Short-range communications within emerging wireless networks and architectures: A survey

Published in
14th Conference of Open Innovations Association (FRUCT), 11-15 November 2013, Espoo, Finland

DOI
10.1109/FRUCT.2013.6737949

Short-Range Communications Within Emerging Wireless Networks and Architectures: A Survey

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***Abstract*—The paper presents an overview of known approaches to evaluate performance of short-range communication technologies, when handling diverse types of traffic, generated by several recently emerging applications. In particular, very specific cases, like machine-to-machine communications, heterogeneous networking and device-to-device communications are considered. These scenarios have some specific traffic patterns, on one hand, and a number of supplementary requirements for network performance characteristics, on the other. Due to such a gap, there is a strong need for adapting well-known evaluation techniques with respect to listed priority changes, which gives motivation for our work. The paper presents commonly-used set of three evaluation strategies: analytical approach, simulation and measuring. For each of those a classification of know techniques is presented, as well as their applicability assessment for named developing applications. Possibility of combining techniques from different strategies to decrease the level of uncertainty is also discussed. Finally, some useful pieces of advice related to emerging applications performance prediction are given.**

Keywords*—*Analytical approach, Performance evaluation, Overload control, Saturated network analysis, Channel modeling, Short-range networks, Wireless networking, Markov models, IEEE 802.11, Wi-Fi, Machine-to-Machine.

I. INTRODUCTION

Short range wireless technologies, like Wi-Fi, ZigBee, etc., play a very important role in existing local area networks. The reason behind is that deployment, configuring and maintaining costs are low, while the data rate they offer are comparable to wired links. As such, wireless networks are now used in a variety of scenarios, starting from simple point-to-point communications, and up to enterprise solutions where user mobility between access points is supported by seamless handover. Due to such a high popularity, there is a set of methods to assess the network applicability to a given scenario and estimate major characteristics, like capacity or delay.

However, new applications, like Machine-to-Machine (M2M [1], [2], [3]) communications, Heterogeneous Networking (HetNet, [4]) and Device-to-Device (D2D [5], [6]) links support raises new challenges in existing networks analysis and emerging technologies design. Moreover, with respect to different traffic patterns and requirements of the applications, some modifications in evaluation techniques are to be made.

In this paper we present a survey and classification of existing approaches for short range networks analysis. Then, we highlight bottlenecks in each of them, when focusing on emerging applications, like M2M, D2D or HetNet. Finally, we conclude about possible improvements in named methods, aiming to extend the techniques applicability from conventional scenarios (file transfer, web-browsing, VoIP) up to much broader set of those ([7], [8]).

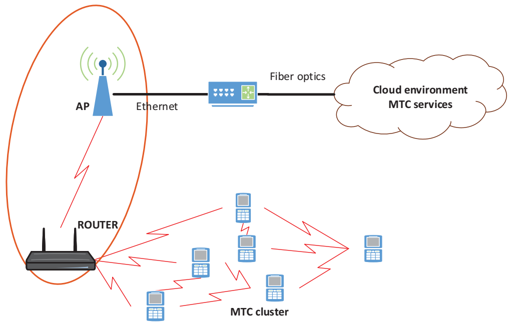

Fig. 1. Considered segment of MTC-aware network

The rest of the paper is organized as follows. Major network characteristics and requirements for different applications are listed in Section II. Section III presents an overview and classification of existing approaches to evaluate the network performance as far as suggested improvements to support emerging applications. Major results are summarized in Section IV. The paper ends with some conclusion remarks.

II. REMINDER OF MAJOR NETWORK CHARACTERISTICS AND APPLICATION REQUIREMENTS

We focus on the behavior of a single 802.11 link carrying the considerable amount of MTC-specific traffic from the underlying MTC cluster to the application servers. Even though IEEE 802.11 has not been originally designed for MTC, there is a strong trust that it might be applicable at least to some extent. We are thus interested in establishing how far the conventional network architecture could be used for MTC.

