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Demand-oriented selection and combination of industrial bus systems for advanced energy management purposes

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Abstract

Industrial bus systems are the backbone of production control and management. Regardless of the utilised technology, industrial communication systems realise feedback loops from sensors and control values to actuators. Industrial communication is also the basis for an operative energy management system. Energy demands are metered and send to management and decision support tools to be analysed and evaluated. Present industrial bus technologies from production and building automation domains offer different functionalities to support an operative energy management. This paper aims to discuss the requirements of an advanced energy management system regarding the technical issues of appropriate data communication means. By describing the properties of various bus systems the advantages and disadvantages of each one is shown and the applicability for the described utilisation is considered. Finally, the possibilities to apply machine control mechanisms through the bus systems are analysed.

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Keywords: industrial communication; field bus; energy efficiency; energy monitoring; energy management

1. Introduction

In 2010 the industrial sector caused 28.9 % of final utilisation of coal, oil, natural gas and eletricity worldwide [1] and equivalent greenhouse gas emissions of 14.16 $GtCO_2eq/yr.$ [2]. Energy management plays a key role in reducing this industrial energy demand and greenhouse gas emissions of the industrial sector. To establish an effective energy management system, the continuous monitoring of demand behaviour of energy utilising entities and the knowledge of energy flows within a production environment is essential [3]. Energy management systems consist of various functions. Figure 1 shows a selection of these functions and a generic structure for data collection on field level. These functions can range from simple allocation and controlling issues with low requirements on update times, up to more superior control and data analytic issues with closed-loop feedback to machine's programmable logic controller (PLC) and high dynamics on sensor readings. A special challenge arises when energy management systems should have the ability to generate process information or knowledge for e.g. predictive maintenance purposes from the acquired data. For this purpose, higher data update frequencies are generally necessary. To comply with these needs, the communication infrastructure between elements of an energy management system, as shown in Fig. 1, must fulfil specific requirements. Against this background, this paper presents a literature overview regarding different classes of bus systems applicable for energy management purposes. A systematic approach to select and combine suitable bus systems to create a demand-oriented matching of energy management system's requirements and bus system's technical specifications is derived. The findings are discussed and applied in two scenarios within one case-study setup. The presented procedure enables manufacturing enterprises to select and combine suitable bus systems, dimensioned for their specific energy management use cases.

2. State of the art

2.1. Basic energy management functions

In the following sections energy management functions according to Fig. 1 are identified, characterised and analysed. In Chapter 4 the results of the literature review will be condensed within an evaluation matrix and matched with the available communication technologies presented in the Chapter 2.2.

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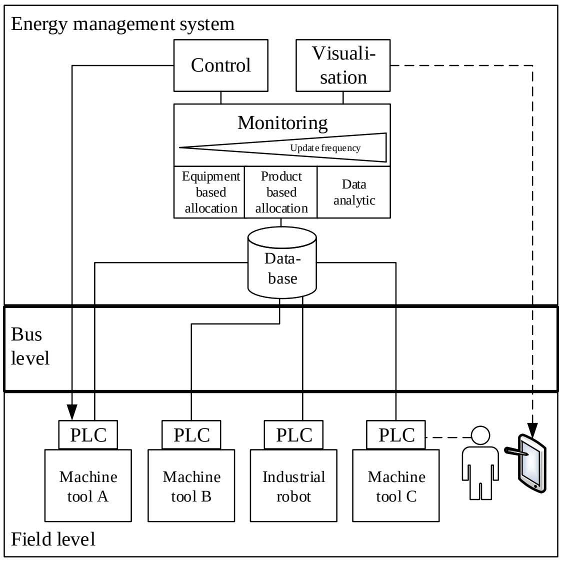

Fig. 1. Possible structure of an energy management system

Subsequently important key requirements are written in italics. The terms will be picked up again in the following review on bus systems.

