Technological and Architectural Advances for Fast Data Acquisition in Wireless Networks

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***Abstract.* The present paper presents the ongoing research under FP7 ICT-AGRI "STRATOS" project. The previous research has identified the direction for further research and highlighted several problems that should be solved. The current research focuses on radio signal interference decrease and TDMA timing synchronization. Also the system architecture is specified in detail in the article, and specific devices are considered for prototype construction.**

Tests have shown that the proposed solutions decrease TDMA frame jitter six times and allow interference-free coexistence of sensor network and Wi-Fi devices.

***Keywords* – wireless data acquisition, embedded systems, time critical systems.**

I. INTRODUCTION

The aim of FP7 "STRATOS" [1] project is to incorporate wireless networks in ISOBUS [2] standard. The authors of the article are currently dealing with the connection of wireless sensor nodes to the task controller (TC) in the tractor. The task is to use physical sensor measurements, process and transfer them wirelessly to the access point. The last step is to provide measurements to TC by wired ISOBUS link (see Fig. 1). There are several features that make this research challenging. The number of nodes (140) and data measurement frequency (300Hz) are higher than in any of the existing wireless data acquisition (DAQ) systems [3]. Besides high data acquisition frequency, nodes should maintain low power consumption and use only licence-free radio bandwidth.

All of the above-mentioned tasks were solved in the previous research. However, the tests showed that the proposed solutions were not perfect and several problems needed to be solved.

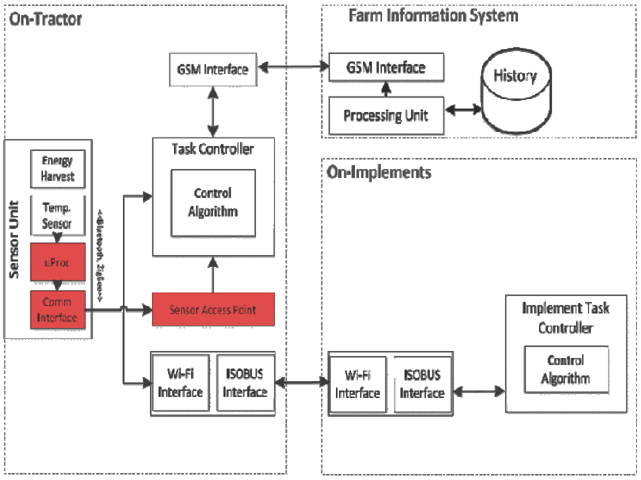


Fig. 1. "STRATOS" project scheme with the research area marked in red

II. THE PREVIOUS RESEARCH AND CURRENT TASKS

To achieve the required measurement frequency (300 Hz) and the number of nodes (140), the authors have used all available bandwidth in ISM band (2.400–2.485 GHz). After testing this setup in the real environment, interference problems have been found. During the experiments, approximately 2% of packets have been lost. To check the source of errors, the external sniffer has been used. It has allowed capturing all transmitted packets, even if checksum is incorrect. As seen in Fig. 2, occasionally some packets become corrupted. Such a behavior is observed only if nodes are not isolated from the environment. Also, Wi-Fi (IEEE 802.11b) devices decrease their data rate, if the distance to sensor nodes is less than one meter. It leads to a conclusion that sensor nodes interfere with Wi-Fi devices. Since all available bandwidth is occupied, there is no chance to separate networks by bandwidth. Therefore, the first task is to solve interference issues.

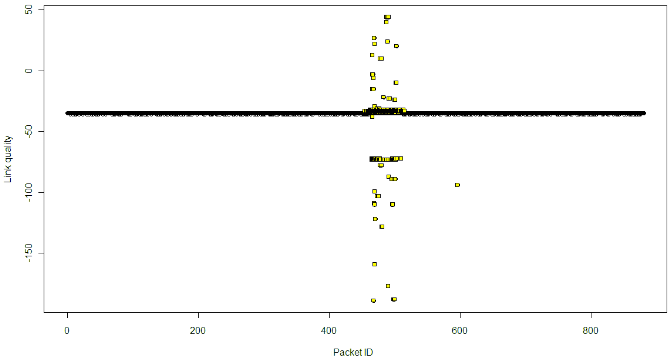


Fig. 2. The effect of Wi-Fi interference on the tested sensor network

Along with interference issues, nodes are not perfectly synchronized. Therefore, guard time is high. It results in the inefficient transmission and increased energy consumption. The next section provides solutions to these issues.

