Performance Modeling and Evaluation of Millimeter-Wave Based WPANs

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***Abstract*—The large amount of unlicensed bandwidth available in the millimeter-wave has enabled very high data rate wireless applications. The IEEE 802.15 Task Group 3c has completed standardization efforts for multi-gigabit data rate communications on both the physical (PHY) and medium access control (MAC) layers. In this paper we use Performance Evaluation Process Algebra (PEPA) to evaluate a typical WPAN system's performance. The approach is more convenient, flexible, and lower cost than the former simulation method which needs develop special hardware and software tools. Moreover, we can easily analysis how changes in performance depend on changes in a particular modes by supplying ranges for parameter rate values.**

***Index Terms*—WPAN, IEEE 802.15.3c, Performance Evaluation Process Algebra, Performance Analysis, Formal Modeling.**

I. Introduction

WIRELESS system designers dream of replacing all cables for indoor data communication with high-speed wireless connections. Unfortunately, the dedicated unlicensed frequency spectrum for this purpose was insufficient until the U.S. Federal Communications Commission (FCC) declared that the 57-64 GHz band could be used. Japan, in turn, allocated the 59-66 GHz band. With the latest adoption of the European Telecommunications Standards Institute (ETSI) 57-66 GHz band, there is now a common continuous 5 GHz band available around 60 GHz in most of the major markets. As the wavelength of a signal at 60 GHz is around 5 mm, it is called millimeter wave (mmWave) band.

Another important breakthrough was the introduction of relative cheap and power-efficient complementary metal oxide semiconductor (CMOS) processing for semiconductor manufacturing of 60 GHz band devices. As a result, the price and power requirements for consumer devices were met. For successful commercialization, the final need for developers was a standard the would support almost all usage models.

The IEEE 802 LAN/MAN standards committee has many success stories in developing global wireless standards, such as 802.11 (WiFi)and 802.15.4 (Zigbee). Within IEEE 802, interest in developing an mmWave physical layer (PHY) began in July 2003, with the formation of an interest group under 802.15 working group for wireless personal area networks (WPANs). According to the IEEE 802 procedure, if the interest group is successful, it is followed by a study group, which decides the scope of the new standard. In March 2004, a study group for mmWave PHY was formally created. The study group members agreed that development fo new PHY to transmit 1 Gb/s or higher data rates is feasible. It was decided to reuse an existing medium access control (MAC) layer (IEEE 802.15.3b), with necessary modifications and extensions. After the approval of the project authorization request, a task group was created. The task group firest focused on creating usage models, aa 60GHz indoor channel model. and evaluation criteria. After two years of hard work, three PHY modes and multiple MAC improvements were selected to support different usage models. After various letter ballots sponsor ballots, and resulting improvements, in September 2009 the IEEE-SA Standard Board approved IEEE 802.15.3c-2009 [1, 2]. It took four and a half years for the task group to complete the standard. Such a duration has been common for many IEEE standards that provided new PHYs.

The rest of this article explains the salient features of the standard, as well as some important outcomes. The organization of the article follows the order of the task group's standardization process. First, we provide channelization is explained, which is common for all PHY modes. Details of the three different PHY modes, new MAC layer features, and beamforming procedures are explained in the following sections, respectively. Moreover, we propose a framework for combined timed behaviors and stochastic process algebra. This done with a modeling language, called Performance Evaluation Process Algebra (PEPA), for describing the timed stochastic behaviors of wireless networks. This methodology can then be analyzed using an automatic tool. With this performance analysis methodology it is possible to obtain the design parameters of implementation using simulation with a lower computational time and cost.

