Analysis of Bluetooth Protocol in Presence of Bursty Traffic

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***Abstract*—Bluetooth (BT) technology through its considerable functionality and flexibility is incorporated in many modern personal electronic devices, offering reliable and sufficient wireless connectivity. On the other hand, the new generation of cellular communication systems while providing wide coverage and mobility are unable to offer a cost effective interconnection of so many personal devices. Web browsing, e-mail, chat, gaming, voice and video are just a part of the services inquired from the modern communication systems. Here web-browsing performance of BT enabled devices is treated through analytical, numerical and simulation analysis. The foreseen scenarios assume that a personal device (PDA, Laptop) is connected to Internet through phone or WLAN, using BT as a connecting technology.**

For the purpose of the examination, a new generic simulation-based analysis and precise performance evaluation method is introduced. The method uses the formal language representation of the analyzed protocol specification, hereafter called *behavior model*. The behavior model code obtained from the IEEE 802.15 standardization committee has been assimilated and upgraded into a novel, comprehensive and standalone Specification and Description Language (SDL) - based simulator. A WWW traffic generator was created in accordance with the 3GPP specifications. The Bluetooth protocol performance was assessed in network scenarios with different traffic amounts and characteristics. This new concept is flexible and versatile, and can be easily performed for any other kind of traffic, or any other communication standard.

The analysis show that the simulation-based results match with the analytical and numerical calculated values, remarkably.

***Index Terms*— IEEE 802.15, performance-estimation model, Specification and Description Language, WWW traffic.**

I. INTRODUCTION

The analytical calculations and simulation-based performance evaluation processes are the basic approaches to avoid a poor protocol specification and to evaluate the real performance of communication protocols. The analytical and numerical approaches usually require certain amount of system simplification and controlled introduction of approximations. Still though, this concept is the most valued one. On the other hand, simulations provide assessment of the system's quality in far more complex and realistic working conditions [1]. The one and only condition here is to perform a suitable simulation method and to build a comprehensive simulation model. As it is elaborated in [2] and extended here, the Specification and Description Language appears to be the most competitive formal based technique for communication protocol engineering and performance evaluation. The SDL have played a dominate role in the development of communication systems and protocols. It is a standardized language by the ITU [3]. SDL is a formal description technique wildly used when specifying the most complex parts of the communication protocols. The major advantage of SDL is its formal syntax and formal semantics.

The relevance of the analyzed scenarios in this paper is justified by its increasing practical usage. As depicted in Fig.1, there are several application scenarios where

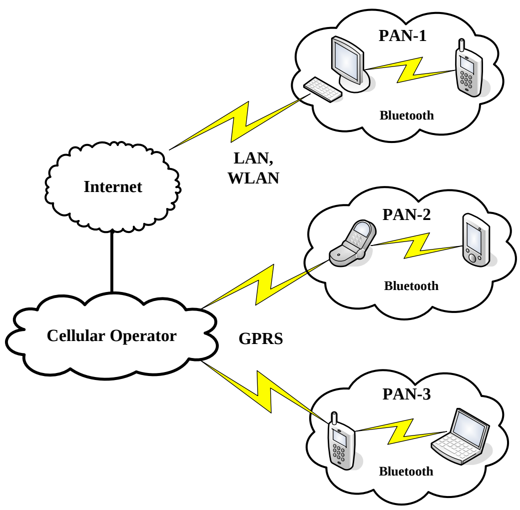

Figure 1. Application of BT for Web browsing

Based on "Web Traffic over Bluetooth: Modeling, Analysis and Performance Evaluation" , by P. Latkoski and L. Gavrilovska which appeared in the Proceedings of the *ICWMC 2007*, Guadeloupe, French Caribbean, March 2007. © IEEE 2007

