Application of distributed wireless measurements in wind tunnels

Stefan Lishev, Petia Pavlova, Grisha Spasov

Abstract*: In recent years, a number of researchers have focused on expanding the possibilities for testing prototypes in wind tunnels. One of the main directions is the use of wireless sensor networks and technologies in measuring two groups of parameters - during a stationary test and during a flight in a controlled environment. In this article are examined several WSN protocols for use in data acquisition system suited for wind tunnel "Ulag-1". It is performed an analysis on the different parameters of communication protocols like energy consumption, latency and data rate. The proposed system architecture is a platform for remote and wireless measurements in wind tunnels.*
Key words: *Bluetooth, LoRa, WPAN, Wind Tunnel, WSN, ZigBee*

1. INTRODUCTION

In experimental research and testing of aircraft models and their elements - wing, propeller, etc., subsonic wind tunnels with an open working section are often used. The experiments make it possible to calculate the aerodynamic characteristics on the basis of the measurements performed. One of the guidelines for improving the research capabilities of wind tunnels is aimed at the use of wireless sensor networks and distributed measurements in order to connect and remove the connecting cables for measuring probes and sensors [1][2][3]. There have been some efforts for improving research capabilities of wind tunnels in Europe like the ESWIRP (European Strategic Wind tunnels Improved Research Potential program), in which more than 100 scientist from 17 different nations were involved with the goal to ensure the future of European aeronautical research and industrial development [4]. For example, one of the wind tunnels that was included is S1MA, situated in Modane. The sensors and probes required to be as close as possible to the data acquisition instruments in order to limit cable length and to improve respective signal to noise ratio and resolution [5]. This could be a serious problem in some cases. A solution to this could be the using of a wireless sensor network. The architecture and the communication protocols are open question and challenge because of the requirements of the specific domain.

2. SYSTEM OVERVIEW

In Fig. 1 is presented ULAG-1 wind tunnel that is located at Technical University of Sofia Branch Plovdiv. It is subsonic wind tunnel for experimental research and educational purposes. There were made some modernizations of the facility using National Instruments DAQ devices in the past years that successfully added new capabilities [6].

The system block diagram of the system is presented in Fig. 2. The module NI 9237 is used for measuring air dynamic pressure behind the test model using PC24 type sensors; the module NI USB-6211 is used for measuring position of the sensors using ELPT 700/500 resistive position sensors. The both modules use USB interface, and for the coordinate module – LPT interface.

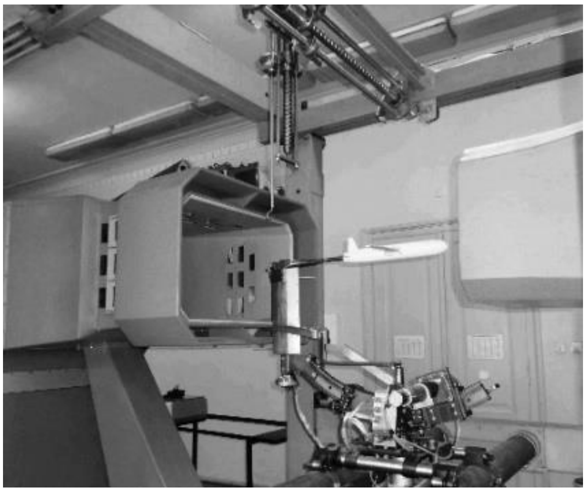

Fig. 1. *View of "Ulag-1"*

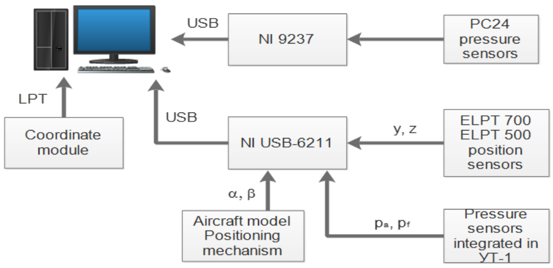

Fig. 2. *DAQ system*

The modules used where more than adequate for the measurements, but lack capability for wireless communication.

