# FOUNTAIN CODES FOR RELIABLE DATA TRANSMISSION IN LOW VOLTAGE POWER-LINE NETWORKS

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Keywords: Fountain codes, Online codes, Power-line communication, HomePlug AV, Home networking.

Abstract: Home appliances are becoming information devices which can be networked to exchange information. No-new-wires networks are the most promising candidate networking technologies to provide both residential and Small and Medium Enterprise (SME) networking services. Among them, broadband communication over power line networks has attracted much interest in academy and industry recently. The HomePlug Powerline Alliance has developed a new specification for in-home networking called HomePlug AV. The HomePlug AV MAC layer provides a connectionless, prioritized contention service based on CSMA/CA to support best-effort applications. When there are connections competing for the channel utilization, UDP connections lose a big amount of packets. In addition, the bidirectional nature of TCP protocol may not be the adequate transmission mechanism in a half-duplex channel. In this scenario, the use of Fountain codes could be a good alternative to UDP and TCP to transmit reliable data. Online Codes are a free-software Fountain codes version. In this work, it is evaluated the feasibility to use Online Codes for binary data transmission in a low-voltage PLC network.

## 1 INTRODUCTION

Nowadays, home appliances are becoming information appliances and they can be networked to exchange their information. Therefore, it is necessary a home network able to provide support for video and data transmission from a variety of sources in the home. Candidate networking technologies to provide convenient and widespread residential networking services may be categorized as wireless, wired and no-new-wires networks. For the no-new-wires networks category, broadband communication over low voltage (220v) power lines or PLC (Power Line Communications) has attracted much interest in the academic and industrial context recently. The HomePlug Powerline Alliance (Afkhamie et al., 2005) has developed a new specification for in-home networking called HomePlug AV (HomePlug Audio and Video, or simply HPAV). HomePlug AV employs advanced physical and medium access control (MAC) technologies that provide a 200 Mbps power line network. The physical layer utilizes this 200 Mbps rate to provide a 150 Mbps information rate. Nowadays, there are about 70 certified HomePlug products (HomePlug Certified Products, 2009). They range from a simple HomePlug Ethernet adapter (which connects the Ethernet devices to the HomePlug network) to 1 Gbps high performance low-voltage PLC modem (Gigle, 2009). On the other hand, nowadays some companies are adding HomePlug circuits directly into multimedia home entertainment equipment. By this way, it will not be necessary any additional equipment (like Ethernet adapters) to connect the electrical appliances to the PLC network

However, it is necessary to take into account that there are several aspects of the PLC medium that make it difficult to share resources fairly. For example, all the electronic or electrical equipments connected to the power lines are considered as noise resources on the power grid (Jensen and Kjarsgaard, 2007). Therefore, our first goal in this work is to characterize the network behavior in presence of electrical equipment of a typical home when using a commercial HPAV modem.



Pedro Muñoz-Gea J., Jose Piñero-Escuer P., Malgosa-Sanahuja J., Manzanares-Lopez P. and Carlos Sánchez-Aarnoutse J. (2009).
FOUNTAIN CODES FOR RELIABLE DATA TRANSMISSION IN LOW VOLTAGE POWER-LINE NETWORKS.
In *Proceedings of the 4th International Conference on Software and Data Technologies*, pages 135-140
DOI: 10.5220/0002252001350140

Another important aspect in PLC networks is that, although the HPAV MAC layer provides a connection-oriented service based on TDMA to support QoS requirements, almost all commercial HPAV modems only support traditional connectionless, prioritized contention service based on CSMA/CA to transmit best-effort applications and applications that rely on prioritized QoS. In other words, the PLC channel is broadcast (i.e. shared) and half-duplex by nature. This fact made us think that the use of unidirectional rateless codes to transmit the information may be advantageous as opposed to traditional solutions based on bidirectional (full-duplex) TCP protocol. Rateless codes are also known as Fountain codes because the sender is theoretically always sending coded packets. Some of them are lost in the noisy channel but when the destination node has received enough of them, the information can be completely restored. They are mainly used in multimedia applications, such as IPTV or radio broadcasting, because in these cases there is usually no feedback channel, and it is impossible to take advantage of any type of error or flow control. Online Codes are a free-software Fountain codes alternative, which achieve linear cost for encoding and decoding operations. In this work, the feasibility to use Online Codes for reliable data transmission in an in-home PLC network is evaluated.

