Analytical model validation using OPNET Modeler

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Abstract
This paper presents and validates through simulation an analytical model for multihop connections in AMR systems (Automatic Meter Reading). The model is based on a Markov Chain and has been validated with a Monte Carlo Simulation based on OPNET Modeler in order to obtain a verification of the explicit formulas calculated from analytical model. The model is applied to the AMR case where the normal operating scenario of the system may be in a high probability of errors. Other systems that make extensive use of multihop polling are bluetooth scatternets and ad-hoc wireless networks.

Introduction

AMR can be accomplished by using different communication techniques such as Power Line Communication (PLC) or Wireless. Communication systems which use the power cables themselves as communication medium are potentially more convenient for the utilities and, in fact, many utilities around the world use their own power cables to reach the meters as well as to communicate with their customers for low rate applications.

Narrowband PLC has stable standards in Europe [1][2] since the nineties and it is a mature and low cost technology which may achieve nominal transmission speeds up to 9600 bit/s in the transmission band from 9 to 95KHz for utility uses and up to 140,5KHz for customer applications.

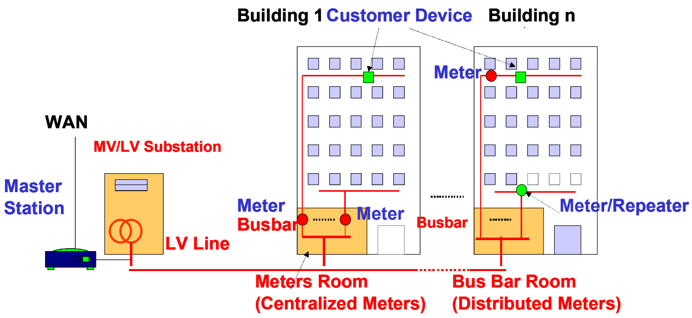

Figure 1: AMR Architecture

Broadband PLC or BPL achieves far greater capacities (nominally up to 200Mbit/s) and technically speaking is also a candidate for AMR but still lacks of the necessary standardization and has a much larger cost. In any case this technology also makes use of multihop polling, the technique modeled here.

Narrowband PLC due to the characteristics of power lines imply low throughput rates and high bit error rate levels such as 10E-3 [3][4][5][6][7][8]. That typically mean retry probabilities in the range from 1% to 20% or even worse. Another essential characteristic of the narrowband power line channel is its tree-like nature with high and complex attenuation and noise patterns that leads to the management of multihop logical structures [5][9][10][11][12] that from the concentrator usually located in the transformer or Medium Voltage (MV) substation, communicate with meters or customer devices through several intermediate relays.

Creating and managing these multihop structures is a main issue in AMR and since polling is a widely used mechanism in AMR systems for managing them. This paper tries to explain how we are using OPNET Modeler in order to verify a model based on a polling mechanism. The developed Markov chain model takes into account multihop trees and will be used to extract conclusions from it. The model is validated by the help of a Monte Carlo simulation using OPNET Modeler.

The results allow for the explicit calculation of throughput and delay with respect to several system parameters such as number of hops, number of retries and time out values, and it provides an in-depth sight into AMR systems and that may help to researchers on this field.

The model includes sending an error packet indication to the master in case of exhausting the maximum number of retries in any of the hops and allows the assessment of the improvement implied by the use of such an error indication packet. It also allows for the assessment of the improvement achieved by reducing the global time-out value below its level to assure that no simultaneous packets are transmitted.

The problem of cost, which is very significant for meters is also very important in the other networks, specially in the sensor networks. We may even say that the situation is more stable for meters. Just take into account besides the lack of mobility that there are no restrictions from the consumption point of view since they are connected to the mains and are not fuelled by batteries.

Architecture

It is assumed, as it is usually the case in many systems, that there is a master polling station connected to the low voltage side of the MV transformer that polls the meters and possibly other customer devices connected to the low voltage network.