II. PHY Layer Design in 802.15.3c

Due to conflicting requirements of different usage models (UMs), three different PHY modes have been developed:

- Single carrier mode of the mmWave PHY (SC PHY)
- High-speed interface mode of mmWave PHY (HSI PHY)
- Audio/visual mode of the mmWave PHY (AV PHY)

The SC PHY is best suited for kiosk file downloading and office desktop usage models. The HSI PHY is designed mainly

Manuscript received on May 3, 2012.
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for the bidirectional , non-line-of-sight (NLOS), low-latency communication of the conference ad hoc model. The AV PHY is designed to provide high throughput for vide signals in video streaming usage models. The main difference between the different PHYs is the modulation scheme. The SC PHY uses single carrier modulation, whereas the AV PHY and HSI PHY use the orthogonal frequency-division multiplexing (OFDM) modulation. In SC modulation, one symbol occupies the whole frequency band, and thus its duration is very short. In OFDM, the available frequency band is divided into orthogonal subcarriers, and data symbols are sent using those subcarriers. In general, SC modulation allows lower complexity and low power operation, whereas OFDM suits well in high spectral efficiency and NLOS channel conditions. Orthogonality of the subcarriers in OFDM allows the use of inverse fast Fourier transform (IFFT) at the transmitter and fast Fourier Transform (FFT) at the receiver.

All PHY modes have a typical signal frame format consisting of a preamble, header, and payload. The preamble is used for frame detection, channel estimation, frequency recovery, and time acquisition. The header contains essential information such as payload size, modulation, and coding used in the payload. the Pay load includes the data to be transmitted.

A. Audio / Visual Mode of the mmWave PHY

As video and audio devices could be designed only as a wireless data source (e.g., DVD player) or only as a data sink (e.g., HDTV), highly asymmetric data transmission is possible; hence, the designers of the AV HPY mode created two different sub-PHY modes: high-rate PHY (HRP) for video transmission and low-rate PHY (LRP) for control signal. Both of the sub-PHY modes use OFDM.

The HRP mode has an FFT size of 512 and uses all the channel bandwidth available. There are three classes of modulation and coding schemes (MCSs) with equal error protection, delivering data rates of 0.952, 1.904, and 3.807 Gb/s. There are two MCSs with unequal error protection and two MCSs , in which only the most significant bits are sent.

On the other hand, the LRP mode occupies only 98 MHz bandwidth, and three LRPs are arranged per HRP channel. This allocation is to accommodate three different networks in one channel, because the HRP modes are assumed to have high beamforming gains.

The AV PHY use Reed-Solomon(RS) block code as the outer code and convolutional coding as the inner code in the HRP mdoe, whereas only convolutional coding is used in the LRP mode. Modulation schemes used in the AV PHY are limited to $\pi/2$ quadrature PSK (QPSK) and 16 quadrature amlitude modulation (QAM).

III. MAC Layer Enhancements of 802.15.3c

Before going into the details of MAC layer enhancements, we briefly introduce the IEEE 802.15.3c MAC. It is based on the IEEE 802.15.3b standard. which itself is an improvement over IEEE 802.15.3. In the standard a network is called a piconet, which is formed in an ad hoc fashion. Among a group of devices (DEVs), one will act as the piconet coordinator (PNC) to provide the piconet's synchronization and to manage access of rest of the DEVs. The necessary control information is embedded in beacons. Upon receiving a beacon from a PNC, the DEVs become aware of the existence of piconet. Beacons provide information about when and how DEVs can access the network.

During network operation, time is divided into sequential superframes (SFs). Each SF has three segments: a beacon period, a contention access period (CAP), and a channel time allocation period (CTAP). During the beacon period, the PNC sends one or multiple beacons. The CAP is reserved mainly for command and control communication between PNC and DEVs. Since such a communication is mainly asynchronous, a suitable access method is selected, carrier sense multiple access with collision avoidance (CSMA/CA). The remaining time of an SF includes the CTAP, which provides time-division multiple access (TDMA) communications. The CTAP is composed of multiple channel time allocations (CTAs). Each CTA is a time slot granted by the PNC for a certain pair of DEVs. Time-sensitive applications such as AV streaming use the CTAP for guaranteed data transmission. With these specifications, system designers had already developed an efficient and well structured MAC layer that only required improvements in three major areas:

- Providing coexistence among different PHYs and avoiding interference from hidden devices
- Improving transmission efficiency to enable MAC SAP rates over 1 Gb/s and providing low-latency transmission for delay-sensitive applications
- Supporting directivity inherent to 60 GHz signals and beamforming antennas

In the next two paragraphs, we explain enhancements in the first two areas.