A. Characteristics

Nowadays, it is decided to divide network and node related characteristics, this subsection is more precisely describing them.

Firstly, we consider network related characteristics: *Goodput* - how many bits per second can be transmitted via network;

Range - maximum distance where the access point can communicate; *Nodes* - the maximum number of handling nodes. Secondly, we consider user characteristics: *Energy efficiency* - an amount of energy spend for the transmission of one information unit; *Collision probability* - the probability that there was more than one transmitting user at the same time; *Delay* - how long does it take for an information unit to travel from the starting point to the destination [9].

The key question of this research is establishing the maximum number of typical MTC devices a network can potentially support. The following analysis indicates IEEE 802.11 parameters that are applicable to handle the expected number of MTC devices across some specific area.

Consequently, the main problem we address below is handling an excessive amount of small packets from the underlying MTC network. Despite the fact that MTC traffic may be delay-tolerant and not too intensive [10], small burst transmissions might bring a shortage of goodput and thus hurt network efficiency. In fact, most part of MTC devices periodically send small amounts of data to the network. The reference case here may be an intrusion detection sensor that sends its status information to the network every couple of seconds even if no intrusion is detected just in order to ensure that the sensor is still alive.

As far as WiFi is inherently designed for transmission of large blocks of data [11], each single packet is supplemented with some overhead signaling. Therefore, regardless of the fact that sensors do not generate heavy traffic themselves, the problem of providing high effective goodput for MTC is topical.

B. Application requirements

We can not analyze the system without any specific connection to the application, because for different technologies there would be various important characteristics. For example, the requirement for service traffic the most important would be system reliability, because the successful probability for this type should be high. On one hand, for audio and video the important factor is the average system delay. On the other hand, for file transfer the goodput is more important than delay. Moreover for an emerge apps there are some other special needs also: for M2M the most important factor is network handling of a huge number of nodes with lots of short packets; for D2D it is high goodput for short distances; for HetNets it is the opportunity to configure cells with less inter cell interference. In the next section the approaches of system analysis are described for the specific application requirements.

III. Evaluation Methodology

The most accurate approach proposes usage of a combination of three evaluation strategies: simulation, analysis and measurements (see Figure 2)

Combining approaches from three different strategies, one can minimize the chances to make a mistake in the evaluation by performing direct comparison of numerical results given by different approaches. However, this way is costly, especially for measuring system-level performance (see explanation further). As such, for the rough estimation of network

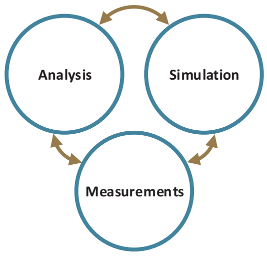

Fig. 2. Evaluation strategies combination

characteristics in particular scenario a single approach from any of the strategies could be used.

Then, the question is, which one to choose. Generally speaking, as it seem possible to design an accurate analytical model of the system, the analytical strategy becomes the most beneficial one. The reason behind is that a number of closed-form equations for every network parameter can easily describe the system behavior in a variety of scenarios, while obtaining same results by simulation and, especially, measuring could take much longer time. Therefore, we start with description of analytical approaches, then come to simulation and measuring, respectively, and, finally, highlight possible ways and the benefit of combining approaches from different strategies.

The description of the approaches is usually illustrated with concrete examples and details of adaptation to emerging application analysis.

A. Analysis

In this subsection the analytical approaches for short range network evaluation are presented.

Fig. 3. Single link network topology

1) Single link analysis: For single link analysis we assume a simplified model based on 802.11-12 standard based on noise- and distortion-free channel, saturated traffic, equal time slots, synchronized time and no hidden terminals. As we have error-free medium during the transmission may appear only three different types of slot for every user: $success$, $collision$ or $idle$. Idle is the slot when there were no transmission by any user. We use saturated traffic in order to calculate the throughput analytically.

