Analysis of Medium Access Control Protocols for Home Networks

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Abstract

Nowadays, there are many different home networking solutions: wired, wireless, and the so called "no new wires"; all competing for their share of the market. The most widely used metric to compare these technologies is the transmission, or line, rate. Nevertheless, this metric does not reflect the peculiarities of each MAC protocol, which limit the bandwidth actually available to users. In this article, we analyze different home networking technologies taking the main features of their MAC protocol into account. We choose the saturation throughput as the basic metric and provide analytical results. Then, through simulations, we vary the number of nodes in the network to see how each protocol deals with contention and analyze their efficiency. The results show that, generally, collision-avoidance protocols have lower efficiency than collision-detection protocols. Nevertheless, there may be exceptions. HomePNA 3.0 has a relatively low efficiency because it uses the same basic rate as HomePNA 2.0, to keep compatibility. The same happens within a protocol family, IEEE 802.11g at 54 Mbps is less efficient than IEEE 802.11b at 11 Mbps.

Key words: home networks, medium access control, throughput analysis.

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1 Introduction

Home networks aim to interconnect computers, network devices, and household appliances inside the houses, sharing Internet access and resources. Different technologies provide these home networking services. Home networks can be classified as wired, wireless, and “no new wires” [1]. Wired networks use special cables, which are not available in most homes. Wireless networks mainly use radio frequency to transmit data and do not use cables. Phone or power lines already deployed in the house can be used to create no new wires networks. As these networks do not require any new cabling infrastructure, costs may be reduced.

Concerning wired networks, Ethernet is a conventional solution, but most homes do not have the infrastructure needed. Additionally, the installation cost of new wires can be high. Fast Ethernet is presently being used where the required infrastructure is available, but Gigabit Ethernet may reach this niche as price goes down.

On the other hand, wireless networks are now a success with different products and technologies available. Even if the wireless technology is the best when dealing with mobility, there are problems related to performance, coverage, and quality of service guarantee, besides the classic security problem. IEEE 802.11 is the most widespread wireless technology. The 802.11 family includes several standards, which differ in the physical layer. IEEE 802.11b operates in the 2.4 GHz band and provides a maximum physical data rate of 11 Mbps. IEEE 802.11a supports physical data rates of up to 54 Mbps in the 5 GHz band. The most recent specification is IEEE 802.11g, which can reach up to 54 Mbps in the 2.4 GHz band.

In the last few years, the no new wires technologies received special attention due to their ubiquity and low cost infrastructure. Thus, there is a great effort, especially from the industry, to standardize home phoneline networks and home powerline networks.

The Home Phoneline Network Alliance (HomePNA) defined a standard for data transmission over home phonelines [2]. The HomePNA 2.0 standard supports physical data rates of up to 32 Mbps. Based on the second version, a new one called HomePNA 3.0 was specified. HomePNA 3.0 can use two kinds of Medium Access Control (MAC) protocols: an asynchronous (AMAC) and a synchronous (SMAC). HomePNA 3.0 can reach up to 128 Mbps, with an optional extension to 240 Mbps.

The Home Powerline Network Alliance (HomePlug) defined a standard for data transmission over home powerlines [3]. The HomePlug 1.0 standard supports physical data rates of 14 Mbps. A new standard called HomePlug AV is also being developed.

Home network applications range from the distribution of information (audio, video, and data) to the sharing of an Internet link. The main quality of service metric for many applications is the bandwidth. As a consequence, the marketing of a technology is frequently based on its transmission rate at the physical layer. Nevertheless, the physical layer rate may not be the most appropriate parameter to be taken into account since the link layer often limits the maximum throughput achievable. Considering shared medium technologies, different MAC protocols have different network efficiencies. Therefore, we aim to analyze the maximum throughput provided by the MAC sub-layer of different home network technologies that have in common the use of a contention protocol over a shared medium.

Several researchers investigate the performance of MAC sub-layer protocols for home networks.

The saturation throughput of the Ethernet was analyzed by several researchers. For instance, Wang and Keshav [4] present performance results through simulation while Boggs et al. [5] perform measurements on an Ethernet network.

Chung et al. [6] and Kangude et al. [7] present mathematical analyses of the saturation throughput of HomePNA 2.0. Kim et al. [8] performs a similar analysis for the HomePNA 3.0 AMAC.

Jun et al. [9], Xiao et al. [10], Anastasi et al. [11], and Wijesinha et al. [12] analyze the theoretical saturation throughput of IEEE 802.11, 802.11b, 802.11a, and 802.11g. Doufexi et al. [13] present a throughput performance evaluation for 802.11a and 802.11g through simulation in different conditions of radiowave propagation. The results are specific to the scenario, which includes an access point and other few nodes. Wijesinha et al. [12] present experimental results on a network of four nodes.

Lin et al. [1] and Jung et al. [14] present the theoretical saturation throughput of HomePlug 1.0. Lee et al. [15] analyze the throughput for HomePlug 1.0 through simulation on a network of only three nodes. Experimental results are presented by [1] and [15], but they only consider networks of a few nodes.

To the best of our knowledge, there is no work that makes a throughout comparison of the medium access control techniques used by the different home network technologies. Thus, the main objective of this paper is to analyze the peculiarities of the different techniques. We use mathematical analysis to evaluate the one-node maximum throughput of Ethernet, HomePNA 2.0 and 3.0 AMAC, IEEE 802.11b and g, and HomePlug 1.0. We verify our analyses by simulation. Then, we also evaluate the saturation throughput on scenarios with higher number of nodes.

The results show that, as expected, most collision-avoidance protocols have lower efficiency than the collision-detection protocols. Nevertheless, there may be exceptions, due to compatibility issues, which may force a part of the bits to be transmitted using a basic rate lower than the line transmission rate.

This paper is organized as follows. Section 2 describes the basic operation of the home network protocols. Section 3 presents mathematical analyses for the home network protocols. Section 4 reports simulation results. Finally, concluding remarks and future directions are presented in Section 5.

2 Home Network Protocols

In the following subsections, we give a brief overview of the MAC sub-layer and some physical layer characteristics of Ethernet, HomePNA, IEEE 802.11, and HomePlug. Detailed information can be found in [16,17,18,19,2,20,21,22,3].

2.1 The Ethernet Protocol

The Ethernet network uses Carrier Sense Multiple Access with Collision Detection (CSMA/CD) to control medium access. A station willing to transmit first senses the medium. If the medium is idle, after an inter-frame gap the station transmits the frame. If the medium is busy, the station continues to listen to the medium until it is idle and then, after an inter-frame gap, starts the frame transmission. During the transmission, the station senses the medium to detect collisions. If there is no collision, the frame is considered transmitted. If a collision is detected, the station stops the transmission and sends a jam signal. After the jam transmission, the station enters a binary exponential backoff phase. In this phase, after the nth collision, the station waits for a random number of slot times, ranging from 0 to 2^{n-1}, and then senses the medium again.

The Ethernet frame format is shown in Figure 1. The frame is composed of a preamble, destination and source addresses, a type field, data, and a Frame Check Sequence (FCS) using Cyclic Redundancy Check (CRC) [16]. If data field is less than 46 bytes, padding is used to reach 64 bytes, from the destination address to the FCS.

Ethernet evolved in the last years. Higher speed specifications like Fast Ethernet and Gigabit Ethernet came out [16]. These standards differ from the Ethernet in the physical layer but maintain frame format and minimum and maximum frame sizes to remain backward compatible with the Ethernet.

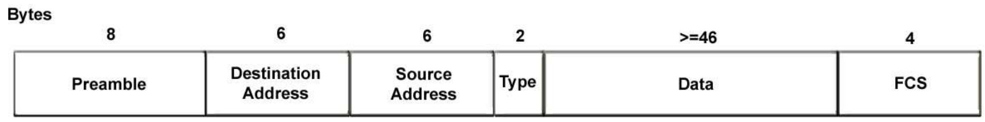

Figure 1. Ethernet frame format.

2.2 The HomePNA Protocol

The HomePNA 2.0 MAC protocol is based on the Ethernet CSMA/CD. HomePNA has a priority mechanism with eight levels of priority for QoS support. Different classes of traffic can be labeled with priorities from 0 to 7, where 7 is the highest one. Based on the frame priority, the transmission occurs in a specific time interval after an Inter-Frame Gap (IFG) of 29 μs, as shown in Figure 2.

Time intervals are organized in decreasing order of priority. Thus, higher priority frames are transmitted earlier, without contending with lower priority ones. The duration of each priority slot, PRI_SLOT, is 21 μs. Stations must transmit their frames at the beginning of the slot whose number is equal to or lower than the frame priority. Any transmission after slot 0 is considered to happen at slot 0.