The remainder of the paper is organized as follows. Section 2 presents the HomePlug AV specification. Section 3 introduces the encoding and decoding procedure used by Online Codes. Section 4 evaluates the use of Online Codes for data transmission in a real scenario. Finally, Section 5 concludes the paper.

# 2 HOMEPLUG AV

As it was previously introduced, there are several aspects of the PLC medium that make it difficult to share resources fairly. In order to solve these problems, advanced coding and modulation mechanisms are used. The Physical Layer (PHY) operates in the frequency range of 2 - 28 MHz and provides a 200 Mbps channel rate and a 150 Mbps information rate. It uses OFDM and a powerful Turbo Convolutional Code (TCC). OFDM is a spectrum efficient modulation technique, which uses simultaneous transmission of a large number of narrow band carriers. These carriers divide a large frequency channel into a number of subchannels. Subchannels can differ greatly in their quality, defined by their signal to noise ratio-SNR-. Adaptive coding modulation for each subchannel solves this problem by giving each subchannels an appropriate capacity, and by switching off those with a poor channel condition.

HomePlug AV provides two kinds of communication services: a connection-oriented contention free service, based on periodic Time Division Multiple Access (TDMA) allocations of adequate duration, to support the QoS requirements of demanding applications; and a connectionless, prioritized contention service, based on Collision Sense Multiple Access/Collision Avoidance (CSMA/CA), to support both best-effort applications and applications that rely on prioritized QoS. To efficiently provide both kinds of communication service, HomePlug AV implements a flexible, centrally-managed architecture. The central manager is called a Central Coordinator (CCo). The CCo establishes a beacon period and a schedule which accommodates both the cotention free allocations and the time allotted for contention-based traffic. The Beacon Period is divided into 3 regions: beacon region, CSMA region and TDMA region.

# 3 FOUNTAIN CODES

## 3.1 Description

The main idea behind Fountain codes is that the transmitter is represented like a fountain of water that is able to produce an infinite number of water drops. The receiver represents a bucket that needs to collect a number of these water drops to obtain the information. The main advantage of these codes is that the receiver can obtain the information irregardless of which drops it has collected. Therefore, Fountain codes should have the following properties:

- A transmitter can generate a potentially infinite amount of encoded packets from the original data.
- A receiver can decode a message that would require $K$ packets from any set of $K'$ encoded packets, for $K'$ slightly larger than $K$.

The most important implementations of Fountain codes are LT codes (Luby, 2002), Raptor codes (Shokrollahi, 2006) and Online Codes (Maymounkov and Mazières, 2003). LT codes were the first practical realization of a fountain code. The only drawback of these codes is that their encoding and decoding costs scale as $K log_e K$, where $K$ is the file size. Raptor codes are an evolution of LT that achieve linear cost for encoding and decoding. Finally, Online Codes are a free-software alternative to Raptor codes that also achieve linear cost for both operations.

There are lots of application of Fountain codes in digital communications. They are mainly used in multimedia applications, such as IPTV or radio

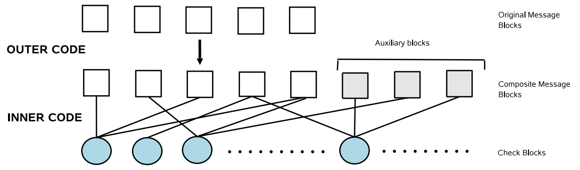


Figure 1: Structure of Online Codes.

broadcasting because in these cases there is no feedback channel. Therefore, it is impossible to take advantage of any type of error or flow control. Another kind of service that could also use these codes is multicast transmission. When a transmitter sends a file to different receivers, each of these receivers could experience independent losses, delays, jitter, etc. Without the Fountain codes facility, the number of control packets needed to maintain the multicast connection could be very high.

## 3.2 Online Codes

Online Codes are characterized by two parameters $\varepsilon$ and $q$. The first parameter is related to the number of coded blocks (also called *check blocks*) that the receiver needs in order to decode the original message, and the second one has an effect on the probability of succesful decoding. In particular, the receiver can recover the original message from any $(1+3\varepsilon)K$ check blocks with a success probability determined by $1-(\varepsilon/2)^{q+1}$