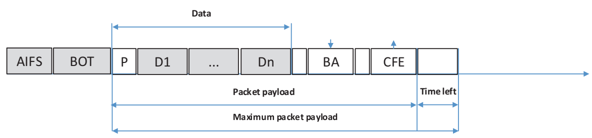

Fig. 4. BASIC signaling

We assume RTS/CTS mechanism in our model, which is shown in figure 5. We analyse our model from throughput point of view, it is calculated as follows:

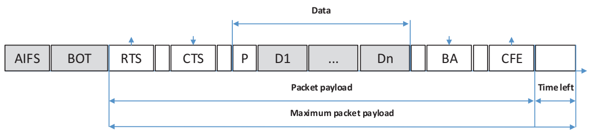

Fig. 5. RTS/CTS signaling

$$C_{\mathrm{RTS/CTS}} \cong \frac{N_{pac} * Length_{pac}}{AIFS + M[BOT] + RTS + CTS + BA + CFE + 4 * SIFS + \frac{N_{pac} * Length_{pac}}{R}} \quad (1)$$

where parameters were chosen according to 802.11 standard.

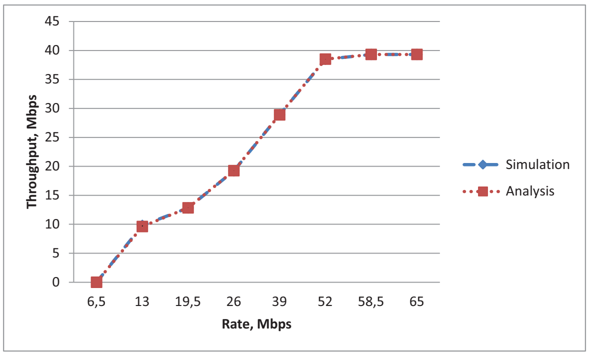

Fig. 6. IEEE 802.11 throughput on rate

In spite of the fact that single-link systems are rarely make use of emerging applications, there are cases, when presented analysis is suitable. In particular, the following network topology could be considered for M2M communications in the enterprise company infrastructure (see Figure 1).

In this case, the technique, presented above, could be used to estimate the number of supported M2M devices in the network by rescaling the single-link throughput (bottleneck in such a system) as it is shown in Figure 6 with different rate values. That approach was used in [12] to estimate the number of supported M2M devices for both *Basic* and *RTS/CTS* signaling. It appears, that only high aggregation threshold values can help IEEE 802.11-2007 to handle traffic from M2M devices in a given scenario (see Figures 7 and 8).

2) Saturated system analysis: Despite the fact, it is possible to easily obtain a closed-form solution for a single Wi-Fi link, the system-level analysis of this protocol if much more complicated. First of all, packet losses, caused by a conflict, have to be taken into account. Secondary, we have to admit, that under high load these losses are the major reason for performance degradation. In addition to, we have a number of difficulties with so-called "memory effect of the system". When nodes' behavior depends on a result of all the previous events, happened in the system. As such, the analysis is hard to perform. In order to mitigate this issue, the saturated system analysis approach was proposed. In general, it works as follows: we assume, that every node in the network at every moment of time has a packet ready to be transmitted. So when the packet number i from the node is successfully transmitted, the node immediately switches to transmitting the packet number $i + 1$. Moreover, due to simplicity, network

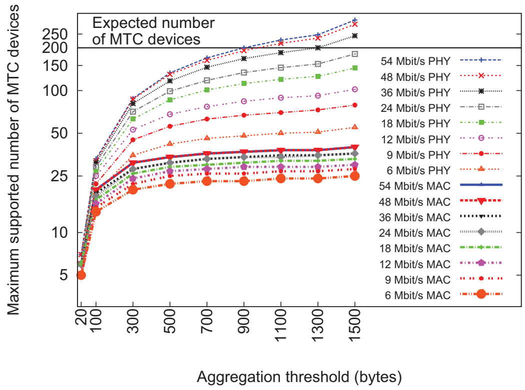

Fig. 7. Maximum supported number of MTC devices. Enhanced system. PHY and MAC aggregation. Reproduced from [12]. *Basic* scheme