To achieve better coexistence among DEVs using different PHY modes, a sync frame is introduced. A sync frame includes information about the duration of the SF and timing information of the CAP and each CTA. Sync frames are modulated using the common mode signaling (CMS) mentioned in the previous paragraph. According to 802.15.3c rules, it is mandatory for all PNC-capable DEVs to transmit a sync frame in every SF. In addition, any PNC-capable DEV shall be able to receive and decode sync frames and other command frames modulated with CMS.

As a result, any PNC-capable DEV, regardless of its PHY mode in operation, will be informed about the existence of nearby piconets. It will then have the opportunity to join one instead of starting another independent piconet. The sync frame transmission can thus be seen as an effective coexistence method to mitigate potential co-channel interference from other piconets. Apart from the rule for PNC-capable DEVs, an optional rule related to non-PNC-capable DEVs is also defined in the standard: Any DEV capable of transmitting a sync frame may do so in the first granted CTA in an SF and in every predefined number of SFs.

This rule is intended to further extend the coverage area of the sync frame. It allows non-PNC-capable DEVs to participate in the sync frame transmission.

In high-speed WPAN and WLAN systems transmission efficiency decreases with the increase in transmission speed due to the increased ratio of overhead time to payload transmission time. To improve transmission efficiency and throughput performance, frame aggregation can be employed. The basic idea of frame aggregation is to reduce the overhead, such as the preamble and PHY/MAC header, by concatenating multiple MAC service data units (MSDUs) to form a frame with a long payload. In the IEEE 802.15.3c standard, two novel aggregation methods are specified standard aggregation and low-latency aggregation.

Standard aggregation is designed to support transmission of uncompressed video streaming. The MAC layer of the transmitter, upon receiving an MSDU from the upper layer, divides the MSDU into small pieces of data blocks if the length of the MSDU exceeds a predefined threshold. This process is called fragmentation. The MAC attaches a frame check sequence (FCS) to each data block to form a subframe. For each subframe, there is a subheader (Sh) created to carry information needed for the receiver to decode individual subframes, such as subframe length, MSDU sequence number, and used MCS. The MAC header, on the other hand, carries high-level control information applicable to all the subframes, such as source and destination addresses. All the subheaders are placed back-to-back and attached to a single header check sequence (HCS) to form a MAC subheader. The MAC layer then transfers the subframes, MAC subheader, and MAC header to the PHY layer. The PHY layer performs channel coding and modulation, and delivers the data to the receiver over the wireless channel afterward. An important aspect of this method is that instead of distributing the subheaders between the subframes, all the subheader are concatenated and put in front of the subframes. The reason for such a design is that video streaming contains both data and control information, which should be treated with different priorities. Changing MCS over subframes is a common approach to support priority. However, when operating at a speed of gigabits per second, timely changing of the MCSs subframe by subframe can be difficult for the receiver. However, putting the subheaders in front enables the receiver to know the MCS of each subframe in advance, helping to realize timely MCS switching. It was reported that over 80 percent efficiency improvement and above 4 Gb/s throughput are achieved with standard aggregation.

IV. Performance Modeling and Tools

Performance Evaluation Process Algebra (PEPA), developed by Hillston in the 1994s [4, 5], is a timed and stochastic extension of classical process algebras such as Communication Sequential Process (CSP) [6]. It describes a system as an interaction of the components and these components engage in activities. Generally, components model the physical or logical elements of a system and activities characterize the behavior of these components. An exponentially-distributed random variable is associated with each activity specifies the duration of it, that leads to a clear relationship between the model and a Continuous Time Markov Chain (CTMC) process. Via this underlying Markov process performance measures can be extracted from the model. The PEP A formalism provides a small set of operators which are able to express the individual activities of components as well as the interactions between them. We provide a brief summary of the operators here, more details about PEPA can be found in [3, 4].

Prefix: (a, r).P The component will subsequently behave as P after it carries out the activity (a, r), a represents the action type and r represents a duration which satisfies exponential distribution with parameter r.

Choice: P + Q The component represents a system which may behave either as P or as Q. the choice depends on which activity is completed first.

Cooperation: $P \underset{L_1}{\bowtie} Q$ The component represents the interaction between P and Q. the set L is called the cooperation set and denotes a set of action types that must be carried out by P and Q together.