Up to now, there has not been a detailed definition of architecture for the wireless sensor network. The existing model defines the intersystem relation and junction points. The first stage of the project has been devoted to the searching and testing of different approaches. Now, when all requirements are satisfied, it is possible to specify a detailed architecture for a wireless sensor network. Along with the architecture design, all hardware modules should be specified to allow constructing a full system prototype. The next section contains a detailed architecture scheme and specification of each device.

III. RESEARCH RESULTS

The first and most important issue is interference. There are several ways to deal with it, e.g., separating transmissions spatially by time or by frequency. Our project setup does not allow separating devices in space, since all of them are located in the same tractor. Moreover, it is not efficient to use time division, since the project aims for high data acquisition rate. Therefore, frequency division is the only way. However, the existing approach does not allow applying this technique, since sensor devices use all available bandwidth. To free up some bandwidth, we need to increase spectral efficiency of the overall transmission system.

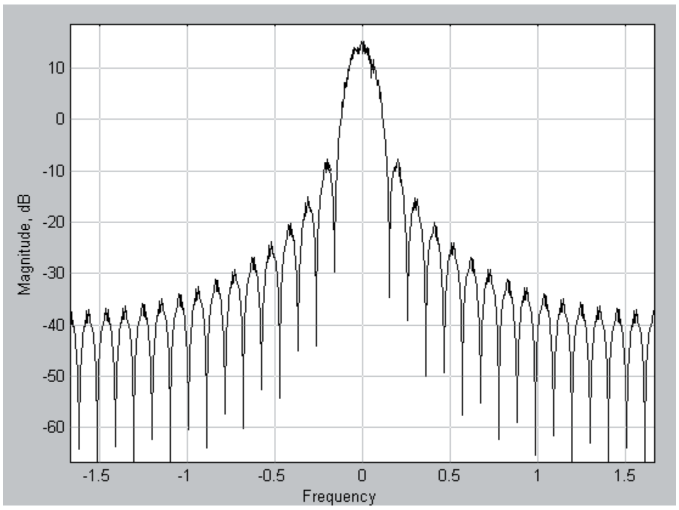


Fig. 3. OQFSK signal power spectrum [4]

Current radio modulation technique uses 2 MHz channels with 3 MHz spacing. Since one channel data rate is 250 kbps, efficiency is 0.05 bps/Hz. It is necessary to find a transceiver that is at least 26% more efficient, but keeps power consumption at the same level or even lower.

The existing transceiver (TelosB working under IEEE 802.15.4) uses offset quadrature phase-shift keying (OQPSK) modulation technique, which is not so efficient [5]. By looking at the spectrum of the OQPSK modulated signal (see Fig. 3), we can see that out-of-band spectrum is significantly larger than the carrier signal itself. It could be explained with rapid change of the OQPSK modulated waveform [5].

To overcome the out-of-band problem, it is possible to use radio signal smoothing technique. Gaussian Frequency-Shift Keying (GFSK) modulation technique uses the Gaussian filter to smooth rapid frequency changes. By using this technique, it is possible to significantly lower the out-of-band spectrum (see Fig. 4) and therefore increase transmission system efficiency.

Among the existing solutions, only nRFGo modules satisfy all project requirements (data rate, channel bandwidth, energy consumption and analog IO amount). Moreover, nRFGo modules are able to transmit data at 2 MHz rate, while keeping energy consumption in the acceptable range. Also, total channel bandwidth of 2 MHz gives 1 bps/Hz efficiency, which is 20 times better than that in the previously used TelosB nodes.