The new trends in aerodynamic investigations put new requirements for conducting experiments and the need of modernization. The new features that are needed are measuring two groups of parameters – during stationary test and during flight in controlled environment. The first group are [7][8]:

- pressure across the surfaces of the model
- lateral forces
- temperature
- drag

And the second group of parameters in test flight are [9][10]:

- yaw
- roll
- pitch moments
- atmospheric pressure

To be able to test these two groups of parameters at stationary state and during flight in test conditions, arise the need for wireless connection to the measuring devises installed on the test model. In the following sections will be discussed the adaptation of WSN for the current system as a heterogeneous platform with uses in other aerodynamic tunnels and UAV's.

3. WPAN PROTOCOLS OVERVIEW

There are different types of protocols used for communication in wireless networks for UAV's. These protocols are generic IoT protocols [11] that have different parameters in terms of data rate, latency and range [12]. In the following section different communication protocols are examined for use in communication networks for studying UAV aerodynamic parameters and behavior in test conditions. We discuss and analyze four protocols - ZigBee (IEEE 802.15.4), Bluetooth 4.0 (IEEE 802.15.1), Wi-Fi (802.11) and LoRa.

Bluetooth 4.0.

Bluetooth 4.0 is WPAN protocol, based on the 802.15.1 standard. It is used for exchanging data between mobile and fixed devices over short distances – for about 10m to 100m. In June 2010 version 4.0 was adopted with two versions that exist since then - Classic Bluetooth and Bluetooth Low Energy (BLE), known as Bluetooth 4.0 or Bluetooth LE. The first version is connection oriented, while the second version enables multi-hop networks that are connectionless. Data rate is <1 Mbps, with latency of 50ms. In BLE connection is quickly made only when transmitting data and is transient. This reduces significantly power consumption because the radio hasn't to be on when there's no data exchange. The main focus of BLE is on wireless communication between low power, low cost devices that can operate with coin-cell batteries for months or even years.

The architecture of BLE consists of three main parts – controller, host and applications. It is presented in Fig. 3.

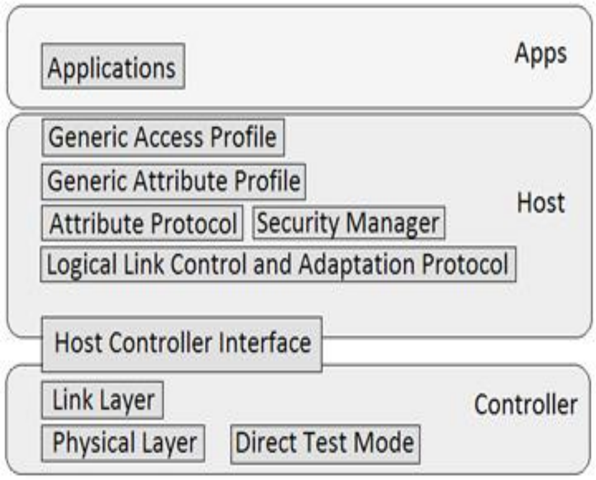

Fig. 3. *Architecture of BLE*

The controller's function is to provide the physical layer – receiving and transmitting radio signals. The radio band that is used is in the Industrial, Scientific and Medical (ISM) band – between 2.4000 GHz – 2.4835 GHz. It is divided into 40 channels, each 2MHz apart from one another. The modulation scheme is Gaussian Frequency Shift Keying (GFSK). Three of these channels are used for advertising and scanning and the other 37 for exchanging data packets. This band is shared between other WPAN protocols like 802.11b (Wi-Fi) and 802.15.4 and it is necessary to avoid interference. This is accomplished using Adaptive Frequency Hopping and also using variable transmit power between 0.01 mW (-20 dBm) and 10 mW (+10 dBm). Direct Test Mode is a mechanism for testing the physical layer that is standardized. It is used for production testing the RF parameters like sensitivity and transmit power according to the specification. The link layer is the direct interface of the physical layer. Usually it is implemented as hardware but also can be implemented as part of the software stack or as a combination of the both. The link layer is responsible for generating header information of the packets – preamble, access address, CRC, encryption and data whitening. It has several states:

- Scanning
- Advertising
- Standby
- Initiating
- Connected

The state diagram is presented at Fig. 4.

