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Model of the network physical layer for modern wireless systems

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Abstract: In the article the detailed and flexible model of physical layer PHY for discrete events simulations (DES) is proposed. The model was implemented using SimPy simulator and evaluated using simplified 802.11 protocol model. To proof the correctness of the model some results of selected 802.11 parameters verification are presented.

Keywords: DES, PHY model, wireless network simulation, SimPy

1. Introduction

Recent development in wireless technologies increases popularity and coverage of wireless networks. To meet the demands of contemporary wireless network users (expressed by QoS parameters) require more and more complex mechanisms, especially in the lower layers. That technologies includes Multiple Input Multiple Output (MIMO) systems [5], highly elaborate coding and keying technologies such as OFDM(A) [7], SC-FDMA [9] and others [2]. In dense systems importance of the role of the physical properties of a transport medium, environment influence and the interference between clients increases. Wireless networks are more often used in mobile systems, where role of Doppler effects and surroundings changes should not be neglected. High bit-rate (or symbol-rate) of modern networks make the multi-path behaviour, mobility effects, internodal range and path-loss of the signal crucial in the estimation of the quality of the link.

Both for infrastructure planning and to allow testing of new protocols and technologies, one needs modelling tools and related network models that allow to perform off-field network analysis. Discrete event simulations (DES) has appeared as the most convenient approach for the performance evaluation of network protocols and architectures. In DES, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system [15].

The simulation of detailed physical properties and effects could be both computational and resource demanding. That problem is particularly important for the simulation of wireless networks, due to the complexity of the physical layer (PHY), shared medium and possible interferences. Furthermore complicated models make the results dependent on a large number of parameters that define the simulation scenario. That makes the formulation of the scenario very difficult (topology of the obstacles, dynamics of the environment, etc.) and makes analysis of simulation results less straightforward. Highly realistic models of the physical effects present in the wireless communication affect strongly performance of simulations [1, 6].

A solution is to simplify the PHY model to reduce the number of events and computational complexity. Simplifying the complexity of the model increase scale of simulated scenarios, however, leads to less accurate simulation. Different simulation tools are different degrees of detail of the PHY implementation enforces the use of simplified models, as the trade-off between the accuracy and the scalability of simulators. Unfortunately it could lead to inaccuracy of the results and to divergence between simulation results and experiments [8, 12, 13].

In order to compromise between the simulation performance and the accuracy of the results in the paper we present a formalised yet usable for implementation the PHY model, derived from elementary equations for an electromagnetic wave amplitude. The model allows to calculate Frame Error Rate (FER) for frames transmitted between simulated nodes. With formal description of the physical phenomena and technologies of the wireless communication we are able to easily implement various model of the physical effects in the simulator, and test their influence on the results.

Because of strong impact of the physical models on the accuracy, we find it important to check results of investigated simulation scenario for different models. Thus we believe that to maintain possibility of testing the impact of the physical models on the simulation results it is of the key importance to have an modular model of the PHY. The model should be constructed and implemented in a way that gives the possibility of changing physical effect models without any other impact on the simulation scenario.

In subsequent parts we present a prototype implementation of this model and, to verify correctness of the model, results of simulations of the simplified 802.11a/g network in prototype implantation of the model in the SimPy environment.

2. Model of the physical layer

Description of the physical phenomena in a radio communication is based on the linear equations of the amplitudes of electromagnetic wave received by a given antenna i, which are based on vector field description of the electromagnetism:

$$R_i(t) = \sum_{k=1}^{\infty} \sum_{j=1}^{M} h_{ijk}(t) T_j(t - \delta t_{ijk}) + n_i(t) \tag{1}$$

where $T_j(t')$ is an amplitude of the signal emitted by the j antenna at time $t' < t$, t_{ijk} is a time of signal propagation between the transmitter j and the receiver i through path enumerated as k. $h_{ijk}(t)$ coefficient describes path-loss of the amplitude of the signal on the path k, but also hides properties of the antenna such as gain or polarisation. $n_i(t)$ describes noises both received by antenna and generated by the antenna itself. It is important to note that both h_{ijk} and n_i are time dependant.

