Experimental Evaluation of Bluetooth Real Time Capabilities in Communication Intensive Applications

Christos Antonopoulos*, Konstantinos Antonopoulos, Christos Petropoulos and Nikolaos S. Voros
Technological Educational Institute of Western Greece
Computer and Informatics Engineering Department
National Road Antiriou-Ioanninon, 30020, Antirio, Greece, 30020, Greece
(*) Corresponding author email: cantonopoulos@teimes.gr

Abstract- **During the last years Bluetooth (BT) standard has received increasing acceptance as a prominent communication technology concerning a wide variety of critical applications, posing demanding communication and strict real time constrains. In that respect the main objective of this paper is to offer comprehensive experimental evaluation analyzing BT time constrained performance and critical network parameters. Performance evaluation presented focus on specialized real-time metrics, such as, standard delay deviation, and delay distribution measurements. The study presented, through qualitative and quantitative analysis, reveals significant observations and conclusions. Furthermore, critical trade-offs are presented as far as network conditions are concerned, facilitating optimal network configuration with respect to realistic requirements and parameters posed by critical applications such as medical ones.**

Keyword: Short Range wireless networks, Experimental Study, Critical Applications, Medical Measurements' Requirements, Bluetooth Technology, Real-Time Constrained Performance, Delay Deviation, Delay distribution, Bluetooth Development platform.

I. INTRODUCTION

Short-range wireless communication paradigm offers significant advantages leading to active interest both by academia and industry [1,2,3]. One of the most well-known and widely used technologies of respective communication area is the Bluetooth standard (BT) [7]. This is due to its main advantages over counterpart technologies, which propelled the degree of acceptance and its widespread use in actual commercial implementations, addressing a wide range of application scenarios [4,5,6]. Bluetooth technology encompasses all the advantages of short range wireless communication, while mitigating respective shortcomings often encountered in Personal Area Networks (PAN) networks (e.g. IEEE 802.15.4) mainly related to limited performance capabilities [8].

Over the last years, BT devices have been utilized in a substantial variety of demanding applications, such as high quality video and audio transfer, as well as, for critical applications such medical data acquisition and wireless transferring [9, 10]. Even more Bluetooth protocol poses as a prominent relative radio technology adopted as the main communication infrastructure of many medical commercial products [11,12,13].

Critical applications are characterized by strict time constrained communication requirements. For example, when video transmission is considered metrics such as packet delay deviation and packet delay distribution, comprise the most important performance metrics. However, since BT technology is not typically considered as a real-time capable solution, relative performance evaluations rely on less detailed and network wide performance metrics (i.e. mean packet delay, mean throughput etc) thus omitting specialized performance parameters of paramount importance pertaining to the time constraint communication capabilities [16, 17]. Furthermore, most relative efforts rely on simulation based evaluations of questionable accuracy and validity.

Aiming to enhance in-depth knowledge in this area, in this paper an experimental evaluation study is presented focusing specifically on real-time performance relying both on qualitative and quantitative analysis. Focusing on the respective metrics, while using a highly flexible and configurable BT based development platform [14] and varying critical network parameters, the paper draws valuable conclusions concerning BT capabilities and trade-offs.

The rest of this paper is structured as follows. Section II presents a detailed configuration analysis of the undertaken effort, while Section III analyses the main results of the experimental evaluation. Finally Section IV discusses the main conclusions and presents the future directions of this effort.

II. CONFIGURATION OF EXPERIMENTS

Aiming to offer useful, objective and comprehensive evaluation the following network parameters are taken into consideration:

- Traffic workload imposed by respective data flows. Low traffic rate corresponds to 10 packets transmitted per second or to a 10 Hz packet creation frequency adequate for accelerometer or ambient measurements. High traffic rate corresponds to 1000 packets transmitted per second i.e. 1 kHz adequate for EEG data acquisition.
- Concurrent transmitting nodes lead to competition and need for channel arbitration and scheduling. In that respect, 1 aggregation node and data creating nodes varying from 1 up to 6 concurrently transmitting BT nodes are considered.
- Data packet size assumed values equal to 9, 15 and 20bytes.