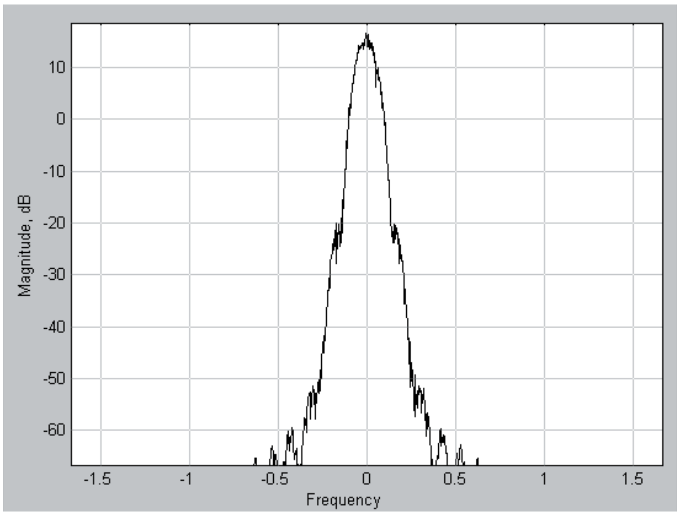
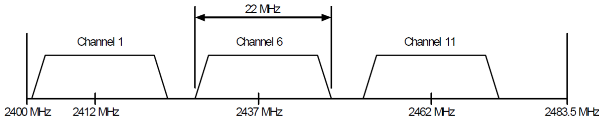
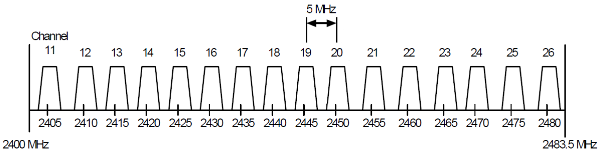


Fig. 4. GFSK signal power spectrum [4]

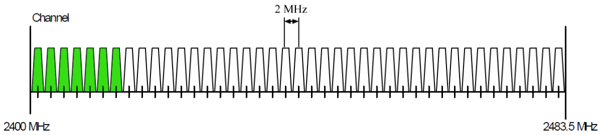
With the increased transmission rate, it is possible to shorten TDMA slot, thereby allowing more nodes to fit in the same time frame. Since GFSK modulation lowers the out-of-band spectrum, the total channel bandwidth is 2 MHz that allows stacking more parallel channels in the same bandwidth. Since the total bandwidth has decreased from 5 to 2 MHz, 16 channels occupy only 32 MHz. Even without decreasing TDMA slot size, there is bandwidth left for one interference-free Wi-Fi channel. Since TDMA slot time will also be shortened, only seven channels will be used (see Fig. 5). Therefore, two Wi-Fi channels can operate without interference.