Physical properties of the propagation medium are hidden in the h_{ijk} elements. We state that they factorize to:

$$h_{ijk}(t) = P_0 \cdot p_k(\vec{x_i}, \vec{x_j}) \cdot v(\vec{v_i}, \vec{v_j}) \cdot r(\theta_{ij}, \phi_{ij}) \cdot r(\theta_{ji}, \phi_{ji}) \cdot \mathcal{M}, \tag{2}$$

where p function describes path loss between receiver i and transmitter j, v is a function that describes effects of mobility, and r describes spatial distribution of the antenna radiation in direction described by angles θ, ϕ and $\mathcal{M}$ is a function dependent on other properties of the system. Proposed approach allows to use in simulation various models. For example, path loss coefficient may be calculated with use of popular propagation models, for instance free-space, Okumura or Hata model. $\mathcal{M}$ may be used to include effect of shadowing and fading of the signal or any other effect that affects the signal at the receiver. Proposed form of the h_{ijk} allows to perform simulations on various levels of complexity – from simple case of free-space propagation, to models describing such phenomena as Doppler effect, influence of the environment, antenna construction and others, depending on the explicit form of the factors forming h_{ijk}.

Infinite sum of the amplitudes is impractical for computer analysis. Fortunately, physical properties of the medium and antennas allows us to reduce sum to finite number of the elements. Because of the signal degradation with a path length (and a propagation time) and finite sensitiveness of the antenna we may neglect in considerations signals with amplitudes below certain threshold. Moreover, we may eliminate summation over all possible paths from equation 1 in two ways. One may use a Huyghens description of the wave propagation and introduce additional radiation sources at discrete points of space and analyse interference of all signals at the antennas. On the other hand one may describe multi-path fading statistically, by modifying h_{ijk} elements. Both cases give possibility of rewriting equation 1 as:

$$R_i(t) = \sum_{j=1}^{N} h_{ij}(t) T(t - \delta t_{ij}) + n_i(t), \tag{3}$$

where N is number of radiation sources.

Such description is still inconvenient for computer simulations because of description of the phenomena at electromagnetic wave phase and amplitude level. It leads to necessity of evaluation of the environment and signal properties with electromagnetic wave frequencies, which is at inefficient in the simulations. To improve simulation efficiency we will use fact that aplitudes are connected with power received by the antenna:

$$P_i \sim |R_i|^2. \tag{4}$$

Using the relation it is possible to describe the PHY properties using powers of the transmitted signals and perform simulations with time-scale of the bit-rate or even the frame-rate. Unfortunately, to be able to describe such important phenomena like an interference between electromagnetic waves and effects of a spatial distribution of antennas in Multiple Input Multiple Output (MIMO) systems we may not neglect information carried by phase of the electromagnetic wave. To partially resolve the problem we introduce phase of the signal ϕ_i. Furthermore, with assumptions concerning maximum allowable phase shift between signals, we may include both constructive and destructive interference signals, keeping simulation on the frame-rate timescale.

To make interference-based phenomena possible to simulate we assume that both constructive and destructive interference is possible only between signals carrying the same information (with same encoding and keying) and with small phase shift (because amplitudes of such waves are mutually proportional). Then received power is given by:

$$P(t) = \left| \sum_{i=1}^{N} P_i + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{n} \sqrt{P_i P_j} \cos(\phi_i - \phi_j) \right|. \tag{5}$$

Signal phase ϕ_i at the receiver is dependent on the i-j propagation time and on the initial signal phases. With use of above equation we may reduce number of incoming signals substituting interfering signals with one, with power given by the equation.

In cases where signals are different or have large phase shift we treat them as a mutually interfering noises, which may be further used to evaluate a values of the Signal to Noise (SNR) or the Signal to Interference and Noise (SINR) ratios.

Our approach allows to include signal-interference effects, necessary in description of MIMO systems and environmental effects, yet is usable in simulations due to high level of abstraction and high timescale.

