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Traffic Modeling in Industrial Ethernet Networks

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***Abstract*—This article discusses the traffic types typically used in industrial networks. The authors propose a number of methods of generating traffic that can be used in modeling traffic sources in the networks under consideration. The proposed traffic models have been developed on the basis of the ON/OFF model. The proposed solutions can be applied to model typical traffic types that are used in industrial systems, such as Time-Triggered (TT) traffic, Audio-Video Bridging (AVB) traffic or Best Effort traffic. The article discusses four traffic models with modifications and shows how the proposed models can be used in modeling different traffic types used in industrial networks.**

***Keywords*—Internet of Things, Traffic Modeling, Industrial Ethernet Networks**

I. Introduction

OVER the past decades the rapid growth in Internet-based applications has been accompanied by a steady increase in the number of available internet services based on the IP protocol and the Ethernet technology. One of the newest areas in the implementation of new services are the solutions introduced to the so-called (*Internet of Things*) and its industrial version (IIoT - *Industrial Internet of Things*) [1], [2]. The sheer popularity of IIoT continues to grows along with the increase in the popularity of the concept of Industry 4.0 [3] and the benefits it offers. The new IIoT networks will carry traffic streams that are known from industrial networks and traffic that has so far been known from office computer networks (LAN) and the Internet. To obtain efficient outcomes in a network with such varied traffic requires consideration as early as possible, i.e. during the designing and dimensioning stage. Appropriate traffic modeling is also important from the point of view of the analysis of the traffic management mechanisms to be used in such networks.

The evolutionary changes that are being introduced to industrial networks are followed by changes in communications and control systems. Recommended industrial networks standards offered by leading manufacturers of devices and device drivers for industrial automatics, initially closed, now tend to be open standards. A large number of these standards are based on Ethernet standards, using Ethernet as a transmitting network or modifying it slightly. As compared to the solutions hitherto used, the solutions based on the Ethernet technology provide greater efficiency, potentially unlimited number of devices within a production network and support a larger geographical reach. In addition, the interest in industrial applications of Ethernet-based solutions has greatly contributed to world-wide standardization process that aims to develop an independent standard dedicated for industrial networks [4].

In order to broaden our knowledge on the nature of traffic generated in Ethernet-based industrial networks it is necessary first to know the traffic parameters of traffic generated by all sources in a network. For each of the type of services these parameters include:

- packet generation intensity;
- distribution of gaps between individual packets for a given traffic stream;
- traffic stream generation intensity for a given type;
- time interval between successive streams in a given service.

The knowledge of these values allows any models based on the ON/OFF source concept to be appropriately paramaterized.

The article is divided into five chapters. The article starts with the Introduction. Following this, Chapter 2 introduces the reader to the measurement environment that allows us to obtain extensive information on the structure of transmitted traffic streams. Chapter 3 describes the proposed methods for modeling traffic sources that are to be found in IIoT networks. This chapter presents models that can be used to model three basic traffic types used in present-day industrial networks, i.e. Time-Triggered traffic (TT), traffic that is characteristic for Audio-Video Bridging (AVB) and Best Effort traffic (BE). The results obtained in the study allowed approximate models of traffic sources based on the ON/OFF concept to be developed. The models are discussed in Chapter 4. Thereafter, Chapter 5 presents the traffic types in industrial networks and their characteristic features. The chapter also contains a table with recommended applications of particular traffic models for modeling different types of traffic. The last section of the article briefly sums up the study.

II. Measuring environment

During the process of the development of an environment to collect information on traffic generated in Ethernet industrial networks the initial assumption was to take into account traffic generated by individual end users and the devices that were elements of the network under consideration. Hence this traffic was to be related to all services that are available on the Internet, such as www, e-mail, VoIP, Video, etc., but also to traffic streams typical for universal industrial networks: *Time Sensitive Network* and/or to particular company's solutions. The study also was to take into consideration traffic generated by proxy servers that serviced other Internet users and traffic generated by applications supervising the operation of a network or data archiving systems. Three levels of measurements were adopted for the implemented measurement environment. The first level of measurement was to provide information on

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traffic streams (*flow level*), the second dealt with collecting information at the packet level, based on how packets were stored and on an analysis of the information included in the headers within individual streams (*packet level*). The last level was similar to the second level, except that, due to the industrial Ethernet-specific properties, the information unit to be analyzed was the Ethernet frame.

