Effectiveness of Bluetooth Address Space Usage

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Abstract

In this paper, we have constructed the Colored Petri Net models of master and slave devices of the Bluetooth protocol. On the series of examples of piconets models with various numbers of slave devices, the effectiveness of protocol address space usage has been estimated. For the construction and investigation of models, well-known simulation system CPN Tools has been used. The possibility of information exchange slipping at the growth of the number of slave devices attached to piconet has also been discovered.

1. Introduction

At the initial stage of development, due to high cost of devices, the Bluetooth [1, 2] protocol was mainly involved in military and special applications as the basic protocol for mobile sensor networks. It was used to collect the information obtained by autonomously working sensors at a radius of about a kilometer for visual observation, audition, radiological monitoring etc. In [3] the application of the Bluetooth protocol for battlefield panoramas creation was also mentioned.

Recently, as a result of reduction of prices for Bluetooth devices, the protocol finds wide office applications for construction of wireless piconets. Moreover, we now have a wide choice of computer peripheral devices supporting information exchange according to the Bluetooth protocol like: printer, keyboard, mouse, acoustic system etc. Also these days hand free mobile phones have become part of one's basic need.

As the construction of analytical models for the Bluetooth protocol is quite difficult due to high complexity of technology, the simulation technique is a prospective direction for investigation. There are well known applications for the specialized simulation systems like NS for the investigation of Bluetooth energy-saving modes [3]. But the application of specialized simulation systems possesses a series of disadvantages; many of them are in the models integration in heterogeneous networks. Colored Petri nets [4, 5] of simulation system CPN Tools [6] are the universal algorithmic system which allow the modeling of telecommunication devices and networks [7, 8]. Earlier proposed method of measuring fragments [8] provides the measurement of nontrivial characteristics behavior on simulation.

The goal of the present work is the construction of typical models of Bluetooth master and slave devices in the form of colored Petri net and to estimate the effectiveness of protocol address space usage.

2. Survey of the Bluetooth technology

Recently the selling of Bluetooth equipment considerably exceeds that of IEEE 802.11 equipment – well-known standard of Wireless Local Area Networks (WLAN). Therefore, IEEE organization has created a special group for the development of 802.15 standard mainly based on Bluetooth specifications named by standard of Wireless Personal Area Networks (WPAN) (also called a Piconet).

Special Interest Group (SIG) founded in May, 1998 by companies such as Intel, 3COM, Ericsson, IBM, Motorola, Nokia, Toshiba are also involved in the development and maintenance of Bluetooth standards. The basic specifications of the protocol are presented in documents [1].

The architecture of the protocol is represented in Fig. 1. The interface of the protocol with the air is presented by the Radio Frequency (RF) layer. The nominal power of the antenna is in the range of 1-100 mW, which provides 10-100 m radius of operation. The protocol uses frequency hopping in the unlicensed range from 2.402 to 2.480 GHz. There are 79 frequency levels (channels) in the mentioned frequency range. The Baseband layer provides a random sequence of channels for transmission of information and a special procedure for sequence concordance. The random sequence of channel hopping guarantees a joint operation of few piconets in the same frequency range. Each piconet is constituted by one Master device and a few Slave devices. The packet are transmitted in slots (1, 3 or 5) where, transmission of each slot requires 625 µs (each of which may be transmitted through its own channel). The standard frequency of channel hopping is 1600 channels per second, which provides the rate of information exchange to 721 Kb/s. Each device has unique 48 bits address compatible with IEEE 802.15. For coordinated pattern of frequency hopping the Global identifier (Global ID) of piconet is used, which the master device communicates to all the slave devices. The state diagram of piconet devices provided by Link Management Protocol (LMP) is represented in Fig 2.
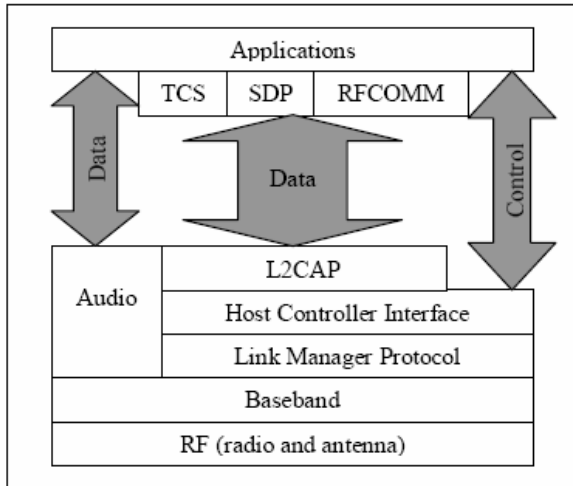
Fig. 1. The architecture of the protocol Bluetooth [2]