Finally, to include various modulation and keying and multi-access techniques in frame-rate timescale we assume that a Bit Error Rate (BER) may be calculated from a function G dependant only on powers of incoming signals which are proportional to h_{ij}:

$$G(t) = G\left(h_{ij}(t)\right). \tag{6}$$

Explicit form of the $G(t)$ depends on the used modulation, keying and multiaccess techniques, and usually is proportional to SNR (SINR). As incoming signals change during frame reception, one may have to re-evaluate $G(t)$ and BER. After reception of the given frame, FER may be calculated from subsequent BER values, taking into account correction codes.

3. Implementation of the model

An implementation of the model is straightforward. In simulation without mobile nodes all necessary h_{ij} components are evaluated once at the beginning of the simulation. To improve simulation performance (especially in case of a mobile network) h_{ij} elements don't have to be calculated for each i-j pair, but one may provide list of possible pairs of antennas. Moreover, it may reduce number of nodes engaged in communication and allows to simulate networks with certain link-topology like wired networks. Pairs of communicating nodes may be evaluated basing of the link model (sphere model, threshold range model) or may be assumed.

Simulation is performed as follows. After pre-calculations and setup of the simulation scenario simulation begins. In each step of simulation there is taken an event from simulator event queue. If it requires a signal to be sent, there are generated two events of reception of a signal at each receiver (for given topology). One of them is placed in time after propagation time and marks beginning of the signal reception. The other is placed in time after propagation time plus a signal-duration time. If the event concerns on a reception, evaluation of it depends both on an event type (start of the signal or end of the signal) and on the inner state of the node. If node is in a waiting state, and event is the start of reception, node changes it state to the receiving. If node is in receiving state and the incoming signal starts, current time is stored. If the incoming signal ends and is not the receiving one, BER is recalculated and added to the list of bers. Procedure evaluating the BER uses calculated values of h_{ij} if none of engaged node has moved or calls a procedure of the h_{ij} calculation otherwise. If incoming signal ends and is the receiving one, receiver changes state do the waiting, FER is calculated basing on the BER list and list of time intervals between BER changes, and the BER list is flushed. Then, the received signal is sent to be processed by a higher network layer of the node along with calculated FER. There it could be retransmitted, may cause generation of a new signal and simulation event, may be just dropped, depending of receiving node type and

FER value. Then the event queue is sorted (internally by the simulator) and next event is evaluated. At the end of the simulation statistics are generated to measure performance and behaviour of the simulated network.

In our research we prototyped an implementation of the model in the SimPy environment. SimPy is a discrete event simulation framework designed for the Python programming language. It has been chosen because of low programming effort needed to complete task comparing to lower-level languages without resigning of complex algorithms. The whole simulator with simplified 802.11 model takes less than 600 lines of code. Moreover, SimPy allows to describe nodes (and in practice whole environment) without concern on inner elements of simulator such as simulation events and synchronisation messages. Interpreted nature of the Python language allows easy modularisation of the simulation and chagneability of physical models. Structure of our implementation is presented on Figure **??**. Because of internal implementation based on lower programming languages of the SimPy the performance of the simulation was enough for our research purposes, allowing to evaluate up to few millions of events per second in certain scenarios.