Location of subsequent points of observation depends on a specific architecture of a network and on the level of its analysis. In any analysis of traffic in a network at the frame level, in individual segments of an Ethernet network, limited by Ethernet switches, the assumption should be that each of the Ethernet switches will form a single observation point in which an element that stores data, i.e. the ”collector” is placed. The developed system for data acquisition allows network traffic at the single packet level to be analyzed and makes it possible to adjust every transmitted packet to a stream generated by individual network users. In addition, this system will be capable of collecting data at the level of individual frames. As a result, data acquired in this way, i.e. on the basis of long-term and periodic analyses, will allow statistical patterns for streams generated by particular services to be generated. To obtain information on transmitted data streams the NetFlow protocol or similar solutions can be used. The NetFlow protocol is implemented in most of network devices manufactured by Cisco, Juniper, Alcatel-Lucent and Huawei for collecting IP traffic information from routers. It should be stressed, however, that the implementations of this protocol in the devices manufactured by a large number of other manufacturers generate sampling data only to decrease the load in these devices. Depending on the version of the operating system used in network devices, there is often a possibility to change the frequency of sampling. The use of sampling data obtained in pre-defined time intervals is followed by purposeful omission of information about a large number of traffic streams. Therefore, to capture information about all streams, the *softflowd* program is recommended, which allows a maximum number of flows to be tracked simultaneously. As a result of the application of *softflowd* (stream export function), the obtained data additonally include information on the source and destination IP address as well as the numbers of the source and destination ports that are used for each of the transmitted stream. Moreover, it should be noted that the acquisition of such detailed data by softflowd generates a significant processor load on the server. The ”collector” function should be activated on a server dedicated for the purpose of a study. This server also can serve as an exporter of traffic streams and a device that can capture all traffic (at the packet level and frame level). It should also be remembered that if NetFlow data come from different measurement points it, is necessary to appropriately synchronize the clocks of all stream exporter and collector devices to secure consistency in collected data.

1) Storage of information on captured data streams: To provide the possibility to store a large amount of data about captured streams and to make them easily available in retrieval, collected data should be stored in a database system. One of the most common solutions of this type is the MySQL database. Performance/efficiency tests prove that MyISMA is one of the most efficient database engine used in MySQL. While selecting workstation hardware configuration for a data ”collector’ device it is also necessary to make sure that it does not introduce any additional delays caused by waiting time for in/out operations during the database disk storing operation.

2) Storage of information on data streams at the packet level: To store data at the packet level, a ”collector” on a dedicated server can be used as well as the port monitoring function activated at individual switches of a network under investigation. The ”port monitoring’ function is based on duplication of input and output traffic for a port of the switch under observation. Traffic is directed to the indicated port to which a monitoring device is connected. *tcpdump* was chosen as the program for data capture most appropriate for the purpose of the study. *tcpdump* is available in all distributions of the Linux operating system. There is yet another implementation: (*tshark*), a powerful command-line network analyzer and its version with advanced user graphical interface - *Wireshark*. All these tools operate in the same file format (pcap) and the same filter structure. The capture of all information requires a large amount of data to be generated. This may cause problems with capturing, storage and the subsequent analysis of stored data. On account of the sheer amount of information and conceivable confidentiality of data, a necessity may be imposed to reject the transmitted content serviced by the protocols of the fourth layer in the OSI model, such as TCP (*Transmission Control Protocol*) or UDP (*User Datagram Protocol*). The tool described in the article, i.e. *tcpdump*, makes it possible to save packets with required length. To define the required length of packets that are to be captured, it is necessary to establish the maximum acceptable header length of a packet. The length of a header of the second layer in the OSI model is 14B. The IP header is variable and can have up to 24B. The UDP header has a fixed length of 8B. The first four bits from the twelfth octet of the TCP header determine its length. The value of the first bites of the twelfth octet multiplied by four results in the TCP header length being expressed in bytes. Hence the maximum length of a TCP header is 60B. It is worthwhile to emphasize here that if we do not want to omit any important data, it is necessary to capture the first 96B of each of TCP packets and the first 46B for each UDP packet in the second layer.

To increase the effectiveness of data capturing it is necessary to make the number of captured bytes independent of the type of a protocol in the second, third (UDP/TCP indication) and the fourth layer (port number) as well as of the data source (devices in an industrial network / end users). For example, in the case of data generated by end users, it is possible to capture only the first 46B from an UDP header, while in the case of the segments of an Ethernet industrial network it may be necessary to capture all data (this problem is discussed in more detail in the following chapter). *tcpdump* and *Wireshark* programs can also be used to capture the basic information on Ethernet frames, that includes frame control fields, all addresses in the header 802.11 and the length of a packet. These data are sufficient to determine the type of captured data and an evaluation of the amount of data necessary to be captured.