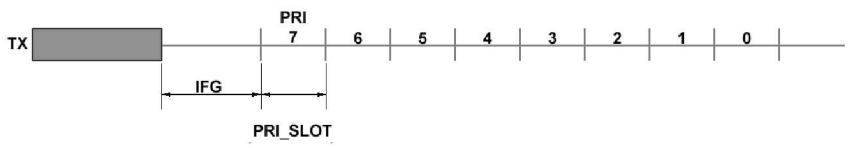

Figure 2. HomePNA priority slots.

Before transmission, the station senses the carrier and defers transmission if any carrier is detected before the time slot associated to the frame priority. In this case, the time slot counting is restarted after the medium is idle and after the IFG.

All stations monitor the medium to detect collisions of frames transmitted by other stations. A collision can be detected through the transmission duration. The minimum duration of a valid frame is 92.5 μs whereas the maximum duration is 3122 μs. Any station that detects a collision ceases transmitting no later than 70 μs after the beginning of this frame. Any frame fragment too short or too long is considered as a collision.

If there is a collision, all stations start a distributed collision resolution algorithm called Distributed Fair Priority Queuing (DFPQ) [23]. After the execution of the algorithm, all stations involved in the collision are ordered in

Backoff Levels (BL), which indicate the order these stations will transmit. The desired outcome is for only one station to be at BL 0, enabling this station to acquire the channel. After a successful transmission, all other stations decrement their BLs, and the new station(s) at BL 0 attempt transmission. All stations, even the ones not involved in the collision resolution procedure, monitor the activity on the medium to keep track of the Maximum Backoff Level (MBL). By monitoring the MBL, stations with frames that did not collide are not allowed to contend for access to the medium until all collided frames are transmitted successfully. The only exception is when a station has a frame with priority higher than the priority slot where the collision occurred. All stations must have 8 BLs and 8 MBL counters, one for each priority.

As shown in Figure 3, after a collision occurs, there are 3 special collision resolution signaling slots, numbered S0 to S2, before the priority slots. The BL and MBL counters are determined through these signaling slots. These slots have a duration of 32 μs, and are used only after a collision.

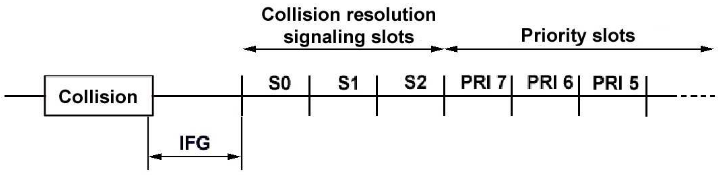

Figure 3. Collision resolution signaling slots.

After a collision, the stations involved in the collision resolution randomly choose a signaling slot to transmit a backoff signal. More than one station may transmit a backoff signal in the same signal slot. If a station involved in the collision listens a backoff signal in a slot before the one the station chose, the station increments its BL counter. The MBL counter is incremented for each backoff signal listened and decremented for each successful transmission occurs. The MBL counter is non-zero whenever a collision resolution cycle is in progress. The stations not involved in the collision resolution keep their BL counters equal to the MBL counters, these stations only transmit after the end of the collision resolution cycle.

The HomePNA standard can adaptively use payload transmission rates from 4 to 32 Mbps, according to the channel conditions. Nevertheless, the header and the trailer are always transmitted at 4 Mbps, with a more robust modulation and symbol rate to guarantee that all stations can receive these fields correctly. The format of the HomePNA frame is shown in Figure 4.

This frame format is based on the IEEE 802.3 Ethernet frame. The Ethernet frame is preceded by a preamble and a frame control field, and followed by CRC, padding, and end-of-frame fields. The padding is used when the transmission time of the complete frame is less than 92.5 μs to guarantee the minimum valid frame duration. The minimum frame duration is used to

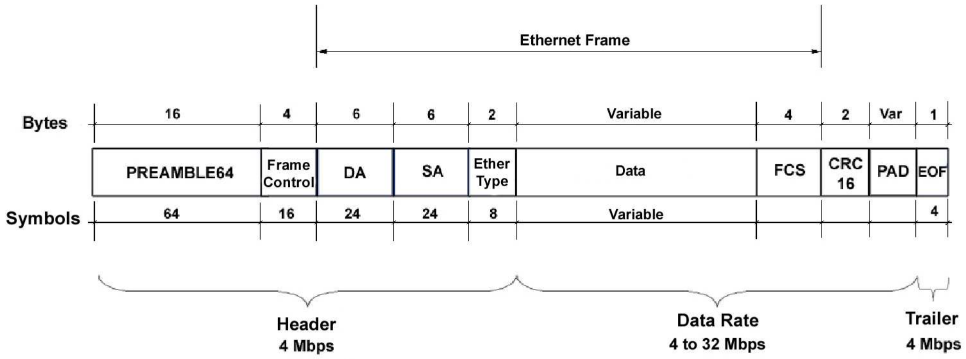

Figure 4. HomePNA frame format.

distinguish valid frames from collision fragments.

2.2.1 HomePNA 3.0

HomePNA 3.0 supports synchronous (SMAC) and asynchronous (AMAC) medium access control protocols. While HomePNA 2.0 supports up to 32 Mbps data transmissions, HomePNA 3.0 can reach 128 Mbps, with an extension that allows 240 Mbps [24].

The synchronous mode was created to offer a deterministic quality of service, which is not guaranteed by HomePNA 2.0. SMAC uses a master-slave mode with admission control mechanisms and resource reservation techniques. Moreover, SMAC also uses packet aggregation to improve the MAC protocol efficiency [25,26].

The asynchronous mode keeps compatibility with HomePNA 2.0. In order to reach higher rates, two changes were made. First, the transmission rate can reach up to 128 Mbps by using different QAM constellations and a higher bandwidth. Nevertheless, the basic transmission rate for the header fields and EOF is still 4 Mbps. Moreover, the AMAC mode does not use packet aggregation, keeping the maximum frame size of 1500 bytes.

The second difference to HomePNA 2.0 is a new collision management scheme to reduce the number of collisions. Each node is assigned a set of three predefined collision resolution slots, called A, B, and C. The collision management protocol guarantees that two nodes do not use the same set. Each slot A, B, or C can be defined as one of the existing collision resolution slots (S0, S1, or S2). When a collision occurs, the node will use the first slot (A) from its set. If another collision happens for the same frame, the node will use the slot B. In the case of a third collision, slot C is used. As there is no slot sets repetition, each frame will collide at most three times, and after the third collision, every frame will be transmitted. This technique reduces the number of collisions and improves the network efficiency, but limits the number of nodes in the network to 27, which is the number of different sets.

Figure 5 shows an example of a collision resolution process between 27 nodes in HomePNA 3.0. The nodes are represented by H0 to H26, and C1 to C13 represent the collision, in order of occurrence. The slots sets for each node are represented in the collision sequence. Thus, the set for H15, for example, is (S1, S2, S0). Note that in HomePNA 3.0 AMAC a collision is resolved in 3 levels at most, what guarantees that no frame will collide more than 3 times. Thus, a finite medium access time is guaranteed, while in HomePNA 2.0 this finite medium access time was not deterministic, as there was a probability that frames could collide indefinitely.

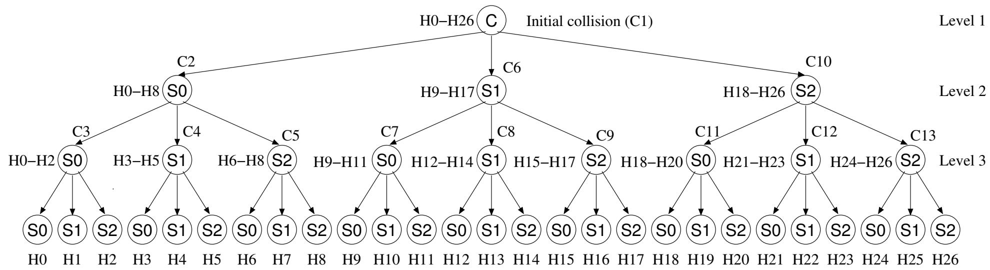

Figure 5. Collision resolution between 27 nodes in HomePNA 3.0.

2.3 The IEEE 802.11 Protocol

The IEEE 802.11 MAC protocol specifies two medium access algorithms: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is a distributed mechanism, in which each node senses the medium and transmits if the medium is idle. On the other hand, PCF is a centralized mechanism, where an access point controls medium access. Therefore, this mechanism is designed for infrastructured networks.

The DCF function uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and positive acknowledgments (Figure 6). A station that wants to transmit first senses the medium. If the medium is idle for at least a time called Distributed Inter-Frame Space (DIFS), the station transmits. Else, the transmission is postponed and a backoff process is initiated. A station chooses a random number distributed between zero and the Contention Window (CW) size and starts a backoff timer. This timer is periodically decremented by a slot time after the medium is sensed idle for more than DIFS. The backoff timer is paused when a transmission is detected. If the medium gets idle for DIFS again, the station resumes its backoff timer. When the timer expires, the station sends its frame.