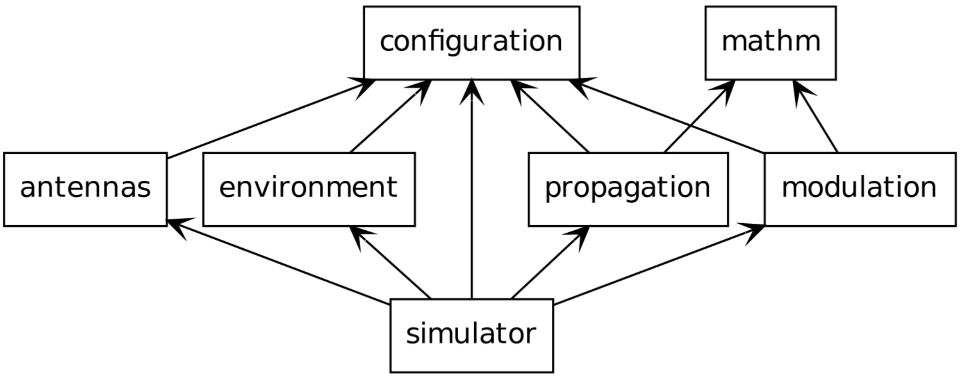

Fig. 1. Dependency structure of the modules comprising the implementation. Each module contains implementation of models describing some part of the physical layer model. mathm module contains supplementary mathematical methods. Names of the other modules correspond to their role

4. Verification of the parameters of the 802.11 family model

We found it difficult to test wireless communication only at the PHY level. The simplified model of the MAC sublayer was adopted. This model, however, remains consistent with the Distributed Coordination Function (DCF) of the IEEE 802.11-2007 standard [4, 10], i.e. the most popular setup used in existing wireless networks. Model simulates the DCF collision avoidance algorithm whereas each network node must ensure it can access the medium before transmission starts. Once started, transmission cannot be interrupted (eg. by interfering signal) until frame transmission finishes. This is consistent with radio devices found on the market (eg. Atheros chipset). Nodes only exchange frames without using acknowledgements (ACK), what reflects a multicast transmission. In addition, the new IEEE 802.11n standard [11] introduces programmable support for disabling this facility. The RTS/CTS mechanism is not used – it has been poorly adopted by the ISP industry due to its performance and is rarely used nowadays. A few mechanisms modeled according the standard are used: carrier sensing (CS), NAV timers (NAV), inter-frame spacing (IFS) and exponential back-off (EBO).

The main goal of the evaluations was to initial verification of the developed analytical and simulation model. Therefore we concern on testing a well established standard against its modifications. In our research we modified some of the important 802.11 protocol parameters: sensing and interframe times (DCF Interframe Space DIFS, Short Interframe Space SIFS), back-off times, and presence of the probing of the medium. Moreover we tested the model with different enviromental and setup conditions, i. e. space distribution and power of nodes and number of nodes.

One of expected results was to prove the correctness of the parameters adopted as standard against our simple modifications. In an indirect way this shows the correctness of the adopted model and will be the basis for further work and verification based on the results of real network.

In following part if not stated otherwise simulation results are obtained for a set of 10 pairs transmitter-receiver, distributed randomly over 2m square, two-dimensional box, with transmitter power of 1W, SLOT=9μs, DIFS=62μs and:

$$B(r) = \mathrm{random}\left(\mathrm{SLOT}, \mathrm{SLOT} \cdot \left(\min(1023, 2^{3+r} - 1)\right)\right). \tag{7}$$

Each transmitter attempts to send 1000 frames to its receiver.

The most important for the network performance and link quality is a property of the medium probing. In 802.11 networks each node before transmitting listens medium and checks if it is free (i. e. no other nodes are transmitting). If the medium is busy, node waits for so called backoff time and probes medium again. Therefore in the case of all station are in each other range (like in small area networks) there are almost no frame collisions. In our research we tested both cases of presence and absence of medium probing, with varying number and distribution of communicating pairs of nodes. Our results with absence of medium probing are presented on Figure 2.

As one may see, for one and two pairs of communicating nodes probability of frame error is small and allows nodes to communicate. For more than two pairs the FER increases rapidly and for ten pairs is already almost equal 1. In such environment collisions between packets makes communication impossible.