The information about the traffic structure at the level of individual packets/frames and streams, obtained as a result of further measurements, will make it possible to determine the average amount of resources required by traffic streams of particular service classes accurately. This, in turn, will allow simple models of traffic sources based on the ON/OFF source concept to be developed and then will facilitate their use in a simulation environment with the parameters obtained in the analysis of real traffic. The obtained results from measurement system can be used to develop models of traffic sources which has not been described in Chapter 5. In this chapter the models that can be used in the test network launched in Austin are presented. Data obtained from measurements can also be used to detailing proposed models based on the description of sources that are used in the test network.

III. MODELING OF TRAFFIC SOURCES IN INDUSTRIAL NETWORKS

An important element in modeling traffic phenomena in industrial networks is to describe all the sources that are component sources in these networks. Therefore, this chapter provides a classification of the traffic sources in industrial networks and discusses the source models for Time-Triggered (TT) traffic and traffic that is typical for Audio-Video Bridging (AVB).

A. Traffic sources in industrial networks

The general assumption is that in present-day industrial networks different types of traffic coexist and use the same network resources. Beside traffic typical for industrial networks, called Time-Triggered (TT) traffic, Audio-Video Bridging (AVB) traffic and Best Effort (BE) traffic, there is also traffic typical for computer networks, discussed in [4].

Due to the importance of TT traffic in the process related to the execution of production tasks, this type of traffic has the highest priority and precedence in the network. The way this traffic is generated is also characteristic on account of the deterministic behavior of traffic sources. A source of TT traffic can be any device or a sensor that participates in the process of production. TT traffic sources can be divided into the following groups:

- **passive sources** - characterized by a regular generation of packets. A good example of such sources are different types of sensors that send the results of measurements to control devices on a regular basis;
- **active sources** - characterized by a generation of both regular and irregular messages. Regular messages can result from, for example, forwarding reports on a device's status, whereas irregular messages can be sent, for example, as replies to a demand sent by a controller;
- **support message sources** - that generate messages necessary to maintain the effective production process. The activity of these sources results from the algorithms that control the execution of individual tasks in the production process.

TT traffic sources can be modeled by appropriately designed and developed analytical models known from the literature of the subject. The authors of this article are of the opinion believe that the available ON/OFF traffic sources models best serve the purpose. Over the past years these models have been successfully used in modeling traffic in packet networks [7].

B. Time-Triggered traffic

One of the basic TT traffic source models in industrial networks is the ON/OFF model. This model corresponds well to real traffic sources that are characterized by alternately repeated active states (ON) and idle states (OFF). During the active state a source generates packets, whereas in the idle state the source is inactive (switched off). The simplest example of a source of this type is a telephone subscriber that is making a telephone call. The time in which the subscriber talks corresponds to the active state, whereas the time whe the subscriber listens corresponds to the idle state. The basic ON/OFF traffic source model [8] assumes that the duration times in the active and inactive states have exponential distribution with the parameters $1/\alpha$ (state ON) and $1/\beta$ (state OFF), respectively. The parameter α is the intensity of the transition from state ON to state OFF, whereas the parameter β is the intensity of the transition from state OFF to state ON. The operation of the source is represented by two-state Markov process shown in Figure 1.

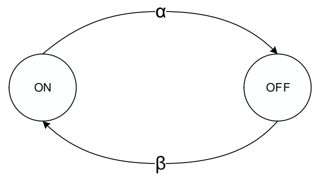

Fig. 1. Two-state Markov chain.

The traffic source model under consideration assumes that in state ON packets are generated with constant rate, equal to $1/T$, where T denotes the fixed time interval between successive packets. In state OFF packets are not generated by the source. The presented ON/OFF source model can also be viewed as a simple example of a modulated process that is a combination of two different processes (Fig. 2).

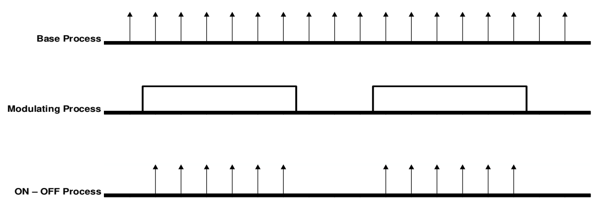

Fig. 2. ON/OFF traffic as an example of a simple modulated porcess [6].

The reference process is characterized by fixed rate in packet generation $(1/T)$. The process is modulated by the process whose Markov chain is shown in Figure 1. As a result of the modulation process, the packets are not generated in those periods in which the modulation process is in state OFF. By taking into account the nature of traffic generated by TT sources, it is possible to model them by appropriately parametrized ON/OFF sources. The operation of passive traffic sources is limited to sending messages in regular time intervals. To determine the parameters of an/the OF-OFF source that analytically corresponds to and is an analytical counterpart of a real source, it is necessary to first determine the intensity of transitions between states ON and OFF. Taking into account uninterrupted and sustainable work time of an industrial network, duration time of state ON is typically far higher than duration time of state OFF, which means that the intensity of the transition to the inactive state (α) is very low (inactive state is a marginal state). A traffic source can be switched off only when all of the system is switched off, during a failure or, alternatively, when prompted by a driver. The rate at which messages are generated in state ON depends on the parameters of a real device (sensor).