The meters are assumed to perform two functions: one is to act as slave station waiting for a poll and the other is as intermediate repeater to reach other meters. These two functions allow for structuring the system as a logical tree with the concentrator at the root, the meters as leaves and different levels of branching connecting both of them by means of repeaters. In this way a tree-like logical structure somewhat mimicking the physical power line structure is created.

The modeled polling protocol is a typical ARQ mechanism where messages are sent with an error detecting code and with the protection of a timer for retransmission at the hop level (from Repeater/Meter to Meter). The receiver answers with positive acknowledgments in case of transmission success. This retransmission procedure is repeated as necessary until reaching some maximum retry value. Upon achieving this value the transmitter no longer repeats the message and remains silent waiting for some higher level mechanism to act. This mechanism can be of two types: a global Time-Out from the concentrator or a period of time for reconfiguring the tree.

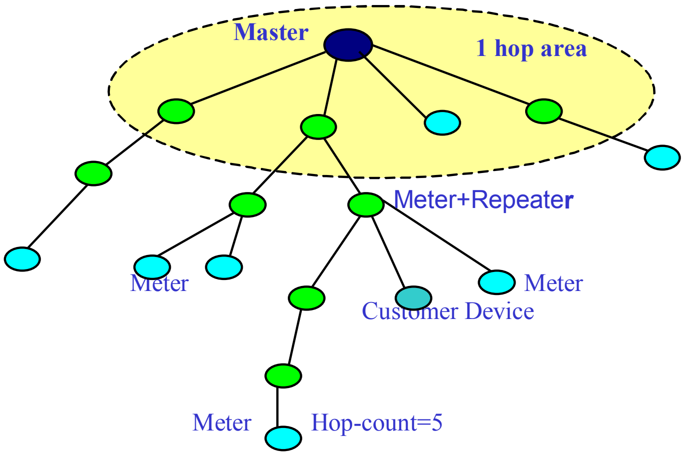

Figure 2: AMR Logical Architecture

The way this tree is created is outside the scope of this paper although the model may help the design of such a tree.

The Model

The polling mechanism is modeled as two dimension discrete-time Markov chain with states formed by two numbers, the hop count level and the number of effective retransmissions at that level. Figure 3 represents this Markov chain. By simple inspection of the proposed Markov chain model it should be clear that all states are recurrent since they are continuously visited and every state is reachable from any other state. This means that the chain is irreducible [9].

The mean recurrence time of the initial state is the basic average delay of the system from which other performance measures like throughput can be derived.

The parameters of the Model are:

- p, single try local retransmission probability
- to, hop time-out period
- tx, duration of a basic dialog
- r, maximum number of hop retries
- h, maximum number or repeater levels
- F, fix time to get the tree reconfigured
- To, end-to-end time-out of the concentrator

Since parameters may depend on the link direction being considered (downlink or uplink), we use a letter "d" to indicate downlink direction and letter "u" to indicate uplink.