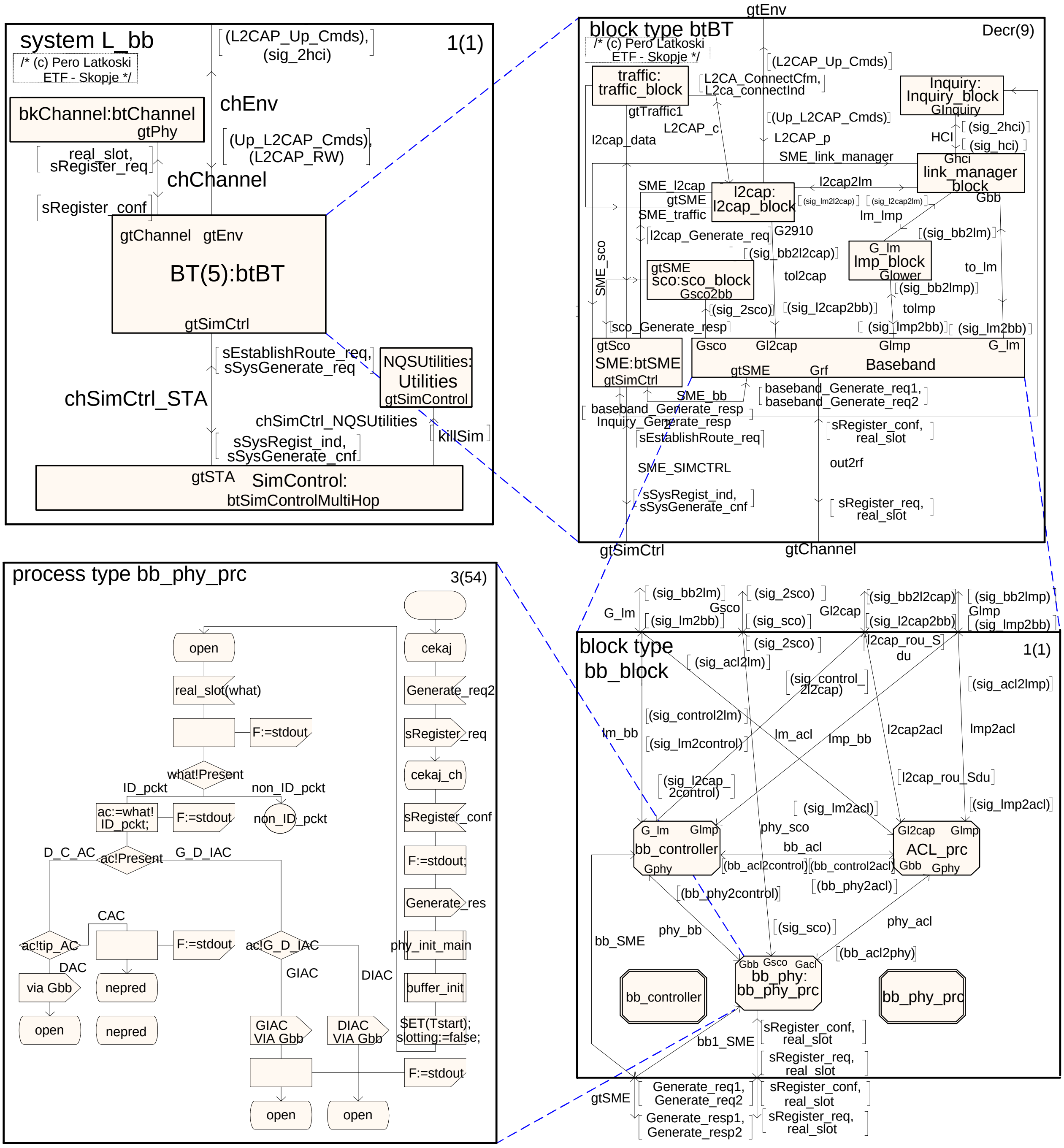

Figure 2. Hierarchical decomposition of the created SDL Bluetooth performance model

Bluetooth [4] is used for establishing connections that carry Web traffic. For example, in Fig.1 Personal Area Network 1 (PAN-1) represents the case where a user browses the Web on his phone connected to Internet through a desktop computer. PAN-2 and PAN-3 enable WWW on a PDA and laptop, respectively, and a cell phone is used as a gateway. Through these scenarios, the state-of-the-art protocol performance evaluation method presented in [2] here is extended and compared with the appropriate analytical and numerical analysis. So far only experimental approach has been employed for this kind of research [5, 6 and 7].

The remainder of this paper is organized as follows: Section II describes the SDL basic principles and benefits, Section III presents the process of creation the new Bluetooth performance model, Section IV describes the Web traffic model, the analytical and simulation results are presented in Section V and Section VI, and finally the paper is concluded in Section VII.

II. SDL Based Simulations

A. Basic Principles

SDL copes with the protocol complexity by using a hierarchical decomposition [8]. The highest level of abstraction is called *system level* (in out case, left upper part of Fig. 2). The system is composed of multiple blocks (e.g. *simulation control block*, *protocol emulation block, channel block*, etc). Inside the blocks, groups of processes are located (right part of Fig. 2: e.g. in the protocol emulation block there are processes for each layer: physical, MAC, etc). Extended Communicating Finite State Machines (ECFSMs) are used for the description of each protocol layer behavior, inside the processes [9]. The layers functionalities are presented unambiguously by using discrete states and signals (left lower part of Fig. 2). In the very same manner, all the protocol primitives are described, along with the signal parameter information exchanged among the protocol layers.