C. Audio-Video Bridging traffic

The models most frequently used to model AVB traffic sources are MMPP models (*Markov Modulated Poisson Process*). These models allow the variability of a packet stream in time to be taken into consideration, and in particular make it possible to take into consideration the abrupt and rapid nature of this type of traffic. The MMPP process is called a double-stochastic process as both the reference process and modulating processes are Markov processes. The simplest, two-state 2-MMPP model [9] is characterized by continously alternating active states (ON1) and (ON2). During state (ON1), the source generates a Poisson traffic stream with the intensity α_1, whereas in state (ON2) a Poisson stream with the intensity α_2. Duration times for states (ON1) and (ON2) have exponential distribution with the parameters ω_1, ω_2, respectively. The parameter ω_1 is the intensity of the transition from state (ON1) to state (ON2), while the parameter ω_2 is the intensity of the transition from state (ON2) to state (IN1). A diagram of the 2-MMPP process is presented in Figure 3.

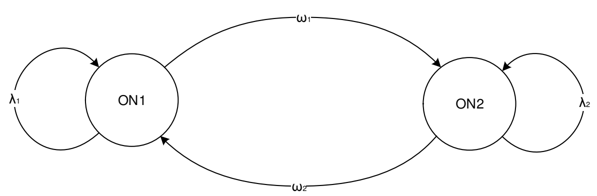

Fig. 3. Diagram of 2-state MMPP process.

Figure 4 shows a Markov process divided into the reference process and modulating process, both defining the operation of a 2-MMPP source.

The 2-MMPP process can be described on the basis of the matrix Q that defines the intensities of transitions of the modulating process:

$$\mathbf{Q} = \begin{bmatrix} -\omega_1 & \omega_1 \\ \omega_2 & -\omega_2 \end{bmatrix}, \tag{1}$$

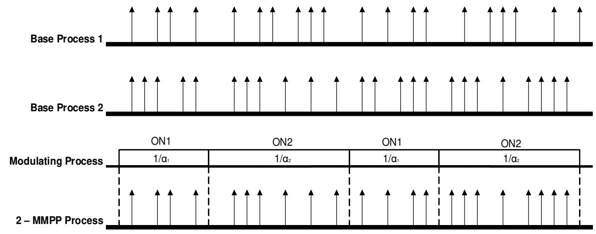

Fig. 4. 2-MMPP traffic.

and the call intensity matrix in individual states of the modulating process:

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}. \tag{2}$$

The state probabilities for the modulating process $P(\mathrm{ON1})$ and $P(\mathrm{ON2})$ determine, on average, this part of observation time in which the process is in respective states:

$$P(\mathrm{ON1}) = \frac{\omega_2}{\omega_1 + \omega_2}, \quad P(\mathrm{ON2}) = \frac{\omega_1}{\omega_1 + \omega_2}. \tag{3}$$

On the basis of Eq. 3 it is possible now to determine the average value $ev(\lambda)$ and variance $var(\lambda)$ of call intensity [23]:

$$\mathrm{ev}(\lambda) = \frac{\omega_2\,\lambda_1 \; + \omega_1\,\lambda_2}{\omega_1 + \omega_2}, \tag{4}$$

$$\mathrm{var}(\lambda) = \frac{\omega_2\omega_1(\lambda_1 \; - \; \lambda_2)^2}{(\omega_1 + \omega_2)^2}. \tag{5}$$

Two-state matrix of the modulating process does not correspond to the intuitive operation, from the engineering point of view, of a given MMPP source. Therefore, a better description of the operation of the source can be given in terms of two, measurable time characteristics: T average time of one cycle $(\mathrm{ON1}) + (\mathrm{ON2})$ and T_{ON1} and the average duration time of a source in a state, e.g. (ON1), measured during the time of observation. Then, the probability estimator $P(\mathrm{ON1})$ (denoted by the symbol $e(\mathrm{ON1})$ can be determined as follows:

$$e(\mathrm{ON1}) = \frac{T_{\mathrm{ON1}}}{T}, \tag{6}$$

And, as a result, the average value $ev(\lambda)$ can be estimated in the following way:

$$\mathrm{ev}(\lambda) = \; e(\mathrm{ON1})\,\lambda_1 + [1 - e(\mathrm{ON1})]\,\lambda_2. \tag{7}$$