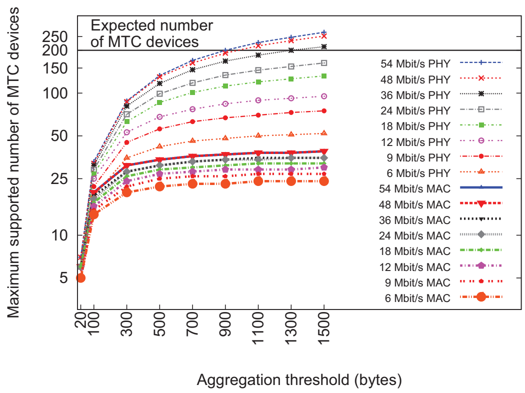

Fig. 8. Maximum supported number of MTC devices. Enhanced system. PHY and MAC aggregation. Reproduced from [12]. *RTS/CTS* scheme

topology is usually assumed being immutable with a given amount of identical nodes sharing the same radio resource (see Figure 9). Moreover, all the slots start at the same moments of time, which means that they are synchronized.

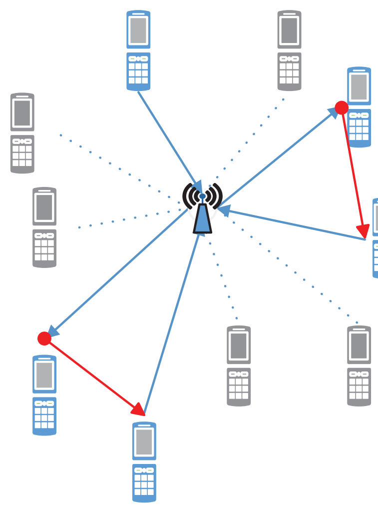

Fig. 9. Saturated network topology

Under the listed assumptions, the network performance could be estimated by e.g. approach, firstly observed by Kwak [13], proposed by Bianchi in [14]. He considered to analyze the working process of one user with a Markov model calculate the probability p_t - that it is a transmission by the specific user at the exact time slot. Such analysis mechanism does not depend on the access mechanism at all. Finally, he expressed the throughput as function at the computed value p_t. He analyzed the situation with saturated traffic and error-free channel. Moreover, each user had to wait for a random back-off time after his success or collision.

One of the serious drawbacks of the Bianchi's approach is complexity of analysis to be performed for getting p_c and p_t values. Therefore, recently was obtained another solution, that gives identical results was proposed in [16]. It was noticed, that in saturated system there are moments of time, when the system behavior is no more dependent on previous events, so-called "regeneration points". And using very simple mathematical apparatus is is possible to get p_c and p_t values as shown below.

$$p_t = \lim_{n \to k} \frac{\sum_{i=1}^{n} B^{(i)}}{\sum_{i=1}^{n} D^{(i)}} = \frac{E[B]}{E[D]} \ , \tag{2}$$

where B^i is the number of transmissions in cycle and D^i is the average number of contending time slots at i transmission attempt. Moreover, collision appears when there were more than one transmitting user at the same time slot.

$$p_c = 1 - (1 - p_t)^{M-1}, \tag{3}$$

After the equations for p_c and p_t are obtained it is possible to estimate the saturation goodput of the network using the following equation.

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\,\sigma + P_s P_{tr} T_s + (1 - P_s) P_{tr} T_c}, \tag{4}$$

where $E[P]$ is data duration, P_s is successful transmission probability, T_s is an average time for a successful transmission, T_c for a collision and σ for an empty slot.

In the following decade a huge set of numerical results were obtained using the listed techniques for many CSMA/CA-based systems ([14] is now one of the most cited paper in the field with citations index being more than 6000 [15]).

3) Dynamic traffic analysis: Saturated traffic analysis gives us only the overestimation of system performance from the goodput point of view. However, sometimes it is good to predict system behavior under some conditions, that are special for Machine-to-Machine and Device-to-Device: sparse data traffic or rush hour for example. As such, there are some methods to analyse the system in dynamic environment.

