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Wireless Traffic Signal Controller with Distributed Control System Architecture

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Abstract

The paper presents a novel concept for traffic signal controller. Instead of the traditional central architecture, a wireless operation with distributed control architecture is proposed for traffic light control. The concept rests on local control units distributed in space as well, i.e. the signal heads also have own control logic. The basis of safe distributed operation is described in detail in the paper. Beside the presentation of the concept the required conformity with the specific standards are also investigated. Moreover, a formal method (Petri Nets modeling) is provided concerning a part of the proposed system, which confirms that the whole system goes to fail-safe state when critical problem occurs in any of the subsystems or communication.

Keywords

traffic signal controller, traffic light, wireless, distributed control

1 Introduction

Traffic signals (also called as traffic lights) are control devices at road intersections or pedestrian crossings to ensure safe and efficient traffic flows [1, 2]. The world's first traffic light (with gas-lit signals) was designed by J. P. Knight, a railway engineer, and launched in London in 1868. Then, the first electric traffic lights, similar to today's traffic signal heads, started operating at the beginning of the 20th century in the USA. Since then, this technology has spread everywhere especially due to the persistent expansion of road traffic.

A signalized road junction basically consists of a central controller unit, traffic signal heads, as well as electric power cables, realizing a fully centralized system (Fig. 1). In this concept all signal commands are sent to the light sources directly from the central controller unit by switching the corresponding relays. Hence, the traffic lights are electrically energized according to the central controller's command which is a one bit information practically, i.e. current does or does not flow to the light sources. This traditional concept has been in use from the beginning of the traffic light's history, for more than 100 years

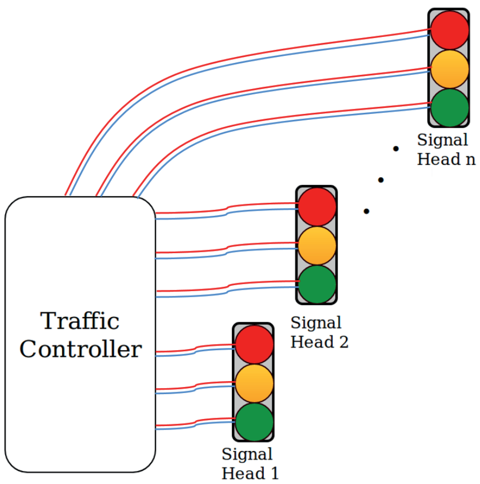

Fig. 1 The architecture of the traditional centralized traffic signal controller with pair power cables to each light source

(the conventional architecture is depicted by Fig. 1). The technology of our days, however, enables completely different system architecture for signalization in which the signal heads can be controlled not only by simple electric power but via digital messages (which is more than a single bit of information obviously).

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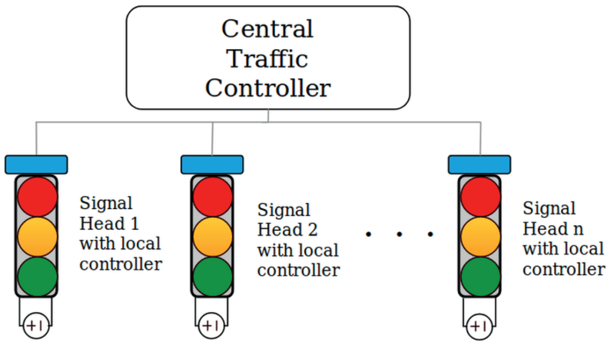


Fig. 2 The architecture of the CAN bus communication based (centralized) traffic signal controller with a single CAN cable to each signal head (power supply is provided in the traffic signal poles)