The parameters $e(\mathrm{ON1})$ and T also allow call intensity estimators $e(\lambda_1)$ and $e(\lambda_2)$ in appropriate states of the process to be determined:

$$e(\lambda_1) = \; \frac{1}{e(\mathrm{ON1})\mathrm{T}}, e(\lambda_2) = \frac{1}{[1 - e(\mathrm{ON1})]\,T}. \tag{8}$$

If we assume that in the 2-MMPP source model the parameter $\lambda_2 = 0$, then the 2-MMPP process becomes an IPP process (Interrupted Poisson Process) whose diagram is shown in Figure 4. This means that the diagram of the IPP source and that of the on-off source are identical. The difference between the sources lies in the assumption that in the case of the on-off source the stream generated in state on has a regular nature.

Technically, the IPP source can be then described on the basis of the following matrices: Q and Λ:

$$\mathbf{Q} = \begin{bmatrix} -\omega_1 & \omega_1 \\ \omega_2 & -\omega_2 \end{bmatrix}, \tag{9}$$

and the call intensity matrix in individual states of the modulating process:

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & 0 \end{bmatrix}. \tag{10}$$

In the general case, it is the s-MMPP process that has to be considered, i.e. an s-state Markovian process in which in each state k $(0 \leq k \leq s)$ a Poisson call stream with the intensity λ_k is generated. The s-MMPP process is described by the following matrices Q and Λ:

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \lambda_s \end{bmatrix}, \tag{11}$$

$$\mathbf{Q} = \begin{bmatrix} -\omega_1 & \omega_{1,2} & \cdots & \omega_{1,s} \\ \omega_{2,1} & -\omega_2 & \cdots & \omega_{2,s} \\ \cdots & \cdots & \cdots & \cdots \\ \omega_{s,1} & \omega_{s,2} & \cdots & -\omega_s \end{bmatrix}, \tag{12}$$

where:

$$\omega_i = \sum_{j \neq i} \omega_{i,j}. \tag{13}$$

A choice as to the parameters of the s-MMPP process depends on measurements of a real stream in the network. The choice pattern is based on quantization of a real stream that corresponds to the number of states in the modulating process. On the basis of the adopted quantization it is possible to determine the intensity of transitions $\omega_(i,j)$ $(0 \leq (i,j) \leq s,\ i \neq j)$ of the modulating process by way of a measurement of the average time in which a process transits from state i to state j [21].

D. Self-similarity of MMPP sources

The importance and significance of MMPP processes in traffic engineering largely stems from the fact that these models approximate well self-similar call streams, including AVB stream [10], that are characterized by long-range autocorrelation. For the majority of processes (that are based on the Poisson model), the autocorrelation function is quick to reach zero (usually according to the exponential function). In the case of self-similar processes, the autocorrelation function declines far slower (hyperbolically) and may never reach the zero value. The effect of self-similarity occurs virtually in every packet network [11], including the Ethernet network [12], [13]. Self-similarity of a call stream manifests itself in a "similar" call distribution (in time) on a large number of time scales. The measure of self-similarity of a call stream is the so-called Hurst H exponent [22] that has the following properties [14], [15]:

- The H parameter can take on values from the interval $(0;1)$.
- If the H value is within the interval $(0.5;1)$, then the process is a positively correlated self-similarity process,
- The higher value of the coefficient (from 0.5 to 1), the higher autocorrelation between calls that belong to a given traffic stream,
- With the instance of $H = 1$, the process on different time scales is composed of the exact copies of itself,
- For $H = 0.5$, executions of the process on different time scales are independent from one another and purely random, just as it is the case with the Poisson stream,
- However, if H is in the interval $(0;0.5)$, then the process is a negatively correlated self-similar process.

The value of the H coefficient of a given call stream can be determined by one of the available methods, [11], [20] e.g.: R/S as a function of time scale, variance of the process rescaled by the time scale and aggregated variance. By having the knowledge of the H exponent (or measured auto-covariance coefficient) for a given call, we can determine the parameters of a relevant corresponding s-MMPP source (sources) that approximates the real call stream. In traffic engineering, such a procedure is called the adjusting procedure, e.g. [11], [17], [18].