SDL could be considered as a high-abstraction level programming language with a graphical user interface. It is especially useful in specifying complex systems with a discrete *stimuli-response* type of behavior, such as the communication protocols. Fig. 2 illustrates the SDL hierarchical concept of the created Bluetooth performance evaluation model.

B. Adventages of SDL

The increasing complexity of the communication systems has demanded highly sophisticated software designing tools (with graphical development environments, simulators, exhaustive debuggers, optimized compilers, and validation and verification tools). The existing assembler and low-level languages can not cope with the complex systems and needed hardware/software co-design approach. On the other hand, SDL provides a well-defined set of constructing concepts for the compound systems. In such a way, SDL (unlike NS2 or C++) gives a clear, precise, unambiguous and concise specification, which is important for avoiding misunderstandings and mistakes when describing systems [2].

Using computer-based tools (like the analyzer, coverage viewer, simulator, validator and target tester) [10], SDL provides creation, analysis, maintenance, simulation and validation of the protocol specification. Even more, SDL affords a confirmation of the specification correctness and completeness, its performance evaluation, as well as conformance testing of the specification implementation.

III. Bluetooth Performace Evaluation Model

The SDL-based Bluetooth simulator executable is produced through several phases: creation of the SDL performance model, its conversion into SDL phrasal representation, generation of C++ code, and compiling of the code into an executable file (Fig. 3).

The SDL performance model is based on the IEEE P802.15.1 Annex B Standard [11], brought by the IEEE 802.15 Working Group for Wireless Personal Area Networks (WPAN™) in 2001. It is a SDL source written using SDL 88. This SDL model describes only the protocol behavior and its abstract data structure. It is called *behavior* model. In order to assess the real Bluetooth protocol performance it is necessary to build a so called *performance* model. The SDL performance model can emulate a real Bluetooth scenario of communicating devices. It is a standalone model that

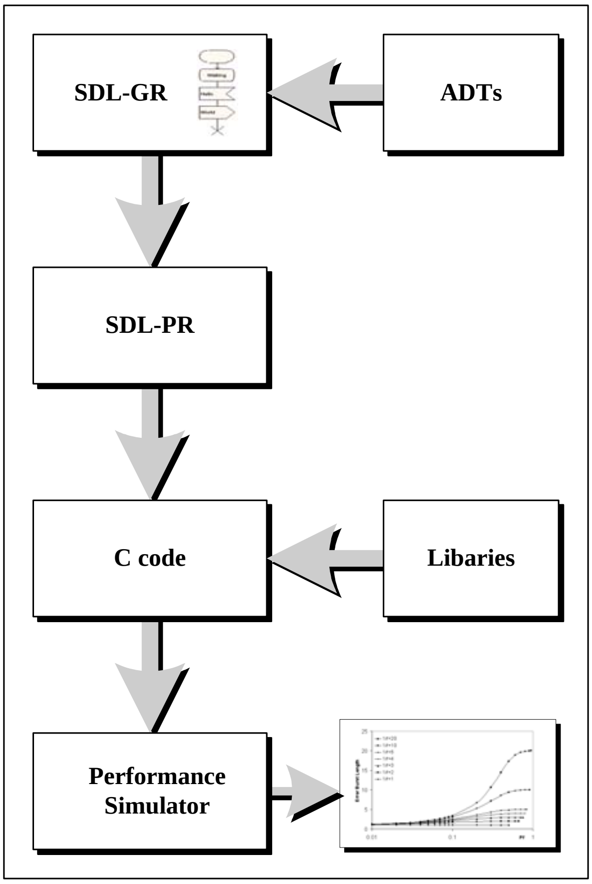

Figure 3. Generation of the performance simulator

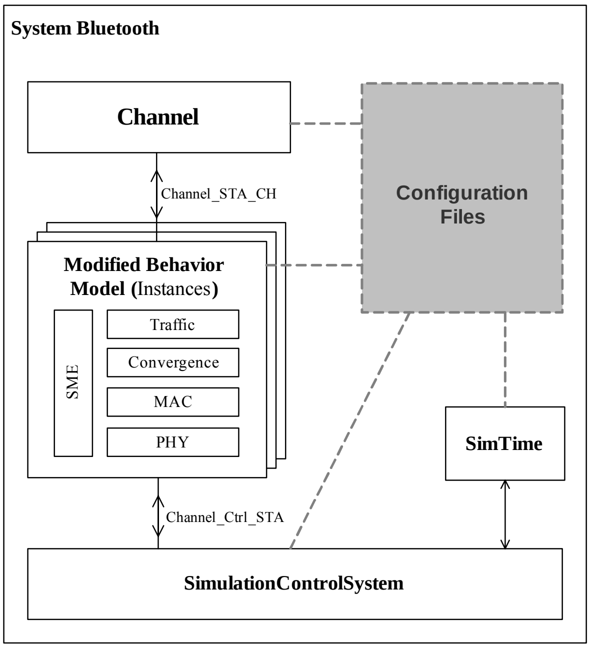

Figure 4. Upgrade of the behavior into a performance model

embeds the obtainable behavior model and canalizes its preciseness into an accurate event driven type of simulator. The assimilation and upgrade of the behavior model into a performance model is depicted in Fig. 4.