MOBIHEALTH 2014, November 03-05, Athens, Greece

DOI 10.4108/icst.mobihealth.2014.257356

The evaluation undertaken is conducted based on Shimmer platform [14], offering BT communication capabilities using the Roving Networks Class 2 Bluetooth modules [15]. Shimmer nodes' software stack is based on the open source TinyOS operating system. The main characteristics of the BT communication affecting performance are as follows:

Two or more units sharing the same channel form a piconet, where one unit acts as a master controlling the communication in the piconet, and the others act as a slave. In the context of evaluation, the receiver (i.e. a Linux running PC) assumes the role of Master while the BT enabled nodes act as slaves. The Master also determines the transmission link type between master-slave among the two supported by BT i.e. Asynchronous Connectionless Link (ACL) and Synchronous Connection-Oriented Link (SCO) [18]. In this paper, we are only investigating packets on ACL links being adequate for packet-switched, point-to-point or point-to-multipoint data connections. In case of multiple concurrent slaves, channel sharing follows a round-robin polling approach controlled by the Master device.

Furthermore, in order to offer objective conclusions and in-depth analysis was required with respect to the functionalities of the TinyOS Bluetooth driver on Shimmer motes. The most interesting characteristic concerned the role of a buffer of 128 bytes maximum length. In order to send data via Bluetooth, the application invoke a method that directly writes data to Bluetooth driver then read byte per byte from that buffer using a repeated task until reach the last byte of the buffer, and finally write each acquired byte to the UTXBUF buffer of the microcontroller for transmission.

Finally, it is noted that the receiver is a standard x86 PC running the Linux Ubuntu operating system and the BT communication is based on the Linux RFComm BT driver.

III. EXPERIMENTAL RESULTS

The evaluation results and their analysis are organized in two subsections focusing on the *packet delay* and *delay distribution.* It is also noted that due to lack of space and high number of measurements, only selected scenarios are presented offering the most interesting observations. It is emphasized that in all cases the Shimmer platform managed to transmit all data without any packet loss being recorded, leading to 0% packet loss.

A. The Effect on Delay Performance

Aiming to offer new insights in delay performance, the evaluation focuses, on measurements indicating the standard deviation calculations. Standard deviation offers an objective quantitative metric, which allows evaluating the degree at which the user delay experience is close to the mean delay reported.

Considering the effect of concurrent transmitting slave nodes as well as the traffic rate, Table 1 offers the most interesting indications. As depicted focusing on the first row an example where the mean delay provides a myopic view of the network time constrained capabilities is presented. In this example, one BT transmitter is assumed in a stressed scenario (i.e. 1 msec packet creation period) as opposed to a relaxed scenario (i.e. 10 msec packet creation period). As observed, although the mean delay is in favor of 1 msec scenario (13msec mean delay compared to 24 for 10msec packet creation interval) standard deviation reveals another aspect. Specifically respective calculations indicate that low packet rate scenario offers much lower deviation (i.e. 15msec), compared to the stressed case (26msec), which, consequently, exhibit a higher maximum delay as well as tendency to lead to an overall higher delay performance. These indications are further validated from qualitative observation of delay graphs for each successful packet transmission not presented here due to lack of space. According to such observations, both the number of delay spikes significantly surpassing mean values and the absolute values of these spikes observed indicate that the 10msec packet creation period leads to a much more controllable and time constrained behavior.

On the contrary in the second row (concerning 4 concurrent transmitters), conclusions drawn from mean delay and standard deviation converge. In this case, the mean delay indicates a much better behavior by the less stressed scenarios. Respective indication of degraded real-time behavior of the 1msec scenarios is further strengthened by the calculation of the standard deviations. As calculated the 1msec scenarios' deviation is equal to 341 msec as opposed to the only 10 msecs deviation regarding the 10msec packet creation period. Therefore, the stressed, 1msec scenario, not only resulted in drastically increased mean delay, but it is also accompanied by even more drastically increased deviation significantly degrading time constrained behavior. Qualitatively, focusing on packet delay measurements of 1msec packet creation interval, it is extracted that in most cases indicating excessive delay observations, the respective delay spikes depict more than 100% delay overhead. In substantial number of cases, the delay was measured in the area of 600 msec to 1000 msec, while there were cases where a delay of 1200 msec or even 1800 msec was recorded. Analogous conclusions, as well as of even more emphatic absolute differences, are extracted when the number of competing BT nodes is increased to 6, as depicted in the 3rd row of Table 1.