E. Simulation of MMPP sources

A simulation of an s-MMPP call stream is not complicated. For this purpose, for the modulating process, the GLL (Random Number Generator) is used with the exponential distribution in which time ξ_i, ξ_i, i.e. the time of staying in state i $(0 \leq i \leq s)$, is consistent with the distribution:

$$\zeta_i = \omega_i \, e^{-\omega_i \, \tau_i}, \tag{14}$$

whereas a transition from state i to state j can be determined on the basis of GLL with the uniform distribution, in which the transition probabilities $q_(i,j)$ $(0 \leq (i,j) \leq s)$ are as follows:

$$q_{i,j} = \begin{cases} 0 & \text{for} \quad i = j, \\ \frac{\omega_{i,j}}{\omega_i} & \text{for} \quad i \neq j. \end{cases} \tag{15}$$

In each of the states of the modulating process, a call stream is generated by GLL with the exponential distribution that is subject to the following distribution:

$$\zeta_i(t_i) = \lambda_i \, e^{-\lambda_i \, t_i}. \tag{16}$$

IV. ON/OFF MODELS PROPOSED IN THE ARTICLE

This chapter provides basic information on the ON/OFF traffic source model. During our study, four variants of the ON/OFF traffic source model were distinguished. The variants differ from one another in:

- *the method for a determination of frame length*: frame length can be fixed or variable (length distribution can be either exponential or normal);
- *the method for a determination of the distance between successive frames*: gaps can be interpolated between each of the frames, duration time of these frames can be fixed or random with required distribution (normal or exponential);
- *the way duration time for state ON is generated*: it can be fixed or random with required distribution (normal or exponential);

- *the way duration time for state OFF is generated*: it can be fixed or random with required distribution (normal or exponential).

The above mentioned parameters influence duration time of state ON. The period of state OFF can be pre-defined, or its length, and can be a random variable with required average value and selected distribution. Table 1 shows four selected variant configurations for ON/OFF source models.

TABLE I
ON/OFF SOURCES IN TESTBED / ENVIRONMENT

	M1	M2	M3	M4
duration time state ON	fixed	fixed	expon.	expon.
duration time state OFF	fixed	expon.	expon.	expon.
frame length	fixed	fixed	fixed	expon.
gap length between frames	fixed	fixed	fixed	expon.

Each of the variants of the ON/OFF source models can be further modified, thus making it possible to randomly determine the type of each successive event in state ON. In state ON, the type of an event is determined randomly (i.e., a frame or a gap between frames, which is a random variable). Then, service time for an event is chosen randomly (frame duration time or gap time between frames). Therefore, the letter R is added to the names of the ON/OFF models in which the type of an event is a random variable, as in the example: M2-R. Figures 5-8 show graphical representations of traffic defined by the models M1-M4.

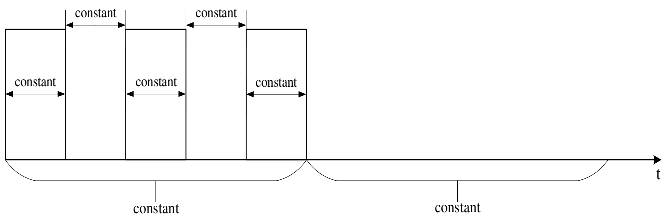

Fig. 5. Model M1: all parameters are fixed.

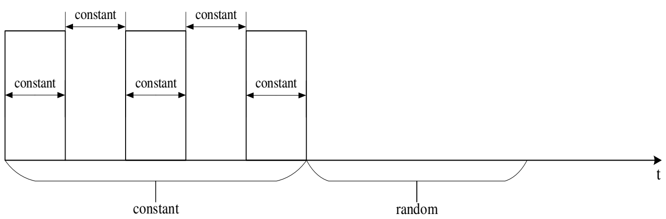

Fig. 6. Model M2: duration time for state OFF is determined by a random variable (with normal or exponential distribution), other parameters are fixed.

A. Model M1

In model M1, duration time for state ON is pre-defined, whereas the number of frames generated within this time is fixed. Also, duration time for state OFF is fixed, just as are the length of frames and gap time between them. In the boundary case, the length of gaps can be equal to zero, i.e. frames are generated uninterruptedly.

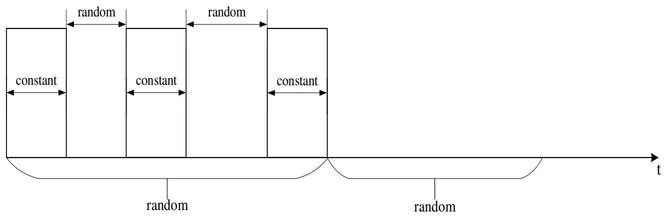

Fig. 7. Model M3: duration times of states ON and OFF are determined by a random variable (with normal or exponential distribution), lengths of frames and gaps between them are fixed.

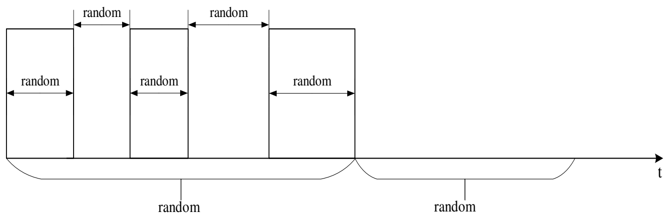

Fig. 8. Model M4: all parameters are variable.