2.1.1. Visualisation

Energy data acquisition and monitoring has been known for several decades and is standardised internationally in the ISO 50 001 [3]. First references for systematic characterisation of energy utilising entities can be found in the early 1980s [4]. In energy economy the provision of load profiles with an *update frequency* of 15 minutes is state of the art for many years. In the domain of production environments monitoring of energy data is not widely distributed, but essential to evaluate and improve energy efficiency of production processes [5]. For monitoring of cycle time demand specific consumption Mueller et al. recommend *update times* in the dimension of seconds. To make statements about energy efficient machine operation an *update time* in the dimension of minutes is requested [6]. Panten et al. state that for energy monitoring purposes in real-time high *update frequencies* are needed to recognise power peaks during tool changes [7]. To gain informations about tool conditions within a machine tool, Al-Sulaiman et al. used electrical power signals at an *update frequency* of 250 Hz [8]. For data mining purposes Denkena et al. suggests an update frequency of 500 Hz to capture applied forces on the tool of a milling machine. Resulting process data is evaluated and used to increase efficiency and flexibility in process planning [9]. For energetic evaluation of production processes, the measurement of a whole process becomes necessary. To be able to allocate dynamic energy demands to single events, at least an *update frequency* of ten samples within one steady state are recommended [5].

To realise machine based energy budgeting functions based on data monitoring and visualising, Stüger demands the *maximum data security and system reliability* as an important requirement [10].

In a medium-sized car manufacturing plant with a yearly output of 250 000 vehicles, more than 500 permanently installed *measurment points/bus participants* are necessary to allocate energy demands and resulting costs to a certain machine or cost center [6].

2.1.2. Control

Fig. 2 shows the generic communication pyramid within a factory and the seperation into machine near (PLC and sensors/actors) and production side or line wide (ERP/MES/SCADA) sections. In addition, the requirements regarding the update time and the data volume changing in vertical direction are depicted. The update time decreases with the transition from PLC to control level. On field level, real-time for sensor/actuator communication is needed [5]. Control of machines can be realised based on the ERP/MES/SCADA level or on machine level (PLC and sensors/actors) [11][12]. On sensor/actor level, as an example, the DMG EnergySave Box is available as a control unit to switch machine tools into an energy saving mode refer to Fig. 2 (1). When the energy demand of a machine tool drops below a predefined threshold for a defined period of time, the machine will be automatically switched to emergency stop condition and the light in the working chamber will be switched off. The control command is realised by a direct switching device at the machines emergency stop mechanism and the working chamber light. Therefore, the EnergySave Box is a closed, embedded system. Hence, *safety* issues are fulfilled [11]. Other solutions are implemented directly inside the PLC of a machine tool e.g. Heidenhain EnergyOpt refer to Fig. 2 (2). Standby and switch off times for components of a machine tool can be individually defined [13]. Obviously, controlling solutions usually are located at the lower end of the automation pyramid according to Fig. 2. Therefore, *interoperability* in vertical direction of the automation pyramid plays a less important role. On the level of production site, line wide solutions, such as the Siemens SIMATIC powerrate, offer the possibility to switch off consumers from a central process management system refer to Fig. 2 (3). Controlling issues are realised by serial fieldbus communication [12]. By this means, *real-time* and *safety* issues are respected.

2.2. Categories of buses and their technical requirements

According to Klasen et al., two main categories are differentiated [14]. The specifications of the various bus technologies (and protocols) are described according to the requirements demanded by the previously introduced energy management functionalities written in italics.