TABLE1: DELAY PERFORMANCE FOR 9BYTE PACKET PAYLOAD

	10msec Packet Interval		1msec Packet Interval	
Tx Nodes	Mean Delay (msec)	Standard Deviation (msec)	Mean Delay (msec)	Standard Deviation (msec)
1	24	15	13	26
4	15	10	255	341
6	26	20	650	710

Aiming to extract the effect of different packet payload, Table2 offers respective useful insights. As extracted from the two first rows, when traffic rate is low, packet payload does not influence significantly the performance either considering mean delay or calculated standard deviation. It is noted that this observation holds true for both cases of concurrently transmitting nodes (i.e. one and four Tx nodes). Qualitative analysis of successfully transmitted packet delay graphs indicate that the delay pattern is analogous with small differences which does not affect significantly` the overall network performance as far as the time constrained behavior is concerned. An interesting observation is that the spikes reaching up to 100 msec have increased (which could be of importance in hard real time applications) but this does not influence the overall behavior.

However, the effect of payload variation becomes a critical parameter when assuming highly stressed scenarios of high traffic rates (i.e. 1msec packet creation period) in conjunction with competitive environments (i.e. 4 concurrent BT transmitters). The second and third raw indicate respective comparison. As observed, in such cases a large payload appears to be a stabilizing factor offering not only lower mean delay but also a much steadier and compound delay behavior throughout the experiment. Such behavior pattern is further strengthened by the standard deviation calculations since for the 20 Byte payloads the standard delay deviation is 91msecs, whereas for the 9 Bytes and an emphatic 341 msec standard deviation is calculated. This behavior is attributed to the buffering process occurring at the transmitter side due to the combination of high payload and rapid data packet creation. In such case, buffer is filled up more quickly so, when the slave is given the opportunity, it has aggregated more data to transmit and exhibits higher channel utilization.

TABLE2: DELAY PERFORMANCE WRT TRAFFIC RATE AND TX NODES

	9 Bytes Payload		20 Bytes Payload	
Packet Creation Interval / Tx Nodes	Mean Delay (msec)	SD (msec)	Mean Delay (msec)	SD (msec)
10/1	24	15	24	16
10/4	15	10	18	10
1/4	255	341	95	91

B. *The Effect on Packet Delay Distribution*

The study concerning the characteristics of communication's delay distribution offers further insights with respect to the real-time capabilities and the effect of the network parameters on these capabilities. Delay distribution graph indicates the percentage of packets the delay of which is measured inside a specific range. In this way, it is possible to evaluate if, and to what degree, a specific network configuration may adhere to specific real-time requirements. Such graphs depict both the concentration of delays around one or more values (i.e. a value around which maxima are identified) as well as the maximum delay recorded.

Figure 1 depicts the effect of concurrently transmitting nodes of this metric assuming a payload of 9 Bytes while each transmitter creates a packet every 1 msec. In order to be easily compared three graphs have been merged into one using different color shade, so as to distinguish one from the other. It is apparent that in demanding scenarios (i.e. 1 msec packet creation interval) the competition created by multiple concurrent transmitters significantly degrades the real time capabilities of the network.

Given that each step in the graphs represents a 5 msec delay range, in the 1 transmitter scenarios the delay exhibits considerable concentration degree in the area between 5 and 10 msec delay (specifically more than 25% of all packet delays are recorded in this range). Furthermore, a significant ~25% of successfully transmitted packets' delay is lower than 5 msec and yet another ~23% of the packet exhibited delays in the range of 10 -15 msec. Overall, more than 90% of the packets recorded delays below 50 msec which in conjunction to previous observation offer a quite predictable behavior advocating the use of such configuration in time constrained scenarios. Finally, a maximum delay of less than 500 msec is depicted in this case.

However, delay concentration is significantly reduced when the nodes transmitting concurrently increase to four (4). As shown in Figure 1, the highest concentration is ~10% and concerns a packet delays range of less than 5 msec. Following these measurements, a significant reduction of packet concentration percentages is observed resulting into a much more "spread out" graph. It is noted that considerable percentages (although small) of packet concentrations are recorded for delay range up to 1 sec, as indicated in the figure. Even more, small percentages are observed for even higher delays reaching up to 1,8 sec.