B. Model M2

In model M2, duration time for state ON is pre-defined, whereas the number of frames generated within this time is fixed. Duration time for state OFF is determined by a random variable with exponential distribution. The length of frames and gap time between them are fixed. In the boundary case, the length of frames can be equal to zero, i.e. frames are generated uninterruptedly.

C. Model M3

In model M3, duration time for state ON is determined by a random variable with exponential distribution. The size of frames is fixed, whereas their number is proportional to duration time for state ON. Duration time for state OFF is determined by a random variable with exponential distribution. The length of frames and gap time between them is fixed. In the boundary case, the length of gaps can be equal to zero, i.e. frames are generated uninterruptedly.

D. Model M4

In model M4, duration time for state ON is determined by a random variable with exponential distribution. The size of frames is determined by a random variable with exponential distribution, whereas their number is proportional to duration time for state ON. Duration time for state OFF is determined by a random variable with exponential distribution. The length of frames and gap time between them is also determined by a random variable with exponential distribution.

E. Modification R - „Random event”

The ”Random event” modification is based on the fact that events in state ON have random characteristics. This means that each event can represent a frame or a gap between frames, depending on a random variable. This modification can be applied to any of the models from 1 to 4.

F. Modification D

The ”D” modification is based on the fact that part of frames and gaps between frames can have fixed length or random length, i.e. such that is determined by a random variable with any distribution (exponential or normal). The assumption in the ”D” modification is that the time characteristics of a variable of states ON and OFF can be described by either exponential or normal distribution.

G. Modification T – determination of duration time of state ON on the basis of the number of events

In models M1-M4, duration time for state ON took on a fixed value or was determined by a random variable with required distribution. The assumption in this modification is that duration time for state ON is strictly determined by the number of events (frames or gaps between them) with required time characteristics (fixed or random). Due to a possibility of a random duration time of all events in state ON, duration time for this state will be defined as the sum of all its component events. Duration time for state ON is considered to be terminated when all events defined as component for state ON will be serviced. The number of events in state ON will always be fixed.

V. Types of traffic in industrial networks

The test network Flexible Manufacturing Testbed has been created by National Instruments, in the laboratory Industrial IoT Lab Demonstrations [24]. It is one of the three most important test networks in the world, along with Labs Network Industrie 4.0 (LNI) in Europe [26] and Huawei’s OPC UA TSN testbed [25]. The network, the graphical representation of which is presented in Figure 16, has been created as a result of the work of Industrial Internet Consortium’s (IIC) Time Sensitive Networking Group. Over 12 largest firms from across a wide spectrum of industries have been participating in the test network. Most of the participants in the test network come from industrial automation and control environments, but the participating companies also include networking and technology companies. The most outstanding IIC companies participating in the TSN Testbed include: Belden/Hirschmann, Bosch Rexroth, B&R Industrial Automation, Cisco, Innovasic, Intel, KUKA, National Instruments, Renesas Electronics, Schneider Electric, SICK AG, and TTTech and Xilinx, among others [24].

The network has been constructed by a large number of providers of industrial and network devices that combine their efforts in supporting TSN functionality. The test network offers a possibility to examine and test coordination and synchronization between the infrastructure, switches and routers and prototype end devices. Manufacturers and producers test capabilities of prototype systems to ensure that their products will cooperate well enough with products made by other manufacturers and that will meet requirements of the next-generation manufacturing systems. Therefore, tests that are carried out in this environment constitute an important element in the evaluation of the maturity and applicability of the TSN to mass-produced devices.

Tests carried out in the TSN Testbed are designed to examine possibilities of synchronization and differentiation (variability) in the quality of scheduled traffic. Most of the participants in the tests are currently working on service control issues in critical control traffic and successive transfer of protocols for the TSN network environment. The continuous and sustainable development of the test network/bed is related to, among others, the growing number of companies taking part in tests. All participants – providers of devices for network infrastructure, manufacturers of end devices and producers of measuring systems - can acquire knowledge about practical conditions and circumstances surrounding TSN solutions. In this way, they are in position to evaluate what is still to be resolved or improved, what is to be further developed and extended, or what is to be changed to make their products cooperate well with one another. Experience thus gained also influences works in TSN standardization [24]. The issues tested in TSN Testbed in Austin, Texas at the NI Industrial IoT Lab, included [24]:

- synchronization of devices by a common time signal provided by the network,
- reliability and maintainability in TSN data transfer between devices manufactured by different producers,
- definitions of TSN traffic flows in Central Network Controllers (CNCs) and their distributed transmission to network infrastructure,
- traffic transmission from the input to the output, using TSN traffic flow,
- demonstration of the capabilities of TSN to protect critical flows against high-bandwidth traffic,
- connection, via gateways, of non-TSN traffic into TSN flows
- demands and requirements of TSN CNC flows to be met by the network infrastructure (schedule distribution)
- data consistency over OPC UA Pub-Sub over TSN.

