BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 4, 2020
DOI: 10.24425/bpasts.2020.134173

ELECTRONICS, TELECOMMUNICATION
AND OPTOELECTRONICS

# The influence of the data packet size on positioning parameters of UWB system for the purpose of tagging smart city infrastructure

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**Abstract.** The paper presents a concept of the vehicle/road infrastructure in vehicle-to-infrastructure (V2I) communication for tagging and informing vehicles about the surrounded environment. A frame analysis and the influence of the data packet size on Ultra-wideband (UWB) were investigated. The authors have determined the distance that could be traveled by a vehicle at the given speed in relation to the amount of data that has to be transmitted during the ranging procedure. The authors propose a data frame format (using the IEEE 802.15.4a protocol) for coding/encoding the information about the road infrastructure efficiently during the positioning procedure. It affects to minimum the time that is required to exchange messages during the ranging and communication process. The whole system is an efficient and reliable element that enhances/extends the existing components of advanced driver-assistance systems (ADAS), which will facilitate validation of the information obtained from devices such as lidar, radar or video. The impact of the transmitted payload to the distance traveled by car opens the door to future research on the possibility of implementing efficient vehicle-to-vehicle (V2V) communication for autonomous driving or and other smart city solutions.

**Key words:** UWB, positioning, V2I, smart city, infrastructure.

## 1. Introduction

The users of rapidly developing urban centers are increasingly utilizing the latest technological advancements to navigate these areas. The current navigation systems that are already used in smartphones use numerous sources of data [1], especially for improving the mobility of finding public facilities. However, the constantly growing car industry – and hence the growing interest in the automotive branch – has forced the creation of point-of-interest (POI) equivalents for vehicles, cyclists, and other road users. Finding a location using systems such as GPS has become insufficient to meet the needs of today's strongly urbanized urban centers (to improve the GPS object position, e.g. mems or video analysis are used [2, 3]). The answer to this problem is multidimensional maps for the vehicle-based systems that already contain not only information about the streets on which the vehicle is moving, but also about their type, speed limitations or passage. However, this information must constantly be updated and its accuracy depends on the precision of the GPS system and the position it will give to a car.

In part, this information can be provided from other systems that are currently on a vehicle [4]. An example of this could be lidar [5], which measures the target of the light pulses with a sensor. Then, based on the acquired points and the earlier knowledge base regarding their characteristics, it can determine with a certain probability what objects are within its range. However, it is not able to see any objects that are hidden by other objects (e.g. signs covered by trees). Multivariate maps also use video analysis; an example is a publication [6] in which the authors used maps from the Open Street Map (OSM) portal and combined them with image analysis to describe the reality surrounding a vehicle. Although this gave very good results, it should be remembered that this solution does not work well with obscured objects. Video processing also requires time, which is why its analysis in the context of UWB has become one of the elements of this work. Vision is also worse when the weather conditions are unfavorable, which generates additional demand for computing power for such mundane things as detecting the raindrops on the glass through which the camera looks [7] or at night, when there is reduced visibility [8].

To deal with these issues small, compact devices that consume small amounts of energy are proposed [9, 10], which will facilitate the improvement of safety and reliability of critical road infrastructure points by precisely defining their position and by providing detailed information about them and their environment. As research shows [11, 12], in order to ensure the highest possible energy efficiency, it is necessary to use both the proper network parameters and topology. One type of these devices is a system that is based on Ultra-wideband (UWB) technology that enables both locating objects [13–16] and transferring the data that can carry useful information about the infrastructure. However, a detailed analysis was needed to answer the questions how data transmission affects the transmission, which packets are best for transmitting additional data, and how to optimize the data frame to effectively use it at various vehicle speeds. The authors tried to address all these questions in this paper. These devices also have an advantage over the currently used systems, not only in terms of their resistance to unfavorable atmospheric conditions, but

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Manuscript submitted 2020-02-21, revised 2020-04-28, initially accepted for publication 2020-05-11, published in August 2020

also their range [17]. What is more, tagging infrastructure is already utilized on a large scale by the railways. An example of this is the European Train Control System (ETCS), which uses devices that provide information about the route being taken by the train and ensure the transfer of information about the signs to the driver's cockpit. Because of this unification and the concentration of route information on the on-board computer, safety is increased and it is possible for the train to go faster [18–22].

What is more, the latest research shows the direction of technology development related to smart traffic signal control (STSC). In these systems, properly tagged vehicles can already enter into communication with the surrounding infrastructure elements, and their position that the information directly affects, e.g. the behavior of traffic lights [23].

In the paper, first an analysis of the current elements of road infrastructure (overview of the information objects that are currently being used and their characteristics in the context of road and perimeter infrastructure) is presented, then a platform which is based on the concept of V2I communication and the UWB frame that is currently being used are discussed. These issues are even more important considering the fact that for the V2V model research is already being conducted on the propagation of the packets in the UWB network [24] and developing a future complementary approach to the communication problem, because either V2V or V2I will require consistent solutions and knowledge of rich application. Based on the presented information, this paper intends to present a structure for tagging the road infrastructure elements using the UWB-based system. The solution we proposed has not been discussed in scientific journals yet, although the use of intelligent road surface for driver support is being considered [25]. The transmission that is based on the UWB system, which is presented in the next chapter to describe the current and future possible use, is sufficiently capacious and at the same time is sufficiently precise to minimize the number of referrals to the supporting server, thereby enabling a quick decision to be made by the vehicle systems, e.g. in an emergency situation. In addition, we also tried to keep the frame size compact and use the ranging procedure to exchange additional information to minimize the number of data packets that are required. This was because as the amount of data and the number of transmissions increase, the ranging frequency decreases. Finally, the distance that could be travelled by a car at the given speed in relation to the amount of data that have to be transmitted during the ranging procedure was presented, which enabled tailoring individual solutions to specific use cases.