The receiver uses CRC for error detection. If the frame seems to be correct,

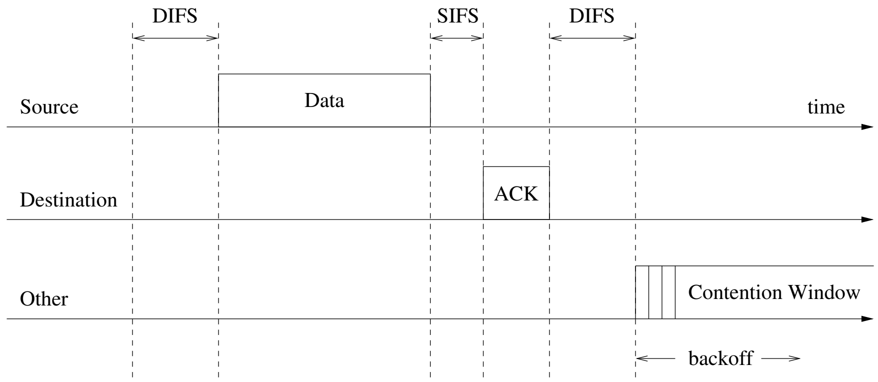

Figure 6. Transmission of a data frame using the IEEE 802.11 protocol.

the receiver sends an acknowledgment frame (ACK) after sensing the medium idle for a period of time called Short Inter-Frame Space (SIFS). By definition, SIFS is smaller than DIFS. If the sender does not receive the ACK, it schedules a retransmission and enters the backoff process. To reduce the collision probability, the contention window starts with a minimum value given by CW_{min}. After each unsuccessful transmission, the contention window increases to the next power of 2 minus 1, until reaching a maximum predefined value called CW_{max}. CW_{min} and CW_{max} values depend on the physical layer used. Moreover, if a maximum number of retransmissions is reached, the frame is dropped. To avoid medium capture, prior to transmitting another frame the sending station will enter the backoff phase.

The DCF method also optionally uses Request to Send (RTS) and Clear to Send (CTS) frames to avoid the hidden terminal problem [20].

The format of the IEEE 802.11 data frame in a fully connected ad hoc network is shown in Figure 7. The frame is composed of frame control, duration, three addresses, sequence number, data, and FCS fields. Only three addresses are used in a fully connected ad hoc network. A general data frame format may include a forth address in other network configurations.

Bytes	2	2	6	6	6	2	>= 0	4
	Frame Control	Duration	Address	Address	Address	Sequence	Data	FCS

Figure 7. IEEE 802.11 frame format.

ACK frames have frame control, duration, one address, and FCS fields.

The original IEEE 802.11 uses the 2.4 GHz band and supports 1 and 2 Mbps data transmission rates. IEEE 802.11b [21] also uses the 2.4 GHz band and supports up to 11 Mbps using DSSS (Direct Sequence Spread Spectrum). IEEE 802.11a [27] uses the 5 GHz band and defines up to 54 Mbps data rates using OFDM (Orthogonal Frequency Division Multiplexing). IEEE 802.11g [22] uses OFDM in the 2.4 GHz band and supports 54 Mbps.

The physical layer is composed of two sub-layers: A physical layer convergence sub-layer and a physical medium dependent sub-layer. The physical layer convergence sub-layer is supported by the Physical Layer Convergence Protocol (PLCP). Different PLCPs are defined for each IEEE 802.11 extension.

The IEEE 802.11 extensions have short and long PLCP Protocol Data Unit (PPDUs). Long PPDUs are used for backward compatibility. The long PPDU for the 11 Mbps HR-DSSS (High Rate - DSSS) 802.11b, which is mandatory, is shown in Figure 8.

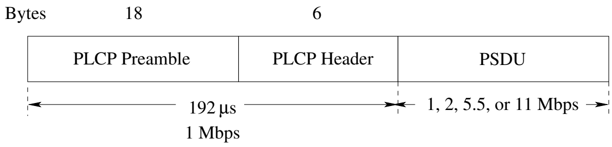

Figure 8. Long PLCP PPDU for 11 Mbps HR-DSSS 802.11b.

The PPDU for 802.11g using the 54 Mbps ERP-OFDM (Extended Rate PHY - OFDM) is shown in Figure 9.

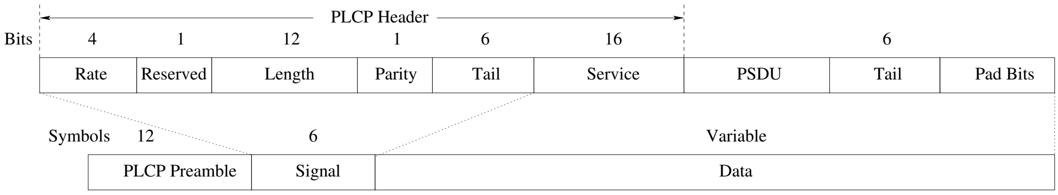

Figure 9. PLCP PPDU for 54 Mbps ERP-OFDM 802.11g.

2.4 The HomePlug Protocol

Similarly to IEEE 802.11, HomePlug 1.0 uses CSMA/CA. CSMA with collision avoidance is needed because it is not possible to guarantee collision detection over the electrical wiring. This is due to attenuation and noise, which can produce signal variations similar to collisions [15].

In order to provide quality of service, the standard defines four priority levels in the medium access. These levels are assigned according to the type of traffic, as standardized in IEEE 802.1D [28]. The priorities are associated to classes ranging from CA0 to CA3, where CA3 is the highest priority. These classes are known as channel access priority classes (CAP).

To avoid collisions, every station must sense the medium before transmitting a data frame. To detect if the medium is busy, the stations use Physical Carrier Sense (PCS) and Virtual Carrier Sense (VCS). Using only PCS, a node cannot assure whether there is another ongoing transmission [15]. The physical layer reports the physical carrier sense by detecting preambles or priority slot assertions. The MAC sub-layer uses virtual carrier sense to determine the transmission duration of the frame "listened" in order to establish an allocation vector. Stations only contend for the medium after the expiration of their allocation vectors.

When the medium is idle for CIFS (*Contention distributed Inter-Frame Space*), a time interval of 35.84 μs, the station starts the priority resolution phase. Otherwise, if a station is waiting for CIFS and the medium gets busy, it waits again for the medium to become idle for CIFS. Two time slots are used during the priority resolution (PR) assertions, in order to restrict the contention period only to stations with higher priority flows (Figure 10).

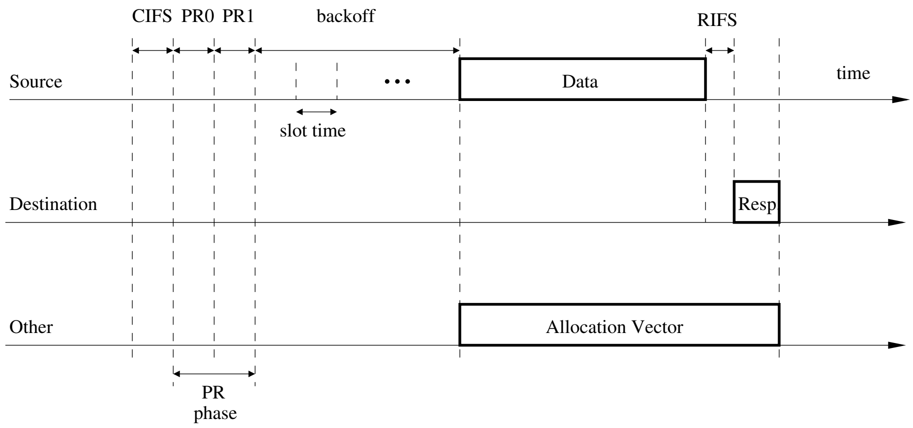

Figure 10. Transmission of a data frame using HomePlug.

The priority resolution occurs before the contention period through the signals called PRSs (*Priority Resolution Signals*). The priority resolution signals use *on-off* modulation, where the number of each class is represented by a binary signal sent at the priority resolution periods, PR0 (*Priority Resolution 0*) and PR1 (*Priority Resolution 1*) [29]. Therefore, when a bit 1 at PR0 is sent, every station with frames from classes lower than CA2 postpone its transmission, and wait for the medium to become idle for another CIFS time units. The PR0 and PR1 time slots have the same duration of CIFS.