One of the possible approaches is to reuse the mathematical apparatus called switched Bernoulli process (SBP). Application of these technique can give some intuition about losses rate [17] and performance level [18], [19].

Also, the fixed-point approximation technique can be used to determine throughput of TCP sources in CSMA/CA environment [24]. However, there is a serious drawback of this model requiring a serious computational power.

Talking specifically about M2M traffic, with respect to it being very rare, numerical approaches from [10], [11] and [25] could be reused.

4) Channel modeling: An overwhelming majority of authors who analyse the network performance under certain conditions assume wireless channels to be stationary due to simplicity. When evaluation the HetNet or D2D scenarios, this might be not sufficient, as far as users move from one location to another that might have different channel conditions. So some non-situationally channel modeling approaches might be very useful. Starting from Konrad et al. [20] there is a set of research papers, aiming to propose a mathematical model for non-stationary wireless channels.

In particular, two efficient methods, based on change-point statistical tests and covariance stationary error processes, were proposed in [21], and [22], respectively. In [22] second approach was further developed to support the real bit and packet error statistics, measured for IEEE 802.11b. This resulted in simple, accurate and computationally efficient algorithm for channel modeling, proposed in [23].

They noticed, that SNR values, observed on a long time period, follow normal distribution with geometrically decaying NACF. As such, capturing of them using autoregressive process was proposed in the following form:

$$X(n+1) = \phi_0 + \phi_1 X(n) + \epsilon(n+1), \tag{5}$$

where $n = 0, 1, \ldots$, with ϕ_0 and ϕ_1 representing some constants.

B. Simulation

There are lots of simulation tools. Simulation is really important tool for modern research because of the analytical calculation's limitations. In other words, we can obtain analytical values only for specific scenarios. Some classification is given in [26]. In this section we explain the difference between *time-driven* and event-driven simulation approaches, discuss the limitations of both *link-level* and *system-level* simulation tools. Also the applicability of named techniques for emerging applications is assessed.

1) Time-driven: The whole system can be analysed from different points of view. The traditional one is time-driven simulation where model works continuously tracked over time. Moreover, time is divided into small slots that may be different or equal length. Hence, system status is updated after the end of each time slot according to the activities inside it. So the code is simple: we settle the network parameters, deploy the nodes and start the cycle from time frame 1 till time frame T with τ as the time slot duration, where $T \cdot \tau$ appears to be the total simulation time.

Typical assumption for time-driven simulation frameworks is that every transmitting node knows the result of its transmission by the end of the time frame. As such, the node behavior at time frame $t+1$ depends only on node behavior at frame t and events, that appended during frame t. Therefore, in many simulation tools (e. g. [27]) the node behavior could be described using a Markov chain with a finite number of states.

Such kind of a tool works very fast, when limited number of nodes with intensive traffic communicates via a simple network protocol. That is somehow a good solution for HetNet pico cells and femto cells environment or network overload. However, performance of such kind of tools handling sparse traffic from high number of nodes (typical M2M work scenario) could be intolerably low due to the fact, that the long period of time (up to hours) have to be simulated and majority of cycles are empty (no traffic, no events), but we still have to call *updateState()* function for every node. So to prevent such a resource cost, another simulation technique, called *event-based simulation* was proposed.

2) Event-driven simulation: In contrast to time-driven simulation, event-driving method of simulation models the system as a discrete order of events. Each event that occurs during the process of modelling causes another event in future, simplified model is shown in Figigure 10. So the upcoming events are stored in a queue or stack. Furthermore, the event-driven simulation has no need to wait for the time with idle events - it simply jumps to the next one. But time is still stored for each event during the simulation process. It is not used as a loop counter but for setting an event priority in the queue. In other words, events are scheduled according to their future time dynamically. The end of event-driven simulation can be defined as some time value or an appearance of a certain event.