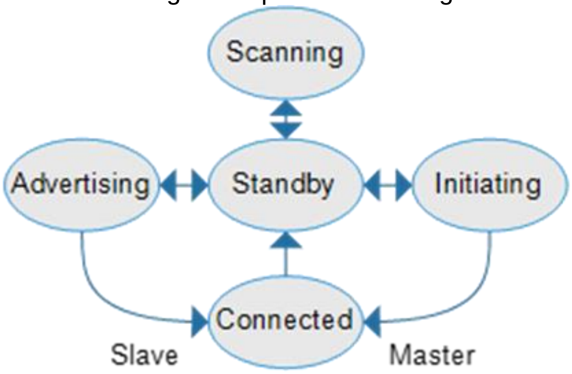

Fig. 4. *State diagram of BLE*

The standby state is the initial state, when the device is powered and it is possible to move into it from any other state when there's no active communication. Actually most of the time is spent in this state. In scanning state the device performs active or passive scanning. From advertising state the device can become slave after initiating connection with master or master after advertising. The link layer packed minimal size, as seen in Fig. 5 is just 80 bits without data payload, which makes radio on time and respectively power consumption very low for control and measurement applications that don't require sending big chunks of data.

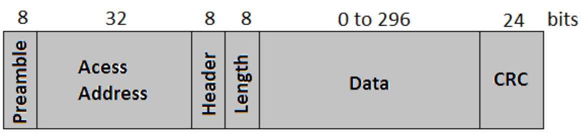

Fig. 5. *BLE packet format*

Host Controller Interface (HCI) is the standard interface between the physical layer and the host, which is the core of the BLE stack. It defines commands and events to translate data to packets. It is implemented with different physical interfaces, depending on the application – UART, USB and SDIO.

ZigBee

This standard is mainly focused on low cost, low power devices that are closely situated – no more than 100 m. Different topologies are used – peer to peer, star, mesh. Maximum speed is <250 kbps with latency of 50 ms [13]. The protocol operates on three bands – 2.4 GHz, 915 MHz and 868 MHz depending on the region. They are based on the Direct Sequence Spread Spectrum (DSSS). ZigBee is based on IEEE 802.15.4 and defines the upper layers. IEEE 802.15.4 specifies the first two layers according to OSI model – physical (PHY) and medium access (MAC) layers. There are two types of devices according to the specification – Full Function Device (FFD) and Reduced Function Device (RFD) [14]. The first type have three operation modes – Personal Area Network (PAN) Coordinator, Coordinator and simple device. The first two modes are responsible for network creation and synchronization. The second type of device operates with minimal implementation of the protocol. Typically it performs simple tasks like on/off switching or sensing binary signals like from a PIR sensor and don't send large amounts of data.

The MAC layer of the protocol is based on two modes of operation – Beacon-enabled and Non Beacon-enabled mode. The first one uses beacons that are periodically generated by the coordinator, and in the second one devices simply send their data using unslotted CSMA/MA (Carrier Sense Multiple Access / Contention Avoidance). In Fig. 6 is presented the Beacon-enabled mode of operation.

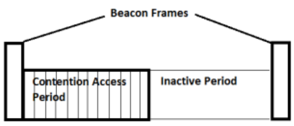

Fig. 6.

LoRa

This protocol uses a derivative of Chirp Spread Spectrum (CSS) modulation for the physical layer that is proprietary. The carrier signal consists of chirps – signals whose frequency changes over time. The change is from lower frequency to higher or vice versa. LoRa operates in the sub-gigahertz radiofrequency bands in the ISM part of the spectrum that are license-free – 433MHz, 868MHz and 923 MHz. This modulation enables long range of about 15 km and high penetration in urban environment. LoRa supports variable data rate with maximal speed of 50 kbps. The variable data rate gives the possibility of optimization of throughput and coverage range, or robustness, or energy consumption with bandwidth kept constant [15]. The latency is 82 ms. Spread spectrum technique allows high noise immunity and protection against interference because of the capability of demodulating the received signal even when it's 20 dB lower than the noise floor. Some parameters are configurable and have different impact on the network performance – bandwidth, spreading factor, coding rate, transmission power [16]. The basic architecture is shown on Fig. 7 [17].

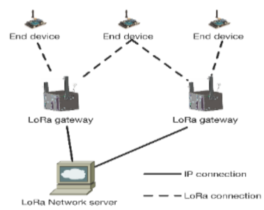

Fig. 7.

It is described as “a star of stars topology”. LoRa defines only the physical layer and the others could be customized. For MAC layer is defined LoRaWAN.