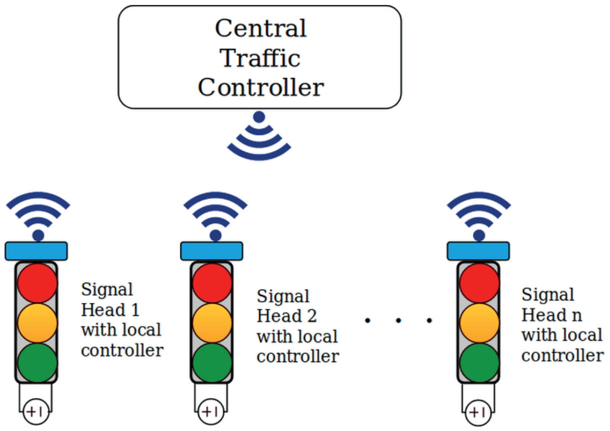


Fig. 3 The architecture of the centralized wireless traffic signal controller (power supply is provided in the traffic signal poles)

An innovative realization in this field is the CAN-communication (Controlled Area Network) based traffic signalization which is just prior to practical introduction provided by the Swarco Group [3, 4]. Also, the Siemens company uses CAN interfaces for external communication for the control of motorway traffic management systems [5]. As CAN protocol has mainly been used in the automotive industry, it is a safe and reliable technology for controlling signal heads as well. In the practical applications of [4] and [5], a central architecture is used where a main controller unit is in charge of control and power switching respectively via CAN. In this setup the electric power for the light sources can be supplied from the central controller unit (as conventionally used) or locally from the traffic signal pole (the latter case is illustrated by Fig. 2).

This technology naturally indicates that some logic is necessary at the signal head directly. The digital information must be processed between the central unit and the signal head unit (local controller). Thus, the light sources are controlled according to the relay switching of the local controllers.

Another unconventional approach is straightforwardly resulted from the emergence of wireless communication technology, i.e. signal heads can be controlled without direct physical connection to the central controller unit. Moreover, the advent of Autonomous Vehicles (AV) make new technologies possible to be applied in traffic control [6–8]. AVs need to visually sense the signal heads to gather information of signal heads, or it can be provided via wireless communication. The traffic control information is also useful for travel time prediction and accordingly for operational control purposes [9]. This way AVs might be involved into traffic control in the near future (discussed later in relation with Signal Phase and Time and Map Data specification in the Appendix), which also confirms today's need for wireless based traffic control units.

The basic concept of the wireless traffic light with central control system architecture (as shown by Fig. 3) has already been introduced by [10–12]. All these works presented a master-slave operation where a central controller (as a master unit) controls all signal heads (slaves) through wireless data transmission (the electric power is provided locally at each signal head). In this setup, again some logic is necessary at the signal head level identically to the CAN bus based concept (presented previously by Fig. 2). Although these papers have shown the basic idea of wireless traffic lights, the presented concepts rest on central control architecture and are limited in terms of reliable and safe engineering design according to the standards of road traffic signal control.

According to today's need, the paper presents a novel concept for wireless traffic signalization with a clear distributed control system architecture by considering safety critical aspects with respect to the technical standards. Section 2 introduces the distributed control architecture for traffic light control based on the signal head control units. Section 3 provides the basis of safe distributed operation by considering the conformity with the specific standards. Section 4 presents the Petri Net model concerning a part of the proposed system. The paper ends up with a conclusion in Section 5. Furthermore, an Appendix is added to the paper as a related practical material, i.e. the basic requirements of road traffic signal controllers for safe operation.

2 The distributed control architecture for traffic light controller

In practice, the traditional traffic light controllers work on the basis of a central control unit. Similarly, the papers investigating the wireless concept [10–12] introduced centralized control system (see Fig. 3). Although in their approach some local processor is also applied at the signal heads, the control logic is operated in a strict centralized way.

Identically to the notions used in control engineering, one can distinguish central and distributed system architectures for road traffic controllers as well. "Centrality means that all the information available about the system is collected at a single location, where all the calculations based on such information are executed [13]." Contrarily, in a distributed realization the computational tasks are divided among the local units [14]. Distributed control scheme is depicted by Fig. 4 where u_i and x_i mean control and state signals, respectively for $i = 1, 2, \ldots, M$ subsystems. Moreover, communication among the controllers and among the subsystems are also applied.