Unlike the behavior model where only single stimuli - response pair is evaluated, the performance model introduces new entities which are necessary for complete

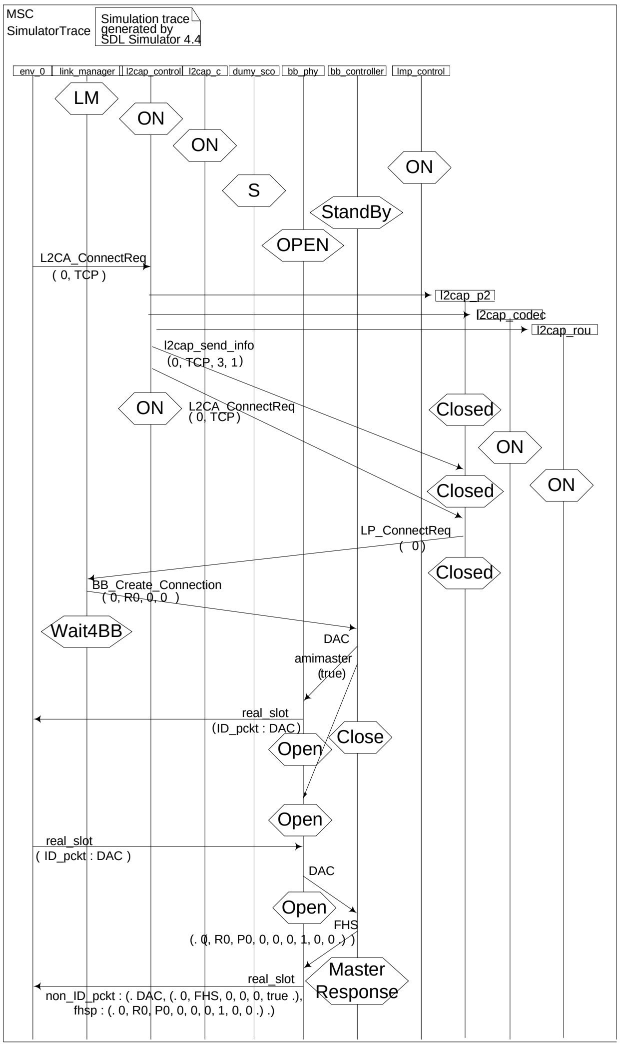

Figure 5. A part of the L2CAP connection procedure MSC

communicating scenario emulation, both on system and on block level. On the system level besides multiple instances of the modified behavior Bluetooth model, it is crucial to introduce a simulation control block and a channel block. The former controls generation of the block instances and simulation time, and the last ensures the exchange of the RF packets among the Bluetooth entities. Each block instance is characterized by a unique PID (Process Identifier), which enables differentiation of the entities.

In the foundation of the Bluetooth-block lays the Bluetooth behavior model. It is necessarily modified (upgraded), in order to conduct its expected role of real Bluetooth device emulation. Many new processes with an appropriate purpose are introduced: controller of the primitive exchange process, procedures for queuing of the signals, for segmentation and reassemble, for simulation time adaptation (timers and clocks). These processes are introduced according to the textual part of the protocol specification demands.

After building the performance model using the SDL Graphical Representation (SDL-GR), abstract Data Types (ADTs) are added in order to introduce important functionalities (e.g. reading and writing to file, different kinds of random number generators, etc.), (Fig. 3).

The analyzer runs this model for detecting all the ambiguities. Next step is the conversion of the built model into a Phrasal Representation of SDL (SDL-PR). Using SDL-PR, the code generator produces C++ source code, compiles it and links it with appropriate libraries. The result of these steps is a standalone simulator executable which requires as an input only the configuration files, which are needed for the desired network scenario description.

Each simulation scenario involves the procedures of *inquiry*, *paging*, *LMP connection*, *authentication*, *L2CAP connection*, *traffic exchange*, *disconnection*. SDL provides complete Message Sequence Charts (MSCs) for all these procedures, as a way of the proper functioning validation. Fig. 5 presents a part of the L2CAP connection procedure MSC.