During the contention period, a station chooses a random number uniformly distributed between zero and the Contention Window (CW) size. This number is used as a backoff counter and will be decreased whenever the medium is idle. To decrement the backoff counter by one, the medium must be idle for a time slot of 35.84 μs. Similarly to IEEE 802.11, the backoff procedure is responsible for the increase of the contention window size. The CW size depends on the number of times the backoff procedure is called during the transmission of one single frame. The backoff procedure is called every time a transmission is not well succeeded or when, during backoff, a Deferral Counter (DC) reaches zero and the station senses another ongoing transmission. The Deferral Counter is a mechanism conceived to avoid collisions. DC is decremented whenever a contending station senses that the medium was captured by another station with same priority flow. When DC reaches zero, the node assumes that there is a considerable number of stations trying to transmit, which increases the collision probability. Thus, a station must call the backoff procedure when it senses that the medium was captured again.

Upon the reception of a frame, the receiver verifies whether the transmitter wants a response. If it does, the receiver waits for RIFS (*Response Inter-Frame Space*) before sending a response. The response can be an ACK (*Acknowledgment*), when a well-succeeded reception occurs; a NACK (*Negative Acknowledgment*), when an error was detected but could not be corrected; or a FAIL, if a frame could not be stored due to lack of space in the buffer.

The electrical wiring may irradiate as an antenna. Hence, privacy is an important issue and must be taken into account by HomePlug. The HomePlug standard uses an 8-byte block size encryption algorithm, which is applied over the ether type, data and ICV fields (Figure 11). The ECtl field defines the encryption parameters and the EPad field is needed to guarantee that the encrypted portion is a multiple of 8 bytes.

The format of the HomePlug data frame is presented in Figure 11.

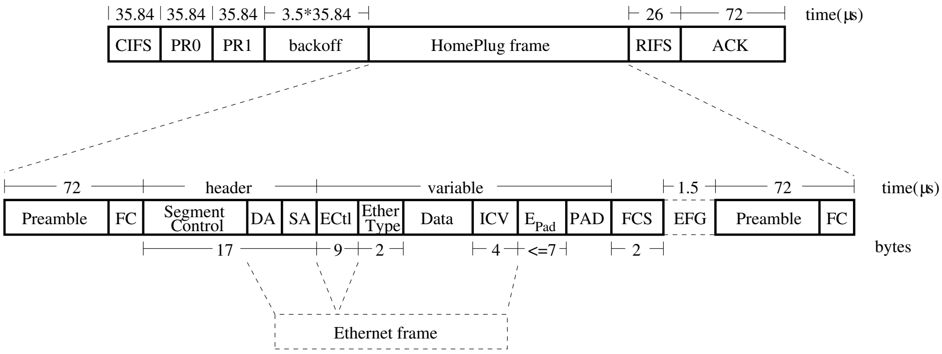

Figure 11. HomePlug frame format.

The HomePlug 1.0 standard uses a spectral band that goes approximately from 4.49 to 20.7 MHz. HomePlug uses OFDM (*Orthogonal Frequency Division Multiplexing*) dividing the band from 0 to 25 MHz into 128 subcarriers evenly spaced, from which only 84 are used, because the others fall outside the spectral band of HomePlug. Additionally, another 8 subcarriers may be disabled to avoid interference with amateur bands, leaving only 76 subcarriers for utilization. The duration of the OFDM symbol is 8.4 μs.

The physical payload of HomePlug consists of a number of blocks with 20 or 40 OFDM symbols each, encoded on a link-by-link basis using a Reed-Solomon code concatenated with a convolutional code. The division that generates these block sizes is used to avoid the impulsive noise that can damage symbol sequences. Especially when differential modulation is used, where at least 2 symbols are lost at a time, the damage can be more severe. The convolutional encoder has constraint length 7 and code rates of $\frac{1}{2}$ or $\frac{3}{4}$, selected during the channel adaptation. The Reed-Solomon code, which is used after the convolutional code, has coding rates ranging from $\frac{23}{39}$ to $\frac{238}{254}$.

Taking the transmission parameters described above into account, the physical layer can offer up to 139 different rate combinations, ranging from 1 to 14 Mbps.

Besides the mentioned transmission modes, there is a special mode called ROBO (*ROBust* OFDM). This mode has greater redundancy to operate under noisy situations. The ROBO mode uses a DBPSK (*Differential Binary Phase Shift Keying*) modulation, with a redundancy level that reduces the symbol rate to $\frac{1}{4}$ bit/symbol/subcarrier. It also uses a *Reed-Solomon* code with different code rates that ranges from $\frac{31}{39}$ to $\frac{43}{51}$. These parameters reduce the maximum transmission rate to 0.9 Mbps.

3 Mathematical Analysis

Home network applications, like video, demand high transmission rates, but physical layer rate is not the most appropriate parameter when analyzing network suitability for these applications. The efficiency provided by the MAC protocols must be used for these analyses. This section provides the mathematical analysis of the maximum throughput that can be obtained using the four different home network technologies considered in this article. In the analysis, the following assumptions were made:

- A single active session (i.e., a sender-receiver couple active) is used.
- Bit error rate is zero.
- Propagation delay is not considered.
- Sending node always has a frame ready to be sent.
- The MAC sub-layer does not use fragmentation.
- Management frames are not taken into account.

In the rest of the analysis, we use the notations given in Table 1.

The throughput (Th) is calculated by dividing the size of the MAC SDU by its transmission time (T). Depending on the size of the MAC SDU, padding

Table 1
Notations used throughout the mathematical analysis.

C_{ERR}	Error correction code rates.
CW_{min}	Minimum contention window size.
L_{ACK}	ACK size (in bytes).
L_{DATA}	Payload size (in bytes).
L_{EPad}	Encryption padding size (in bytes).
L_{IFG}	Inter-frame gap size (in bits).
L_{PAD}	Padding size (in bytes).
N_{BSS}	Number of bits per symbol per subcarrier (in bits).
N_{DBS}	Number of data bits per symbol (in bits).
N_{SC}	Number of subcarriers.
N_{SYM}	Number of symbols.
N_{SPB}	Number of symbols per block.
P	Priority.
R_{CTL}	Physical control rate (in Mbps).
R_{DATA}	Physical data rate (in Mbps).
T_{ACK}	Transmission time of the acknowledgment (in μs).
T_{CIFS}	CIFS time (in μs).
T_{DIFS}	DIFS time (in μs).
T_{EFG}	Transmission time of the end of frame gap (in μs).
T_{EXT}	Signal extension (in μs).
T_{IFG}	Transmission time of the inter-frame gap (in μs).
T_{PHY}	Transmission time of the physical preamble and header (in μs).
T_{PR}	Priority resolution time (in μs).
T_{RIFS}	RIFS time (in μs).
T_{slot}	Slot time (in μs).
T_{SIFS}	SIFS time (in μs).
T_{SYM}	Transmission time of a symbol (in μs).

may be used.

3.1 Fast Ethernet

First, we analyze the maximum throughput of the Ethernet. According to Figure 1, the total transmission time of an Ethernet frame is:

$$T_{Ether} = \frac{(L_{DATA} + L_{PAD} + 26) \times 8 + L_{IFG}}{R_{DATA}} \ \mu s. \tag{1}$$

If $L_{DATA} < 46$, $L_{PAD} = 46 - L_{DATA}$. For the Fast Ethernet, $R_{DATA} =$ 100 Mbps, $L_{IFG} = 96$ bits, and the throughput is given by:

$$Th_{Ether100} = \frac{L_{DATA} \times 8}{\frac{304+8\times(L_{DATA}+L_{PAD})}{100}} \ Mbps. \tag{2}$$

The throughput achieved varies with the frame size. Table 2 shows throughput values for different payload sizes.

Table 2
Throughput of the Fast Ethernet.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	72.46	92.94	95.95	97.16	97.53

3.2 HomePNA 2.0 and 3.0

Now, we compute the maximum throughput of HomePNA. We only consider the HomePNA 2.0 and the HomePNA 3.0 AMAC, because SMAC uses a Master-Slave configuration where there is no contention for the medium.

Based on Figures 2 and 4, the total transmission time of a HomePNA frame is:

$$T_{HPNA} = T_{IFG} + (7 - P) \times 21 + \frac{35 \times 8}{4} + \frac{(L_{DATA} + L_{PAD} + 6) \times 8}{R_{DATA}} \ \mu s. \tag{3}$$

$$T_{HPNA} = 29 + (7 - P) \times 21 + 70 + \frac{(L_{DATA} + L_{PAD} + 6) \times 8}{R_{DATA}} \ \mu s. \tag{4}$$

Then the throughput for HomePNA is:

$$Th_{HPNA} = \frac{L_{DATA} \times 8}{246 - 21 \times P + \frac{48+8\times(L_{DATA}+L_{PAD})}{R_{DATA}}} \; Mbps. \tag{5}$$

If the transmission time of the frame is lower than 92.5 μs, L_{PAD} is the smallest number that guarantees that the transmission time is at least 92.5 μs.