Accordingly, a novel concept (the concept is under national trade-mark protection: [15]) is introduced for wireless traffic signalization with a clear distributed control system architecture where the central controller unit is eliminated (see Fig. 5(a)), i.e. the local controllers of the signal heads shown in Fig. 5 correspond to the subsystems given in Fig. 4. As an illustrative example, Fig. 5(b) represents a case of a simple T-junction containing three signal heads with three corresponding signal phases. The figure presents the basic functioning of the distributed concept. Each signal head control unit knows the whole traffic signal program and only uses its own phase. Furthermore, every unit is able to check the proper functioning of the others (explained in detail in the sequel).

The architecture of the distributed traffic light is already presented in Fig. 5 with power supply provided in the traffic signal pole. Traditionally, the electric power is typically supplied by the public electricity network for traffic lights. However, as a new energy efficient approach solar power system can also be used. An innovative concept of intelligent signal heads with wireless distributed traffic control has been introduced first by [16], where the energy consumption was served with solar cells for each signal head. The intelligence means that the signal head is not only used to show the specific signal but it also has an own logic that serves control and communication tasks. The solution of [16] is further developed in the sequel by directly providing the main safety algorithms to ensure safe functioning even with wireless technology. The concept is shown by Fig. 6.

In order to make a consistent design of the distributed wireless traffic light and be technically correct, all safety critical aspects must be properly addressed with respect to the technical standards, i.e. the system must be able to

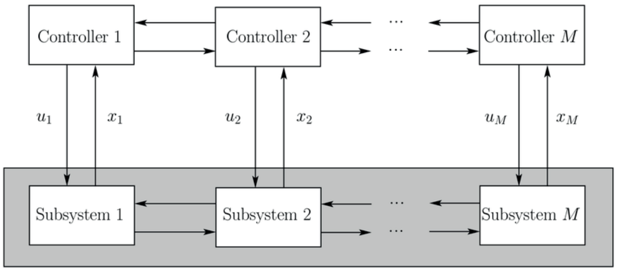


Fig. 4 Distributed control architecture

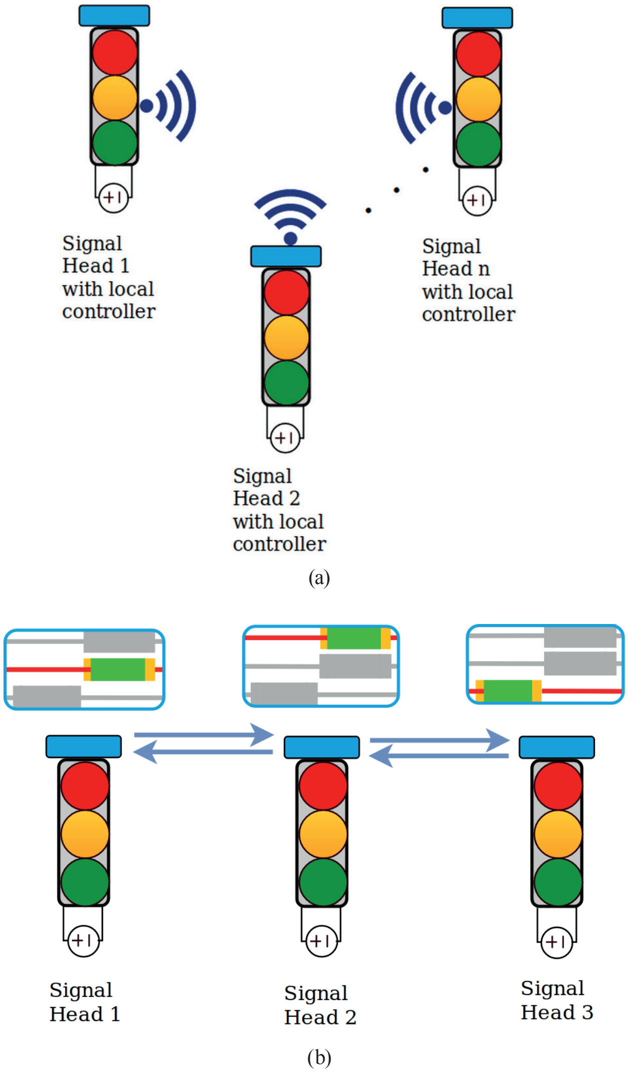


Fig. 5 The architecture (a) of the wireless traffic signal control with distributed control system (power supply is provided in the traffic signal poles) and an example for the distributed functioning (b) representing the common knowledge of the actual signal program