Probabilistic Choice: $P \oplus_r Q$denotes the probabilistic choice with the conventional generative interpretation, thus with probability r the process behaves like P and with probability $1-r$it behaves like Q .

Hiding: P / L Hiding makes the activities whose action types in L invisible for external observer.

Constant: P = Q The equation gives the constant P the behavior as the component Q.

A. PEPA Eclipse Plug-in Tools

The PEPA is a language for modelling systems in which a number of interacting components run in parallel, and whose behaviour is stochastic. The core semantics of PEPA is in terms of Continuous Time Markov Chains (CTMCs), and an alternative semantics in terms of Ordinary Differential Equations (ODEs) has also been developed. PEPA has been applied in practice to a wide variety of systems, and its success as a modelling language has been largely down to its extensive tool support. Most recently, the PEPA Plug-in Project [7, 8] has integrated a range of analysis techniques based on both numerical solution and simulation into a single tool built on top of the Eclipse platform [9]. As with all compositional Markovian formalisms, however, PEPA suffers from the state space explosion problem. A model can have an underlying state space that is exponentially larger than its description, meaning that it can be infeasible to analyse. Fluid flow approximation using PEPAs ODE semantics can solve this problem if we are only interested in the average behaviour of the system over time. However, if we want to reason over all possible behaviours of the model for example, the probability that an error occurs within some time interval then we must consider the CTMC semantics. In this paper, we present a new extension to the PEPA plugin, in which a model can be abstracted by combining, or aggregating, states. To safely over-approximate the behaviour of the original model (for any aggregation of its states), we use two abstraction techniques - abstract CTMCs (a type of Markov decision process with infinite branching), and stochastic bounds. We provide a model checker for the three-valued Continuous Stochastic Logic (CSL), which computes from the abstraction a safe bound of the probability of a quantitative property holding in the original model X if the actual probability is p, then the model checker will return an interval I = [p1, p2] such that p 2 I. The current version of the PEPA plug-in is available from http://www.dcs.ed.ac.uk/pepa/tools/plugin, and provides several views:

Abstract Syntax Tree View

The Abstraction View is a graphical interface that shows the state space of each sequential component in a PEPA model. It provides a facility for labelling states (so that they can be referred to in CSL properties), and for specifying which states to aggregate.

Model Checking View

The Model Checking View is an interface for constructing, editing, and model checking CSL properties. The property editor provides a simple way to construct CSL formulae, by referencing the labels given to states in the abstraction view. It ensures that only syntactically well-formed CSL formulae can be constructed.

State Space View

The State Space View is linked to the active PEPA editor and provides a tabular representation of the state space of the underlying Markov chain. The table is populated automatically when the state space exploration is invoked from the corresponding top level menu item. A row represents a state of the Markov chain, each cell in the table showing the local state of a sequential component. The order in which sequential components are displayed corresponds to the order in which they are found in the cooperation set by depth-first visit of the cooperations binary tree. A further column displays the steady-state probability distribution if one is available. A toolbar menu item provides access to the user interface for managing state space filters. When a set of filter rules is activated,the excluded states are removed from the table. The probability mass of the states that match the filters is automatically computed and shown in the view. Filter rules are assigned names and made persistent across workspace sessions. From the toolbar the user can invoke a wizard dialogue box to export the transition system and one to import the steady-state probability distribution as computed by external tools. The view also has a Single-step Debugger, a tool for navigating the transition system of the Markov chain. The debugger can be opened from any state of the chain and its layout is as follows. In an external window are displayed the state description of the current state and two tables. The tables show the set of states for which there is a transition to or from the current state. The tables are laid out similarly to the views main table. In addition, the action types that label a transition are shown in a further column. The user can navigate backwards and forwards by selecting any of the states listed.