Wi-Fi

The IEEE 802.11 family of protocols, known as Wi-Fi is widely used WLAN standard for short range applications with high speed demand, including IoT applications. It uses several radio bands – 2.4 GHz, 3.6GHz, 5GHz and 60GHz. Wi-Fi is not best suited for applications where there are large number of battery operated IoT sensor devices. The traditional 802.11b/g/n are expected to be complemented with the newer protocols like 802.11ac (Wi-Fi 5), which uses Multiple Input, Multiple Output (MIMO), IEEE 802.11ah (marketed as Wi-Fi HaLow) – a new sub-1GHz Wi-Fi technology for low latency and time critical applications [18][19] and the newest up to date - 802.11ax (Wi-Fi 6) which promises data rate up to 9.6 Gbps and competes with 5G [20]. The disadvantage of IEEE 802.11 protocols are low energy efficiency and short range of operation – from 100m to even a few meters for 802.11ax. With the appropriate antenna the range could be increased.

4. WPAN PROTOCOLS DISCUSSION

Theoretical parameters of WPAN protocols like throughput, latency and energy consumption differ from experimental. There are made some analytical models, for example about discovery latency and discovery probability of BLE networks [21]. One of the major timing parameters are advertising period per channel, scan interval and scan window.

Energy efficiency is one of the parameters that could be optimized at network level [22]. There are four techniques for that:

- radio optimization
- sleep/wake-up protocols
- energy efficient routing
- data reduction

Different techniques could be used for reducing the energy consumption of the radio module. For example – using modulation that uses low energy, directional antennas, that require less power for the same distance, or transmission power control. The latter consists of adjusting the transmit power by using signal strength indicator (RSSI) or link quality indicator (LQI).

Another approach is adopting the node activity – scheduling the on time of the radio according to the used protocol. Using sleep mode for the radio and/or the microcontroller could reduce the consumed energy.

For efficient routing exist many approaches. Packet forwarding, clustering-based hierarchical routing are some of these techniques [23].

In [24] is made a comparison between BLE, IEEE 802.15.4 and SimpliciTI that is a proprietary protocol of Texas Instruments. In the performed analysis for BLE, the maximum throughput on advertising channel is given by (1) :

(1)

$$Throughput_{BLE_{ADV}}(n) = \frac{n.8}{T_{advEvent}}, n = 0..31\ bytes$$

It is assumed, that in each of the advertising events the advertiser sends new data. TadvEvent is defined by a sum of advertising interval and advertising delay. Respectively, the maximum throughput on data channels for master-slave unidirectional data transfer is given by the equation(2) :

(2)

$$(2)\ Throughput_{BLE_{DATA}}(n, m, T_{TXprep}, T_{RXproc}, \tau) = \frac{n.8}{0.16ms + \frac{(n+m).8}{1000} + 2.\tau + 2.\max(0.15ms, T_{TXprep} + T_{RXproc})}, n, m = 0..27\ bytes$$

Here n is the payload of each frame from master to slave, and m is the payload of replay frame from slave to master, 0.16 is the time for transmitting frame headers.

The analytical estimations are compared to experimental results using CC2540 modules for BLE, CC2430 for IEEE 802.15.4 and CC2510 for SimpliciTI. The conclusion is that BLE required two to seven times less energy than the other protocols when transferring 19-byte payloads. If the payloads are higher – 31 to 100-bytes, the results are that BLE consumes two to three times less energy. Similar results are made in [25].

A comparison between different WPAN and WAN protocols is presented in the following table:

Table 1. [26][27]

	BLE	Wi-Fi	LORA	ZigBee
Bandwidth (MHz)	2	20/40MHz		5MHz
Num. of Ch.	40	11		16
Data	1Mb/s	600Mb/s	50 kb/s	250kb/

rate				s
Max power (mW)	10	100		6.3
Range (m)	50	100	>10km	100m
Latency (ms)	6	50		50

Evidently, the two protocols have different advantages and disadvantages which depend on the current application. For uses with low energy consumption and low latency BLE is better, and for high data rate regardless of the power requirements Wi-Fi has more advantages if we sacrifice latency.

If we compare LoRa to the other two protocols it can be concluded that it is suitable for long range applications that require low bandwidth as can be seen from Fig. 8:

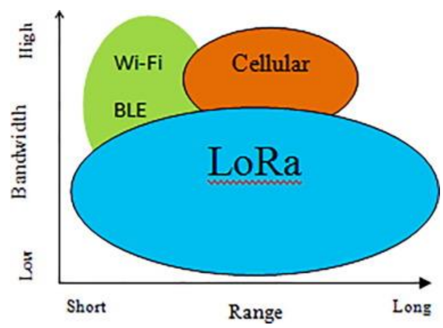

Fig. 8

5. PROPOSED SYSTEM ARCHITECTURE

In Fig. 9 is presented the architecture of the proposed wireless measuring system. Data are collected from heterogeneous smart sensors. They have MCU unit that perform signal conditioning and analog to digital conversion. Depending on the parameters that are measured, some of the measuring nodes have to be able to do some data analyzing, buffering, aggregation and compression.