ensure all safety functions given in the Appendix. As the communication is wireless, the main guarantee for the fulfillment of all requirements is the safe and reliable communication among the signal head units (see Fig. 5 and 6) and the fail-safe event handling in case of communication loss. Therefore, the proposed control concept is capable of handling the most critical situation, i.e. when any of the signal head units crashes. A spectacular example for such failure is the situation when the signal head unit "freezes" due software error, and thus the signal head cannot produce any light (or even the signal freezes as well). In this case all units of the system must switch off immediately, including the "frozen" unit. As a safe solution for this requirement a redundant control unit is applied in the system, i.e. the solar power unit is not only responsible for power control but also constantly checks the error-free functioning of the signal head unit. If a critical failure occurs, this redundant unit can interrupt the power supply between the battery and the signal head via an emergency relay. At the same time, the remaining signal head units switch off automatically due to the lack of communication from the crashed unit. The algorithm of this redundant safety process is summarized by Fig. 7. Note that the figure only represents the case of two parallel signal heads for simplicity. In the case of more units, every unit is involved in the communication respectively. The communication depicted in Fig. 7 is quasi continuous, i.e. the exchange of messages among the signal head units as well as that of between the solar power unit and its related signal head unit must be repeated with high frequency.

Of course, the proposed system can be built without solar power system as well, e.g. by connecting to the public electricity network. In this case, the safety function of the solar power unit can be substituted with a similar control unit used for the cabled power supply.

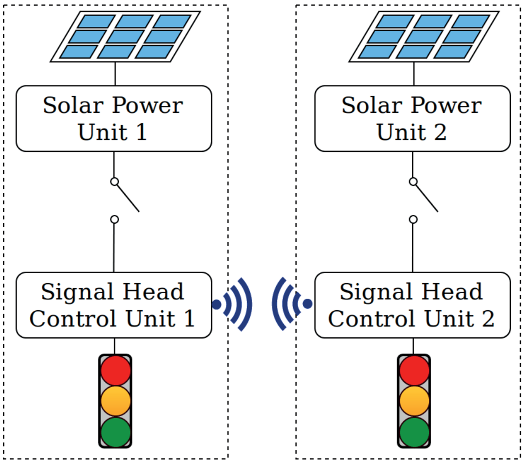


Fig. 6 Wireless and distributed traffic signal head units with solar power

3 The base of safe distributed operation

According to the standard EN 12675:2018 (traffic signal controllers. Functional safety requirements [17]) any signal state endangering the road traffic must be prevented during operation, i.e. a safeguarding facility shall lead to a safe state of operation as defined in [17]. Beyond the typical hardware/software errors in the traffic light system, the distributed architecture might also effect additional hazard for safe operation. Therefore, this necessitates a different safety concept compared to that of the traditional road traffic controller (presented in Introduction).

The distributed logic is ensured in a way that each signal head unit is identical considering the hardware as well as the software. It also means that the units know the whole signal program and this makes it possible that no central unit is needed to dictate the next signal states. The sole master function dedicated to one of the units is the check and control of time synchronization together with program change. If any of the units is delayed or is in hurry