Table 3 gives the throughput values obtained with HomePNA 2.0 for different payload sizes assuming the highest priority, i.e., $P = 7$.

Table 3
Throughput of the 32 Mbps HomePNA 2.0 with $P = 7$.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	6.37	17.74	22.12	24.44	25.24

For HomePNA 3.0 using the AMAC mode, Table 4 shows throughput values for different payload sizes with $P = 7$.

Table 4
Throughput of the 128 Mbps HomePNA 3.0 with $P = 7$.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	7.57	30.62	46.27	57.58	62.14

3.3 IEEE 802.11

In the analysis of the IEEE 802.11, we consider the basic access mechanism (DCF) using 802.11b and 802.11g. The approach can be easily applied to the RTS/CTS mechanism and to the other extensions.

For IEEE 802.11b, according to Figures 6, 7, and 8, the total transmission time of a frame is:

$$\begin{aligned} T_{802.11b} = {} & T_{DIFS} + \frac{CW_{min}}{2} \times T_{slot} + T_{PHY} + \frac{(L_{DATA}+28)\times 8}{R_{DATA}} + \\ & T_{SIFS} + T_{PHY} + \frac{L_{ACK} \times 8}{R_{CTL}} \; \mu s. \end{aligned} \tag{6}$$

Replacing the values for the IEEE 802.11b using the 11 Mbps HR-DSSS [21], Equation 6 becomes:

$$T_{802.11b} = 50 + (\frac{31}{2} \times 20) + 192 + \frac{(L_{DATA} + 28) \times 8}{11} + 10 + 192 + \frac{14 \times 8}{1}\ \mu s. \quad (7)$$

Then the throughput for IEEE 802.11b is:

$$Th_{802.11b} = \frac{L_{DATA} \times 8}{866 + \frac{224 + 8 \times L_{DATA}}{11}}\ Mbps. \quad (8)$$

Table 5 shows throughput values for different payload sizes.

Table 5
Throughput of the 11 Mbps HR-DSSS 802.11b.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	0.83	3.20	4.67	5.68	6.07

For the ERP-OFDM 802.11g, according to Figures 6, 7 and 9, and using a ceiling function to handle the padding bits, the total frame transmission time is:

$$T_{802.11g} = T_{DIFS} + \frac{CW_{min}}{2} \times T_{slot} + T_{PHY} + N_{SYM} \times T_{SYM} + T_{EXT} + T_{SIFS} + T_{PHY} + \left\lceil \frac{16 + 8 \times L_{ACK} + 6}{N_{DBS}} \right\rceil \times T_{SYM} + T_{EXT}\ \mu s. \quad (9)$$

The number of symbols, N_{SYM}, depends on the number of data bits per symbol, N_{DBS}, as shown in Equation 10.

$$N_{SYM_{802.11g}} = \left\lceil \frac{16 + 8 \times (L_{DATA} + 28) + 6}{N_{DBS}} \right\rceil. \quad (10)$$

Substituting the values for the 54 Mbps 802.11g [22], Equation 9 can be rewritten as:

$$T_{802.11g} = 50 + \frac{15}{2} \times 20 + 20 + \left\lceil \frac{16 + 8 \times (L_{DATA} + 28) + 6}{216} \right\rceil \times 4 + 6 + 10 + 20 + \left\lceil \frac{16 + 8 \times 14 + 6}{24} \right\rceil \times 4 + 6\ \mu s. \quad (11)$$

Then the throughput for IEEE 802.11g is given by:

$$Th_{802.11g} = \frac{L_{DATA} \times 8}{286 + \left\lceil \frac{246+8\times L_{DATA}}{216} \right\rceil \times 4} \ Mbps. \quad (12)$$

Table 6 shows throughput values obtained with IEEE 802.11g for different payload sizes.

Table 6
Throughput of the 54 Mbps ERP-OFDM 802.11g.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	2.61	10.93	16.90	21.40	23.35

3.4 HomePlug 1.0

Finally, in this section the throughput of HomePlug 1.0 is analyzed. According to Figures 10 and 11, the time needed to transmit a HomePlug frame is:

$$\begin{aligned} T_{Hplug} = T_{CIFS} + T_{PR} + \frac{CW_{min}}{2} \times T_{slot} + T_{PHY} + N_{SYM} \times T_{SYM} + \\ T_{EFG} + T_{PHY} + T_{RIFS} + T_{ACK} \ \mu s. \end{aligned} \quad (13)$$

All stations must receive the delimiters as well as the priority resolution signals correctly, therefore they are sent using all the subcarriers, with the same modulation and codification.

The number of symbols, N_{SYM}, depends on the number of bits per symbol per subcarrier N_{BSS}, on the number of subcarriers N_{SC}, on the error correction codes C_{ERR}, and on the number of symbols per block N_{SPB}, as shown in Equation 14. Data are transmitted into 20 or 40 OFDM symbol transmission blocks. Thus, the number of blocks must be rounded up.

The number of symbols is given by:

$$N_{SYM_{Hplug}} = \left\lceil \frac{1}{N_{SPB}} \times \frac{(L_{DATA} + 34 + L_{EPad}) \times 8}{N_{BSS} \times N_{SC} \times C_{ERR}} \right\rceil \times N_{SPB}. \quad (14)$$

The encryption padding size is calculated as shown in Equation 15.

$$L_{EPad} = \left\lceil \frac{L_{DATA}}{8 \times 8} \right\rceil \times 8 - \frac{L_{DATA}}{8} \ bytes. \quad (15)$$

For the maximum throughput, we have $N_{BSS} = 2$ bits/symbol/subcarrier, $N_{SC} = 84$ subcarriers, $C_{ERR} = \frac{3}{4} \times \frac{238}{254}$, and $N_{SPB} = 20$ symbols per block [30]. Then, Equation 13 can be rewritten as:

$$\begin{aligned} T_{Hplug} = {} & 35.84 + 2 \times 35.84 + \frac{7}{2} \times 35.84 + 72 + \\ & \left\lceil \frac{1}{20} \times \frac{(L_{DATA} + 34 + L_{EPad}) \times 8}{118.06299} \right\rceil \times 20 \times 8.4 + \\ & 1.5 + 72 + 26 + 72 \ \mu s. \end{aligned} \tag{16}$$

The throughput for HomePlug is given by:

$$Th_{Hplug} = \frac{L_{DATA} \times 8}{476.46 + \left\lceil \frac{272 + 8 \times (L_{DATA} + L_{EPad})}{2361.2598} \right\rceil \times 168} \ Mbps. \tag{17}$$

Table 7 shows throughput values for different payload sizes.

Table 7
Throughput of the HomePlug.

Payload size (bytes)	100	500	900	1300	1500
Throughput (Mbps)	1.24	4.92	6.27	7.90	8.08

These mathematical analyses considered two-node networks where there is one sender and one receiver. In order to evaluate the throughput on more realistic scenarios using networks with a higher number of nodes, we used simulation models.

4 Simulation Results

The network simulator (ns-2) version 2.26 [31] was used in the simulations. The simulation modules implemented for HomePNA and HomePlug were developed in C++ and oTcl.

The simulations of the different protocols are divided into two sets. The first simulations compare the throughput expected from the mathematical analysis to the results obtained with the simulator modules. The second simulation set analyzes the protocol throughput for varying numbers of nodes in the network.

The network offered load is produced by one node, which sends frames continuously, i.e., the node always has a frame to send as soon as the medium gets idle. In the graphs, the theoretical results are represented by continuous lines whereas the simulation results are plotted with points. The payload of the frames ranges from 160 to 1500 bytes. Each simulation run lasts for 100 seconds.

For the second simulation set, number of senders in the network ranges from 1 to 30. The payload size used is 1500 bytes. Again, each simulation run lasts for 100 seconds. To obtain the maximum occupation of the network, all sender nodes try to transmit frames without interruption. Thus, whenever the medium is idle, all stations will try to transmit causing collisions and triggering the collision resolution process. These simulations investigate the behavior of the different MAC protocols when collisions happen.

The graphs have vertical error bars corresponding to a confidence interval of 98% relative to the average samples.

We evaluated the maximum throughput for Fast Ethernet, HomePNA 2.0 and 3.0, IEEE 802.11b and 802.11g, and HomePlug 1.0. We also obtained the efficiency of each protocol dividing its throughput by its respective physical data rate.

4.1 Fast Ethernet

The Ethernet module provided by ns-2 had to be modified in order to take the Ethernet preamble and CRC into account.

Figure 12 presents the maximum throughput of Fast Ethernet. The throughput increases as the payload size raises. Ethernet efficiency reaches 97.5% when payload size is 1500 bytes. Moreover, we can say that the simulated model reproduces the behavior of the analytical model.