Our SDL based Bluetooth simulator overcomes all the limitations of the existing NS2-based Bluetooth simulators (e.g. BlueHoc and Blueware), such as the rigid following of only the inquiry, paging and connection procedures, the absence of a channel and radio interference emulator, providing only simple simulation network scenarios, etc.

IV. Web Traffic Modeling

Due to its small size, substantial flexibility and functionality, but mostly because of its very low cost, Bluetooth is incorporated in many modern communication devices. On the other hand, the exchange of different multimedia content among the personal electronic devices is a tendency in the modern communications [12]. The Web browsing is expected to be one of the most needed applications for every personal device in the future. As a result, it is interesting to evaluate the Bluetooth protocol performance when the upper layers emulate Web traffic generation.

A modified WWW browsing model based on [13] is used in the simulations. As it is depicted in Figure 6, WWW traffic is a set of so called browsing sessions (Fig. 6 presents two browsing sessions separated by T_{OFF} - time interval). Each browsing session consists of a sequence of packet calls. The number of packet calls per session is N_{pc} and each packet call corresponds the downloading of a WWW file. After every packet call interval (S_d) there is so called reading time interval (D_{pc}).

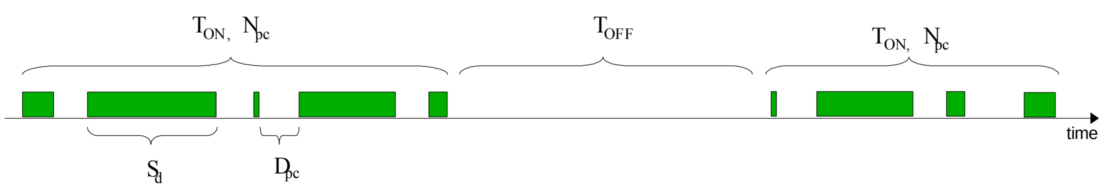

Figure 6. Traffic Model

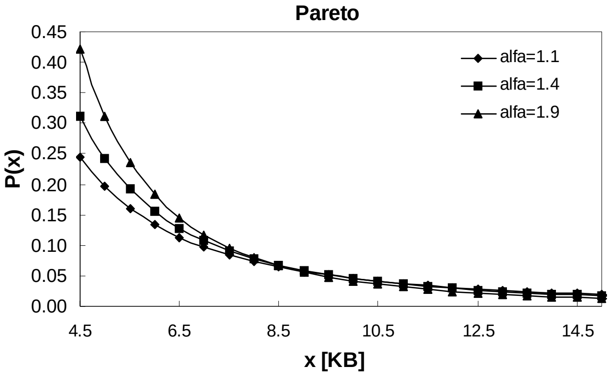

Figure 7. Pareto distribution for packet call size

The following distributions are used when creating the model. The session arrival is a Poisson process. The number of packet calls per session is geometrically distributed variable with a mean μ_{Npc}=5. The reading time is geometrically distributed variable with a mean μ_{Dpc}=5 sec. The packet call size (Sd) is Pareto distributed random variable with mean μ=25 kB, cut-off values of k=4.5 kB and m=2 MB and shape parameter α=1.1 (Figure 7).

The mean of the Poisson arrival process that determines starting moments of each browsing session (beginnings of the T_{ON} periods) is calculated using the desired traffic Load Factor - L (abr. Load), defined as

$$L = \frac{\overline{T}_{ON}}{\overline{T}_{ON} + \overline{T}_{OFF}} \tag{1}$$

where $\overline{T}_{ON} = \mu_{N_{PC}} \cdot \overline{S}_d + \mu_{N_{PC}} \cdot \mu_{D_{PC}}$. (2)

Using (1) and (2) it is easy to calculate the mean of the T_{OFF} intervals (needed for the traffic generator in the simulations) as

$$\overline{T}_{OFF} = \frac{\overline{T}_{ON}(1-L)}{L}. \tag{3}$$

The Web traffic generator model is created in SDL as a constitutive block of each Bluetooth entity. A part of its validation is presented in Figure 8 as a comparison between the simulation-generated and the calculated (expected) histogram of the packet lengths.