2.2.1. Serial field buses

Serial buses are commonly used for data connections in the lower layers of the automation pyramid. Typical use cases are interconnections between field devices and control units. This paper focuses on the most commonly used technologies as identified by Klasen et al. [14]. Accordingly, the most common field bus systems are CANopen, CC-link, CIP, INTERBUS and PROFIBUS. Generally, serial field buses operate in one or more possible *topological* forms such as line, star, ring and/or tree topology. Most of the buses follow a master/slave model, where only one bus participant can have the role of the master. The bus participant with this role is the only device that can initiate data transfer. Participants with the slave role can only send data if a master requests them. That behaviour leads to a low *update frequency* if a query of many devices should occur. To avoid this behaviour, there are serial field buses available which support a multi master mode. A further characteristic regarding the *topology* is the limited number of *bus participants* which are typically between 60 and 256. The maximum supported cable length is of importance. The specific bus system values are between 100 m and 1000 m. Some bus systems have to decrease their transmission speed to enable longer distances between the interconnected devices. Also the physical connector can vary between bus systems and causes difficulties in horizontal interoperability according to Fig. 2. While most of the bus systems possess realisations which can be used for *safety* relevant applications, they typically do not address *security aspects*. This is because serial field bus systems are localised in smaller but isolated areas and an invader therefore would require physical presence.

2.2.2. Industrial Ethernet

Ethernet was firstly standardised by the Institute of Electrical and Electronics Engineers in the year 1983 [15]. Now it is the dominant solution in the field of home, office and industry local area networking. It represents a technology that is technically easy to install, administrate and to maintain. Ethernet-integrated circuits (ICs) are cheap and most computers come with an integrated ethernet interface [16]. Usually the Ethernet bus *topology* is radial and in this case easy to expand. Beside this a line setup or point to point setup is possible with a cable length up to 100 m.

There are a variety of reasons why real-time tasks within industrial environments can not be realised by ethernet. Carrier Sense Multiple Access/Collision Detection (CSMA/CD) is an access method that includes collision controlling mechanisms [17]. Under certain circumstances, packages could be dropped or the arrival is strongly delayed. Under this assumptions Ethernet technology is without modification not recommended for *real time* sensor/actor applications on machine level. Fig. 2 highlights a good *interoperability* in vertical direction of the automation pyramid. Volz proclaims to use standard information protocols (TCP, HTTP) for communication from field to office level e.g. for data visualisation purposes [14].

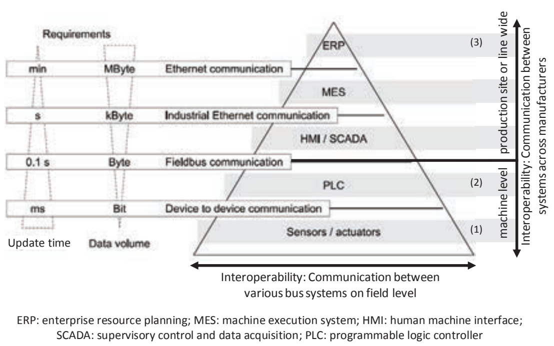

Fig. 2. Communication structure within a factory with requirements regarding data update time and data volume

By means of the technical advantages of ethernet, as stated above, the further development to real-time ethernet technology emerged for use in sensitive industrial environments [16]. Industrial Ethernet allows *real-time* applications as well vertical integration between all layers inside the automation pyramid, paricularly on sensor/actuator level, as depicted in Fig. 2 [14]. The term real-time designates the ability that the processing results will be available within a predefined time-frame. The time-frame is determined by the process requirements [18]. Additional to conventional ethernet applications, real-time ethernet features methods for prioritisation and scheduling of ethernet packets. Packet collisions will be avoided [19]. In the field of *safety* for industrial Ethernet, several vendors provide safety solutions. To name but a few: Safety over EtherCAT or openSAFETY. *Security* measures arisen from IT technologies can partially adapted to industrial Ethernet applications [14].