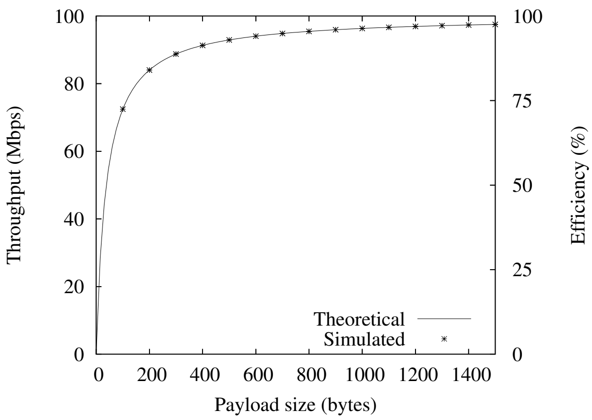

Figure 12. Throughput of Fast Ethernet for different payload sizes.

An analysis related to the Fast Ethernet performance when varying the number of nodes is also performed. In Figure 13, throughput decreases as the number of nodes increases, but even with 30 nodes transmitting at the same time, throughput is higher than 70 Mbps, or approximately 70% of the data transmission rate.

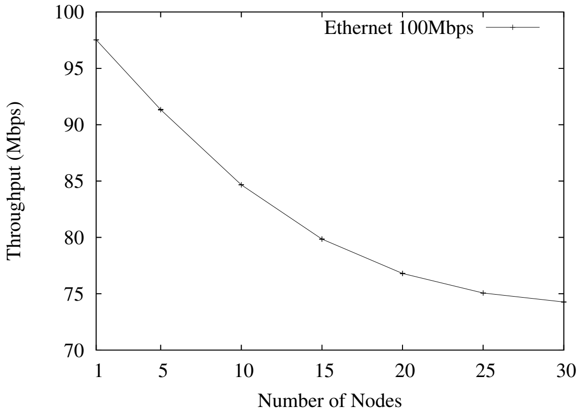

Figure 13. Throughput of Fast Ethernet for varying number of sources.

4.2 HomePNA

The HomePNA module is based on the Ethernet module available in ns-2. Besides the differences between the access methods of HomePNA and Ethernet, the priority and collision resolution functionalities, which are specific to HomePNA were implemented [32]. Moreover, we implemented a simplified physical layer, which has a propagation delay of 4 μs, the same value used by the Ethernet simulation module. We implemented simulation modules for both HomePNA versions 2.0 and 3.0.

The first simulations verified the HomePNA module operation. All stations transmit using the highest priority, 7. Figure 14 presents the throughput obtained for varying frame sizes. Note that the simulation results reproduce the mathematical model.

The second simulation set evaluates the network throughput with 1 to 30 nodes sending 1500-byte frames. The physical layer transmission capacity is 32 Mbps.

Figure 15 plots the throughput obtained by the HomePNA 2.0 module. Note that the throughput tends to stabilize for a high number of nodes. This is due to the collision resolution algorithm of HomePNA, which produces a number of collisions proportional to the number of initially collided frames. For a large number of nodes in the network, a group of $3n$ nodes that collided tend to be divided into three sets with n nodes each. If each group of n nodes collide C times in average, the whole group (with $3n$ nodes) collide $3C + 1$ times, which

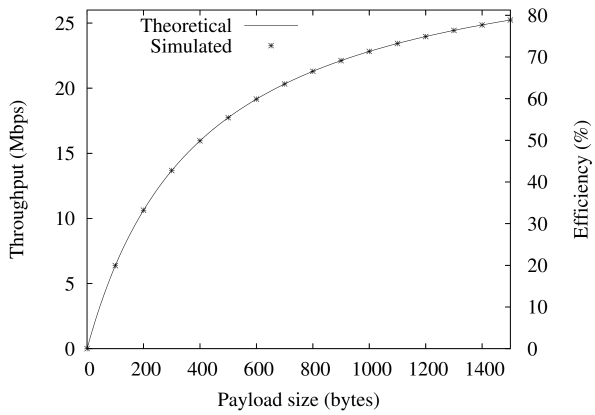

Figure 14. Throughput of HomePNA 2.0 for different payload sizes.

is $3C$ for large C. Therefore, for large n, the collision resolution mechanism is linear, i.e., the number of collisions needed to solve the initial collision is proportional to the number of stations involved in the initial collision. Then, we can show that the throughput tends to a constant for large number of nodes [32]. For 1500-byte frames and a large number of nodes, the aggregated throughput of the network is 17.7 Mbps, or 55.3% of the physical data rate.

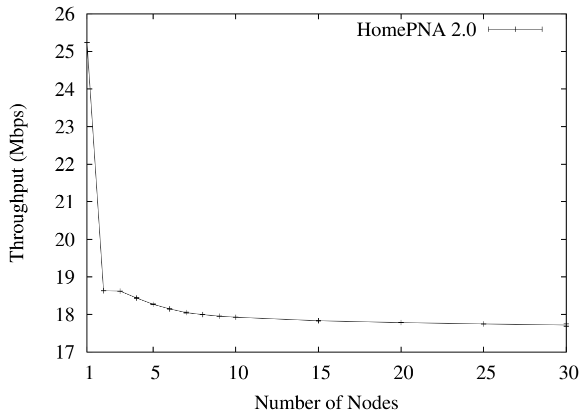

Figure 15. Throughput of HomePNA 2.0 for varying number of sources.

4.2.1 HomePNA 3.0

For the simulation of HomePNA 3.0, the number of nodes in the network varies from 1 to 27, the maximum number of nodes allowed by the 3.0 standard. The physical layer transmission rate is 128 Mbps. The slot sets used for the resolution of collisions are randomly chosen by each node. All nodes in the network have the highest priority, 7, to obtain the maximum throughput.

Figure 16 presents the throughput obtained by HomePNA 3.0 with 128 Mbps physical rate for varying frame sizes. Small frames present the smallest throughput, for 160-byte frames the throughput is as low as 5 Mbps. The maximum throughput is 62.1 Mbps using 1500-byte frames, which gives an efficiency of 48.5%. The small efficiency is due to the low basic rate used for backward compatibility to transmit the headers and end of frames, in comparison with the 128 Mbps data transmission rate.

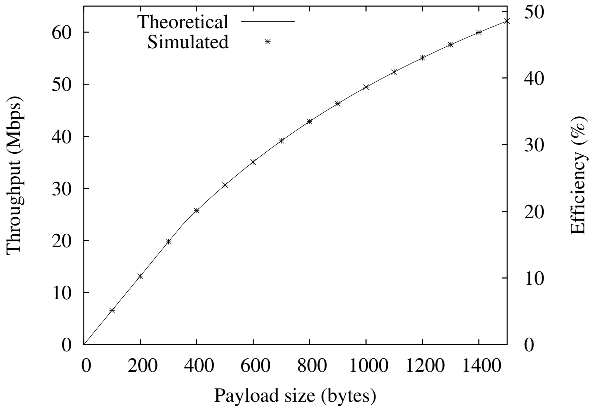

Figure 16. Throughput of HomePNA 3.0 for different payload sizes.

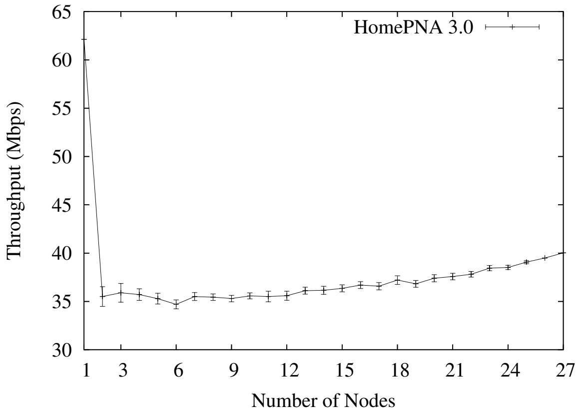

Figure 17. Throughput of HomePNA 3.0 for varying number of sources.

Figure 17 shows the throughput using the 128 Mbps physical transmission rate, 1500-byte frames, and a varying number of nodes. We can note that, as opposed to HomePNA 2.0, where the throughput tends to a constant for large number of nodes, for HomePNA 3.0 the throughput increases with the number of nodes. The maximum throughput is reached for 27 nodes. This is due to the collision management protocol, which reduces the number of collisions per frame transmitted for large numbers of nodes, as shown in [8].

Figure 17 also shows a huge difference between the physical layer transmission rate and the maximum throughput obtained. For more than one node, the throughput falls to approximately half the one-node throughput, or 34.7 Mbps. In HomePNA 2.0, as soon as a collision is detected, the frame transmission is stopped. The same is valid for HomePNA 3.0. But to keep compatibility, HomePNA 3.0 uses the same collision resolution slot times and minimum frame duration as HomePNA 2.0. Thus, the time spent with one collision is longer than the time spent with the transmission of one frame at 128 Mbps in HomePNA 3.0, reducing its efficiency.