a) IEEE 802.11b



b) IEEE 802.15.4



c) nRFGo @ GFSK

Fig. 5. Bandwidth occupation by three network channels

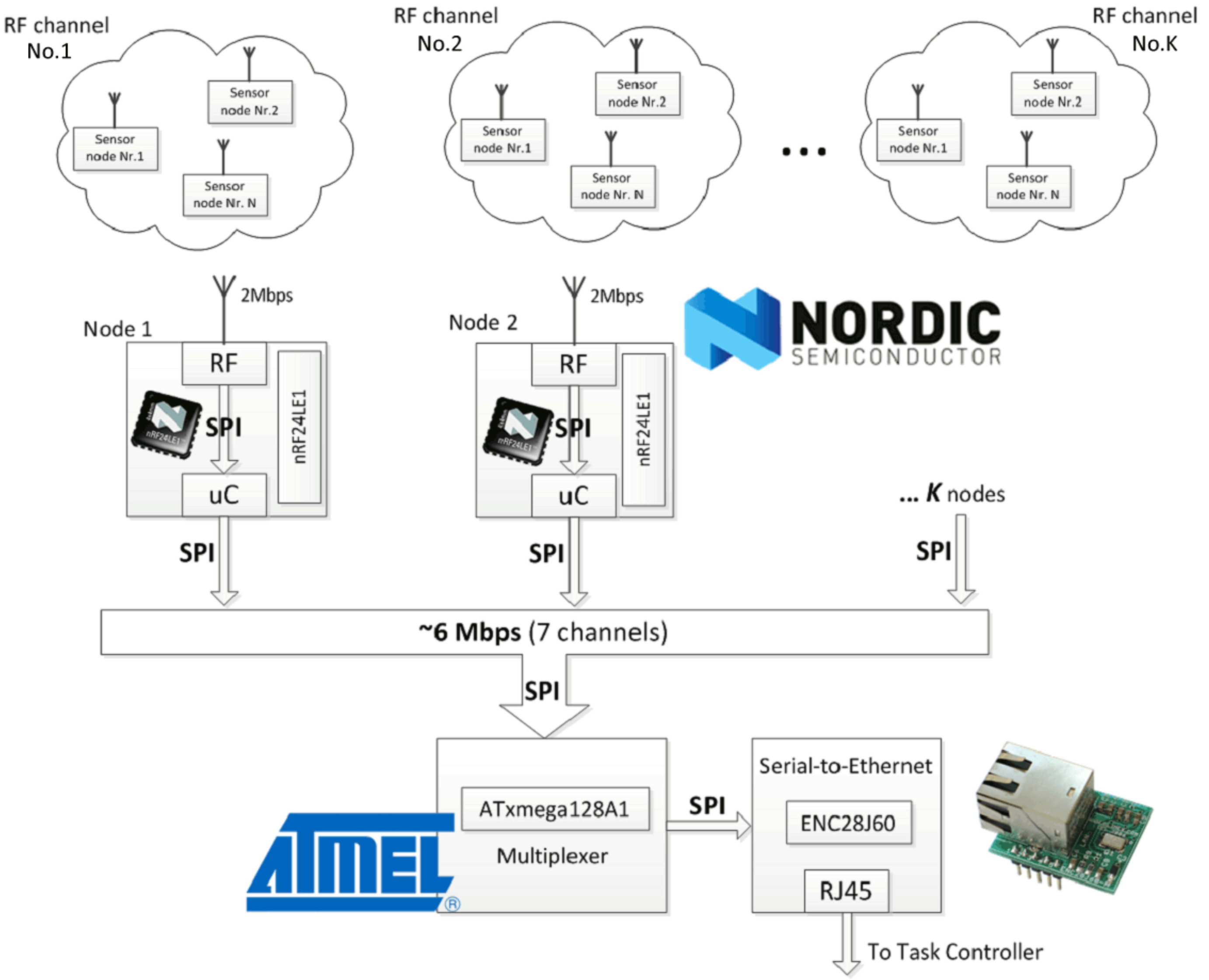


Fig. 6. Wireless data acquisition system scheme

The first task has been solved; transmission technique has been evaluated and sensor devices have been specified. Therefore, it is possible to define the overall system architecture and specify all devices.

Fig. 6 illustrates the scheme of the whole system, starting with physical sensors and finishing with the TC link. Project partners have tested Multiplexer and Serial-to-Ethernet devices and reported their ability to sustain load of 6 Mbps. The detailed analysis of overall system tests will be provided in the next paper. The gateway between sensor nodes and TC is connected to seven nRFGo nodes acting as TDMA masters. Each node gathers data from its own radio channel. Since nodes are separated by frequency, no interference issues arise. Atmel ATxmega128A1 serves as a multiplexer that uses SPI to receive data from each TDMA master node.

Since transmission technique and specific wireless nodes are chosen, it is possible to test wireless data acquisition network. For the test setup, one radio channel is used. One nRF24LE1 node is configured as TDMA master. Other slave nodes send the measured data in the predefined TDMA slots. Slaves are synchronized to the master’s beacon signal. Along with synchronization feature, beacon packet contains configuration information for slave nodes.