The structure of Online Codes is depicted in Fig. 1. The encoding process is divided into two layers, the inner code and the outer code. The inner code is in charge of generating the *check blocks*. Every check block is computed as the XOR operation of $d$ blocks uniformly chosen from the message ($d$ represents the degree of the check block). The probability that $d=i$ is given by the probability distribution $\rho_i$:

$$\rho_1 = 1 - \frac{(1+1/F)}{(1+\varepsilon)} \quad (1)$$

$$\rho_i = \frac{(1+\rho_1)F}{(F-1)i(i-1)} \quad i=2,3,...,F \quad (2)$$

where F is given by

$$F = \frac{ln(\varepsilon^2/4)}{ln(1-\varepsilon/2)} \quad (3)$$

However, due to the random selection of the message blocks, some of them may not be selected in the inner coding process. One solution to this problem is to add a preliminar coding process (called outer coding) which generates $0.55q\varepsilon K$ auxiliary blocks from the original message. The message blocks that do not participate in the inner process will be able to be decoded thanks to this redundancy. In fact, the input blocks of the inner coding are the message blocks plus auxiliary blocks. All this set is called composite message.

From all the available procedures to generate redundancy (Reed-Solomon, Cyclic Redundancy Check, Parity Bits, etc.), Online Codes uses one of the simplest: for each block of the original message, $q$ auxiliary blocks are chosen. Each auxiliary block is computed as the XOR operation of the original message blocks assigned to it.

The original message can be decoded from the check blocks, with the success probability showed before. The decoding process is also divided into two steps. In the first step a $1-\varepsilon/2$ fraction of composite message blocks should be recovered. The knowledge of this fraction of blocks is enough to decode the original message: the composite message has such a property thanks to the redundancy added by the outer code. The second step consists of recovering the original message from the composite message blocks recovered in the first step.

In order to successfully recover the needed fraction of composite message blocks, it is necessary to get to know the degree of each check block and the composite message blocks from which it is made up (also called *adjacent blocks*). A way to send this information to the receiver must be implemented on the transmitter side. However, if the receiver uses the same random number generation algorithm as the transmitter, it will only be necessary to send the seed to reach this objective. Next, the decoding process can start. It has the following steps:

1. Find a check block with only one adjacent block ($d=1$) and recover this composite message block.

2. Remove this recovered block from other check blocks that also have this recovered block as adjacent (by simple substracting it; that is, computing the XOR again). After this, some check blocks can become degree-one blocks.

3. Continue with this process until a $1-\varepsilon/2$ fraction of composite message blocks is recovered.

   The process can fail if in some of these steps there are no degree-one blocks.

When all the needed composite message blocks are recovered, the same process can be used to obtain the original message blocks. In this case the success probability is close to one because only the auxiliary blocks have a degree higher than one.

# 4 EVALUATION

In this section we want to evaluate two characteristics of HomePlug AV specification: First, the variable capacity model of the physical layer; and second, the contention-based service of the MAC layer. All the evaluations presented in this section have been made using a laboratory test-bed. The lab has three phases of 220 volts, and all the PLC adapters and PC computers used in the evaluation are connected to the main phase. We have used the PLE200 HomePlug AV Ethernet adapters of Linksys (Cisco-Linksys, 2009). This adapter connects the Ethernet device of a computer to the 220 V power line.

## 4.1 Evaluation of the Variable Capacity of the Physical Layer

Our first objective is to evaluate the adaptation of the data transmission rate according to the noise level. For this aim, we use two computers connected to the HomePlug AV network using the corresponding Ethernet adapters. Their power suppliers are connected to another electrical phase of the lab, different from the one used to implement the HomePlug AV network. Knowing that in Europe the common point of two distinct phases is located in the low voltage transformer, the distance between two elements connected to different phases is around 300 meters. This distance is large enough to ensure the absence of interference among devices connected to different phases.

In order to measure the capacity of the network, we used a UDP traffic generator which transmits traffic to the maximum capacity allowed by the physical network. We achieved the results presented in Fig. 2. In particular, it can be observed that the network is able to achieve a maximum capacity around of 80 Mbps (which is nearly to the maximum capacity assigned to the CSMA region). Next, after 8 seconds, we connected the power suppliers of all the available computers in the lab to the electrical phase of the HomePlug AV network. In Fig. 2 it can be observed that the connection of all the computers to the power line causes the reduction of the network capacity to 60 Mbps. After 17 seconds, we disconnected all the computers from the electrical line and we detected that the transmission rate increased up to 80 Mbps again. The reason for this phenomenom is that the powerful coding and modulation technique used in HomePlug AV is able to adapt the transmission speed according to the noise level generated by the electrical devices in order to avoid the losses of packets.