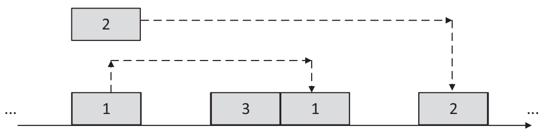

Fig. 10. Event generation in event-driven model

In comparison with time-driven simulators, event-driven ones are much more applicable to M2M scenarios [10], [11], where huge number of nodes (up to 30000) have very seldom traffic arrivals ($1 - 2$ per minute).

3) link level simulation: Independently from *time-driven/event-driven* classification, simulation tools could be also divided into two groups, depending on theirs focus: *link-level* and *system-level*.

The link level simulator is basically working only with the medium between two devices. The benefit of this type of simulation is simple to develop, use and upgrade. But the most important issue is that we can not consider any external influences from other users in the real system. Finally, we can analyze only the link between two users but not the overall system. After all, their results can vary greatly.

4) system level simulation: When a system level simulator is used, so it is possible to process the work of the whole system in one piece.

We are modeling a group of users with their shared medium. System level simulation is harder to develop and to upgrade, but we can calculate the results for the system, which are more accurate and more acceptable for the evaluation of the real model. But we do not have so many real time resources to simulate a real system, so we simplify it, as it is shown below.

TABLE I. SIMULATION PARAMETERS.

Parameter	Value
BitRate	$1.0, 53.0MBps$
Number of users	$5 - 55$
Initial Back-off window	32
Back-off window power	3
Short Retry Limit	7
Modelling duration	$50\mu s$
Slot length	9μ
SIFS	16μ
Block Acknowledgement duration	48μ
Request-To-Send duration	48μ
Clear-To-Send duration	44μ
CF-End duration	44μ
Maximum Transmission Opportunity	1300μ
MAC Header	$244bits$

During the simulations, close to real scenario is observed. We select link parameters as they are defined in 802.11 standard. Our model observes the work of Request to Send/Clear to Send (RTS/CTS) mechanism that is shown on Figure 5.

System parameters can be observed from Table I. Our model proposes an access point (AP) with M users connected to it and the channel access model is based on 802.11 standard. The simulation starts from the Arbitration Inter Frame Spacing (AIFS) which is the same for everyone, because of the same data type. Next, a Back-off Counter (BC) initializes as a random number from 0 to $CW-1$, where CW is a primary initial back-off window. BC is decremented every time there is an idle slot time. When back-off counter reaches zero the user is going to try transmitting his package. A collision appears when there are more than one user transmitting at the same slot. After such an event each user that took part in the collision doubles his CW, chooses new slot to transmit and the competitions starts again. CW can be doubled until its maximum ($CWMax$) is reached. $CWMax$ can be calculated as follows: $W0 * 2^m$, where $W0$ is initial back-off window length and m is a power of growth. Such a BC increase is made for the reduction of the collision probability. Transmission is repeated until the success (that system is called a lossless one) or until the packet is discarded (that system us called lossy one and is considered below). In Lossy system packet can be dropped after some specific number of the transmission attempts. To store its number we use Retransmission counter (RC) that is initialized by a specific integer. After every collision it is decremented by one. When this counter reaches zero the packet is considered as discarded and BC is reinitialized. As we consider an error free channel we use only one counter from IEEE 802.12 standard ShortRetryLimit (SRt) which can be used with an error during RTS/CTS. Finally, the user can send a packet only when channel is free, BC is zero and RC is more than zero. If the medium is senses to be idle for DIFS, RTS that contains information about total duration of the oncoming transmission is sent. If AP indicates that the channel is idle, it sends CTS to this specific user, so the last one can transmit his data. Finally, AP send ACK back to user.

C. Test bench

Despite the fact, the measuring approach is very costly, it gives the most feasible results, especially when authors propose some enhancements for the standard. Even though, world leading standardization committees (IEEE [28] and 3GPP [29]) are satisfied with simulation results, the device manufactures are only-confident, when see a real test bench based on existing protocol, then a test bench with enhanced protocol and can verify that, first: the enhanced protocol works correctly for a long period of time and different node behavior, second: it gives better performance.