4.3 IEEE 802.11

We modified ns-2 to implement IEEE 802.11g and used the 802.11b module available in ns-2. The simulation scenarios are composed of stations inside the same transmission range resulting in a fully connected ad hoc network. We used the free space model to calculate attenuation and we considered a null channel error probability.

First, we run simulations to evaluate the maximum throughput obtained by IEEE 802.11 for different payload sizes. The simulation scenarios have only one kind of node, either 802.11b nodes or 802.11g nodes. The scenario is composed of one source and one destination. The IEEE 802.11b station uses the 11 Mbps HR-DSSS and IEEE 802.11g station uses the 54 Mbps ERP-OFDM. Figures 18 and 19 plot the maximum throughput for varying payload sizes using IEEE 802.11b and 802.11g, respectively. The results obtained by the IEEE 802.11b module agree with the mathematical analysis. Besides, the results of IEEE 802.11g confirm the computed throughput.

The efficiency of IEEE 802.11b is higher than IEEE 802.11g because the overhead of 802.11b is proportionally smaller. Using 1500-byte frames, 802.11b has an efficiency around 55% whereas 802.11g efficiency is below 45%. IEEE 802.11g transmits data at 54 Mbps with a basic rate of 6 Mbps where 802.11b uses 11 Mbps and 1 Mbps, respectively. On the other hand, 802.11g uses the same SIFS time, the same slot time, and maximum CW. Only the minimum CW value is reduced from 31 to 15. Therefore, to have the same efficiency as 802.11b, 802.11g should have reduced the medium access times correspondingly, which is not the case. Nevertheless, the standard defines an optional version of 802.11g, called 802.11g Short Slot Time, which provides higher throughput by reducing the slot time from 20 to 9 μs.

In the next simulations, the number of nodes in the network is varied. Again, the networks have only 802.11b or only 802.11g nodes. Figures 20 and 21 show the throughput obtained by IEEE 802.11b and 802.11g, respectively. The frame size is 1500 bytes and the transmission rates are 11 Mbps for IEEE 802.11b stations and 54 Mbps for IEEE 802.11g stations. As the number of stations increases, the throughput decreases due to a higher number of collisions. It is worth noting that the throughput gets higher when the number of sources varies from one to 3 nodes. This happens because the initial contention window (CW_{min}) size is too large adding more idle slots than

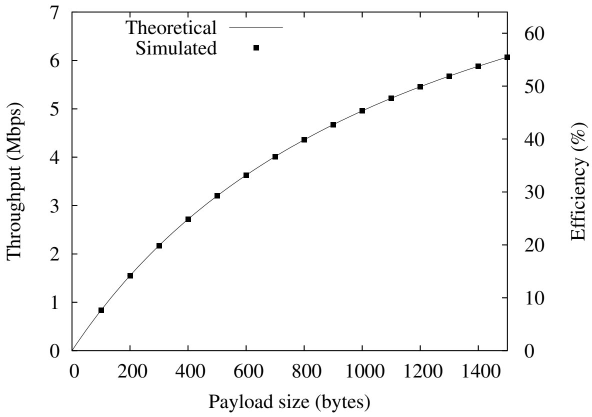

Figure 18. Throughput of IEEE 802.11b for different payload sizes.

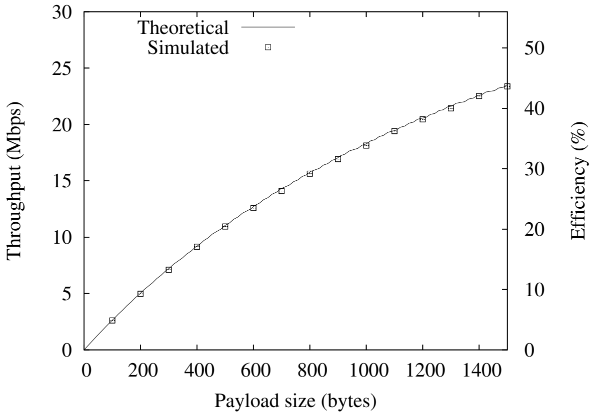

Figure 19. Throughput of IEEE 802.11g for different payload sizes.

needed. When the number of sources increases until 3 sources, the contention for the medium reduces the average number of idle slots therefore increasing the throughput. When the number of nodes is higher than 3, the throughput decreases due to the increase in collisions, although the number of idle slots is no longer high.

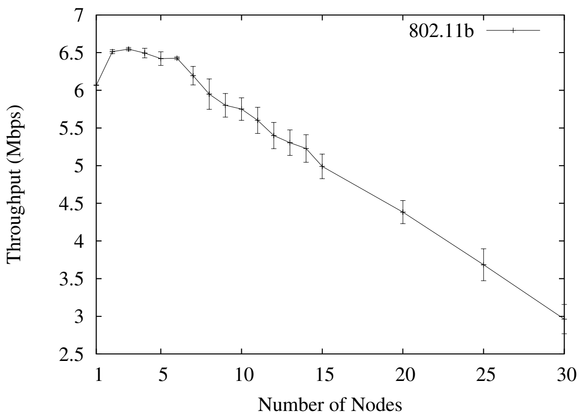

Figure 20. Throughput of IEEE 802.11b for varying number of sources.

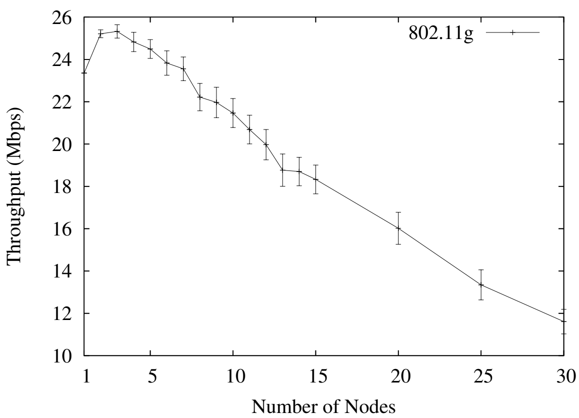

Figure 21. Throughput of IEEE 802.11g for varying number of sources.

4.4 HomePlug 1.0

We implemented two HomePlug 1.0 modules for ns-2, the physical layer model and the MAC sub-layer [33]. The MAC module is based on the HomePlug version 1.0 standard. To calculate the attenuation we introduced the echo model presented in [30] to model the physical layer. Due to a series of ramifications that an electrical network may have and due to reflections caused by impedance mismatches, the transmitted signal may be received from multiple paths. Depending on the path, the attenuation can be higher reducing the influence of some components at the receiver. Thus, the echo model consists of the sum of all the signals that reach the receiver, which may be out of phase and have different amplitudes.

The echo model computes a transfer function that varies with frequency. This function may also vary with time as devices are turned on and off. Some parameters depend on the physical characteristics of the electrical wires and on the network topology. The simulations used a channel that presents the best behavior among the examples provided by Langfeld [34]. The echo model neither varies in time nor models the noise, being restricted to the attenuation.

In the simulations, we configured the module with the equation parameters for maximum throughput as we did in the mathematical analysis. These are the number of subcarriers (84 subcarriers), the redundancy introduced by the error correction codes (the $\frac{3}{4}$ from the convolutional encoder and the $\frac{238}{254}$ from Reed-Solomon), number of symbols per block (20 symbols/block), and type of modulation (DBPSK).

The module achieves maximum throughput by using a null channel error probability. The scenario is composed of a transmitter node and a receiver located 5 meters away. The transmission is done at 14 Mbps for varying payload sizes. Figure 22 shows that the throughput obtained by the module is the expected from the mathematical analysis of Section 3.4.

The graph of the theoretical maximum throughput has a saw-tooth shape. This is due to the padding inserted in the frames to keep the number of symbols per frame a multiple of 20. The periodic falls in the throughput happen when an additional symbol block is used. As the payload increases, the padding decreases and consequently the throughput will get higher until another block is needed.

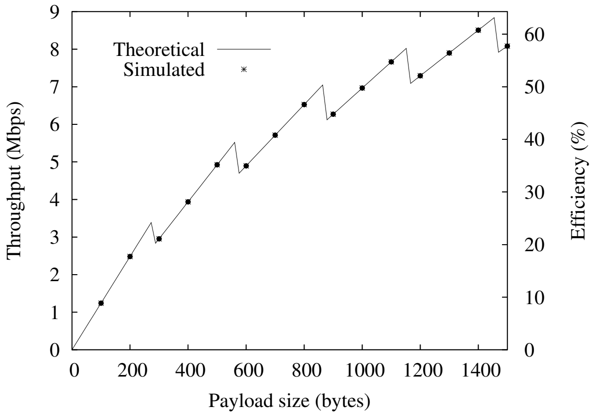

Figure 22. Throughput of HomePlug for different payload sizes.