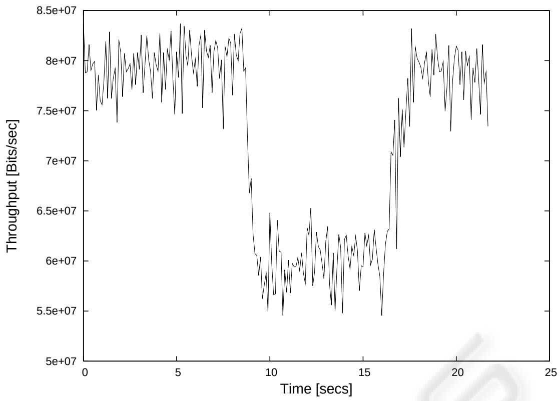


Figure 2: Evaluation of the network capacity.

## 4.2 Evaluation of the Contention-based Service of the MAC Layer

As it was previously introduced, the HomePlug AV MAC layer offers a contention service based on CSMA/CA. In packet communication networks, contention is a media access method that is used to share a broadcast medium. In this method all the hosts connected to the medium compete in order to transmit to the broadcast medium and they can only do that when the channel is “idle”. In order to evaluate this characteristic of HomePlug networks, in our next experiment we establish three simultaneous (compete against one another) file transmissions using UDP connections, and we evaluate the performance of one of them. The size of the transmitted file varies from 1 up to 20 Mbytes and the distance between the PLC devices of the measured connection is about 45 meters. This is aproximately the longest distance between two PLC devices in a real in-home scenario (worse case). The most remarkable result is the big proportion of lost packets, represented in Table 1. It means that the UDP receiver is not able to receive the full files. These losses are mainly due to the buffer overflow at the PLC interface because the incoming packet rate is greater than the outgoing rate at which CSMA/CA can transmit packets. Therefore, in this environment the use of UDP applications which do not implement any flow control is not recommended for reliable data transmission.

In order to avoid the losses of packets in a contention environment, like a HomePlug networks, there are two options: first, using a protocol that implements a flow control mechanism, for example TCP (Transmission Control Protocol); second, using an application that implements some kind of forward error correction, for example, the use of Fountain codes. In the following experiments, we want to compare the

Table 1: Proportion of lost packets in UDP connections.

| File size [MB] | Losses [%] |
|---|---|
| 1 | 0 |
| 2 | 16.66 |
| 3 | 36.5 |
| 4 | 38.17 |
| 5 | 30.84 |
| 6 | 40.77 |
| 8 | 34.73 |
| 10 | 41.45 |
| 15 | 37.25 |
| 20 | 37.73 |

performance achieved by two file tranmission applications, one of them uses TCP as transport protocol, and the other one uses a kind of Fountain codes (concretely Online codes).

We used the scp program (scp, 2009) as a TCP-based file transmission application. On the other hand, in order to implement the application based on Online codes, we used the Online Codes implementation available in (Implementation of Online Codes, 2009). UDP transmission capability has been added to this implementation. In contrast with some real-time multimedia applications, in a file transmission application the packet loss probability must be zero (i.e., the file must be fully received). In order to achieve this with Online Codes, the decoding failure possibility must be eliminated. This is obtained by trying to decode the original information for every received block. When the process fails, the receiver waits for the next check block and it tries to decode it again. With this method the number of *check blocks* that need to be decoded is a little bigger than $(1+3\varepsilon)K$, but the decoding failure probability is zero.

However, our application does not really decode the received blocks, it only deduces whether the received packets are enough to decode the original file, and it finishes when it has already received enough packets in order to decode it. This program implements a “light decoding” process and it gives as a result the previous amount of packets. The decoding mechanism can be implemented by another concurrent program, or it may be performed when the previous program has finished, that is, when it has received the necessary blocks to decode the original file. On the other hand, the packets can also be stored in a coded way. This second option could be a good choice if the coded packets are going to be retransmited (e.g. in a P2P network) or if a OS implements a facility that is able to recognize this kind of coded files.

Both file transmission applications are evaluated in a contention scenario, with other two simultaneous file transmission connections. The size of the transmitted file varies from 1 up to 20 Mbytes. In this case, both applications are able to receive the full file without errors. Therefore, in the evaluation we are going to compare them taking into account the necessary time to receive the full file. The distance between the PLC devices of the measured connection is about 45 meters, like in the UDP scenario. Fig. 3 shows the average duration of the scp and Online Codes sessions, extracted from 5 different sessions. In addition, the figure also represents the 95% confidence interval. The first result that can be concluded from the previous figure is that the Online Codes sessions are always faster than the scp sessions. In addition, the increase of the scp sessions with respect to the Online Codes sessions is approximately constant and equal to 1 second, though for big files this increment increases up to 2 seconds. Therefore, we can draw that in a contention scenario the performance achieved by an Online Codes-based file transmission application is better than the performance achieved by a TCP-based file transmission application. Although not represented, we have also tested the FTP protocol, which also uses TCP as transport protocol. In this case, the sessions duration are always higher than with scp, and therefore the difference between the Online Codes application and FTP is also higher.