The device not attached to piconet is turned to be in Standby state. In this state the device, which is listening can announce the existed piconet (Inquiry) or request an attachment to piconet (Page). For attachment to piconet master device sends the packet Page containing Global ID. After the attachment to piconet, 3 bits Active Member Address (AMA) is allocated to the device, which is used for data transmission. Thus, there are no more than eight simultaneously active devices in the same piconet. Due to necessity of information exchange with new devices, master device sends the packet Park to one of the active slave devices compelling it to return its AMA into pool and assigns Passive Member Address (PMA) to it. Thus, there are no more than 256 attached devices in a piconet. There are three energy-saving states: Park, Sniff, and Hold. In the Hold state, the device does not release its AMA. However, in the Sniff state, the device may transmit data at certain intervals of time. Bluetooth controllers have to support the standard Host Controller Interface.
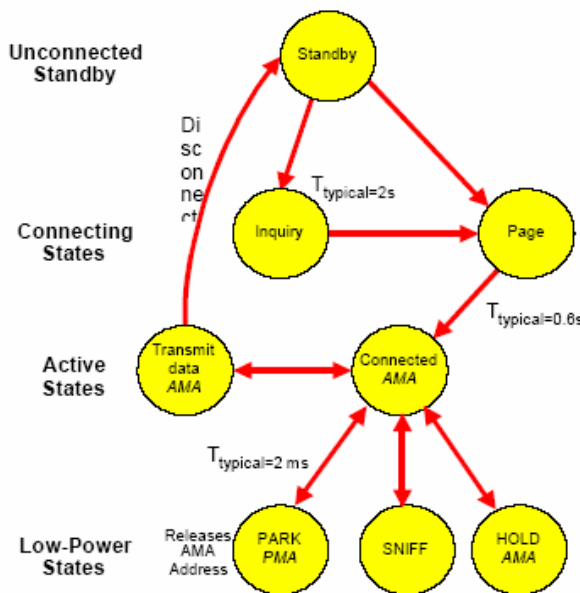

Fig. 2. The state diagram of piconet devices [2]

In the Connected state according to Logical Link Control and Adaptation Protocol (L2CAP) two kinds of data packets are provided: Synchronous Connection Oriented (SCO) and Asynchronous Connectionless (ACL). SCO packets requires connection establishment and are mainly used for the transmission of isochronous data for instance audio. On the other hand, ACL packets are used for transmission of brief messages. For rendezvous with the protocols of application level a series of auxiliary protocols are used for instance Service Discovery Protocol (SDP) protocol for serial cable emulation RFCOMM etc.

3. Model of slave device

CPN (Colored Petri net) Tools [6] embodies the simulation of Petri net graph [4] and programming language CPM ML [5] for attributes description of net elements. Petri nets, in which a token is not elementary but may possess individual characteristics, are traditionally named by colored nets. In CPN Tools a token is an object of abstract data type. Moreover, attributes of transitions are specified to check or transform the characteristics of tokens.

Model of Bluetooth slave device is represented in Fig. 3. An essential item which comprehends model organization is the description of used types, variables and functions as represented in Fig. 4. In the present work, the main type (colset) of tokens is **pkt** (modeling packets of data transmitting among master and slave devices). Notice that, only headers of packets are represented in the model, which contain AMA of sender **srcama**, AMA of recipient **dstama**, type of message **mtype** and PMA of slave device **pma** for only some types of messages. Addresses and the type of following type of packet are modeled by integer numbers: allocation of AMA (mtype=1), release of AMA (mtype=2) and data transmission (mtype=3). Type **RF** models the data transmission in the air and provides the control of transmission order in such a way that the air may be available for transmission by master device **availmaster**, transmission by slave device **availslave** or busy with transmission of packet **r**.