Our considerations can be reduced to the lowest layer of the positioning stage. To illustrate this better, we conducted a descending analysis. The starting point of our consideration is the global positioning system which determines the main coordinates – global.

The next layer is the local positioning system that works for the needs of the global system, but it knows the local coordinates and the dynamics of their changes.

The position in the local system $p(t, x, y)$, depends on $t$ (time) and $\{x\ y\}$, which are coordinates in the local, two-dimensional reference system.

Then we focus on the dynamics of the position change, which can be described by the formula (1).

$$\Delta s = \sqrt{\left(x_i - x_{i-1}\right)^2 + \left(y_i - y_{i-1}\right)^2} \tag{1}$$

Knowing the current vehicle speed (based on odometry, or assumed by the mathematical model), the displacement $\Delta s$ based on the passage of time $\Delta t$ can be found.

For the UWB system, the last value – $\Delta t$ depends on the parameters considered in this article in the form of the length of the transmitted frames. This is also the subject of this article.

## 2. Materials and Methods

**2.1. Analysis of the current elements of road infrastructure.** Although a huge number of objects are addressed here, the authors are aware of different specifics of global road infrastructure. Therefore, all the references that are used in this paper for the infrastructure refer to the commonly used worldwide markings, which are available on the OpenStreetMap. This service, which is owned by the OpenStreetMap Community, is the largest collaborative mapping page and is available in 93 languages. The following are the elements of road infrastructure that are specified based on the signs that were created on the OpenStreetMap website and its documentation. The assignment of elements was made for three important subcategories: 1) Path – describes the type of road and its main purpose; 2) Additional path parameters – presents additional information about the path, which is important from the point of view of an autonomous vehicle; 3) In addition to the path, it distributes the elements of the infrastructure in the area that are important for the autonomous cars and vehicles that move around the smart city area.

1. Type of path
   - Road (motorway, trunk, primary, secondary, tertiary, unclassified, residential)
   - Crossroad:
     - Shape of road segments (three-way intersection: T or Y junction, four-way intersection or crossroads, five-way intersections, six-way intersections, seven or more approaches to a single intersection)
     - Method of flow control (uncontrolled intersections with no signs or signals, or sometimes with a warning sign). Priority (right-of-way) rules may vary by country, yield-controlled intersections, stop-controlled intersections, signal-controlled intersections
     - Intersection lane design (traffic circle, box junction, indirect left turns, right turn and U-turn, advanced stop lines, parallel-flow and continuous-flow intersections, hook turns quadrants, seagull intersections, slip lanes' staggered junctions, superstreets, Texas Ts, Texas U-turns and turnarounds, a roundabout and its variants such as turbo roundabouts, bowties and distributing circles such as traffic circles and right-in/right-out (RIRO) intersections
   - Special road types (living street, service, pedestrian, track, bus guideway, escape, raceway, other)

- Path (footway, bridleway steps, other)
- Cycleway (lane, opposite, track, busway shared

2. Additional path parameters
   - One way, driving side, bridge, viaduct, tunnel, pedestrian crossing
   - Number of lanes (normal, bus passes, size of lane)
   - Restrictions on the type of vehicle traveling on the road:
     - Type (cars, motorcycles, buses and coaches, bicycles, pedestrians, light commercial vehicles (up to 3.5 t), emergency motor vehicles, horse riders, longer heavier vehicles, agricultural vehicles, road trains, military, all vehicles)
     - Parameter (weight, dimensions – width, height, length, hazardous materials)
     - Turn limits (turn / no turn – left, right, straight)
   - Depends on the season (winter road, icy road, dry season, other)
   - Traffic calming (bump, hump, table, cushion, rumble strip, dip, chicane, choker, island)
   - Surface type:
     - Paved (asphalt, concrete, lanes, plates, paving stones, sett, unhewn cobblestone, cobblestone, metal, wood)
     - Unpaved (compacted, fine gravel, gravel, pebble stone, dirt, earth, gravel turf, ground, mud, sand, woodchips, snow, ice, salt)
     - Special (clay, tartan, artificial turf, Decoturf®, metal grids, surfaces with a special texture that are helpful for the blind
3. Next to the path
   - Barrier and gates (ditch, fence, guard rail, curb, block, bollard, border control, sump buster, lift gate, gate)
   - Bus infrastructure, tram infrastructure
   - Streetlamp (lamp, illumination)
   - Power (catenary mast, tower, pole, portal, substation, transformer)
   - Parking lane:
     - Spaces (parallel, diagonal, perpendicular, marked, no parking, no stopping, fire lane)
     - Position (on street, half of kerb, on kerb, lay by, painted area only, shoulder – yes, no, both)
   - Parking conditions (free, ticket, disc, residential, customer, private, disabled, time – from to, day of the week, maximum stay)
   - Natural (trees, hedges, bushes, etc.)
   - Points of interest (entrance, coffee, ice cream, etc.)
   - Amenities (bench, fountain, playground, etc.)
   - Other

The infrastructure elements presented here are just some examples of how to divide and categorize the elements that can be found on the currently available conventional maps such as the commercial Google Maps and Here or the free OpenStreetMap.

The above description is based on the documentation that is available for the OpenStreetMap [26]. Figure 1 [27] is accompanied by an example of a map that presents a description of selected objects around the campus of a university.