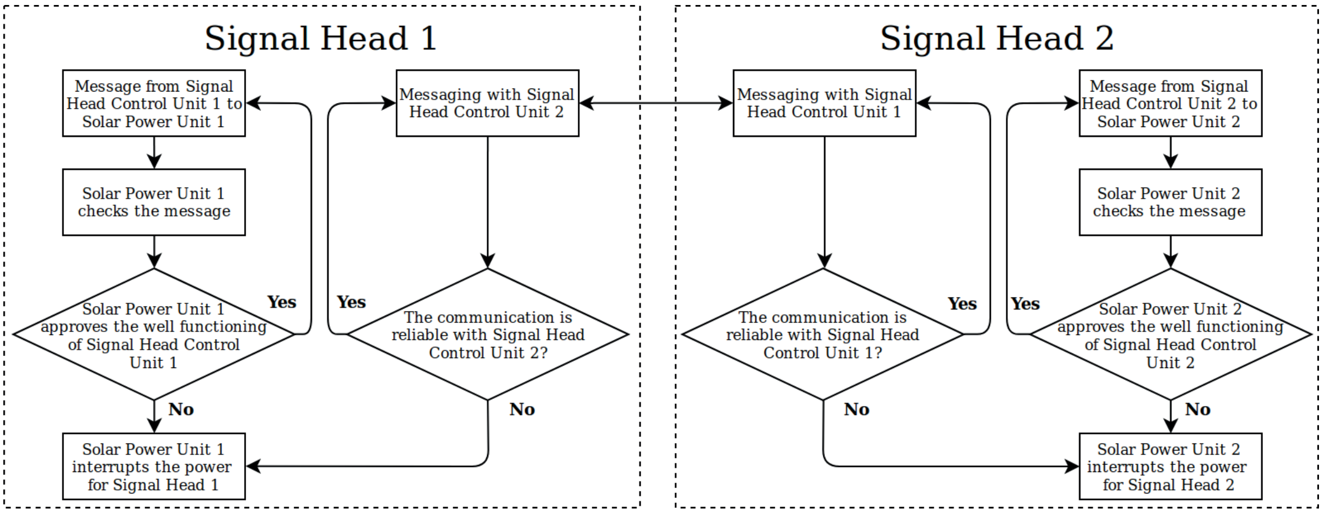
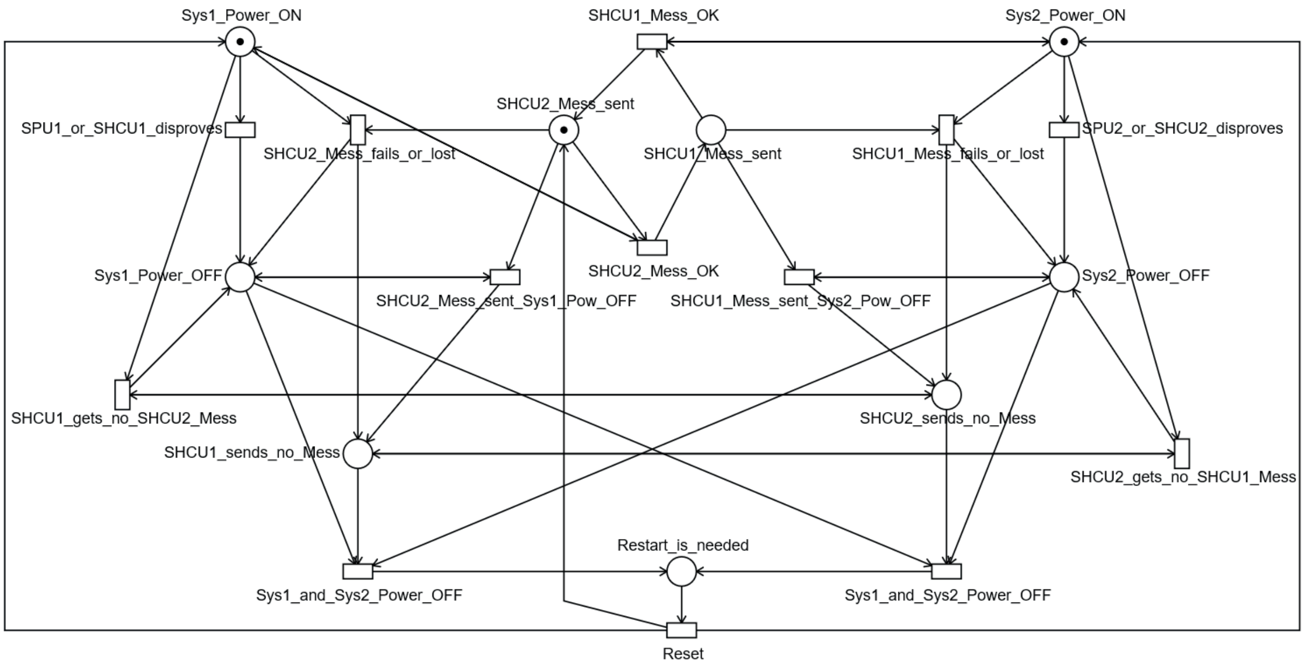