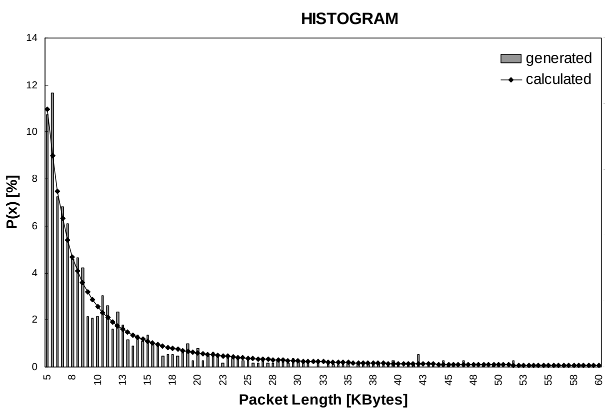

Figure 8. Application of BT for Web browsing

V. Analytical Aproach to the Problem

Before presenting performance evaluation results in the next section, it is necessary to provide analytical calculations for the expected throughput over Bluetooth network. Equation 4 provides analytical means for the throughput estimation.

$$Throughput = MaxRate \cdot \frac{\mu_{NPC} \cdot \overline{T}_{PC}}{\overline{T}_{ON}} \cdot L \tag{4}$$

$$\text{where} \quad \overline{T}_{PC} = \frac{\mu \cdot 8}{MaxRate} \tag{5}$$

is the mean value of the packet call duration, and L and $\overline{T}_{ON}$ are given by the Equations (1) and (2), respectively. We calculate $MaxRate$ according to (6).

$$MaxRate = \frac{PckPayload \cdot 8}{NoSlots_{ConnType}^{PckType} \cdot T_{SLOT}} \tag{6}$$

T_{SLOT} is the time of a single slot (625 μs), and $NoSlots$ is the number of slots used for transmission of the information. Equations in (7) present the $NoSlots$ and $PckPayload$ values for different types of packets as defined in [4]:

$$\begin{aligned}
&NoSlots_{symm}^{DM1} = 2 = NoSlots_{symm}^{DH1}\\
&PckPayload^{DM1} = 17\,Bytes\\
&NoSlots_{symm}^{DM3} = 6 = NoSlots_{symm}^{DH3}\\
&PckPayload_{FOR}^{DM3} = 121\,Bytes\\
&PckPayload_{REV}^{DM3} = 17\,Bytes = PckPayload^{DM1}\\
&NoSlots_{asym}^{DM3} = 4 = NoSlots_{asymm}^{DH3}
\end{aligned} \tag{7}$$

The throughput limit for given parameters is calculated according to (8):

$$\lim_{\substack{MaxRate \to \infty \\ L \to 1}} (Throughput) = \lim_{MaxRate \to \infty} \left(MaxRate \cdot \frac{\mu_{NPC} \cdot \overline{T}_{PC}}{\overline{T}_{ON}} \right) = \frac{\mu \cdot 8}{\mu_{DPC}} \tag{8}$$

It is interesting to stress that the provided value of the

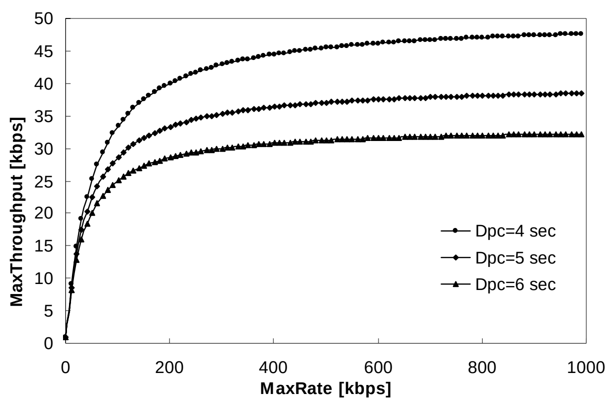

Figure 9. Max throughput in BT network

maximum throughput does not depend on the number of packet calls per session, i.e.

$$Throughput \neq f\left(\mu_{NPC}\right).$$

Figure 9 depicts the dependents of the max throughput of the $MaxRate$ parameter for different values of D_{pc}.

VI. Performance Evaluation

In the following section the simulation and numerical results are presented and discussed. The achieved throughput is evaluated in various simulation scenarios. Figures 10 to 12 directly compare the analytical calculated achieved throughput with the simulations results, for different values of the traffic Load Factor (L) and for different kinds of packets defined in [4] (DM1, DM3, DM5, DH1, DH3, and DH5). The change of L results in varying of the Bluetooth protocol performance, because of the different level of demands from the upper layers. Figures directly compare both numerical and simulation results for the symmetric type of communication between BT devices.

It can be concluded that the throughput experiences linear increase with the value of the offered Load (L). On the other hand, all types of packets provide equal performance (in means of the achieved throughput value).