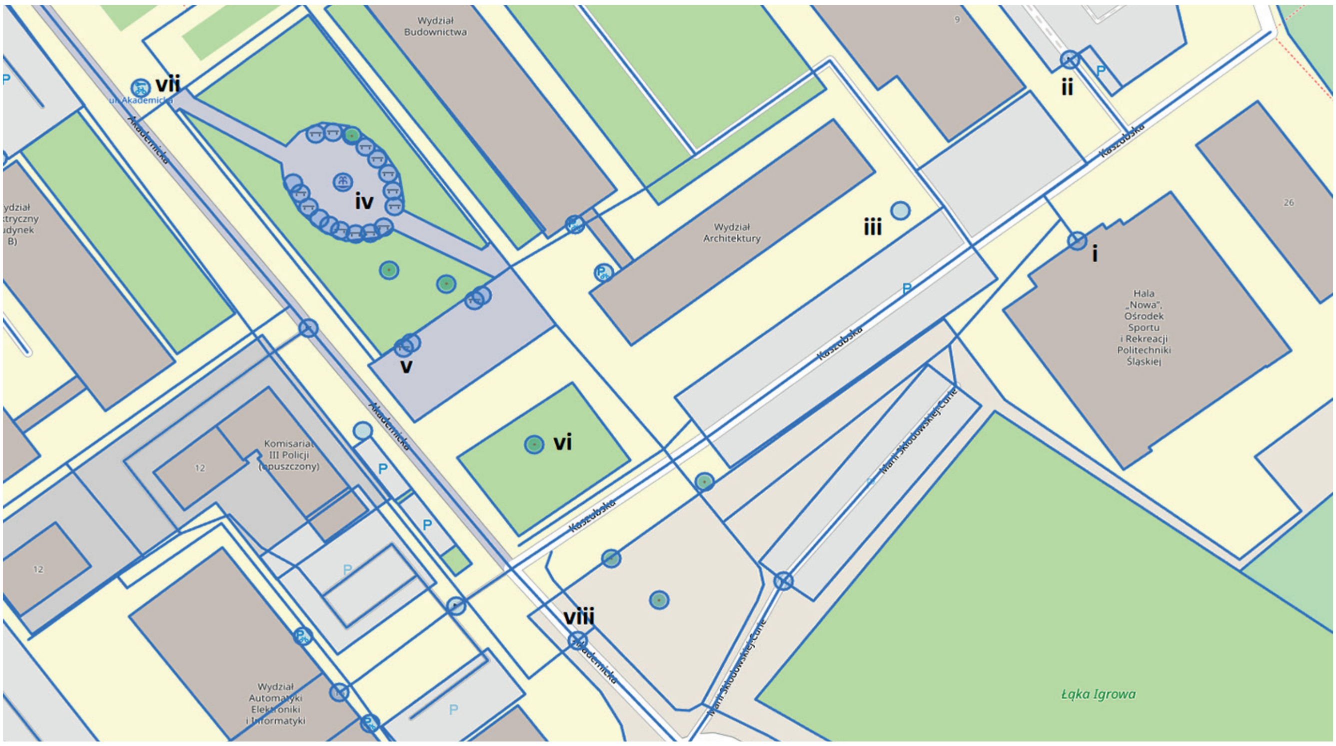



Fig. 1. Example description of the elements on OpenStreetMap (i) type entrance, parameter main, (ii) type barrier, parameter lift gate, (iii) emergency, parameter fire hydrant; detailed parameters: diameter, position, type, (iv) type amenity, parameter fountain, (v) amenity, parameter bench; additional parameters: backrest, color, material, seats, (vi) type natural, parameter tree, (vii) type amenity, parameter bicycle rental; additional parameters: capacity, name, network, operator, ref, (viii) type highway, parameter crossing

As can be seen from the above examples of a review of the current map solutions, additional elements on maps are now common; however, there is no unambiguous interpretation that enables them to be directly translated into a positioning system frame in such a way that permits the unambiguous identification and recognition of elements along with their positioning and the surrounding infrastructure that meet the requirements for building multidimensional maps. As part of further considerations, the authors want to present the possibilities that are offered by the positioning system that is based on the UWB-based positioning technology, current instrumentations and the data frames that are associated with them; show the data transmission possibilities that are associated with the discussed technology and finally present a proposal of a data frame in which all of the necessary information will be included in order to build a system that will enable multidimensional maps based on acquired data to be created and information about the surrounding objects for systems such as radar or lidar to be obtained.

**2.2. A multisensory-positioning platform presentation.** The theoretical basis of the concept is instrumentation in the form of an autonomous vehicle model (see Fig. 2) that is equipped with a range of sensors. Its equipment includes two different types of UWB modules (DWM1000 and DWM1001), GPS, AHRS, an encoder on the main motor shaft, an on-board computer to analyze the driving parameters such as speed or the steering angle.

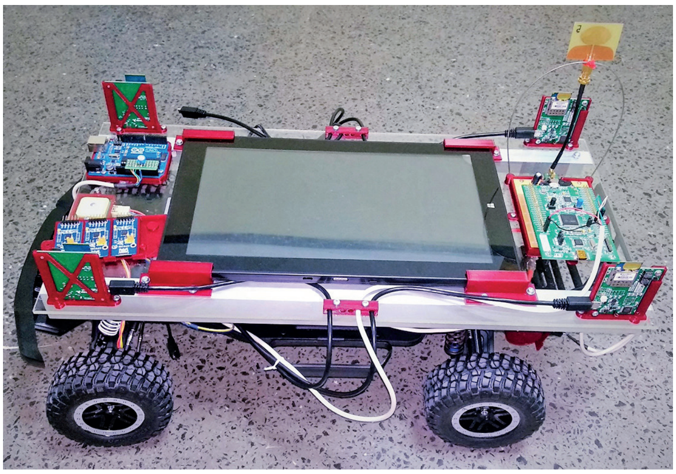


Fig. 2. Vehicle with a set of sensors installed

Figure 3 shows the reference points – anchors. The DWM1000 system was equipped with additional elements – an antenna and housing (a), while the DWM1001 was equipped with a battery pack and stand (b).

The system is based on the commercially known concept of systems for locating IPS objects, which can be found in many reviews [10, 28, 29], but the one developed in the future should have, for example, a better antenna adapted to specific requirements [30].