To reach maximal measurement transmission frequency and the lowest usage of radio channels, it is necessary to use minimal slot and guard times. Previously, TDMA structure was as follows: TDMA master and slave slot length – 300 µs, guard time – 70 µs. Therefore, in each TDMA frame it was possible to obtain measurement data from nine wireless sensors. Since nRFGo node raw data rate is bigger than in telosb, at first we should calculate the minimal theoretical limit for total transmission time. For calculation, it is possible to use formulas (1) and (2), provided in nRFGo device manual [6].

$$T_{OA} = \frac{8\left[{}^{bit}/_{byte}\right]\times(1[byte]+3[bytes]+N[bytes]+1[bytes])+9[bit]}{air\ data\ rate\ \left[{}^{bit}/_{s}\right]}, \quad (1)$$

where TOA is the radio transmission time (time on air) and N is the payload size.

$$T_{UL} = \frac{payload\ length}{SPI\ data\ rate} = \frac{8\left[{}^{bit}/_{byte}\right]\times N[bytes]}{SPI\ data\ rate\ \left[{}^{bit}/_{s}\right]}, \quad (2)$$

where T_{UL} is the time needed to upload measurement data to radio module by SPI serial link, and N is the payload size.

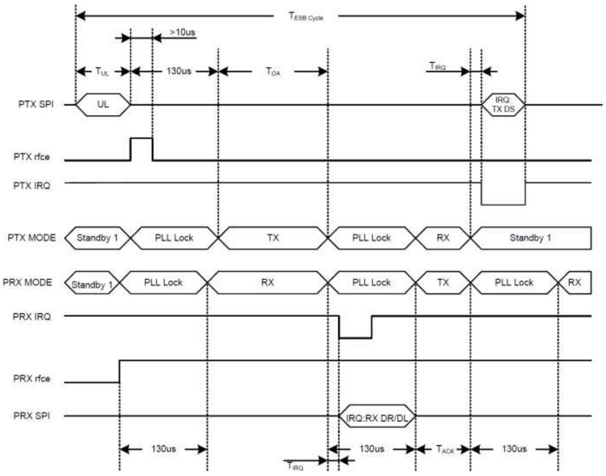


Fig. 7. Transmission time of one packet of nRFGo nodes [6]

By using the provided formulas and radio mode change delays presented in Fig. 7, it is possible to calculate TDMA slot time for master and slave nodes.

Slot time for the master node is composed of the following constituents: T_{UL} + PLL $lock_{RxTx}$ + T_{OA}. By using payload equal to 10 bytes (5 sensors of 2 bytes each), total master slot time is 255µs. The same time is for slave nodes, excluding the first node that follows the master slot. When the master sends the beacon packet, all nodes should receive and process it before starting their measurement transmission. Therefore, we should prolong master slot time for: PLL $lock_{TxRx}$ + T_{UL} + $T_{DataProcessing}$ + PLL $lock_{RxTx}$. Since the master can stay in the receive mode between beacon transmissions, it is able to receive data faster than one node can transmit. It is explained by the fact that the slave node should wait for PLL lock time. Therefore, we should calculate the time master needs to receive and process data from the slave node. Theoretically, the time should be T_{OA} + T_{IRQ} + T_{UL} + $T_{DataProcessing}$. The first two components are known in advance – 114.5 µs, the last one should be found during tests. After several trial and error tests, minimal slot time has been set to 120 µs (see Fig. 8).

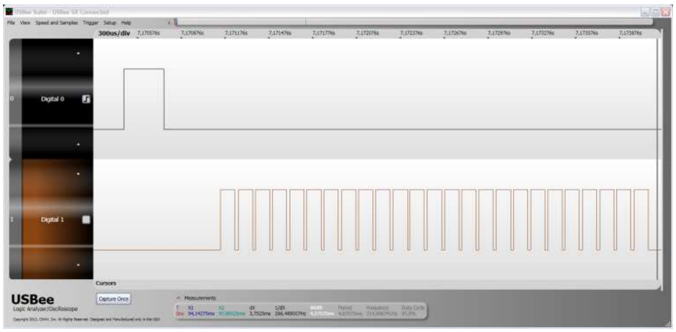


Fig. 8. Packets receiving timing diagram of TDMA master (top line) and slaves (bottom line).

Minimal guard time will be found after testing network with all slaves. In Fig. 8, the logic analyzer program snapshot is shown. The top line of the signal shows the transmission moment of master beacon signal. The second signal shows time moments when data is received from slave nodes. By analyzing gaps between slaves, it is possible to find the guard interval, which should be equal or larger than double jitter time. Histogram shows the comparison of slot time stability between nRFGo (green) and telosb (red) nodes (see Fig. 9).