Second revised case was medium with probing against number of communicating nodes. As expected, communication is possible independently of the number of pairs

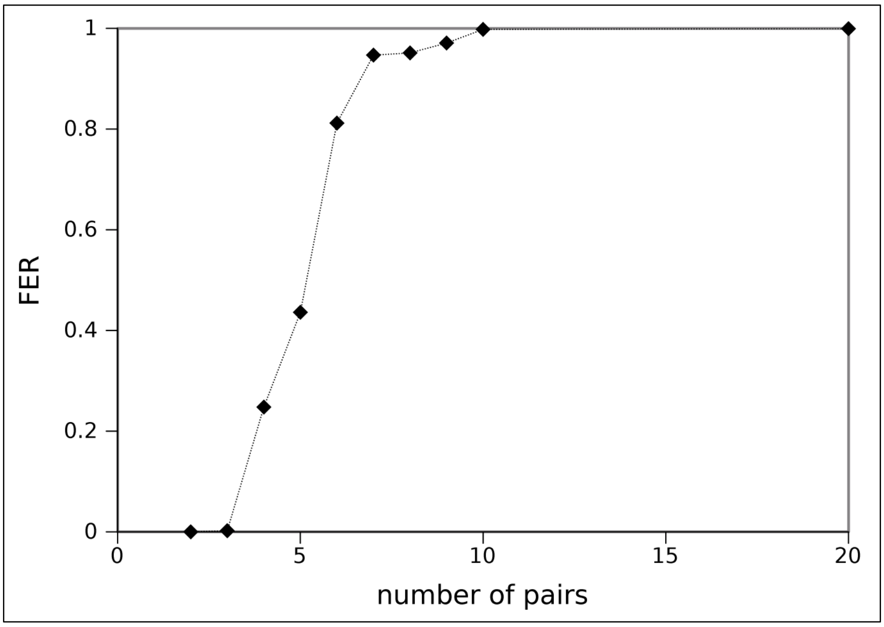

Fig. 2. Frame Error Rate (FER) in network without medium sensing in dependence of number of communicating pairs

with small, constant within statistical FER, but throughput of the network decreases linearly with number of communicating pairs (Figure 3).

Medium probing is quite computational expensive because of complicated transmitter logic. Therefore we found interesting checking if there is possible way to maintain communication by more than two pairs of transmitters and receivers without medium sensing. One possible solution is to increase inter-frame time, to decrease probability of the frame collision. Our results are presented in Table 1.

Indeed, results show that increase of inter-frame time decreases FER for a given number of nodes, simultaneously decreasing the network performance. Simulation results show that performance loss is much faster than in case of medium probing. For example in case with average time of transmission 1kB of data K =0.5s, for random inter-frame space with mean value of 500μs, FER equals 0.11. With medium probing, a network with similar throughput (K =0.5s) in same initial scenario we obtained FER as small as 0.0002.

Next verified case was role of back-off time. In 802.11a/g standard back-off time B is evaluated basing on the number of failures of access to the medium r, i. e. $B = B(r)$. Each time medium is probed with negative result (i.e. the medium is already used) time domain from which back-off time is randomized increases twice (up to SLOT·1023·SIFS). Performing simulations we have checked, if simpler methods could