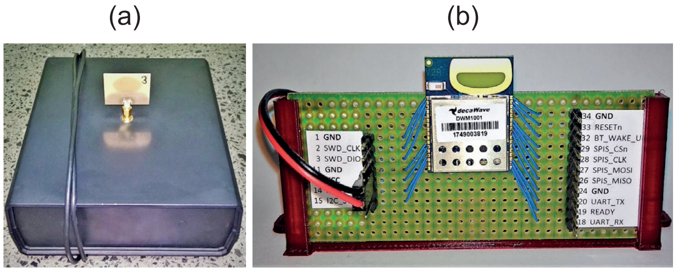



Fig. 3. Currently used platforms for communication and positioning based on the UWB system. a) DWM1000 in the housing, b) DWM1001 on the stand

**2.3. Analysis of the UWB frame in accordance with the IEEE 802.15.4–2011 standard.**

**2.3.1. Introduction to WPANs.** The IEEE 802.15.4–2011 standard [31] was developed for inexpensive low power consumption devices. This standard defines the parameters and functionalities of the physical layer (PHY) and medium access control sublayer (MAC) in wireless personal area networks (WPANs).

- The main attributes of this standard are:
- Star and peer-to-peer topology (communication)
- 64-bit extended address or 16-bit short address
- Two network access methods:
  - Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
  - ALOHA
- Fully acknowledged protocol for transfer reliability
- Low power consumption
- Energy detection (ED)
- Link quality indication (LQI)
- Two types of devices:
  - a full-function device (FFD)
  - a reduced-function device (RFD)

WPANs have small infrastructures or none. Regardless of the applied topology, a private area network consists of at least one full-specified device (which at the same time can establish a PAN and become its coordinator) and reduced-function devices (e.g. light switches, motion sensors, etc.). Each independent PAN has a unique identifier. Inside the PAN, devices can operate using extended 64-bit addresses or short 16-bit addresses. In a star network (see Fig. 4A), the PAN coordinator

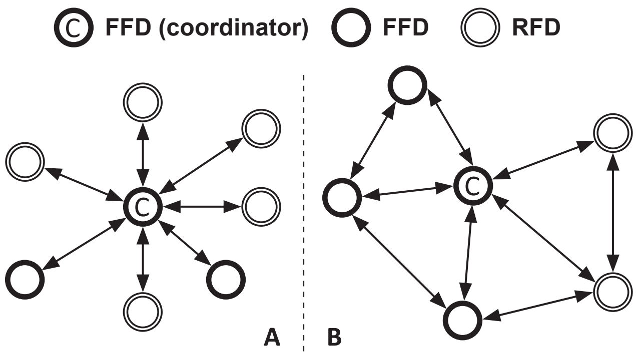



Fig. 4. Topology of WPAN A – Star and B – Peer-to-peer

manages the network traffic and allows other FFDs and RFDs to join its PAN.

In a peer-to-peer network (see Fig. 4B), any two devices within its radio communication range can establish direct communication between them.

**2.3.2. Layer-based network structure.** The architecture of network communication is divided into layers (see Fig. 5). Close to the physical medium, the PHY layer and MAC sublayer in the standard clearly show the process of encapsulation in low layers.


Fig. 5. Layer-based network architecture

The PHY manages the radio transceiver and is responsible for sending and receiving the PHY protocol data units (PPDUs) to/from physical media (radio waves). It provides information about the LQI and has the option of precision ranging. The last feature is the possibility of using UWB technology, which is the subject of this paper.

The MAC sublayer is responsible for sending and receiving the MAC protocol data units (MPDUs). Moreover, it validates the frames, acknowledges frame delivery, manages access to the channels and enables the implementation of the security mechanisms.

**2.3.3. Structure of a PPDU.** A PPDU contains three main fields: a synchronization header (SHR), a PHY header (PHR) and a PHY payload (PSDU). A PSDU, in turn, contains an MPDU from higher layer (MAC sublayer), which is placed in the PSDU during the encapsulation process. Figure 6 shows the general structure of a PPDU and PSDU.

| | | |
|---|---|---|
| MAC header (MHR) | MAC payload | MAC footer (MFR) |

| | | |
|---|---|---|
| Synchron. header (SHR) | PHY header (PHY) | PHY payload (PSDU) |

Fig. 6. PPDU structure

The format of the SHR and PHR fields depends on the modulation method that is used. The UWB PHY uses a combination of burst position modulation (BPM) and binary phase-shift keying (BPSK). The SHR preamble contains two fields – SYNC – which can be 31- or 127-long. Each of the codes has a list of channels in which it can be used. The selected code is repeated $N_{sync}$ times; the SFD is used to establish frame timing.

The PHR header (see Fig. 7) consists of 19 bits and transmits the necessary information (including the data rate, frame

| **Bit** | 0–1 | 2–8 | 9 | 10 | 11–12 | 13–18 |
|---|---|---|---|---|---|---|
| **Field** | Data rate | Frame length | RP | HE | PD | Check Bits |

RP – Ranging Packet, HE – Header Extension, PD – Preamble Duration

Fig. 7. PHR structure

length, preamble duration, which is given in the number of symbols) that is required to successfully decode a packet. The maximum PSDU size (based on the IEEE standard) is 127 octets. The SHR, PHR and PSDU are transmitted at different speeds.

**2.3.4. Structure of a MAC frame.** Figure 8 illustrates the general form of a MAC frame. The order of the fields is determined; however, not every field must be in a frame – the structure of a frame depends on its type. Both the header and the frame payload are of a variable length.

| **Octets** | 2 | 1 | 0/2 | 0/2/8 | 0/2 | 0/2/8 | 0/5/6/10/14 | variable | 2 |
|---|---|---|---|---|---|---|---|---|---|
| **Fields** | Frame control | Seq. number | Dest. PAN identifier | Dest. address | Source PAN identifier | Source address | Auxiliary security header | Frame payload | FCS |
| | MHR | | | | | | | MAC payload | MFR |

Fig. 8. General form of a MAC frame

As was mentioned above, the format of a frame depends on its type but also on the specific implementation (depending on the specific application or module, it decides which fields will be used). Further, the standard length of a data frame that is used in the DW1000 modules in the ranging process is discussed. It was also assumed that the short 16-bit addresses are used.