Fig. 7 Flowchart of the redundant functioning for distributed traffic signal control (the picture considers only two signal head units for simplicity)

compared to that master time, the master shall ensure synchronization. The program changes (e.g. when dynamic signal programs are used) are also controlled by that master unit, i.e. after the confirmation of all other units for program change (and the time of change), the master starts the program change process. The master unit has no any other master function, i.e. every signal head control unit has the same privilege. This also means that any signal head control unit can start a fail-safe process in the case of failure.

In order to make the distributed signal operation safe as possible proper checks have to be performed prior to the physical signal visualization on the light sources. Accordingly, every second (as the smallest discrete time interval in traffic signalization is typically 1 second) just before the light switching each signal head control unit verifies and confirms if the following points (according to the requirements listed in the Appendix) are valid regarding the previous signal states:

1. no conflicting green signals;
2. no failure in safety timings (intergreen time or minimum green time);
3. no display of unintended signal and no failure in correct signal timing;
4. no failure in displaying of correct signal sequence.



Nomenclature for the figure:
- SPU1 / SPU2: Solar Power Unit 1 / 2
- SHCU1 / SCU2: Signal Head Control Unit 1 / 2
- Sys1_Power_ON / Sys2_Power_ON: the electric power of system 1 (SHCU1 and SPU1) / system 2 (SHCU2 and SPU2) is on
- Sys1_Power_OFF / Sys2_Power_OFF: the electric power of system 1 (SHCU1 and SPU1) / system 2 (SHCU2 and SPU2) is off
- SHCU1_Mess_sent / SHCU2_Mess_sent: the message of SHCU1 / SHCU2 is sent
- SHCU1_Mess_OK / SHCU2_Mess_OK: the content of the message from SHCU1 / SHCU2 is confirmed by SHCU2 / SHCU1
- SHCU1_Mess_fails_or_lost / SHCU2_Mess_fails_or_lost: the content of the message from SHCU1 / SHCU2 fails or the message is not arrived
- SPU1_or_SHCU1_disproves / SPU2_or_SHCU2_disproves: SPU1 or SHCU1 / SPU2 or SHCU2 disproves error-free functioning of SHCU1 or SHCU2
- SHCU1_Mess_sent_but_Sys2_Pow_OFF: the message of SHCU1 is sent, but the electric power of system 1 (SHCU1 and SPU1) is off
- SHCU2_Mess_sent_but_Sys1_Pow_OFF: the message of SHCU2 is sent, but the electric power of system 2 (SHCU2 and SPU2) is off
- SHCU1_sends_no_Mess / SHCU2_sends_no_Mess: SHCU1 / SHCU2 is not able to send message to SHCU2 /SHCU1
- SHCU1_gets_no_SHCU2_Mess / SHCU2_gets_no_SHCU1_Mess: SHCU2 / SHCU1 gets no message from SHCU1 / SHCU2
- Sys1_and_Sys2_Power_OFF: the electric power of both systems (SHCU1 and SPU1 as well as SHCU2 and SPU2) / is off
- Reset: reset operation is necessary to restart both systems (SHCU1 and SPU1 as well as SHCU2 and SPU2)

Fig. 8 The Petri Net (carried out in PetriDotNet [20]) of the redundant functioning for distributed traffic signal control (the model considers the operation of two signal head units)