Let us consider the organization of the model. Contact place **myPMA** holds PMA (and myAMA holds AMA) of slave device. The initial marking of myAMA has the value 8, modeling the absence of assigned AMA. Contact place **Air** models the air, in which packets are transmitted. Transition **AlloAMA** sends request of AMA allocation for information exchange; the request is sent only in the presence of data packets in the output queue **outbufs**. Transition **FreeAMA** sends request of AMA release on the completion of information exchange when the output queue **outbufs** becomes empty. Transition **send** models the transmission of data packets in the presence of a valid AMA associated with slave device.

Let us consider in detail the process of data packets generation represented by the left part of the model. Periodicity of the data generation is represented by the place **clock**; it initializes various data packets, the

number of which is given by the random function **NSend ()** having the uniform distribution in a random interval of time given by the function **Delay ()**. Generated packets arrive in the intermediate place **data**, from which they are moved in to the output queue represented by the place **outbufs** of the list type

lpkt. Dispatching of data into air is modeled by the transition **send** and is implemented only if the slave device possesses a valid AMA. Notice that, transition **send** listens the air and implements the transmission only in the presence of permissive label **availslave**.
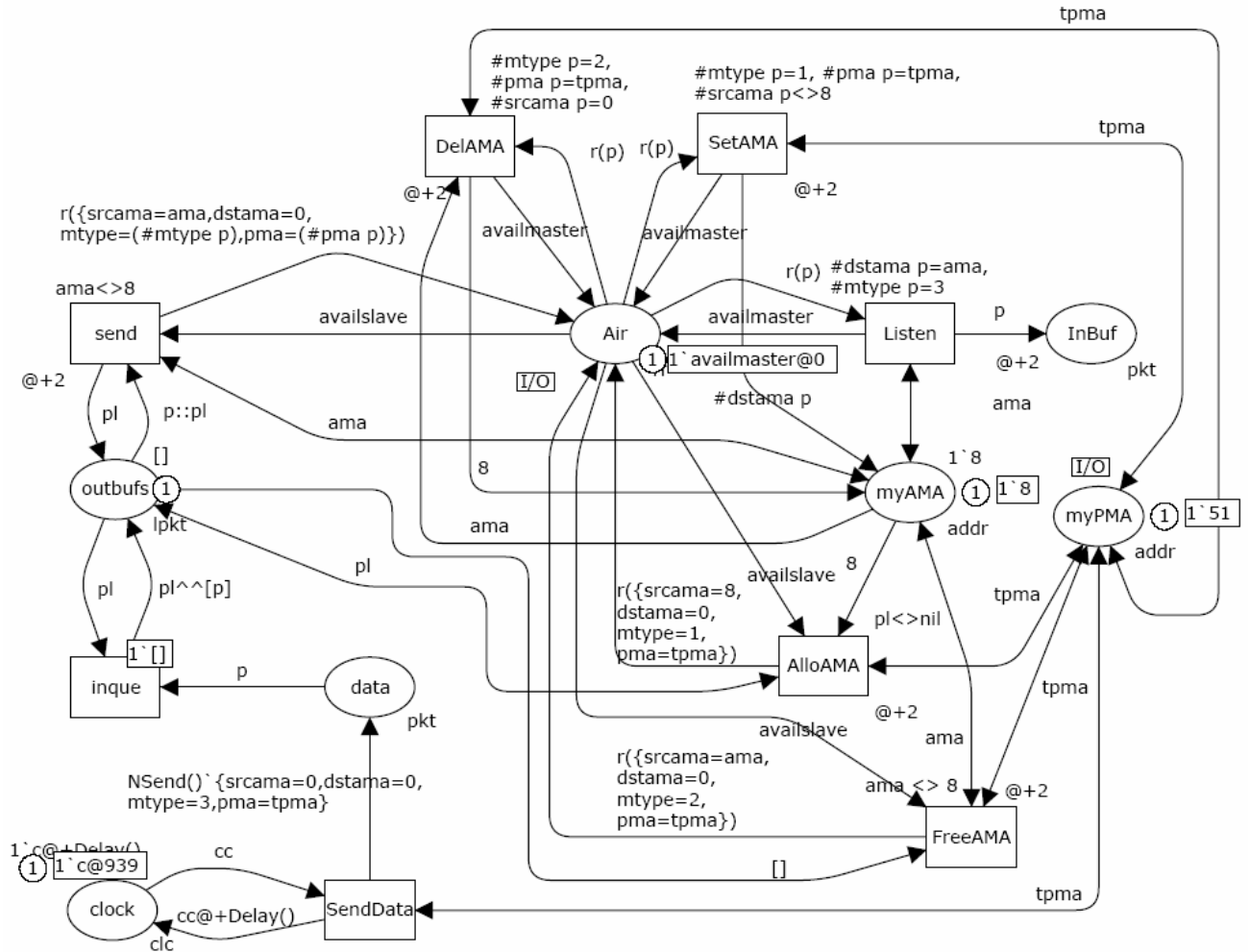