3. Concept

3.1. Generic selection procedure

In this section practise-oriented rules to find a proper bus system for a specific scenario are presented, based on the key requirements identified in chapter 2. Fig. 3 indicates graphically how the bus system combination for a specific scenario can be found. Step number I (Identification of requirements) in Fig. 3 describes the selection of the specific scenario requirements concerning an energy management functionality

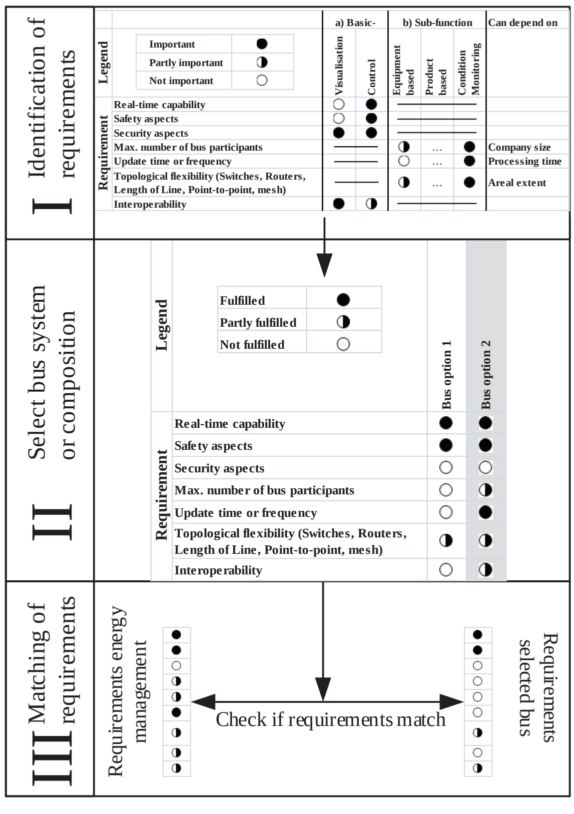

Fig. 3. Overall procedure

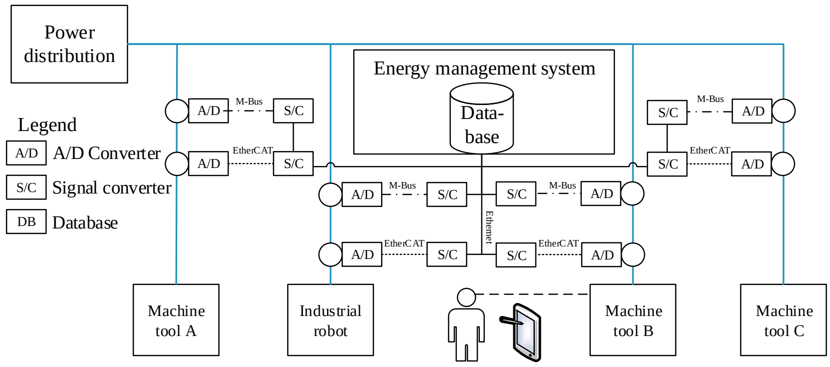

Fig. 4. Case study specific setup

(see also Fig. 1). First, the basic energy management functionality (a) visualisation or control must be selected. Some requirements are predetermined by the basic functionality. Others (max number of bus participants, update time or frequency and topological flexibility) must be selected case specifically. The second selection depends on the the sub-function (b) and can depend on company specific characteristics. E.g. the processing time affects the update time or frequency of the energy management system. Hence, the importances of a requirement for a specific scenario are to be seen as guidelines and depend strongly on the type of enterprise. After deriving the importance of requirements for a specific scenario, a proper bus system or a composition of bus systems according to the matrix depicted in Fig. 5 step II, must be selected. The last step III (Matching of requirements) provides the examination whether the requirements of the specific energy management scenario matches the selected bus system or the composition of bus systems. If the bus system or the composition do not match, another bus system has to be selected from Fig. 3 step II.

4. Application in a case study environment

A factory is a complex system with production machines, near-machine peripheral equipment (e.g. coolant filters) of the production machines, equipment for material transport and energy distribution, central peripheral units (e.g. compressed air and steam generation) and technical building service to maintain production environments, comfort and safety [6]. There are interrelationships and dependencies between these entities. In order to reduce the complexity of a factory, a reference setup is used to show the application in two application scenarios. Fig. 4 is related to the reference setup, that consists of an industrial robot, and three generic machine tools. In this setup the industrial robot and the machine tools represent the production equipment on the shop floor. Monitoring takes place with two types of installed metering hardware.