On the one hand, the signal head units must go through the above checklist concerning itself (for which no communication is needed with the other units). On the other hand, every unit has to check the error-free functioning of all other signal heads in parallel based on the wireless communication. Obviously, the frequency of the communication is critical in this checking process. Beside the technical capability of the radio unit, one has to consider the standard EN 50556:2018 (Road traffic signal systems [18]) which defines 7 different classes for handling dangerous failures: from 100 ms up to 850 ms intervals. The time intervals defined by the standard mean the maximum times from the dangerous signal is present until the state has been removed. Accordingly, the safeguarding operation shall become active within 850 ms at most. This value has to be prudently considered when setting the frequency of the communication for the distributed traffic signal control system.

4 Safety analysis of the fail-safe distributed traffic controller using Petri Nets

Petri Nets (PN) modeling is a powerful mathematical technique for the description of discrete event dynamic system [19]. Moreover, PN can be used for the analysis of safety-critical systems. As a justification for practical applicability of the proposed distributed traffic control system, the redundant operation (Fig. 7) was modelled by Petri Nets. For this reason PetriDotNet, a PN editor and analysis tool was used [19]. Fig. 8 shows the Petri Net model of the redundant functioning for distributed traffic signal control. The model only considers two signal head units for the sake of clarity. Nevertheless, the same operation can be extended for further signal head units due to the identical safety protocol of the units, i.e. any of the units can lead the whole system to a fail-safe state.

The operation modelled by Petri Net in Fig. 8 assumes periodic processes inside, i.e.

- SPU1 / SPU2 periodically checks the error-free functioning of SHCU1 / SHCU2,
- SHCU1 / SHCU2 periodically sends messages towards SHCU2 / SHCU1,
- SHCU1 / SHCU2 periodically receives and checks the messages from SHCU2 / SHCU1.

Based on the Transition-Invariants (T-Invariants) of the modelled Petri Net, one can justify that the whole system goes to fail-safe state whenever a critical problem occurs in any of the subsystems, i.e. any of the signal head control units fails or communication is lost among the units of the system. The calculated T-Invariants simply showed that all firing series of the Petri Net induced by any error result in the "Power OFF" state of both subsystem, i.e. SPU1, SPU2, SHCU1, and SHCU2 are switched off.

On the other hand, as the modelled Petri Net is deadlock-free, it is confirmed that the proposed system might work infinitely if error-free operation is guaranteed.

Finally, the Petri Net based analysis also showed that the system is bounded (1-bounded safe net) which means that the number of tokens is limited in the state space. Thus, the state space is bounded as well.

5 Conclusions

A novel concept for wireless and distributed traffic control system has been introduced, which enables that local traffic management of intersections is controlled without a central control unit. The system realizes a distributed control method based on the signal head control units. The solution can reduce installation and maintenance costs, especially if electric power supply is ensured by solar panels.

As a justification for practical applicability, the fail-safe and redundant operation of the proposed distributed traffic control system was modelled by a formal method (Petri Nets).

The presented concept is under continuous development and will be extended to make it usable for coordinated traffic signalization, i.e. when several signalized junctions are coordinated on an arterial road.

Acknowledgement

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Appendix

Requirements for road traffic signal controllers

Road traffic controller constitutes a safety critical system which also means that relevant technical and legal rules are clearly determined by international standards as well as by national legislation. As the paper presents a new technological concept for traffic light, all rules must be reviewed and one has to prove their feasibility. Accordingly, the wireless traffic signal controller with distributed system architecture must also ensure the fulfillment of all relevant requirements.