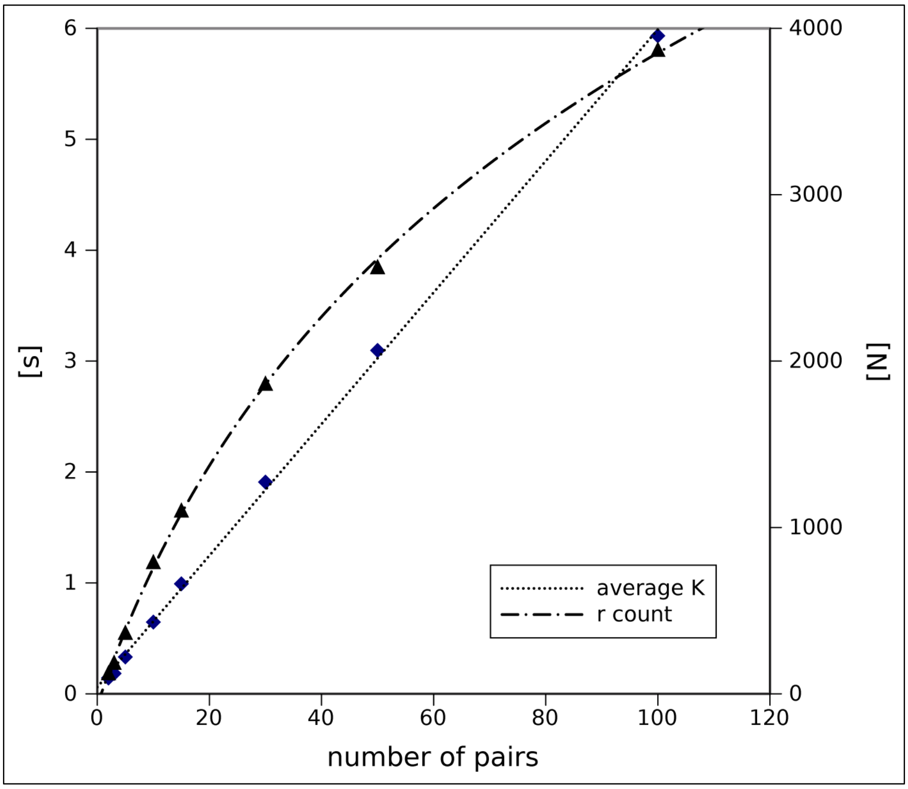

Fig. 3. Throughput expressed in time needed to send 1kB of data (K) in network with medium sensing in dependence of number of communicating pairs and average count of backoffs r

give similar performance. Because of probing presence, FER doesn't depend on B(r) form. Obtained results are shown in Table 2.

As we see, performance of the network with exponential B(r), which is used in standard 802.11a/g, is highest (it has lowest value of the K). Change of the K value is slightly small, if we change $B(r)$ form as long as its mean value is in same order as in exponential case. Simulations show that that in that case the number of failures in medium access r increases rapidly. High r value increases cost of equipment, which has to have ability of fast switching from transmitting to the receiving state. On the other hand, if we increase mean time of the $B(r)$ the number of failures decreases, but increases the mean value of K. Our results show that exponential $B(r)$ allows to keep both K and r small simultanousely.

In our research we tested also spatial distribution of antennas. We tested set of simulation scenarios on variable space area, with uniformely distributed set of 20 antennas over a box with variable side length. To analyze the impact of the internodal distance on

IFS[μs]	FER	K[s]
0	0,996	0,04
9	0,997	0,05
20	0,997	0,065
200	0,39	0,24
random(0,40)	0,94	0,06
random(0,400)	0,30	0,24
random(0,1000)	0,111	0,541
random(0,2000)	0,055	1,043
random(0,20000)	0,0043	10,047

Table 1: Influence of the interframe space (IFS) time on the model performance. K is an average time of sending 1kB of frames. Results are obtained for model without medium sensing

$B(r)$[μs]	K[s]	r
EBO	0,53	246
random(0,SLOT)	0,55	5704
random(0,10*SLOT)	0,56	3770
random(0,100*SLOT)	0,57	880
SLOT	0,59	5939
10*SLOT	0,55	2658
100*SLOT	0,60	500

Table 2: Role of the form of the Back-off time $B(r)$ on the performance of the network. K is average time needed to transmit 1kB of data. r is average number of backoffs. EBO is an exponential form of the $B(r)$ presented in equation 7, taken from 802.11a standard. Random numbers random(a, b) are sampled from interval (a, b) with uniform distribution. SLOT time is given from 802.11a standard and equals 9μs

the packet collisions we neglect path-loss of the signal. As one may expect results show that for high inter-nodal distances (large size of the box sides) FER increases (Table 3).

side of an box[m]	FER
2	0,00020
20	0,00047
200	0,00762
2000	0,07630

Table 3: Impact of the area of the node dispersion on the frame error rate. Antennas are randomly set in a square two-dimensional box. Path-loss is neglected

Because path-loss was neglected, the only reason of FER increasing is that for large distances listening time and inter-frame times are small comparing to propagation time, and the probability of simultaneous transmission increases. However distances, where such fenomena occurs are of range of kilometers, which are far beyond practical applicability of the 802.11 networks, which were developed as local area networks and don't have to perform well on such large distances.