In this case a serial bus (M-Bus) and an industrial Ethernet bus (EtherCAT) are implemented according to Fig. 4. The power demand of a machine tool consists of the accumulation of sundry power consumers inside the system boundary [20] and peripheral units outside the machine boundary that are crucial for the machining but considered to be adjacent to the core process [21]. In this example, measurement takes place directly at the machine's power distribution cabinet. Hence, the control unit, drives, actuators and very close adjacent peripheral units are monitored within one metering point.

4.1. Application of concept

Fig. 5 depicts the results of the concept applied on two specific scenarios. On the upper left section scenario A and B and the specific requirements are depicted. Both scenarios represents sub-functions of the basic visualisation. While scenario A shows an equipment based energy and cost budgeting, scenario B represents a system for analysing electric load profile for data mining purposes. The specific requirements results out of step I according to the generic selection procedure introduced in Fig. 3. The upper right section of Fig. 5 shows the range of bus classes and the resulting requirements according to the literature review in chapter 2.2. As shown in step II of Fig. 3, a suitable bus system or a combination of bus systems must be selected. By the composition of different classes of bus systems specific requirements appear dominant in the resulting system. For example by the combination of a serial bus with an Ethernet network (scenario specific combination A) the update time of selected M-Bus system represents the rate-determining step, if the resulting bus system capabilities are considered. As a result, the requirement update time or frequency is not fulfilled for the joined bus system, as presented on the lower left section of Fig. 5. Anyway, the resulting bus system suffices the scenario specific requirements of machine based energy and cost budgeting.

4.2. Technical insight into scenario specific bus combinations

Fig. 4 shows exemplary the layout of a metering system for electric power attached to entities of the specific use case. Data communication is realised by M-Bus and the industrial Ethernet bus EtherCAT. In both cases the measured data is transferred to a gateway unit and is written by an Ethernet connection into a remote database. M-Bus communication is realised by a two wire connection with a maximal data transfer speed of 9600 baud. EtherCAT communication is based on a 100BASE-TX Cable in Full Duplex Mode with 100 Mbit/s. Fig. 6 shows exemplary the load in byte for the transmission of actual power, voltage, current and phase shift over an EtherCAT and a M-Bus