Figure 23 shows the maximum throughput varying the number of transmitters. Every node is transmitting at 14 Mbps and their flows have the same priority. HomePlug limits the number of nodes in the network to 16. A higher number is possible if all nodes operate in the ROBO mode. We verified the decrease in the throughput due to a higher number of collisions. The collisions increase because the probability of two or more nodes choosing the same slot time increases as well. Unlike IEEE 802.11, the HomePlug throughput does not increase for a few nodes because its CW_{min} is low, not adding many idle slots.

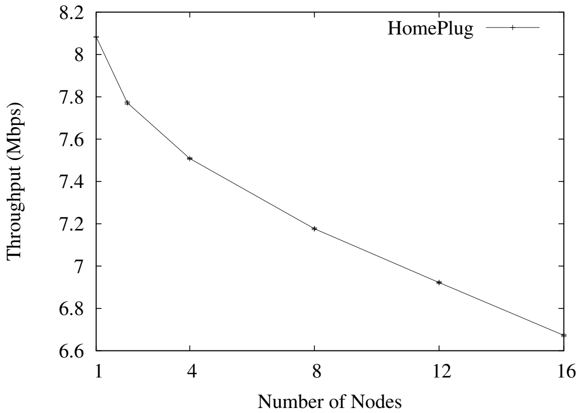

Figure 23. Throughput of HomePlug for varying number of sources.

We also analyzed the efficiency of different home network technologies to verify the influence of the medium constraints and implementation peculiarities over the performance of each protocol. In the following graphs the errorbars were omitted for better visualization.

Figure 24 plots the efficiency of the protocols for varying payload sizes in an one-node transmission. We observe that Ethernet and HomePNA 2.0 present the best efficiency among all. This result is expected because these protocols detect collisions. Nevertheless, the efficiency of HomePNA 3.0, which detects collisions, is similar to the efficiency of a collision-avoidance protocol. HomePNA 3.0 transmits at higher rates but, to keep compatibility with HomePNA 2.0, it uses uses the same basic rate as HomePNA 2.0. To improve efficiency, it would be necessary to increase its basic rate to reduce the amount of time spent with the overhead transmission. Similarly, IEEE 802.11g is less efficient than IEEE 802.11b despite the higher transmission rates. IEEE 802.11g does not decrease the amount of time needed to transmit the overhead as it does for data transmission. A variant of IEEE 802.11g, Short Slot Time, uses a smaller time slot to increase the protocol efficiency, which becomes similar to the efficiency of IEEE 802.11b.

In addition, HomePlug has the best efficiency among the collision-avoidance protocols. This is due to its lower minimum contention window (CW_{min}) size, which causes a lower average backoff time. Consequently, the time spent with overhead decreases.

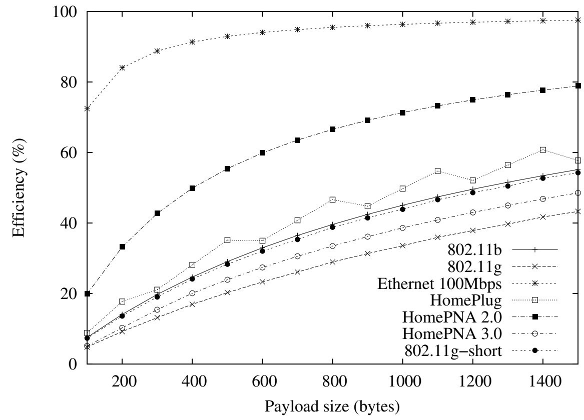

Figure 24. Efficiency of the protocols for different payload sizes.

Figure 25 plots the efficiency of the protocols for varying number of sources. Once again we observe that the collision-detection protocols react better than collision-avoidance ones because they can suspend their transmission after detecting a collision. This avoids wasting time with transmissions that have already resulted in a collision. HomePNA 3.0 shows the worst performance for a few number of nodes because of its low basic rate. As the number of nodes increases, HomePNA 3.0 performance improves due to its capacity to detect collisions. We note that the HomePNA 3.0 efficiency gets better than the efficiency of IEEE 802.11b, 802.11g, and 802.11g-short only for 27 nodes. Besides, IEEE 802.11g presents an efficiency worse than IEEE 802.11b and g-short due to its proportionally higher overhead. Unlike Figure 24, where IEEE 802.11g Short Slot Time presents an efficiency similar to IEEE 802.11b for varying payload size, the efficiency of IEEE 802.11g-short is lower than IEEE 802.11b for varying number of nodes. The initial CW_{min} of IEEE 802.11g Short Slot Time is lower than that of IEEE 802.11b, which means that initially the probability of collisions is higher for IEEE 802.11g-short than IEEE 802.11b. Analogously, HomePlug also presents an efficiency worse than IEEE 802.11b because of its lower CW_{min}. As the number of nodes increases, HomePlug reacts better than IEEE 802.11b because of its deferral counter mechanism. For 12 nodes, HomePlug is already better than IEEE 802.11b. The collision-detection protocols scale better than the collision-avoidance protocols due to their capacity of stopping transmissions after detecting collisions. Increasing the number of nodes, the efficiency decrease is more accentuated in the collision-avoidance protocols.

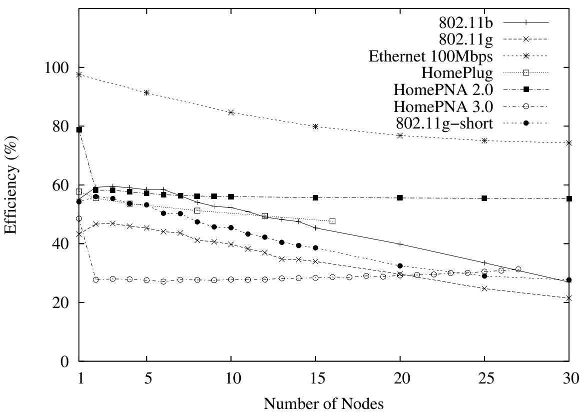

Figure 25. Efficiency of the protocols for varying number of sources.

Collision-avoidance protocols are, generally, less efficient than collision-detection ones. This is expected, because if the station detects the collision, it can stop the transmission immediately. On the other hand, if the collision cannot be detected, the transmitter waits for an acknowledgment from the receiver and therefore must rely on the expiration of a timer to conclude that the transmission was unsuccessful. The only exception among the protocols analyzed was HomePNA 3.0 because of the backward compatibility.

5 Conclusion

Currently, there is a great effort to provide communication networks to interconnect home devices. Different technologies based on wired, wireless, and "no new wires" solutions exist. Our work analyzed the efficiency of the most successful home-network technologies emphasizing on the different access methods and MAC sub-layer protocols.

First, we derived mathematical expressions for the maximum throughput obtained in a one-node transmission by the different protocols. We also performed similar evaluation using simulation. This analysis has shown the control overhead of each protocol for variable frame sizes. As expected, collision-detection protocols performed better than protocols that cannot detect but only avoid collisions. The exception is HomePNA 3.0, a collision-detection protocol, due to the basic rates used to keep backward compatibility. For 1500-byte frames, Ethernet, HomePNA 2.0, and HomePNA 3.0 achieved an efficiency of 97.5, 78.8, and 48.5%, respectively. On the other hand, the collision-avoidance protocols HomePlug, IEEE 802.11b, and IEEE 802.11g reached 57.7, 55.2, and 43.2% efficiency, respectively. HomePNA 3.0 performs similar to collision-avoidance protocols, showing that implementation peculiarities impact the protocol efficiency. A similar unexpected result was obtained in the IEEE 802.11 analysis. We showed that IEEE 802.11b is more efficient than IEEE 802.11g, even though IEEE 802.11g achieves higher transmission rates.

Then, the collision resolution mechanisms of the protocols were evaluated through simulations. We analyzed the behavior of the protocols when the stations start contending for the medium. The contention can result in collisions since we only considered transmissions over shared mediums. Again, the collision-detection protocols performed better than the collision-avoidance protocols, and once again HomePNA 3.0 was the exception. HomePNA 3.0 showed the worst efficiency for a few number of nodes due to compatibility related constraints. Our results also showed that the efficiency of the collision-avoidance protocols depends on the minimum contention window (CW_{min}) size as seen with HomePlug and IEEE 802.11. Higher CW_{min} values means higher performance when increasing the number of nodes in the medium.

This work made a thorough review of the access methods used by different shared-medium home-network protocols. The maximum throughput results obtained with mathematical analysis and simulation results showed how efficiently each protocol shares the medium and treat collisions. Based on the analyses made, one can identify where the medium access methods may be improved and, possibly, combine the techniques used in the different technologies.

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