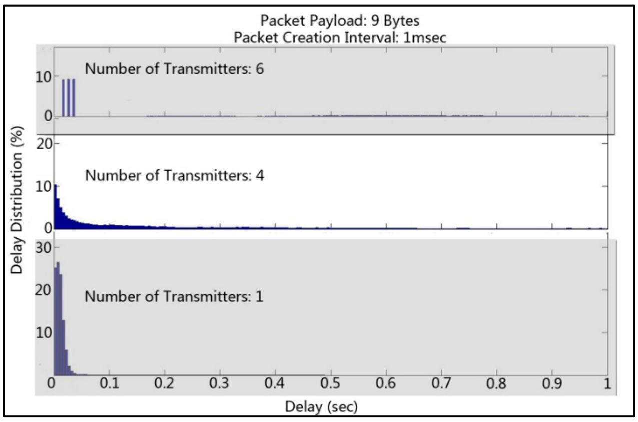

Figure 1. Delay distribution effect wrt to number of transmitters

Finally, by further increasing the competition to six concurrent transmitters even further degraded real-time network capabilities are recorded. As depicted, only in three cases delays below 50 msec recorded concentrations close to 10% of the packets. Consequently, all the rest of more than 70% of packet delays are distributed in a very wide range of possible delays reaching up to 3.8 sec (not indicated in the figure in order to save space) invalidating any requirements of time constrained behavior.

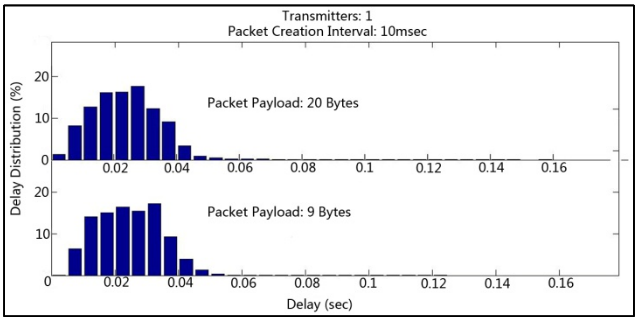

Figure 2. Delay distribution effect wrt to packet payload and one transmitter

Moving on to evaluating the packet payload variation effect on delay distribution, Figure 2 indicates that respective effect is rather negligible. Indeed, Figure 2 indicates that delay distribution, assuming a 9 Byte payload on the one hand and a 20 Byte payload on the other, exhibits almost identical behavior. Specifically a significant concentration is recorded in the area of 10 to 30 msec, where ~70% of all packet delays are recorded. Delays exceeding 40 msec are quite limited and even scarcer up to 120-160msecs where maximum measurements are recorded.

Similar conclusions are drawn when four concurrent transmissions are considered once again exhibiting tight concentration in the delay range between 10 and 30 msec.

However, a drastically different behavior is exhibited when varying packet payload while assuming stressed packet creation conditions (i.e. packet creation interval equal to 1 msec) as presented in Figure 3. As depicted, the 20 Byte payloads offered a significantly higher concentration in the area of 20 - 25 msec reaching up to 50% of successfully transmitted packets. On the contrary, when a 9 Byte payload was considered a wider distribution was observed. Specifically, up to 10% of packet transmission exhibit less than 5 msec delays while the rest of 90% of successful transmission delays are distributed with a decreasing rate up to a 500 msec maximum recorded delay. Such behavior indicates that in stressed conditions (both concerning competition as well as packet creation rate) it is advocated to use large packets over small ones. More specifically, focusing on the delay performance and delay standard deviation the larger packet payload also appeared to be a stabilizing factor for network behavior. This behavior is attributed to the fact than when 4 concurrent nodes are considered the master is forced to poll all four slave devices consequently, so the buffer inside each slave is used (i.e. filled up) more intensely. The result is that when a specific slave is given the chance, it sends out more data (leading to higher channel utilization) and the same time the main factor of the delay of these data is the buffering delay. Buffering delay in combination to a predictable polling procedure leads to much more predictable and steady packet delay, free of stochastic phenomena influencing respective measurements.