Performance Evaluation View and Graph View

Performance Evaluation View and Graph View A wizard dialogue box accessible from the top-level menu bar guides the user through the process of performing steady-state analysis on the Markov chain. The user can choose between an array of iterative solvers and tune their parameters as needed. Performance metrics are calculated automatically and displayed in the Performance Evaluation View. It has three tabs showing the results of the aforementioned reward structures (throughput, utilisation, and population levels). Throughput and population levels are arranged in a tabular fashion, whereas utilisation is shown in a two-level tree. Each top-level node corresponds to a sequential component and its children are its local states. The Performance Evaluation View can feed input to the Graph View, a general-purpose view available in the plug-in for visualising charts. Throughputs and population levels are shown as bar charts and a top-level node of the utilisation tree is shown as a pie chart. As with any kind of graph displayed in the view, a number of converting options is available. The graph can be exported to PDF or SVG and the underlying data can be extracted into a comma separated value text file.

Experimenting with Markovian Analysis

An important stage in performance modelling is sensitivity analysis, i.e. the study of the impact that certain parameters have on the performance of the system. A wizard dialogue box is available in the plug-in to assist the user with the set-up of sensitivity analysis experiments over the models. The parameters that can be subjected to this analysis are the rate definitions and number of replications of the array of processes in the system equation. The performance metrics that can be analysed are throughput, utilisation, or population levels. If the model has filter rules defined, the probability mass of the set of filtered states can be used as a performance index as well. The tool allows the set-up of multiple experiments of two kinds: one-dimensional (performance metric vs. one parameter) or two-dimensional (performance metric vs. two parameters changed simultaneously). The results of the analysis are shown in the Graph View as line charts. For example, a parameter that may have an important impact on the performance of the system is the reset delay of the CPU.

Time Series Analysis

When performing a time-series analysis there are three basic steps to complete; component selection, solver selection and solver parameterization, all of which are handled by the time-series analysis wizard. Rather than simply observing all components, the wizard allows the modeller to select only those components that are of interest. This becomes more pertinent as either the number components in the system or number of observed time points increase - one limitation of the current time-series solvers is that all data is held in memory, and only written out to disk when exporting from the graph view. Solver selection and parameterization are self-explanatory, with the list of visible parameters being dynamically linked to the currently selected solver. In keeping with the rest of the UI, the selections across all three steps are persistent across invocations. Likewise, each unique parameter is stored only once, meaning parameters such as start and stop times are persistent over all solvers. Lastly, the parameters, including selected solver, are attached to the results in the graph view for future reference. Currently this meta data can only be seen when the data is exported. The last feature of the wizard is the ability to export the model in alternative formats, such as Matlab.

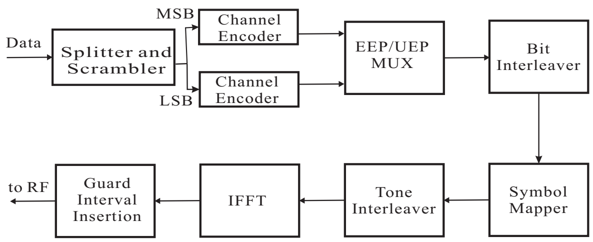

Fig. 1. The block diagram of the transmitter

V. PEPA Representation

The mmWave PHY operates within the 57.24-65.88 GHz band as allocated by the regulatory agencies worldwide, and the spectrum is then equally divided into four channels. This high spectrum leads to dense frequency reuse, smaller sizes of radio frequency (RF) components, high antenna gain and secure data transmission. However, the high attenuation resulted by oxygen absorption, path loss and multi-path effects make the high data rate transmission difficult to deploy. In baseband, modulation methods are of critical challenge for mmWave communications. The PHY layer of both the HSI and AV modes are very similar and are based on the use of OFDM.

Figure 1 describes the block diagram of the transmitter for the IEEE 802.15.3c WPANs. Data are firstly split into upper and lower branches. The scrambled data are encoded with an LDPC encoder in the HSI mode, whereas for the AV mode, a Reed- Solomon (RS) code and a convolutional encoder are implemented. For the unequal error protection (UEP) modulation and coding schemes (MCSs), different coding rates are applied to the most significant bits (MSBs) and least significant bits (LSBs). The binary serial input data is then mapped to data symbols according to the modulation schemes. A normalization factor is multiplied to each modulation scheme in order to achieve the same average power. Overall the equal error protection (EEP) modulation dependent parameters and the data rates. A tone interleaver is applied before the modulated data are sent to the OFDM modulator. 512 sized IFFT is implemented to form one OFDM symbol, and 336 out of 512 subcarriers are data carriers.