Data are transmitted using WPAN/WAN protocols to the gateway. The gateway is connected through TCP/IP protocol to the Internet. Users connect to the gateway like client to server. On the side of the sensors the gateway acts as a client and the smart sensors are servers that listen for requests. The system is intended as a test bed for the used protocols

Here are listed some of the key parameters of interest during design and system identification of UAV and their requirements for the measuring system [28][29], of which require low data rate:

- temperature
- barometric pressure
- And high data rate:
- angular velocity
- pressure
- voltage
- force
- digital impulses

To perform measurements on mobile objects like drones and plane prototypes the system have to meet some specific requirements like high throughput, low latency, energy efficiency

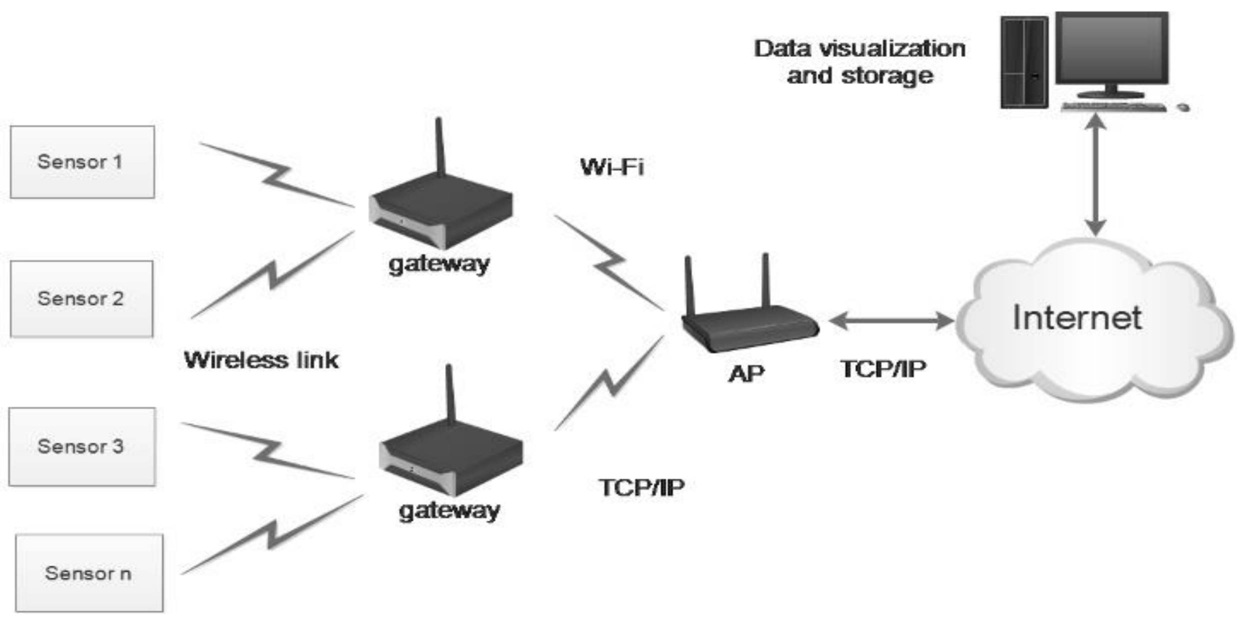

Fig. 9.

6. CONCLUSION

In the article are presented and examined different WPAN protocols for use in the measurement system of wind tunnel “Ulag 1”. The protocol that meets the specific requirements such as low latency, low energy consumption and reliability according to the authors is Bluetooth 4.0 – Bluetooth Low Energy. Future work includes the implementation and test of the proposed system.

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About the authors:

Stefan Lishev, Petia Pavlova, Grisha Spasov, TU –Sofia, Plovdiv Branch, Department of Computer Systems and Technologies, stefan_lishev@tu-plovdiv.bg, p_pavlova@tu-plovdiv.bg, gvs@tu-plovdiv.bg.