In addition to the use case, presented above, sometimes test benches are used to measure the particular network characteristics that are needed for analysis (see the following subsection, describing hybrid evaluation strategies).

One of the most frequently used scenarios for test bench development is wireless channel analysis. Different groups all over the world design their own solutions to measure channel noise, inter-channel interference, etc. and also the MAC layer parameters, depending on this characteristics [30].

That kind of test benches is used to estimate the probability of loosing MAC layer message in short range communication technology (like Wi-Fi or ZigBee). In particular, in [31] the very simple test bench was proposed for Packet Error Rate (PER) numerical measuring for IEEE 802.11-2007 [32].

It is assumed two PCs running Linux connected to one (AP) as it is shown in Figure 11.

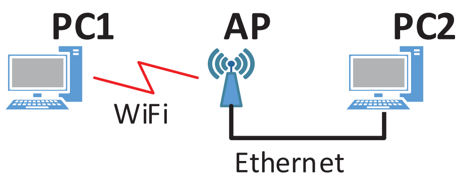

Fig. 11. Test bench for IEEE 802.11-2007 PER measurement [31]

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Moreover, we assume PC_1 generating saturated traffic that goes to PC_2 through the AP with fixed system parameters. *iperf* tool is used [33] in "Single UDP" mode to measure the value of Packet Error Rate (PER). Moreover, the channel quality was established to support rate values ($SNR \approx 30dB$). Finally, all the other networks in range were shut down to admit almost error-free medium.

We use an open-source driver for connection establishment (*ath9k* [34]). To reach usable values of PER, driver is set not to retransmit packets, i.e. retransmission counter is defined as 1 inside the driver.

The PER values help refining the analytical 802.11 goodput and estimating the maximum number of the MTC devices that AP can handle as it is shown below.

D. Combination of evaluation strategies

We use the combination of different methods to analyse our system. E. g. this part presents a combination of analysis, simulation and measurement approaches, that are used to provide correct parameters for future usage.

The main problem is that even a small amount of traffic from a single device can overload the network as a whole. Hence, we can calculate the correct number of supported devices, which can increase the channel throughput in the saturation scenario.

In this work it was used a popular semi-analytical approach for graduating the usage of IEEE 802.11 for MTC. In other words, we gain an effective network's goodput analytically with the usage of realistic PER with help of [30].

Assuredly, we can say that the influence of PER on the goodput is minor only when users are really close to each other. Howbeit, the real network may be planned not really meaningful so the distance may vary and communicate efficiency may be unacceptable.

We identified that is modern wireless networks walls, hidden terminals, distance, etc. have a strong influence on PER performance. Focusing on this issue, we exploit an IEEE 802.11 test bench [31] and calculate the real levels of PER on data rate and packet size.

IV. Conclusions

Emerging applications, like M2M, D2D and HetNets, short range wireless technologies were not originally designed for, raises new challenges in networks configuration and analysis. In order to estimate important network characteristics, when handling traffic from new apps, some improvements in existing evaluations methods have to be done. In this paper we summarize and classify known approaches for short range networks evaluations and suggest some modifications for them to take M2M, D2D and HetNets into account. In particular, we have to admit, that inter-cells interference and multi-channeling have to be noted, when talking about HetNets, saturated system analysis give a good enough approximation for number of supported M2M devices only when aggregation nodes are presented, and user mobility model have to be considered, when analysing Device-to-Device communications.

As illustrated in previous section, the best evaluation methodology to face these challenges is a combination of methods from different strategies: simulation, analysis and measurements. While a single approach from selected strategy can give a very rough estimation of network performance, combination of two or more methods from different strategies give much more accurate results.

Concluding, we have to admit, that besides extension of existing evaluation strategies for emerging applications analysis, there is another trend, when a novel method, originally proposed for a distinct use case, is further generalized to support conventional applications also. This might result in a new evaluation paradigm appearing in the next few years.

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