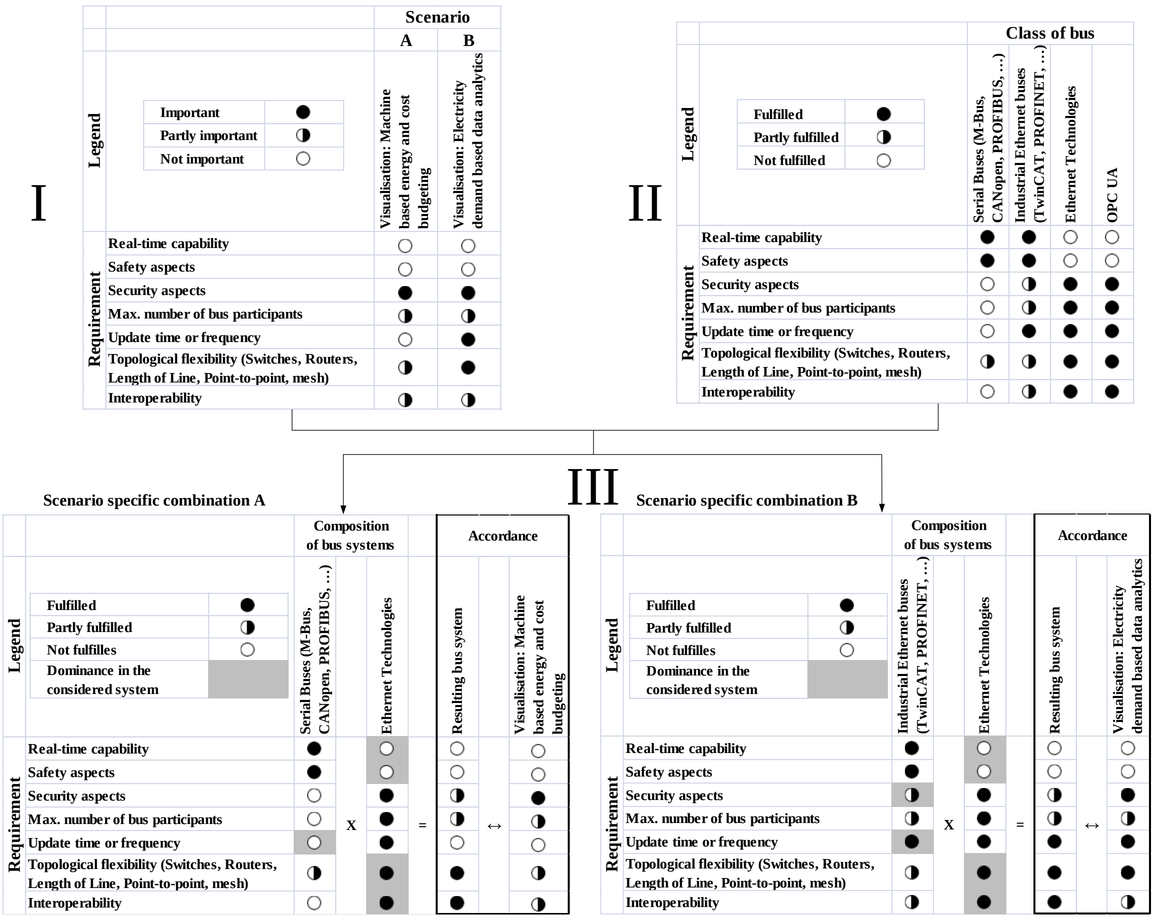

Fig. 5. Evaluation matrices for bus systems and desired functions over correspondent requirements and the combination of both

line spread to payload and overhead shares. EtherCAT uses Ethernet frames with an overhead of 53 Bytes. In the case of information retrieval of more than one device, the payload-capacity of one EtherCAT frame can be up to 1 468 bytes. Therefore the attainable ratio of payload to overhead $\frac{payload}{overhead} = \frac{1468\ bytes}{53\ bytes}$ can be 27 for one EtherCAT frame. Data retrieval of an M-Bus device takes place as a request-response process per device, this means that for a query of more than one device a complete new request with a full overhead stack is needed. The payload per request for the transmission of actual power, voltage, current and phase shift is 30 byte coming along with an overhead of 110 bytes. According to this, the ratio of payload to overhead $\frac{payload}{overhead} = \frac{30\ bytes}{110\ bytes}$ is about 0.27.

Measurement quality and evaluation possibilities depend strongly on the measurement technology and on the applied bus system. The wide range between possible bus data transfer rates is caused by different line transfer capacities and improved data handling realised by industrial Ethernet buses. As stated in Fig. 7 EtherCAT can reach a theoretical sample rate up to 20 000 Hz [22] by the utilisation of the full possible data transfer rate. Data update time of M-Bus technology, particularly for more than one device, is significantly higher, caused by the smaller bandwidth and the request-response concept. Fig. 8 indicates