Figure 3. Model of slave device

Transition **SetAMA** assigns AMA to slave device on receiving receipt from master device; the check-up includes recognition of packet type (#mtype p=1), own PMA (#pma p=tpma) and the absence of available AMA (#srcama p<>8). Transition **DelAMA** models the release of AMA at the receipt of the corresponding packet (#mtype p=2). Note that, we have to check the slave AMA as well as write the special value 8 modeling the absence of AMA into place **myAMA**.

Transition **Listen** models the receipt of data packets and implements their allocation to the buffer **InBuf**. It should be noted that, the received packet is replaced by the label **availmaster** providing the primary usage of the air by master device.

Notice that, the model of slave device contains two contact places **Air** and **myPMA** labeled by the I/O tag. These places are further used for composition of piconets models.

```
colset addr=INT; colset ptype=INT;
colset pkt = record srcama:addr*dstama:addr*mtype:ptype*pma:addr;
colset rf=union r:pkt+availmaster+availslave timed;
colset lpkt=list pkt; colset clc=unit with c timed;
colset amatab=record ama:addr*pma:addr*t:INT; colset lamatab=list amatab;
colset npkt=int with 10..20; fun NSend()=npkt.ran();
colset Interval=int with 500..1000; fun Delay()=Interval.ran();
fun eqpma v (rr:amatab)=((#pma rr)=v);
fun eqt v (rr:amatab)=((#t rr)=v);
fun grec prd [] = zero | grec prd (y::z) = if prd(y) then y else grec prd z;
fun prec prd [] pm ti= [] | prec prd (y::z) pm ti=
        if prd(y) then ({ama=(#ama y),pma=pm,t=ti}::z) else y::(prec prd z pm ti);
fun cT()=IntInf.toInt(!CPN'Time.model_time);
fun mint [] = (cT()) | mint ((y::z):lamatab) = Int.min((#t y),(mint z));
var p:pkt; var pl:lpkt; var x:rf; var ama,pma,tpma:addr; var a:amatab; var al:lamatab;
var i:INT; var cc:clc; val zero={ama=8,pma=8,t=8};
```

Figure 4. Descriptions of types, variables and functions

4. Model of master device

Model of master device is represented in Fig. 5. The key element of the model is the table of AMA allocation represented by place **TabAMA**. Type of table record is **amatab** and it assigns to each valid value of slave device AMA its corresponding PMA. Free AMA is labeled by the special value of PMA equal to zero. Moreover, a record of the table holds the time stamp of the last AMA allocation in order to make the decision about the compulsory release of AMA on the lack of addresses. Notice that, place **TabAMA** has the list type **lamatab** providing the further choice of record with the aid of recursive functions. Transition **Listen** listens the air and chooses the packets sent to master device (#dstama p=0). Received packets are allocated to the intermediate buffer **InBuf** and then processed by transitions **t1**, **t2**, **and t3** according to the type of received packet.