Next, both file transmission applications are evaluated again in a contention scenario, but in this case, with four simultaneous file transmission connections. Fig. 4 shows the average duration of the scp and Online Codes sessions, extracted again from 5 different sessions, and the associated 95% confidence interval. In this scenario, the Online Codes sessions are also faster than the scp sessions. However, in this case the increase of the scp sessions with respect to the Online Codes sessions is higher than in the previous scenario, approximately equal to 2 second, and for big files this increment increases up to 4 seconds. On the other hand, if we compare these results with those presented in Fig. 3, we can observe that the increase of simultaneous file transmission connections causes an increase in the length of the sessions. This result is absolutely obvious because in this case the broadcast medium has to be shared by a bigger number of users.

As a conclusion, in multiple access networks (like in-home PLC based networks), the access control mechanism produces losses in unidirectional (like UDP) transmissions. In these cases, it is necessary to add some type of flow control (e.g. using TCP as transport protocol), or implementing some kind of forward error correction, for example, the use of Online Codes. We have compared the session lengths

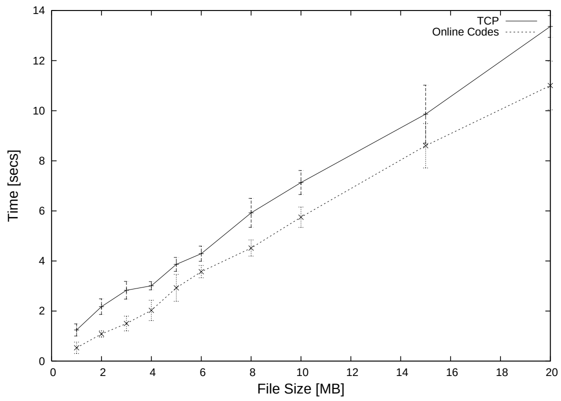


Figure 3: Duration of TCP (scp) and Online Codes sessions in a noisy channel with two (background) data flows sharing the channel. The confidence interval has been set to 95%.

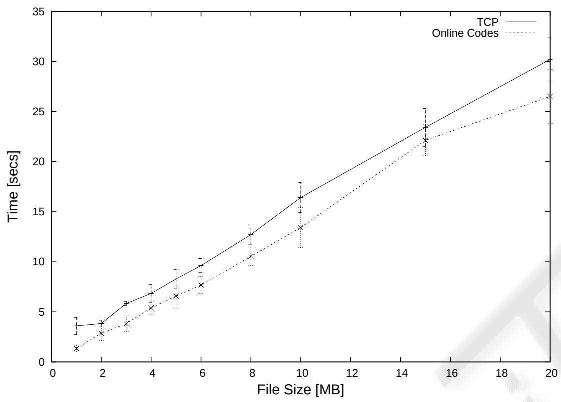


Figure 4: Duration of TCP (scp) and Online Codes sessions in a noisy channel with four (background) data flows sharing the channel. The confidence interval has been set to 95%.

of a TCP file transmission application and an Online Codes based application, and we have extracted that the Online Codes sessions are always faster than the TCP sessions. Therefore, we have proved that in contention scenarios the performance achieved by Online Codes is better than the performance achieved by a TCP-based file transmission application.

## 5 CONCLUSIONS

Online Codes must be mainly used when the network or the application is unidirectional (broadcast-TV, satellite, IP live-TV, etc.) or in applications that cannot directly use TCP (like Application Layer Multicast). However, in a multiple access in-home network (HPAV, wireless 802.11, PhonePNA, etc.) the Online Codes are a good alternative to TCP for reliable data transmission.

## ACKNOWLEDGEMENTS

This research has been supported by project grant TEC2007-67966-C03-01/TCM (CON-PARTE-1) and it is also developed in the framework of “Programa de Ayudas a Grupos de Excelencia de la Región de Murcia, de la Fundación Séneca, Agencia de Ciencia y Tecnología de la RM (Plan Regional de Ciencia y Tecnología 2007/2010)”. Pedro José Piñero-Escuer also thanks “Fundación Séneca” for a Séneca Program FPI pre-doctoral fellowship.

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