter, a symbol which is transmitted multiple times will be re-captured multiple times. The clock information of a symbol shows that the symbol is repeated or first time transmitted. The majority voting scheme which is applied to vote all captured symbols on a same clock to output a data symbol can enhance error rate.
available bandwidth	The bandwidth limited by the upper physical limit of camera; typically by the shutter speed. The lower limit for the available bandwidth is defined by eye cut-off frequency, e.g. 200Hz, for flicker-free application.
global exposure time	(or capturing time) This term is used specifically in rolling shutter camera to differentiate with the exposure time (the time a row of pixel in an image sensor exposes to light). It is the time from the moment the first-row shutter opens to the moment the last-row shutter close.
rolling effect	This happens in a rolling shutter camera receiver in which camera exposes sequentially to light. Different LEDs may be captured at different time instances on an image due to the rolling effect.

proposal number 16-0241-00 and 16-0239-00 available on the IEEE mentor website[17]. In order to transmit data along with its clock information spatially, the terms of data group and reference group of LEDs are being used. For more clear understand, "data group" is a group of data LEDs those operate together to transmit a data symbol; meanwhile "reference group" is a group of reference LEDs those operate together to transmit a reference signal.

4.2.3 Frequency Domain Scheme

The communications scheme is to solve the problem of frame-rate variation in the receiver. A data along with its clock information together are transmitted as one symbol. But before transmission, the packet is encoded in frequency domain.

The system of frequency-domain approach is quite similar to prototype in the time domain in the usage of transmitter type and receiver type. However, for a detail in technology, once again, any refer to Kookmin proposal available on the IEEE mentor website[17] is appreciated. The specific number of document is 16-0240-00. Noticeably, "frequency symbol" which is defined as a frequency in coding table that is encoded from a packet of data long with its clock information is used throughout the document. Some more useful definitions related to three proposed schemes are found on table 3.

4.3 Performance Analysis

There are plenty of ways in employing three proposed approaches. In this limited paper, we introduce some of our modulation schemes regarding to the proposed protocols. The given modulation schemes include:

- Temporal schemes: OOK modulation with Manchester/4B6B line coding;
- Spatial schemes: Spatial 2-PSK; Color Code
- Frequency schemes: FSK series (32-FSK and 64-FSK).

The performance comparison of those schemes is presented briefly in the table 4. Notably, all of proposed modulations support a great compatibility in frame rate variation. The data rate varies from tens of bps up to tens of kbps depending on the modulation. Finally, the distance of communications is specified through the parameters of communication system.

V. Conclusion and Discussion

The letter has reviewed our contributions at the IEEE 802.15.7r1 Task Group. From an inside look of TG7r1, we have shown the important role of the compatibility support to enormous types of commercial image sensors. The revised model of image sensor was introduced to explain how the variation of parameters in camera and how it affects to the communications. Lately, the proposed architectures and communications schemes were given as an essential introduction of our proposals submitted on the TG7r1 meetings.

The first and the second call-for-proposal meetings on the TG7r1 have been witnessed a great success from the communication technologies. Consequently, the first classification of submitted proposals to the TG was concluded in [18]; however, notice that the selected technologies list is

Table 4. Classification and Comparison of Frame-rate Compatibility Approaches

	Temporal Scheme	Spatial Scheme	Frequency Scheme
Range of camera's frame rate	Support any camera which has frame rate greater than 10fps		
Clock rate of transmission	10 clock/sec		
Data rate Estimation	• Manchester line code: 900bps • 4B6B line code: 1.5kbps	• Spatial 2-PSK: 10bps • Color code: 15kbps	• 32-FSK: 40bps • 64-FSK: 50bps
Expected transmission distance	• 1 meter	• Spatial 2-PSK: 20 meter • Color code: 1 meter	• 5 meter

still an early draft of the technical standard, as called the Draft 0 (D0) of the standard. Any interest about the activities on the TG is welcome. And again, for any detail of technologies, any refer to the official website would be appreciated.

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