On the receipt of request at the allocation of AMA (#mtype p=1) and in the presence of free record (ama=0) in table **TabAMA**, the AMA is assigned with the aid of transition **AllocAMA**. For the check-up of free AMA function **eqpma** is used, which checks the presence of a record in the list with **pma** equal to a given value. Modification in the record of the table is done through recursive function **prec**, which corrects the first record with given properties (pma=0). At this instant **pma** of the requested device as well as the current value of the model time taken using function **cT ()** are saved. Furthermore, transition **AllocAMA** creates the packets of response for slave device containing allocated AMA. The packet is allocated to the output queue of master device represented by the place **outbuf** of the list type **lpkt**. Recursive function **grec** provides the search of the first record with given properties (pma=0).

In the absence of free AMA in the table **TabAMA** transition **SwapAMA** fires, which provides the compulsory release of the most protractedly used AMA and its reallocation to the requested slave device. Recursive function **mint** finds a record with the minimal value of the AMA allocation time. Function **eqt** finds a record with a given value of time for its correction by the function **prec**. Notice that, two packets are written into the output queue: the first packet provides the release of AMA and the second allocates it to the new slave device.

On the receipt of request at the release of AMA (#mtype p=2) transition **RlsAMA** fires, **pma** of the corresponding record in table **TabAMA** is then changed to zero and the packet of address release acknowledgement is formed. The processing of data packets is represented by the simple counting of their quantity with the aid of place **C2**.

Let us consider in detail the procedure of the air control. Master device starts the transmission of packets from the output queue **outbuf** into the air with the aid of transition **send**. Master device executes the transmission in the presence of either of the available air labels: **availmaster** and **availslave**. Slave device, as it was described earlier, after the receipt of a packet advances the label **availmaster**. In such a way master device has a primary right on the transmission of packets. The label **availslave** allowing the packet transmission by slave device is formed by transition **check** only in case the output queue of master device **outbuf** is empty.