One of our most important finding concerns random initial values of the simulation (Table 4). Our results shows that the FER vary from simulation to simulation and depends strongly on initial spatial distribution of the antennas. We found that in certain cases (fortunately unphysical ones) it was even possible to generate initial state, where FER is equal to 1 over whole simulation, due to simultaneous accesses to the medium by all transmitter antennas. We found that important, because it highlights how big concern must be made during simulation, to reduce impact of initial conditions of the simulation.

Spatial distribution	startup-time	FER	FER std. dev.
random	random	0,0026	0,001
along box side	random	0,0008	0,0002
random	constant	0,09	0,03
along box side	constant	1	0

Table 4. Statistical parameters of the evaluated FER for given simulation scenarios

5. Conclusions

In present paper we proposed a model of the physical layer of the wireless systems. The model allows modular and flexible implementation of PHY layer in the DES simulators. We prototyped model based on SIMpy simulator and we have tested it in modifications of the 802.11 network simplified model. As expected, we found that 802.11 standard performs better than any modifications that we propose. We found that proposed in standard method of calculating back-off time gives best performance, with little embarrassment in design of the transmitter station. We found that the standard performs well even for high density of nodes, but it performance decreases with increase of area of nodes dispersion. Finally, we found that our simulations (and we claim that all similar simulations) are strongly dependant on initial values and thus it is necessary to analyse statistically results for different initial conditions.

Our research is a part of preparation of methods to parallelize simulations of modern wireless networks. Using parallel discrete event simulation (PDES) [3] it is possible to achieve a considerable speedup. The simulation's scenario is s divided in a number of logical processes, each of them executes a part of the scenario. Parallel simulation of wireless networks, while maintaining accuracy physical layer model, is a particularly difficult issue. It is mostly because of the shared type of the medium and the resulting intensity of communication between objects. We assume, that properly developed model could have strong impact on the performance of the parallel simulation. The developed model will be implemented in a distributed simulator that uses a new, time-stepped method of synchronization [14].

Our simulation model could be extended with use of more complicated and more realistic scenarios and will be the basis for verification based on the results obtained from real network (in preparing laboratory testbed).

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Model warstwy fizycznej dla współczesnych sieci bezprzewodowych

Streszczenie

W artykule opisano szczegółowy i elastyczny model warstwy fizycznej (PHY) współczesnych sieci bezprzewodowych, opracowywany i adaptowany dla symulatorów zdarzeń dyskretnych (DES). Jednym z elementów które można opisać w modelu są zjawiska propagacji. Oprócz tego konstrukcja modelu podejmuje problem interferencji sygnałów, ale także zjawisk związanych z prędkościami węzłów (takich jak ef. Dopplera), budowy anten, umożliwia uwzględnienie takich zjawisk, które można opisać jako wpływające na amplitudę/fazę sygnału odbieranego (a więc np. shadowing, fading). Model został prototypowo zaimplementowany z wykorzystaniem symulatora SimPy.

Ze względu na trudności w interpretowaniu wyników jedynie na poziomie warstwy fizycznej, implementacja została uzupełniona o uproszczony model podwarstwy MAC dla protokołów rodziny 802.11.

Jednym z oczekiwanych i potwierdzonych eksperymentalnie rezultatów było wykazanie poprawności przyjętych parametrów i mechanizmów protokołu 802.11 w stosunku do jego prostych modyfikacji. W sposób pośredni pokazuje to prawidłowość przyjętego modelu i stanowi podstawę do podjęcia dalszych prac.

Opisane prace są częścią przygotowań, których celem jest stworzenie dokładnego i efektywnego symulatora dużych sieci (w tym domen bezprzewodowych) działającego w sposób równoległy. W tym celu konieczne jest opracowanie elastycznego, modularnego modelu warstwy fizycznej. Dalsze planowane prace obejmują analizę wydajnościową modułów modelu, weryfikację poprawności w testowym środowisku laboratoryjnym oraz docelowo implementację i testy symulatora równoległego.