The basic hierarchy of technical legislation is depicted by Fig. 9. The pyramid is nearly identical in all countries. On the one hand, the strongest legislative measures, the laws, contain the general rules for traffic signal control system and determines the framework of operation on national level, i.e. this is valid everywhere in the country. On the other hand, technical specifications encompass the detailed specific requirements for traffic lights on the basis of the industrial standards and codes. This layer is usually not mandatory per se. At the same time, laws frequently

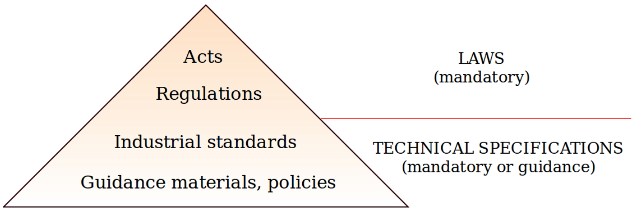

Fig. 9 The hierarchy of the technical legislation (also applicable for traffic signal controller design)

refer to specific technical standards making them or the parts of standards obligatory. Guidance notes or policies are typically created by road authorities or operators and are based on industrial standards partly or fully. An important difference compared to the laws is that the technical specifications are not necessarily held mandatory at all times. They are generally required by the road authority or operator for specific procurement or acquisition, e.g. the installation of a traffic signal system on freeways must always fulfill given technical specifications (note that it can be different to that of urban roads). In conclusion, the manufacturing process of traffic lights and installation on the spot (location of the poles and signal heads as well as other structural considerations) are always subject to the valid industrial standards given by several national and local obligations.

The European organization for public standards (CEN: Comité Européen de Normalisation) works for harmonized standardization creating and maintaining the European Norms (ENs). Accordingly, the EU countries fully adopt ENs or integrate them into the national standards and technical specifications. Three basic European standards hold for road traffic signalization systems specifically:

1. EN 12675:2018 Traffic signal controllers. Functional safety requirements. [17]
2. EN 12368:2015 Traffic control equipment. Signal heads. [21]
3. EN 50556:2018 Road traffic signal systems. [18]

In the followings, only those parts of the above standards are introduced which are relevant to determine the functional safety requirements for traffic signal controllers. Moreover, only the major faults are investigated which are potentially hazardous to traffic (minor faults are defined as events causing no hazardous situation). As a basic requirement for traffic light, in the case of any major fault the system shall switch to a specific failure mode, i.e. a fail-safe functioning is ensured at all times. This failure mode is defined by the standard as "a non operational state of the traffic signal controller in which the normal operation mode is replaced with a flashing yellow or a signals off condition". The major faults can be classified based on standard EN 12675 [17] as follows.

- *Conflicting green signals*: the simultaneous display of green lights allowing conflicting traffic movements.
- *Failure to display a red signal to traffic*: the intended red signal is not displayed.
- *Unwanted signal*: unintended signal causing ambiguous traffic situation.
- *Failure to display the correct signal sequence*: the order and appearance of signals, displayed to traffic, differ form that are prescribed in national requirements.
- *Failure in correct signal timing*: the correct timing of any signal group fails.
- *Failure in safety timings*: critical error when any safety time setting (intergreen time or minimum green time) fails causing hazardous traffic situation.

According to the listed major faults above, it is indispensable that the wireless and distributed traffic signal controller shall fulfill all critical requirements, i.e. it must realize the same fail-safe operation as ensured by the traditional central traffic controllers.

In relation with the wireless technology, the technical specification for Signal Phase and Time and Map Data (SPaT/MAP) [22] must be also emphasized in future traffic controller design. SPaT/MAP offers a potential channel for detailed information exchange between traffic systems and road users. Based on SPaT data the vehicles (or drivers) can be informed about the current status and change of the traffic signal ahead as well as about the next signal stage change. It also provides information about approaching traffic to optimize the signal system. MAP data describes the physical geometry of one or more intersections. In connection with SPaT/MAP the ISO/TS 19091:2017 norm [23] is also important to mention as it defines the message, data structures, and data elements to support exchanges between the roadside equipment and vehicles. Finally, the guidance of the SAE International is worth mentioning [24]. Under the code SAE J2735_201603 the Dedicated Short Range Communications (DSRC) Message Set Dictionary was published. The aim of this document is to provide a message set, and its data frames and data elements, specifically for use by applications intended to utilize the 5.9 GHz DSRC for wireless access in vehicular environments.