Next two figures (Fig. 13 and Fig. 14) present the network throughput in case of asymmetric

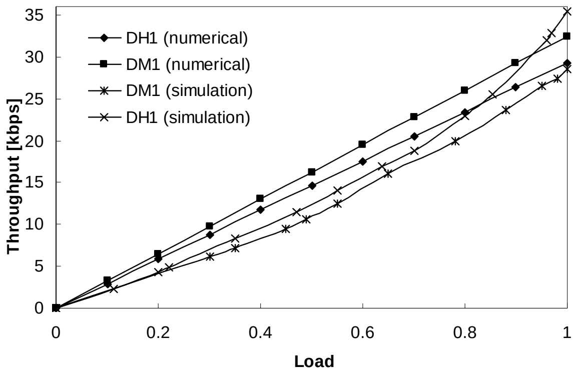

Figure 10. Throughput vs. Load (DM1, DH1)

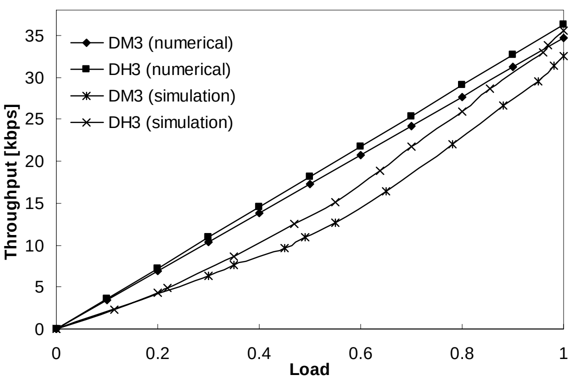

Figure 11. Throughput vs. Load (DM3, DH3)

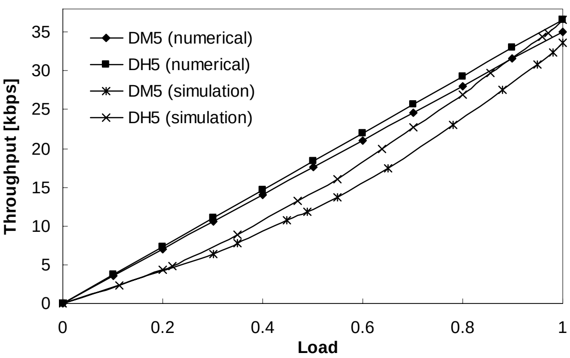

Figure 12. Throughput vs. Load (DM5, DH5)

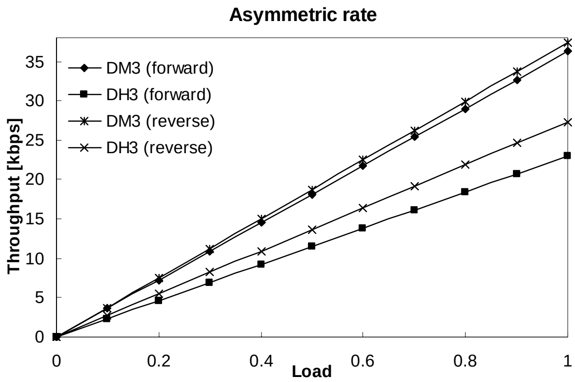

Figure 13. Throughput vs. Load (DM3, DH3)

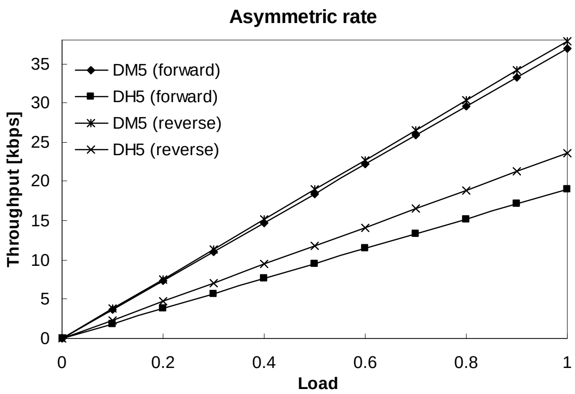

Figure 14. Throughput vs. Load (DM5, DH5)

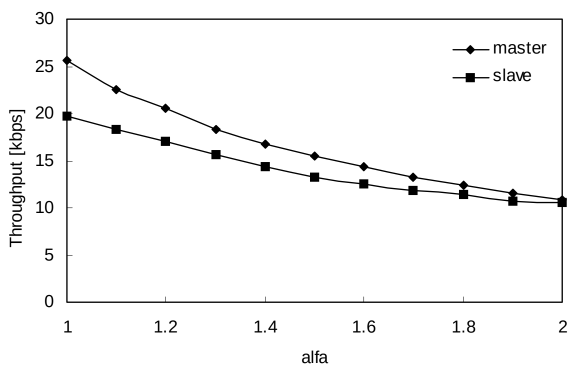

Figure 15. Influence of the shape parameter α

communication between two BT enabled devices, using DM3, DH3, DM5, and DH5 types of packets. Reverse communication is always conducted using DM1 type of packets.