Given the above assumptions, the frame structure is shown in Fig. 9 [32]. The size of the MHR and MFR fields is constant and amounts to 11 octets (25 octets if all of the fields of the MHR and MFR are used) (see Table 1).

| **Octets** | 2 | 1 | 2 | 2 | 2 | variable | 2 |
|---|---|---|---|---|---|---|---|
| **Fields** | Frame control | Seq. number | Dest. PAN identifier | Dest. address | Source address | Ranging message | FCS |
| | MHR | | | | | MAC payload | MFR |

Fig. 9. Data MAC frame that is used by DW1000 (short addressing mode)

Table 1
Size of the MAC frame control fields

| Fields (MHR + MFR) | Number of octets | |
|---|---|---|
| | Discussed frame (see Fig. 9) | Maximum frame (see Fig. 8) |
| Frame control | 2 | 2 |
| Sequence number | 1 | 1 |
| Destination PAN identifier | 2 | 2 |
| Destination address | 2 | 8 |
| Source PAN identifier | 0 | 2 |
| Source address | 2 | 8 |
| Auxiliary security header | 0 | 14 |
| FCS | 2 | 2 |
| **Sum** | **11** | **39** |

During the ranging, different types of message formats are used. These messages are placed in the MAC Payload field. Figure 10 shows the messages that are sent by the DW1000 nodes during the ranging process [33].

**Poll message**

| **Octets** | 1 | 115 |
|---|---|---|
| **Fields** | Function code | Optional user payload |
| | 0x21 | – |

**Response message**

| **Octets** | 1 | 1 | 2 | 112 |
|---|---|---|---|---|
| **Fields** | Function code | Activity | Activity parameter | Optional user payload |
| | 0x10 | 0x02 | – | – |

**Final message**

| **Octets** | 1 | 5 | 5 | 5 | 100 |
|---|---|---|---|---|---|
| **Fields** | Function code | Poll message TX time–tamp | Response message RX time–stamp | Predicted final message TX time–stamp | Optional user payload |
| | 0x29 | – | – | – | – |

**Report message**

| **Octets** | 1 | 5 | 110 |
|---|---|---|---|
| **Fields** | Function code | Calculated ToF | Optional user payload |
| | 0x2A | – | – |

Fig. 10. The ranging messages that are used by DW1000

Table 2 shows:
- column (1) – the amount of data used by the MHR and MFR fields of the MAC frame – the sum of MHR and MFR fields from Fig. 9

Table 2
Optional free space in the ranging messages

| Message | Octets | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) = (1) + (2) | (4) | (5) |
| | MHR + MFR Overhead | Ranging message size | Protocol overhead | Maximum PSDU size | Optional free payload |
| Poll | 11 | 1 | 12 | 127 | 115 |
| Response | | 4 | 15 | | 112 |
| Final | | 16 | 27 | | 100 |
| Report | | 6 | 17 | | 110 |

- column (2) – the size of the control fields in ranging messages – the sum of control fields octets of a particular message from Fig. 10
- column (3) – the sum of MHR, MFR and control fields of ranging message, i.e. the sum (1) and (2)
- column (4) – the maximum size of the PSDU
- column (5) – number of octets can be used for additional purposes – the difference of (4) and (3)

**2.3.5. Payload vs. total frame duration.** The length of a frame affects the time that is required to put the frame into the transmit buffer and to transmit it. Table 3 shows a sample time for the total frame duration that was obtained on 3,000 samples that were received during the experiment. The total duration of a frame – $t_{fdt}$ includes the time when the frame is placed in the transmit buffer – $t_{fb}$ and the time that is required to successfully send a full frame (time required for the full frame to leave the node) – $t_{ftx}$, (2).

$$t_{fdt} = t_{fb} + t_{ftx} \tag{2}$$

Table 3
Total standard frame duration

| MAC frame size [B] | $t_{fdt_{min}}$ [ms] | $t_{fdt_{avg}}$ [ms] | $t_{fdt_{max}}$ [ms] | Description |
|---|---|---|---|---|
| 12 | 3.025 | 3.027 | 3.030 | Poll message |
| 15 | 3.027 | 3.029 | 3.032 | Response message |
| 17 | 3.029 | 3.031 | 3.033 | Report message |
| 27 | 4.035 | 4.037 | 4.040 | Final message |

Table 4
The total duration of the frame with additional payload

| MAC frame size [B] | $t_{fdt_{min}}$ [ms] | $t_{fdt_{avg}}$ [ms] | $t_{fdt_{max}}$ [ms] | Poll message with user payload |
|---|---|---|---|---|
| 44 | 6.041 | 6.043 | 6.050 | 32 B |
| 92 | 9.085 | 9.086 | 9.087 | 80 B |
| 127 | 12.111 | 12.112 | 12.120 | 115 B |

The configuration of the transmission was data rate – 110 kbps; pulse repetition frequency (PRF) – 64 MHz; preamble size – 1,024 symbols; channel number – 2.

**2.3.6. Conclusion to UWB PHY and MAC.** The free space in the MAC payload can be used to transmit different types of data between the network nodes. However, it should be noted that the length of the information that is sent as well as the size of the preamble (and the number of repetitions, speed, etc.) affect the time that is required to exchange messages during the ranging process. As the size of the transmitted data increases, the ranging frequency decreases. The number of nodes in a network that will be used to determine the position also affects the time between the successive ranging processes.

## 3. Results and Discussion

**3.1. Proposal for a structure for tagging the road infrastructure elements.** The authors decided to prepare a proposal for a structure for a UWB system based on the information about the available space for data in a UWB frame and information about the road infrastructure elements as well as the information that is on multidimensional maps, as they provide useful information. Firstly, it was assumed that the best frame part is one that provides information about the positioning of the object, which is an absolute priority within the transmitted data packets. At this stage, we decided to define the approach to the frame due to the structure of the information that is sent and its meaning and examples of the use of such a system, among others.