$Encoder_0 := < listen, \lambda_0 > .Scrambler_0 \bowtie_{L_0} < get, \lambda_0 > .Channel - Encoder_0$;

$EEP_0 := < listen, \lambda_0 > .EEP_1 \bowtie_{L_0} < get, \lambda_0 > .Bit - Interleaver_0$;

$Interleaver_0 := < listen, \lambda_0 > .Symbol - Mapper_0 \bowtie_{L_0} < get, \lambda_0 > .Tone - Interleaver_0$;

$OFDM - Modulator_0 := < listen, \lambda_0 > .IFFT_0 \bowtie_{L_0} < get, \lambda_0 > .Interval - Insertion_0$;

PHY Layer equation defines how the components interact with each other. According to the working cycle and the definitions of model's components we give before, the PHY Layer equation is show below:

$PHY := Encoder_0 < \lambda_1 > EEP_0 < \lambda_2 > Interleaver_0 < \lambda_3 > OFDM - Modulator_0$

A frame header is added to the resulting payload to convey information in the PHY and the Medium Access Control (MAC) Layer headers necessary for a successful decoding of the frame. A PHY preamble is added prior to the frame header to aid receiver algorithms related to frame detection, frequency recovery, frame synchronization, and channel estimation. The format of a PHY frame includes PHY preamble, frame header and payload.

In IEEE 802.15.3c, a hybrid multiple access of contention-based CSMA/CA (carrier sense multiple access with collision avoidance) and contention-free TDMA (time division multiple access) is used. The CSMA/CA is mainly used for control signal transmission, while the TDMA is used for high-speed data transmission. This hybrid multiple access can reduce the data transmission collisions, and also maximize throughput by applying an optimum access time. The MAC layer throughput is determined by the amount of information bits exchanged between the transceiver MAC, and the duration needed for successfully delivering the information. Sources of overhead include gap time, preamble, header fields for the PHY and MAC layers, and ACK frames. The length of the ACK frames depends on the type of ACK, and there are five types of ACK defined for transmitting data frames in the piconet: no ACK (no-ACK), immediate ACK (Imm-ACK), delayed ACK (Dly-ACK), implied ACK (Imp-ACK), and block ACK (Blk-ACK).

$Interface_0 := PHY \bowtie_{L_0} MAC$

$MAC_0 := < Type - ACK. \lambda_0 > . MAC_0$

The overall system becomes *Interface* and *User* :

$User_0 := Interface_0 \bowtie_{L_0} User_0$

$User_n := User_0 < \lambda_1 > User_1 < \lambda_2 > User_2 < \lambda_3 > \bullet\bullet\bullet\bullet$

VI. Performance Evaluation

A. State Space

According to the actions of each action and interactions among them, we can solve out the possible states. And according to the parameters setting of each action, we can derive a corresponding continuous time Markov chain (CTMC) of this model, which allow us to solve out each state's steady-state probability. The state space and steady state probability of this PEPA model is shown in Table I.

TABLE I
State Space and steady-State Probability

No.	State	Steady-state probability
1	(1,1,1,1,1)	0.0749611139221529
2	(1,2,1,1,1)	0.05996889113772232
3	(1,3,2,1,1)	0.09994815189620386
4	(1,3,3,1,1)	2.9984445568861153E-4
5	(1,3,4,1,1)	0.09944841113672284
6	(1,5,1,1,1)	3.12337974675637E-4
7	(2,3,5,1,1)	0.044751785011525276
8	(2,3,6,1,1)	0.06961388779570597
9	(2,4,1,1,1)	0.12431051392090355
10	(2,3,1,2,1)	0.2088416633871179
11	(2,3,1,1,2)	0.08701735974463247
12	(2,3,1,1,3)	0.13052603961694872

The sets III the colunm state stand for the whole states of model, for example the set (2, 3, 1, 2, 1) represents the state (*PHY*, *Encoder*, *EEP*, *Interleaver*, *OFDM − Modulator*). However, the probability distribution of steady state is often not the ultimate goal of performance analysis. Sometimes the designers are more concerned about the throughput, response time or utilization of the systems. In the following sections, we use the tool PEPE plug-in and Imperial PEPA Compiler (ipc) to evaluate the model's performance metrics of those characters.