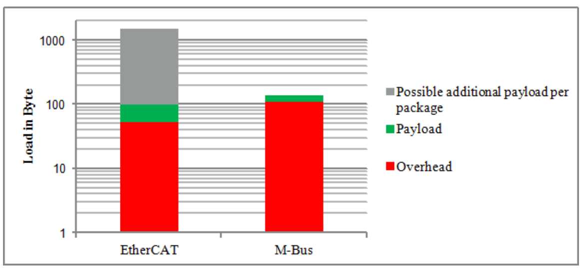

Fig. 6. Ratio of payload to overhead for transmission of actual power, voltage, current and phase shift over an EtherCAT and a M-Bus line from A/D converter to signal converter (S/C)

graphically, how information quality will be affected by the selected type of bus. The exemplary load profile shows the movement of the industrial robot. The solid line represents recorded data acquired by an EtherCAT system with a data rate of 50 Hz, the dashed line represents the same movement recorded by a M-Bus system with a data rate of 5 Hz. Loss of information due to slow data transfer rate is clearly visible. To achieve such a high level of monitoring dynamics (data request of 50 Hz or

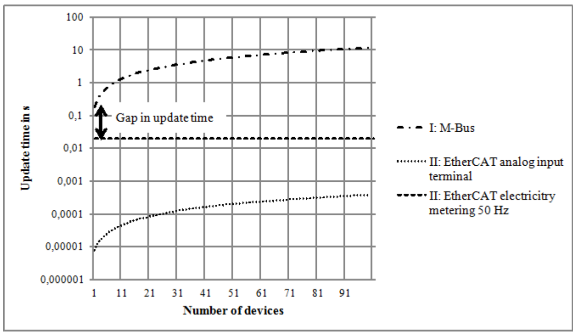

Fig. 7. Theoretical update time in reliance on network load (transport of TRMS total power only)

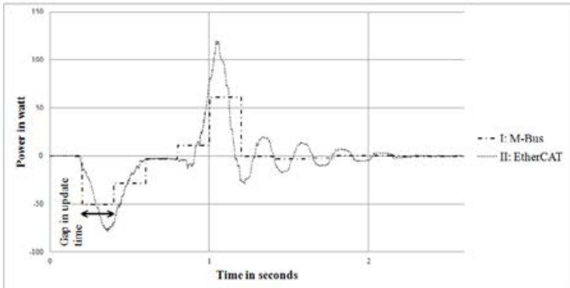

Fig. 8. Load profiles of an industrial robot recorded by EtherCAT with a data rate of 50 Hz and M-Bus with a maximal data rate of 5 Hz

more) the bus system must be designed to handle the occurring data streams. Table 1 presents a summary of the bus characteristics of scenario A and B in detail. Additionally to the already mentioned characteristics, the resulting data volume for the metering of 50 bus participants at a update frequency of 1 Hz for the time of one year, the information loss in reference to Thiede et al. [23] in comparison to an update frequency of 50 Hz and the approximately invest for a bus system including metering hardware and a signal converter is shown.

5. Discussion, conclusion and outlook

The quantity of possible applications and the variety of available bus system vendors is very large. By comparison of different bus systems and the explanation of advantages and disadvantages, it is possible to get a general overview of the applicability of bus systems and solutions and it also enables the reader to select a proper bus system for a case-specific application with highest possible similarity. This investigation does not claim to be complete, but gives an practise-oriented overview. In addition an insight into the performance of different bus systems is given. For two specific use cases scenarios appropriate configurations are proposed and described. Technical drawbacks and advantages of different technologies are shown in a case study.

The use of M-Bus technology is limited and for this reason only recommendable for energy monitoring purposes with a smaller number of devices. Loss of information should be considered based on a coarse granularity of measured data. This could induces difficulties for e.g condition monitoring.

Table 1. Case study scenarios

	Scenario A M-Bus	Scenario B EtherCAT
Update frequency (*Hz*)	approx. 5	50
Payload/overhead	0,27	27
Data vol. 50 dev. @ 1 Hz (*Gbyte*/*a*)	approx. 220	approx. 80
Information loss (%)	approx. 19 [23]	0
Invest (€)	approx. 500	approx. 1 500-2 000

Next work of the authors will be to extend the consideration on more scenarios and to extend the view on more specified use cases with a wider range of applicable bus systems and the possibility to control processes as proposed above.

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