**3.2. Data structure and communication at the positioning stage.** This approach assumes that an object with a UWB system may have different properties. Therefore, the information it obtains is characterized by different parameters and level of significance. The information that is sent using the system – considering the transmission characteristics that the positioning process forces – can be divided into two parts that are always sent and those that will be sent to the terminal device at its explicit request. An example of such a request can be, for example, a situation in which a localized object has more time to make a data transmission (for example, a car that is stopped at a red light) or an object that is moving at a lower speed (a pedestrian, a cyclist or a person using electric personal transport devices).

The authors assumed that the first piece of priority information that would be sent by a system would be the one containing the following information:

- Ranging – because of the general exchange of four frames between the devices;
- Information on the features of the object that constitute a potential hazard (persons and/or objects in which they may be located, electrical devices, gas, etc.);
- Dimensions of the object along with the information about the movement of the antenna relative to the center of the object;
- Object's GPS position – information that is important for placing the object on the local vehicle reference map;
- Main object identifier – in the case of a stationary database that is stored by the vehicle in its local cache.

In an emergency, a car with this set of data would be able to react to a possible collision or to inform a supervised system about a high priority situation. In addition, the type of information that is transmitted is also not random. In the first place, the car must obtain information about the position of the object in relation to the vehicle. This provides the opportunity to correlate this data with other ADAS/autonomous driving systems [34]. Then, the main system is informed about the threat. If the subsystem recognizes a dangerous object that it must avoid, the vehicle knows that it is necessary to minimize the chances of moving toward the object. Other information is about the object's dimensions. Another level of danger is characterized by a bus stop at peak times and another is a fire hydrant or power pole. Next, the system needs to have information about the GPS position. In this case, for example, a car not equipped with other systems that enable the recognition of the surroundings can apply the object to the vehicle's onboard map. The last piece of minimum information is a unique device identifier that allows additional data to be obtained from the local database that is stored on the vehicle in the form of cache memory, for example, for regularly frequented routes.

Information on the features of the object that constitute a potential hazard have been specified in the system based on the United Nations Economic Commission for Europe (UNECE) documents – the United Nations Economic and Social Council [35]. In addition, the authors propose that information about any threat that people's presence may cause (e.g. at a bus stop) should be included.

Based on the above, the authors present in Table 5 a UWB frame format proposal that can be used for the basic tagging of road infrastructure elements.

Table 5
The proposal of a basic UWB frame for tagging road infrastructure

| Type of information | | Proposed data amount |
|---|---|---|
| **Frame version** | Code | 3 bits |
| **Device address** | Based on EUI-64 standard [36] | 8 bytes |
| **GPS position** | Latitude | 1 byte |
| | N S information | 1 bit |
| | Longitude | 1 byte |
| | W E information | 1 bit |
| **Dimensions** | Width | 3 bytes |
| | Length | 3 bytes |
| | Height | 3 bytes |
| **Position of the antenna** | Width | 3 bytes |
| | Length | 3 bytes |
| | Height | 3 bytes |
| | W L H signs | 3 bits |
| **Hazard** | Code | 3 bytes |
| | **Sum** | **32 bytes** |

The second type (part) of information includes the data that are obtained from the tag, only when there is free time to make an additional transmission. Based on the information that is obtained during the review of the road infrastructure elements, it was divided into three sub-categories. The first one is the path and its parameters, the second is the information about any intersections and signs and the third is the information about the infrastructure and buildings in the vicinity of the road. As part of the designed frame, a place was also created that could be used in the future versions of the proposed solution. The detailed arrangement of element categories is presented below:

1. Path and its parameters;
   This point in the first layer will contain information about the type of path (for example, road, pedestrian, cycleway and other). Then, there is a field for the parameters of this type (e.g. type of surface for the road, information on one-way or periodic route, information on the type of path for pedestrians, location of the bicycle path, etc.). This is where the information about the type and number of lanes in a given direction and any permanent restrictions on the passage of vehicles carrying dangerous goods and those that do not follow the outline of the road on the further section, e.g. under a viaduct, exceeding the tonnage of a bridge, etc., but without exact information about a specific object would be found. Information about restrictions on the type of a vehicle in the area (e.g. permitted only for passenger cars, no entry for vehicles with an internal combustion engine or diesel engines) would also be found here. From the point of view of transport, this category contains the relevant information about the vehicle parameters that are acceptable on a given stretch of road.
2. Information about intersections and signs;
   This section is mainly intended for any infrastructure facilities that affect the traffic. This is the most important section from the point of view of motor vehicles. Information about the traffic signs and the traffic lights, but also traffic calming elements, restrictions on turns, barriers, and gates (but only those on the road) would be found here. In addition, it was also decided to include all the information about intersections (type of intersection, priority of passage, detailed characteristics of the exits, etc.) in this category.
3. Infrastructure and buildings in the vicinity of the road;
   This is most important for security related to public utilities. It contains information such as bus stops, streetlights, the elements of electrical and gas infrastructure, barriers and gates (not going straight into the road, e.g. those separating traffic lanes or the road from the bike path, screens), soundproofing, etc. This is also where information about parking lots and their detailed parameters would be found. This category also contains information about any bridges, viaducts and tunnels (there is a section of the road, for example, with a tonnage limit of 40 t, while here is the information about the exact viaduct that starts in 200 m and its tonnage limit is 40 t) – there is a partial redundancy of information about the traffic restrictions.

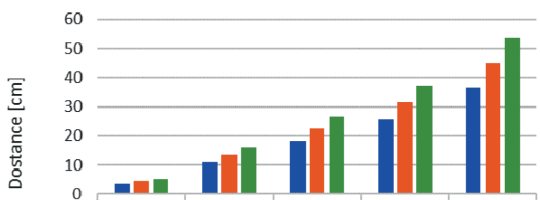
The proposal for the second frame that will contain an extended set of information is presented in Table 6.