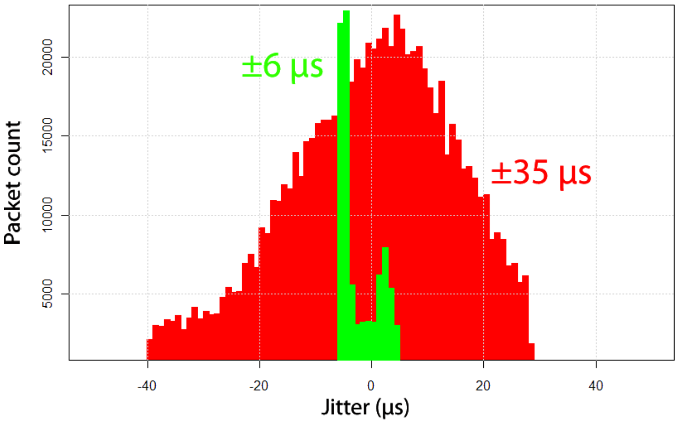


Fig. 9. Histograms of TDMA slave slot jitter. nRFGo nodes are marked in green, telosb – in red.

As seen in Fig. 9, by using Nordic nodes, jitter decreases ca. six times. Such a dramatic decrease can be explained by several factors: precise timer, operation at the lower hardware level. In telosb nodes, one timer division equals 31 µs, whereas nRFGo – 0.75 µs. Also Nordic nodes are programmed using low hardware layer instructions, while telosb is controlled by the micro-operating system, which controls and schedules all tasks. Even jitter is low as compared to telosb device; histogram shows that it can be decreased even more. The histogram shows two spikes as a result of nonsynchronous behavior of slave node slots. Future research will also focus on this problem. As a result of the conducted tests, a new TDMA scheme has been built (see Fig. 10). By reducing the slot time of slaves, node energy consumption is also reduced, since nodes can stay longer in the standby mode.

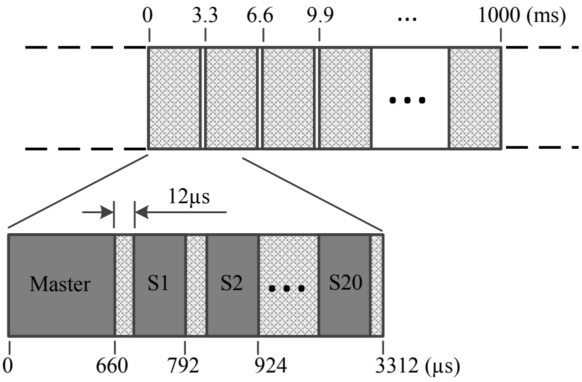


Fig. 10. TDMA timing scheme

IV. CONCLUSIONS

Current research results cover the areas of radio signal modulation, interference issues, bandwidth planning, architecture building, TDMA scheduling. Tests have shown that the proposed changes solve all existing interference issues. By switching to nRF24LE1 sensor nodes, bandwith usage is reduced, along with a slight reduction in energy consumption.

The system architecture has been shown with detailed specification of the hardware, wired/wireless protocols and timing/bandwidth requirements. It uses a modular structure, where all components use standard interfaces and protocols. In this way, it will be much easier to improve the system or migrate to another platform. The gateway to the system TC is composed of three modules. All modules use SPI bus for communication. All wireless gateway transceivers are connected to multiplexing/demultiplexing node, which translates data for Serial-to-Ethernet module. This technique will allow low effort migration to new wired/wireless media and the expanding of a number of nodes by occupying the remaining free bandwidth channels. The detailed analysis of wireless node transmission technique has revealed the limits of hardware and shown the way to further improvements.