B. Throughput Analysis

The study of how changes in performance depend on changes in parameter mode values is known as sensitivity analysis. We can vary some parameter's value a little, and see its influence degree to the model's performance, for example, the throughput or response time. Throughput is an action-related metric showing the rate at which an action is performed at steady-state. In other words, the throughput represents the average number of the activities completed by the system during one unit time.

From Figure 2, it can be observed that the impact of the number of devices on the throughput of transmit is more sensitive than the SC Mode. If we could make some efforts to optimize the cache, and raise the HSI Mode form 0.3 to 0.7 or even more high value, the throughput of transmit could greatly improved.

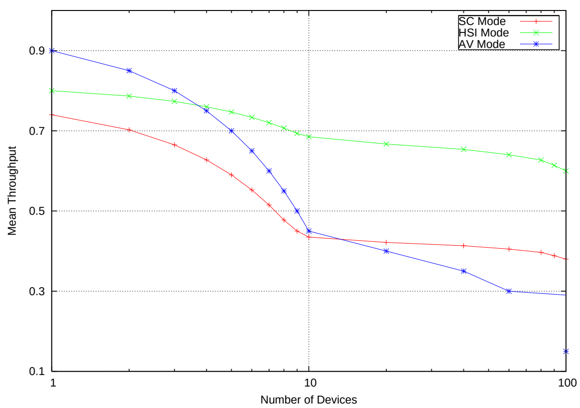

Fig. 2. Throughput versus Number of Devices

C. Response Time Analysis

Form the perspective of the WPAN system, the response time is the interval between the receiving of a request from the client and the transmission of the feedback content to the client. It is an important index of the system performance. The response time of WPAN system is relative to a lot of factors, for example, the configuration of system, the capability of components, the interaction processes among components, the health of the channel, etc. Figure 3 shows the cumulative distribution function of the response time between request and transmit actions. From the figures, it is clearly that when the possibility of hitting the cache parameter mode up from 0.01 to 0.8, the more possibility the response time would finally be a lower value, which is coincident with the result of throughput analysis we have got before.

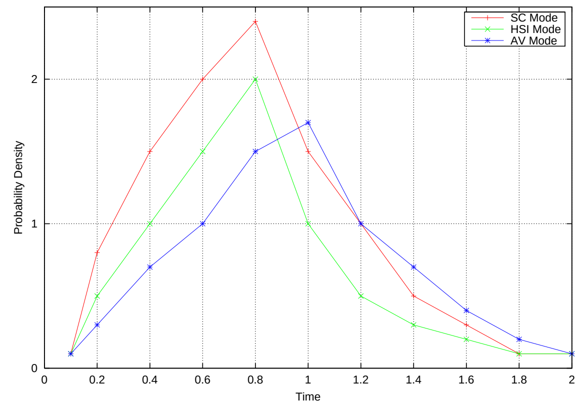

Fig. 3. Throughput versus Number of Devices

VII. Conclusion

In this paper, we have presented a detailed study of the IEEE 802.15.3c standard. The system throughput was studied by simulating both the SC, HSI and AV modes over a 60 GHz typical channel model. The link adaptation mechanism was described and the link throughput results were presented. The achievable number of devices was also investigated. The theoretical MAC throughput for different frame sizes and ACKs was calculated. The maximum achievable MAC throughput also relies on the link quality conditions. A typical PWANs system and the interactions within it, we have investigated it using the highlevel modeling formalism PEPA. This allows early analysis of potential designs and configuration to assess its performance measure. The system considered is simple, but this has allowed us to have a new idea about evaluating the performance of the way system in its design phase. Moreover, the method we used is more convenience, flexible, and lower cost than the former simulation method using special hardware and software tools. For example, when a new part is added into the system, designers just need specify a new component to the system model and express it using PEPA language, enabling designers to evaluate its impact to the system's performance. But the size of the state space of the underlying Markov chain would increase sharply with the increasing of components within system, which may lead to the problem of the state space explosion and cannot be computed easily. We can use two ways to deal with this problem at present, namely, aggregation and ordinary differential equations (ODEs), details can refer to [4, 5].

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