Notice that, the pair of places **C1** and **C2** is used for the accumulation of statistical information and implements the counting of the total number of received packets and data packets respectively.
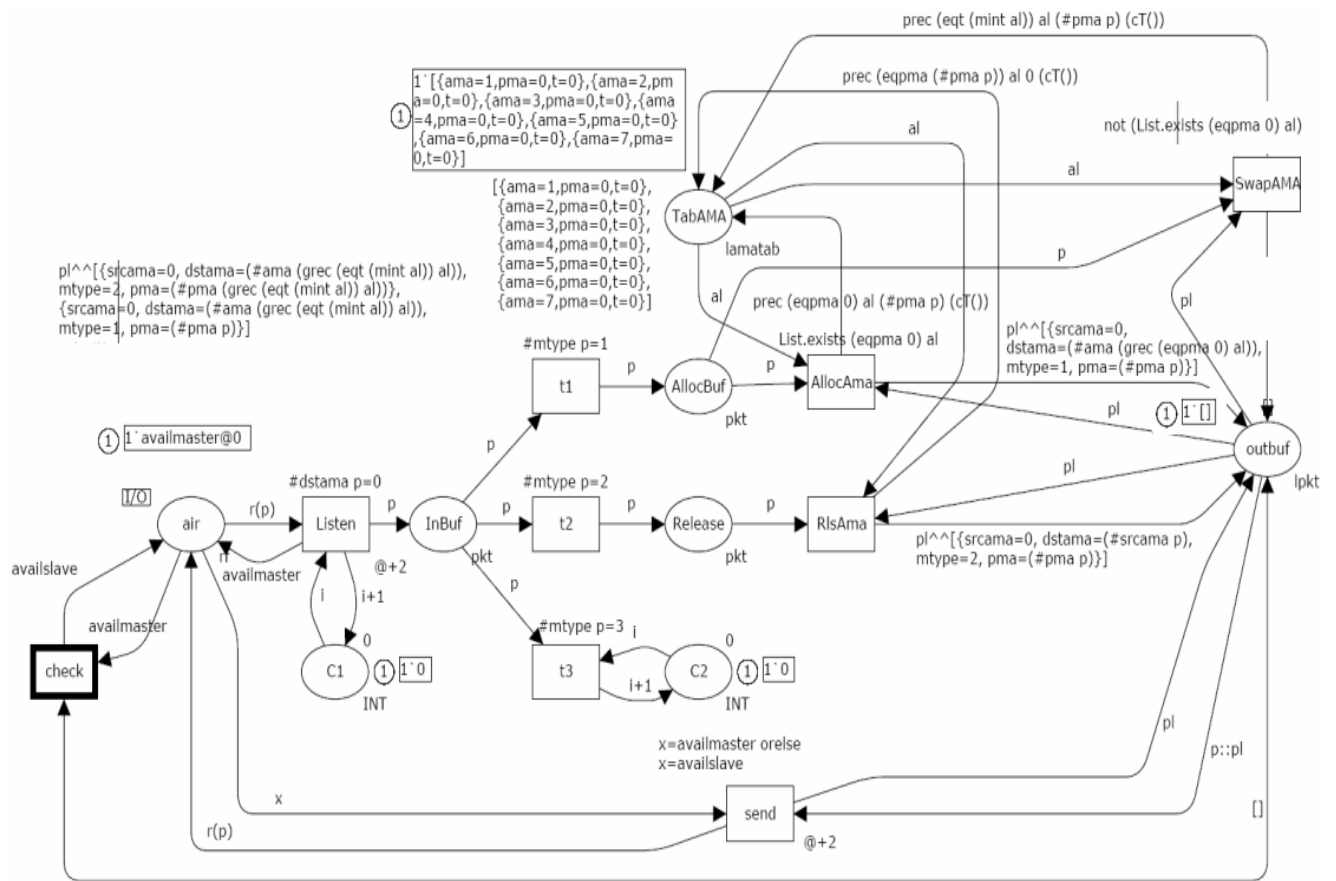
Fig. 5. Model of master device

5. Models of piconets

We suggest composing models of piconets out of earlier constructed sub models of master and slave devices (for given concrete number and PMA). In Fig. 6 a) an example of piconet model with four slave devices is represented. Simulation system CPN Tools provides facilities for hierarchical models construction by the way of transitions substitution. Tag (with the name of submodel) is indicated in the figure besides the corresponding transition. On the transition substitution, the fusion (junction) of corresponding contact places is executed.

Notice that, contact place **myPMA** of slave devices submodels is mapped into places **pma1**-**pma8** defining concrete addresses of piconet devices. For model debugging the mode of step-by-step imitation of Petri net behavior in CPN Tools is used to trace all the packets types passing between pairs of interacting devices.

6. Estimation of effectiveness of address space usage

Since the goal of the present work is an estimation of effectiveness of address space usage for the protocol Bluetooth, we constructed and evaluated piconets models for various numbers of slave devices in the range from 1 to 256. The time characteristics of transitions correspond to the standard of the Bluetooth protocol [1]; the question of times scaling was considered in [8].
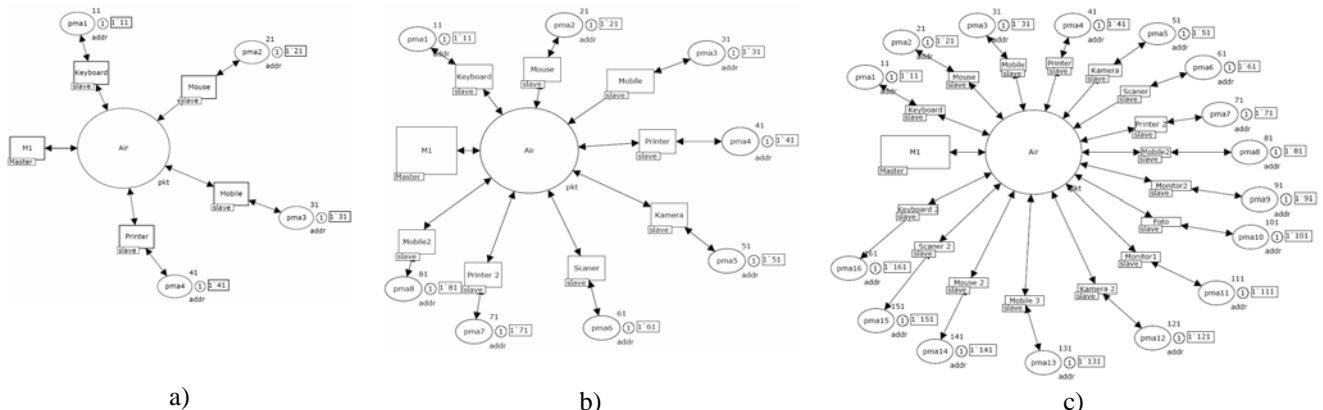