Table 6
The proposal for an extended UWB frame for tagging road infrastructure

| **Type of information** | | **Proposed data amount** |
|---|---|---|
| **Frame version** | Code | 3 bits |
| **Device address** | Based on EUI-64 standard | 8 bytes |
| **Path and parameters** | Kind and parameters | 1 byte |
| | Lanes and restrictions | 3 bytes |
| | Vehicle restrictions | 2 bytes |
| **Intersections and signs** | Traffic signs and lights | 4 bytes |
| | Drive restrictions | 3 bytes |
| | Intersections, passage, exits | 6 bytes |
| **Infrastructure and buildings** | No. of passed objects | 5 bits |
| | Capacity for up to 16 objects and their parameters | 16 * 3 bytes |
| | **Additional information** | **4 bytes** |
| | **Sum** | **80 bytes** |

In this proposal, the processing of data that is not directly dependent on the UWB module (e.g. distance calculation, communication over different interfaces) has been omitted. Based on the dependency between the f and the speed of the vehicle, the distances that might be traveled by a car during the exchange of the ranging frames were calculated. At a speed of 50 km/h (in city environment) a vehicle can travel 8.39 cm for the 32 B frame, while for the 80 B frame, a car can travel 12.61 cm. Moreover, for the full ranging procedure (exchanging poll, response, report and final messages), the distance that could be traveled during the transmission time of these 4 messages is presented in Fig. 11.

Analyzing the table, it can be seen that for low speeds (within 10 km/h) corresponding to, e.g. vehicle movement in a parking lot, the error resulting from is relatively low (compared to the technology itself) and is below 5 cm. It is also com-




| | 10 | 30 | 50 | 70 | 100 |
|---|---|---|---|---|---|
| Standard frame | 4 | 11 | 18 | 26 | 37 |
| Frma with 32B of payload | 4 | 13 | 22 | 31 | 45 |
| Frame with 80B of payload | 5 | 16 | 27 | 37 | 53 |

Fig. 11. The distance that could be traveled by a car at a given speed in relation to the amount of data that has to be transmitted during the ranging procedure

parable to data transmission in a standard frame. This suggests the possibility of sending additional data just in this phase of movement (slow movement, stop at traffic lights). On the other hand, there are values at 70 and 100 km/h. Here, the distance increases to over 15 cm between sending the frame needed for dimensioning and the one that carries the largest data packet.

In such conditions, the computer supervising the subsystems of ADAS should consider whether it is better to obtain information about at a higher frequency, or whether the data on the environment are now more important. That is why a small frame is so important, which shortens this distance by half, creating a compromise between ensuring security and regular acquisition of position information.

Limiting the amount of data that is sent, especially in high traffic areas, would not only enable the lowest possible delays resulting from the use of an additional system for the car supervising system to be provided, but would also enable communication between a larger number of road users with the fewest possible delays.

### 3.3. Proposed usage examples.

**Case 1 – an unidentified object on the road.** An example of a situation in which the UWB tag can be used to increase the safety of road traffic participants is the example of road work. Fig. 12 shows an example in which an object that is not on stationary maps was placed next to the road that has not been dimensioned before or whose dimensions have changed.

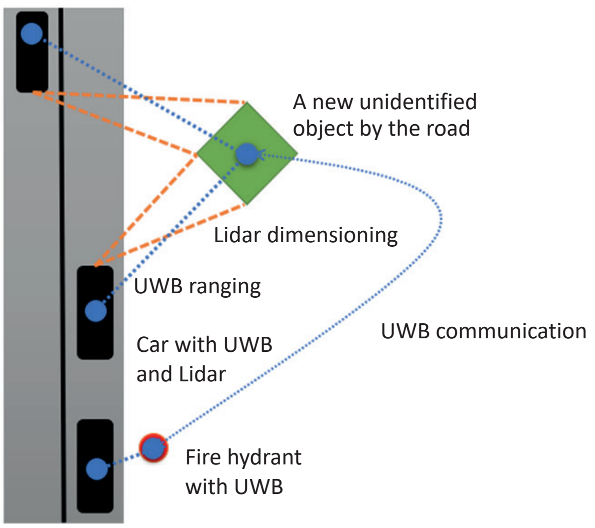



Fig. 12. Example of identifying the dimensions of a new object in the network

Vehicles that pass it can identify it based on the information from the UWB system (the position of the object relative to the car, a unique identifier) and multi-tiered lidar (information on the size of the object). Then, when communicating with the network, vehicles can place such information on the map, and it will then become available to other vehicles, e.g. those that are not equipped with a multi-tiered lidar system. The second proposed solution is reverse communication, e.g. using one of the packets that are used to determine distance. This enables information about the dimensions of the object to be transmitted. On the other hand, a UWB sensor network can also disseminate information about a potentially dangerous object that can be passed on to other oncoming vehicles that are not equipped with a lidar system.

**Case 2 – Infrastructure information.** Another example of using an information system that is based on UWB is to provide information about the infrastructure (the second stage of information transfer). If a car stops at a traffic light – as shown in Fig. 13, it is possible to query the infrastructure with detailed information about the environment of the vehicle.

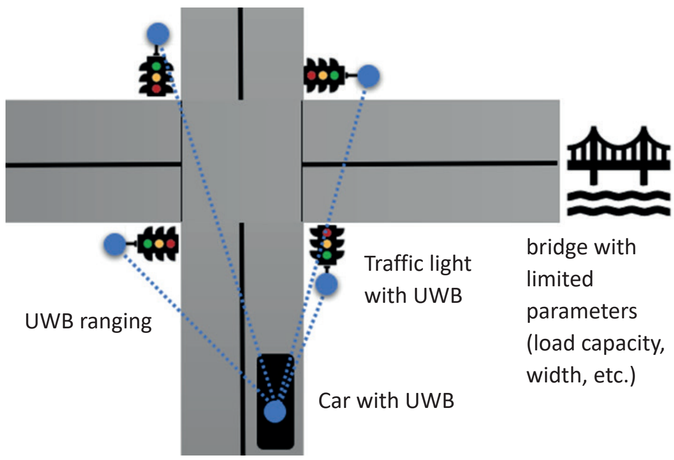



Fig. 13. An example of a situation in which it is possible to send additional information about the road infrastructure

Various information that is contained in the additional information section, for example, about the time until a green light, information about the neighborhood of a bridge and its associated restrictions (permissible total vehicle weight, maximum height or width), etc. can be transmitted.