Regrettably, the descriptions included in the www pages and materials that are made available by Industrial Internet Consortium do not provide sufficient information that would enable us to unequivocally identify all types of devices currently attached to the TSN Testbed. To make up for this shortcoming, we have used in our investigation the report “Time Sensitive networks for Flexible Manufacturing testbed – Description of Converged Traffic Types”, in which the results of measurements of different types of traffic that have been performed using this particular testbed are presented [5]. The report defines 8 types of traffic: Isochronic, Cyclic, Alarm and Events, Configuration and diagnostics, Network Control, Best effort, Video and Audio/Voice.

TABLE II
JUXTAPOSITION OF PARAMETER VALUES FOR DIFFERENT TYPES OF TRAFFIC AND PROPOSED MODEL TO THEM/

	Periodicality	**Period length**	**Network synchronization**	**Data delivery guarantee**	**Tolerance to interference**	**Tolerance to loss**	**Data size**	**Criticality**	**Proposed model**
Isochronic	yes	$120us - 2ms$	yes	deadline	no	no	$30 - 100$	high	M1 with modification R
Cyclic	yes	$2 - 200ms$	no	latency	yes	yes	$50 - 1000$	high	M2-M4 with appropriate parameters
Alarm and Events	no	n.a.	no	latency	n.a.	yes	$50 - 1500$	high	M1-M4 with the modification R and D
Configuration and diagnostics	no	n.a.	no	bandwidth	n.a.	yes	$500 - 1500$	medium	M1-M4 with modification R
Network Control	no	$50ms - 1s$	no	bandwidth	yes	yes	$50 - 500$	high	M1-M4 with modification R
Best effort	no	n.a.	no	none	n.a.	yes	$30 - 1500$	low	M1-M4 with appropriate parameters
Video	no	n.a.	no	latency	n.a.	yes	$1000 - 1500$	low	M1-M4 with parameters imposed by codecs and their characteristics
Audio/Voice	no	n.a.	no	latency	n.a.	yes	$1000 - 1500$	low	M1-M4 with appropriate parameters

Each of these types is characterized by different characteristic values that can be categorized into the following groups:

- *Periodicity* - this parameter describes two types of transmission: cyclic and acyclic (e.g. event-controlled);
- *Period length* - this parameter refers only to periodic data streams and describes planned data transmission periods in the application layer;
- *Synchronization with network* - this parameter describes whether a traffic stream is synchronized with network time in the application layer;
- *Reliability of data delivery* - this parameter marks limitations in application delivery for network intact operations. To select an appropriate QoS mechanism, the scope of this particular feature is limited to data transmission requirements for applications only. Three levels for this parameter have been defined: deadline, latency, bandwidth. For traffic with no defined requirements, in place of this parameter the value "n.a." is assigned.
- *Tolerance to interference* - this parameter has relevance to only periodic data streams and describes the tolerance of an application to jitter;
- *Tolerance to losses* - this parameter describes the tolerance of an application to the loss of successive packets in the stream;
- *Data size* - this parameter describes the size of data transmitted in Ethernet frames;
- *Criticality* - this parameter describes the data critical level for an operation of necessary sections of the system and is used to determine the QoS/TSN mechanisms for them.

Table 2 shows which of the proposed models, and with what parameters, can be applied to model the traffic types distinguished during measurements in the test network.

VI. SUMMARY

All the simulation studies on traffic management mechanisms in IIoT networks known to the present authors did not give much attention to traffic generation methods. Typically, authors limited themselves to selecting traffic sources as they were defined in a simulation environment, i.e. either OMNET++ or GNS3. As a result, these investigations do not take into consideration the influence of the way traffic is generated on the network characteristics, i.e. delay or jitter. The studies and analyses carried out by the present authors, as part of a broader project on the analysis of traffic management mechanisms in industrial Ethernet networks, show that there is a relation between traffic generation and packet delay in the network. This observation made the authors of the article start to investigate simple engineering models of traffic sources for this particular type of network. The present study involved an application of data collection and traffic analysis methods used in real networks as well as a careful examination of the results of the measurements obtained in the test network. The objective of the study was to propose a number of engineering models that would represent characteristics corresponding to real traffic characteristics as accurately as possible. The models were then successfully used in a test simulation environment to evaluate the effectiveness of traffic management mechanisms under investigation. The models of traffic sources developed in the study are presented in this article.

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