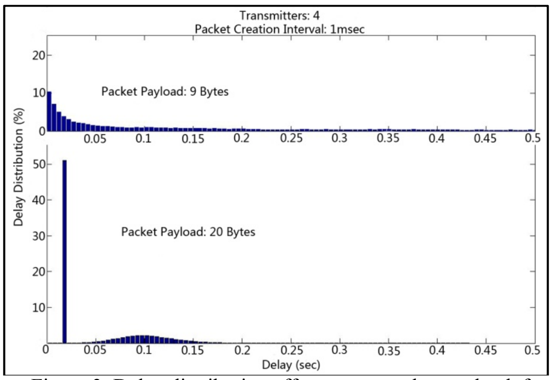

Figure 3. Delay distribution effect wrt to packet payload, four transmitters and 1msec packet creation period

IV. CONCLUSIONS

Short-range wireless communication platforms offering BT communication capabilities while featuring significantly limited resources are increasingly considered for critical applications leading to demanding communication scenarios. Medical application scenarios comprise such a characteristic example where packet creation frequencies as well as concurrent data streams may vary significantly. However, although relative applications (e.g. medical application video, audio transmission etc.) pose specific time constrained communication requirements, relatively limited insight is available in existing studies with respect to BT capabilities and the dependencies to critical network parameters.

Consequently, this paper main objective is enhancing respective experimental knowledge and insight by undertaking and presenting an experimental study based on a prominent BT capable test-bed. Based on TinyOS based WSN nodes, respective measurements focus on specialized real-time performance such as packet delay standard deviation and packet delay distributions. Moreover, critical network communication parameters are considered including packet traffic rates, concurrent data transmission and varying packet payload size. All the above comprise a significantly high number of experiments enabling in-depth analysis of time-constrained performance of BT networks both qualitatively and quantitatively. Through the measurements presented and analyzed, valuable conclusions were drawn with respect to both the dependencies of the parameters considered and the trade-offs between those parameters so as to facilitate time constrained performance.

Furthermore, critical indication were revealed that can drive future work aiming at enhancing BT time-constrained behavior as well as facilitating the optimal network configuration parameters selection with respect to specific application requirements.

ACKNOWLEDGEMENT

This study is partially funded by the European Commission under the Seventh Framework Programme (FP7/2007-2013) with grant ARMOR, agreement number 287720.

REFERENCES

[1] Furtado Hugo et. al. "Applications of wireless sensors in medicine", 34th International MIPRO, 23-27 May 2011, Vienna
[2] Dessart, N. et. al. " Simulation of large scale WSN for medical care", IEEE Symposium on Computers and Communications (ISCC), 2010, 22-25 June 2010, Riccione, Italy
[3] Lawrence, Elaine et. al. "Data Collection, Correlation and Dissemination of Medical Sensor Information in a WSN", Fifth International Conference on Networking and Services, 2009. ICNS '09, 20-25 April 2009, Valencia Spain.
[4] Gil, Yeongjoon , "A wireless EEG monitor system based on BSN node", Symposium on Computer-Based Medical Systems (CBMS), 2011 24th International, 27-30 June 2011, University of the West of England, Bristol,
[5] ARMOR FP7 Project: http://armor.tesyd.teimes.gr/
[6] Chiron EU Project: http://www.chiron-project.eu/
[7] Conti, M. " System level analysis of the Bluetooth standard", Design, Automation and Test in Europe (DATE) 2005, 7-11 March 2005, Munich, Germany
[8] Petrova, M. et. al. "Performance study of IEEE 802.15.4 using measurements and simulations", IEEE Wireless Communications and Networking Conference (WCNC) 2006, 3-6 April 2006, Las Vegas, USA
[9] Kassem Abdallah et.al.2009, "Real time video streaming over Bluetooth using software technique" International Conference on Advances in Computational Tools for Engineering Applications, 2009. ACTEA '09., July 15-17 2009, Zouk Mosbeh, Lebanon
[10] Lama Nachman et. al. " The Intel® Mote platform: a Bluetooth-based sensor network for industrial monitoring" IPSN '05: April 2005
[11] SomnoMedics: http://www.somnomedics.eu/home.html
[12] AvatarEEG: http://avatareeg.com/index.html
[13] TrackIt: http://llines.com/
[14] Shimmer: http://www.shimmer-research.com/
[15] Revoing2011: Revoking Networks "Advanced User Manual" Version 4.77 2/3/2011
[16] Yunbo Wang, "Cross-Layer Analysis of the End-to-End Delay Distribution in Wireless Sensor Networks", Transactions on Networking, IEEE/ACM, Feb. 2012
[17] Pillalamarri, S., "The impact of source traffic distribution on quality of service (QoS) in ATM networks", IEEE International Communications, 2001. ICC 2001. 19-23 May, Beijing, China
[18] AU-SYSTEM, "Bluetooth Whitepaper", www.ausystem.com