If the value of L is fixed near 1, than the influence of the shaping factor α over the achieved throughput can be evaluated, as depicted in Figure 15. The traffic model has a fractal nature if α has values between 1 and 2. It is obvious that the achieved throughput is larger as much as the generated traffic aims a uniform distribution.

Changing either the upper and/or lower tolerable Pareto cutoff values for the packet call length (Sd), the Bluetooth protocol demonstrates a different behavior. The reshaping of the traffic directly influence the throughput values, which is confirmed by the simulation results, Figure 16 and Figure 17 (α=1.1, L=0.99 and DM1 type of packets).

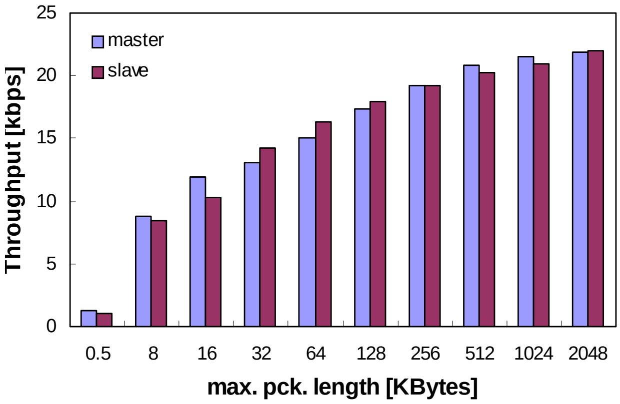

Figure 16. Influence of the upper Pareto cutoff value of the generated packet size

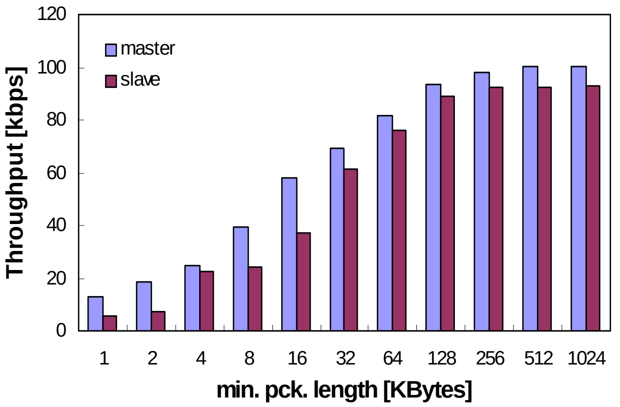

Figure 17. Influence of the lower Pareto cutoff value of the generated packet size

VII. Conclusion

This paper introduces the Specification and Description Language as a tool to produce performance evaluation engineering activities in the early protocol and system development phases. The simulation-based protocol analysis and performance evaluation provides high quality efficient protocols and communication systems, minimizing the designing errors and delays.

The short range wireless communication systems are under strong constraints, for instance low size and power consumption, interoperability, short-time-to-market, low cost. Bluetooth as a representative of this type of systems is an effective and functional technology that enables a reliable connection among personal electronic devices, which number increases every day. Among the variety of new modern application demands, Web browsing is expected to be one of the most preferred. This paper presents a detailed procedure for creation of a simulation model which provides correct and precise results of the Bluetooth system performance. In the basis of the performance model lays the protocol description provided by the standardization committee [11], which means that the correctness of the device's behavior is undisputable. The Specification and Description Language used for the purpose of model creation, provides an additional necessary unambiguousness [14].

The created SDL Bluetooth simulator is validated through various simulation scenarios, distinguished by the values of the traffic generator parameters. Using different values for the traffic Load Factor, shaping parameter α, lower and upper Pareto cutoff value of the generated packet size, we have determined the achieved throughput, as the most competitive protocol performance indicator.

On the other hand, this paper provides basic analytical and numerical calculations and analysis and give direct comparison between analytical and simulation results. Both values matched remarkably.

It can be concluded that the achieved throughput is linear dependent of the offered load. But, in imaginary situation of infinite value for the *MaxRate*, there is an upper limit for the throughput defined by the mean value of the downloaded (or uploaded) file sizes and the mean of the reading time. Analysis shows that both analyzed symmetric and asymmetric types of connection provide almost equal performance. This conclusion is valid for any type of packets that is used.

A larger throughput can be achieved under a more intensive and more uniform traffic demand conditions. Further protocol performance improvement can be achieved by reshaping the traffic (lower and/or upper Pareto cutoff values), under a tolerable information delay.

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