A larger number of UWB sensors enables a vehicle to be precisely positioned and its direction of movement to be determined both in 2D and 3D, by using, for example, TWR (Two Way Ranging). Then the standard trilateration method used for both UWB [37] and other positioning systems based on reference points can be used [3]. It is also less complex than monitoring all intersection by a vision system [38]. As a result, the information about passing vehicles can be used, for example, to perform a traffic volume analysis, manage the traffic by the traffic information systems for drivers or to provide assistance information for traffic-based navigation [39].

**Case 3 – Traffic signs and traffic control.** In the previous case, the possibility of providing information related to the current state of traffic lights was already mentioned. The transfer of information on road signs is also important from, e.g. the point of view of the ETCS system in road applications. Although it is an element that enabled the development of autonomous driving, it can also assist the drivers of current vehicles by presenting, for example, speed limits in a convenient way and can automatically adjust the cruise control for them in the future. At present, vision systems [40, 41] are mainly used for character recognition, but in some situations such systems may fail, e.g. road signs that are covered with a layer of dew or ice (see Fig. 14), reflections of light and unfavorable road conditions such as rainfall and fog, which significantly reduce the visibility and make it more difficult to read the sign.

Fig. 14. An example of a road sign that is difficult for vision systems to identify [43], which could easily be recognized using the UWB system

It may be helpful to use the combined data from systems such as lidar [42] and UWB for detection or – depending on the implementation – the UWB system itself. During the positioning process, we can not only receive information about the current road signs, but also additional information such as the fact of being in a built-up area, a speed restriction zone, the need to turn on the lights before a tunnel or approaching a dangerous turn or a pedestrian crossing.

## 4. Conclusions

Based on the research presented in the article, it can be said that the UWB frame together with positioning would create the possibility of transmitting important information from the autonomous driving point of view. This technology would not only enable the capabilities of current ADAS to be extended, but would also create completely new possibilities for supporting drivers when they are driving (an increased amount of road sign information, the possibility for individual UWB points to cooperate and providing traffic information to the external traffic management centers). The authors also do not exclude that the information about the infrastructure and the proposed solution provides the opportunity to support future elements of the road infrastructure to expand the system. From the time of transmission and the characteristics of the exchange of packets between the devices in the network, it can be seen that the proposed division of data into two stages – the exchange of the key and additional data – is supported in the event that there is a need to provide quick information about the main parameters of the vehicle's environment for the master system and then the possibility of providing additional information when the system has the opportunity to do so. In addition, the empirical analysis of the frame showed what temporal overheads it brings when a payload is added to the UWB frame, which could be used in the future to regulate the proposals that are presented in the paper.

In addition, the authors will also conduct work related to the validation of network performance in the presence of multiple nodes – it should be borne in mind that within one or several tagged objects, e.g. at an intersection or a large roundabout, there may be dozens of cars, all wanting to obtain information. In this case, it would be necessary to consider broadcasting without obtaining information on the position of a single vehicle, but this still requires detailed research in this regard. An important fact is that for the V2V infrastructure such studies are already being conducted and aimed at selecting the appropriate model in packet transmission in the UWB network, among others.

Observation of the V2I segments shows that most solutions are currently focused on the autonomy of a vehicle in relation to the environment in which it moves. The approach that implements tags – especially in a highly urbanized environment where tens of thousands of vehicles would use them every day, requires rebuilding the current patterns. At this time, the ongoing works – outlined in the article – are aimed at the empirical verification of the impact of the packet size on the operation of a network with many reference points. At the same time, it is necessary to implement a master system that will be able to determine the need to disseminate individual pieces of information (about traffic jams, difficult road conditions, random events), which depend on factors such as traffic volume or the balance of vehicles that are passing individual reference points.

Based on the conducted research, our team is currently working on an algorithm aimed at – after taking into account all dependencies such as speed or order of the points polled – making corrections enabling more accurate determination of distance and later position.

**Acknowledgements.** The research was funded partially by project POWR.03.02.00–00-I007/17–00 "CyPhiS – the program of modern PhD studies in the field of Cyber-Physical Systems", and partially by the Polish Ministry of Science and Higher Education Funds for Statutory Research BK-284/RAU11/2020 (02/140/BK_20/0004), and partially by Young Researchers funds of Department of Electronics, Electrical Engineering and Microelectronics, Faculty of Automatic Control, Electronics and Computer Science, Silesian University of Technology, Gliwice, Poland.

**Abbreviation list**

ADAS – advanced driver assistance systems
AHRS – attitude and heading reference system

B – byte
BPM – burst position modulation
BPSK – binary phase-shift keying
CA – collision avoidance
CSMA – carrier sense multiple access
ED – energy detection
ETCS – European Train Control System
EUI – extended unique identifier
FFD – full-function device
GPS – Global Positioning System
LQI – link quality indication
MAC – medium access control
MFR – MAC footer
MHR – MAC header
MPDU – MAC protocol data units
OSM – OpenStreetMap
PAN – personal area network
PFR – PHY footer
PHR – PHY header
PHY – physical Layer
POI – point of interest
PPDU – PHY protocol data units
RFD – reduced-function device
RIRO – right-in/right-out (intersections)
SHR – synchronization header
STSC – smart traffic signal control
SYNC – synchronization (header)
TWR – two way ranging
UNECE – United Nations Economic Commission for Europe
UWB – Ultra-wideband
V2I – vehicle to infrastructure
V2V – vehicle to vehicle
WPAN – wireless personal area networks

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