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Dmitrijs Bļizņuks, Valerijs Zagurskis. Tehnoloģiju un arhitektūras uzlabojumi ātrai datu iegūšanai bezvadu tīklos

Šis raksts satur pētījumu rezultātus kārtējā «STRATOS» Eiropas projekta posmā. Iepriekšējos pētījumos tika piedāvāta ātrgaitas bezvadu datu vākšanas tīkla realizācijas metode. Šāda tipa tīkla izveide joprojām ir aktuāla, jo esošie risinājumi neatbilst prasībām pret mērījumu frekvenci un sensoru skaitu. Piedāvātais risinājums atbilst visām noteiktajām prasībām, bet eksistē daži trūkumi, kuri var kavēt sistēmas īstenošanu. Pētījuma laikā tika konstatētas dažas problēmas, gadījumā, kad blakus darbojas divi vai vairāki radio tīkli. Tā kā nākamajā projekta posmā ir plānots izmantot WiFi (IEEE 802.11b) tīklu, bija nepieciešams sasniegt stabilu abu tīklu funkcionēšanu. Izvēloties iekārtas un to darba režīmus, eksistēja papildus mērķis – sensoru mezglu enerģijas taupīšana.

Pirmajā posmā tika risinātas tīklu radio traucējumu problēmas. Izanalizējot radiofrekvenču spektru un tā modulēšanas veidu (OQPSK), tika ierosināts izmantot sensora mezglus (nRF24LE1), kuriem ir šaurākā radiofrekvenču josla, toties lielāks datu pārraides ātrums. Šo jauno signālu modelēšanas veidu (GFSK) pielietošana ļāva nodrošināt atsevišķu radiofrekvenču joslu WiFi tīklā. Signāla kodēšanas maiņa arī deva iespēju atbrīvoties no traucējumiem starp sensoru un WiFi tīkliem. Izmantot jauno sensoru mezglu, samazinājās arī TDMA (Time Division Multiple Access) laikspraugas, kas savukārt vēl vairāk palielināja radiofrekvenču joslu efektivitāti un par 3% samazināja kopējo enerģijas patēriņu.

Pēdējā posmā tika sastādīta kopējā sistēmas shēma ar visu iekārtu modeļu definēšanu. Turpmākie pētījumi būs veltīti mezglu sinhronizēšanai, TDMA vedēja mezgla laikspraugas samazināšanai, kā arī pilna izmēra sistēmas pārbaudei.

Дмитрий Близнюк, Валерий Загурский. Технологические и архитектурные улучшения для беспроводной сети быстрого сбора данных

Данная статья содержит результаты исследований очередного этапа европейского проекта «STRATOS». В ходе предыдущих исследований был предложен способ высокоскоростной системы беспроводного сбора данных. Задача по-прежнему является актуальной, так как существующие решения не удовлетворяют требованиям по частоте измерений и количеству сенсоров. Предложенное решение удовлетворяет всем требованиям, указанным в постановке задачи, но обладает рядом недостатков, которые могут помешать при реализации полноценной системы. В ходе исследований, были обнаружены проблемы совместной работы нескольких соседствующих радиосетей. Так как в следующем этапе реализации проекта, планируется использовать сеть WiFi (IEEE 802.11b), то было необходимо добиться стабильной работы этой сети совместно с сетью беспроводных сенсоров. После завершения этапа поиска подходящих устройств для сенсорной сети, было необходимо составить архитектурную схему всей системы сбора данных, а также определить конкретные модели всех оставшихся узлов. При выборе аппаратуры и режимов работы, стояла дополнительная цель максимальной экономии энергии сенсорных узлов.

Первым этапом работы было решить проблему радиопомех. Проанализировав спектр радиосигнала и метод его модулирования (OQPSK), было предложено использовать сенсорный узлы с меньшой шириной радио полосы, но с большей скоростью передачи данных (GFSK). В результате использования такого моделирования сигнала, получилось выделить отдельную полосу для радиосети WiFi. Совместно с изменением метода

кодирования, это позволило избавиться от помех между этими сетями. Так же использование новых сенсорных узлов позволило сократить длительность интервалов в TDMA (Time Division Multiple Access) кадре, что в свою очередь дополнительно увеличило эффективность использования радио полосы и на 3% уменьшило суммарное потребление энергии.

На последнем этапе была представлена схема всей системы с указанием конкретных моделей всех узлов системы сбора данных. В дальнейших исследованиях планируется уделить внимание синхронизации узлов, уменьшению длительности интервала ведущего TDMA узла, а так же полноразмерному тестированию всей системы.