a)   b)   c)

Figure 6. Models of piconets for various numbers of slave devices (4, 8, 16)
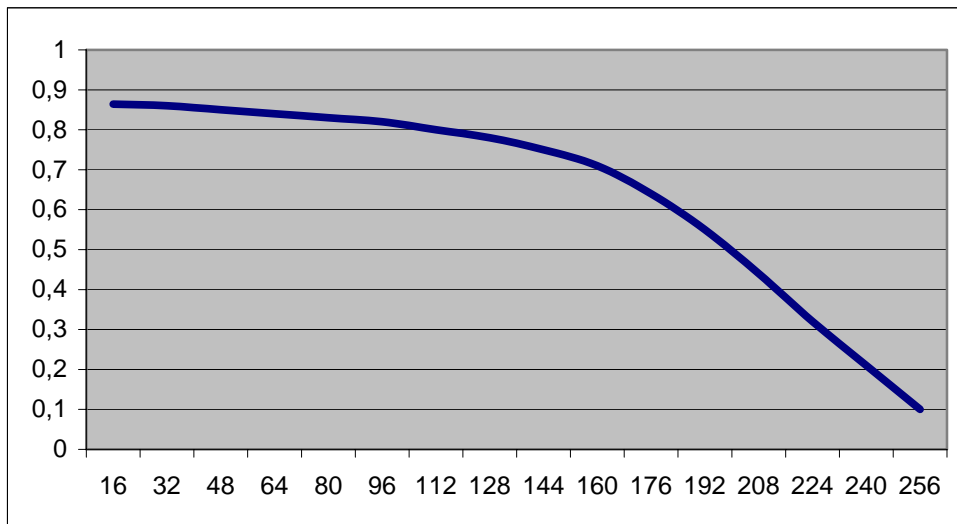
Figure 7. Graph of effectiveness coefficient (Y-axis) depending on number of slave devices (X-axis)

Let us remind the reader that statistical information is accumulated into places **C1**, **C2** of master device submodel. For the effectiveness of address space usage, we estimated the quota of useful information transmitting into the network represented by magnitude $E=C2/C1$ and named it by the coefficient of **information exchange effectiveness**. For average value of the coefficient, we have executed more than twenty simulation experiments under each model (with number of steps providing the state-stable mode [8]). The tendency of the coefficient to decrease under the growth of number of slave devices can be observed in the graph represented in Fig. 7.

Thus, the obtained results allows us the conclusion that, on the growth of number of attached slave devices there is overall decrease of information exchange effectiveness with its practical blocking at number of slave devices greater than 200. The obtained effect, on analogy with operating systems theory, is named as the **slipping of information exchange**.

7. Conclusion

Thus, in the present work, we have constructed the typical models of master and slave devices of the Bluetooth protocol aimed at the evaluation of its address space usage effectiveness. On the series of piconets models for various number of slave devices, we have estimated the evaluation of address space usage effectiveness. The overall tendency of effectiveness decrease under the growth of number of slave devices and the slipping of information exchange at the number of slave devices close to the maximal have been observed. The approach for the construction of models can be generalized for the investigation of other aspects of the protocol Bluetooth as well as other protocols.

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