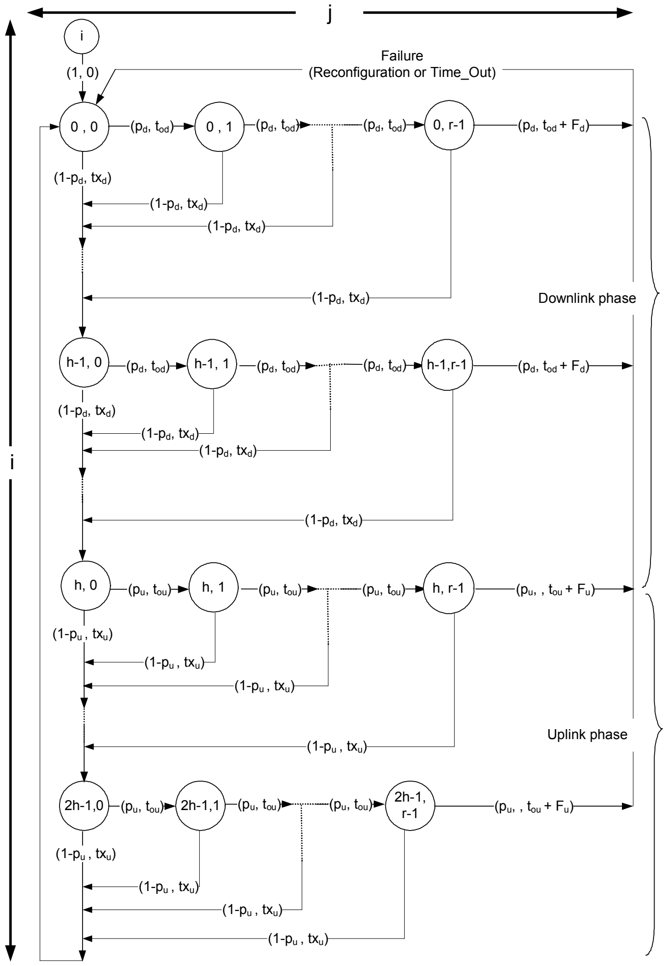

Figure 3: AMR Model

The hop count level in the Markov Chain is twice the maximum hop count distance between concentrator and meters. The reason for that is that a complete dialog includes a downlink transmission with a maximum of h hops and an uplink transmission with h additional hops.

Each transition between states has an associated transition probability and a delay. All the transition probabilities are a function of the single try local retransmission probability (p).

Upon reaching r, two scenarios are considered. One is a global Time-out and the other one is a constant time taking into account the time needed to reconfigure the tree. In Figure 3 only the second one has been represented.

That model was introduced in OPNET in a Monte Carlo simulation basis. The main goal was to verify all obtained formulas from Markov chain model. That verification was possible thanks to thousands and thousand of averaged simulations. Using OPNET scalar statistics we could also obtain valuable information about sigma deviation. After that an scenario was implemented in OPNET to model real AMR situations.

Figure 4: Monte Carlo model with r = 3 and h = 3.

The probability of each state in the Markov Chain is calculated by the use of the classical equilibrium equations for each state and the results are the following:

$$p(i,j) = p(0,0)\cdot(1-p_d^{\,rd})^i \cdot p_d^{\,j} \quad \text{for } i \le h-1$$
$$p(i,j) = p(0,0)\cdot(1-p_d^{\,rd})^h \cdot p_u^{\,j} \quad \text{for } i = h$$
$$p(i,j) = p(0,0)\cdot(1-p_d^{r_d})^h \cdot (1-p_u^{r_u})^{(i-h)} \cdot p_u^{\,j} \quad \text{for } i \ge h+1$$

To check the accuracy of the state probabilities a simulation study based on OPNET has been carried out. The value for p(0,0) when the parameters in uplink and downlink directions coincide is given by:

$$p(0,0) = \frac{(1-p)\cdot p^r}{(1-p^r)\cdot\left(1-(1-p^r)^{2h}\right)}$$

We are interested in the trajectories leaving and coming to the initial state. Each of these trajectories corresponds to the successful transmission of a message and the model allows for the computation of their delay. Based on the previous probabilities, the average number of visits to states (i,0) made by each trajectory starting and ending in the initial state are calculated and, from them, formulas for the average delay of these trajectories are obtained for the two considered scenarios. The formula in the scenario with reconfiguration of the tree is given by:

$$D = d_d \cdot \frac{1-p_d^{r_d}}{p_d^{r_d}} \cdot (1-(1-p_d^{r_d})^h) + d_u \cdot \frac{1}{p_u^{r_u}} \cdot \left(\frac{1}{(1-p_u^{r_u})^h} - 1\right)$$

The formula for the Global Time out scenario is:

$$D' = h\cdot(d'_d + d'_u) + T_0 \cdot \left(1 - \frac{1}{(1-p_u^{r_u})^h \cdot (1-p_d^{r_d})^h}\right)$$

Where d′ is: (*i* may be *u* or *d*):

$$d'_i = \left(1-p_i^{r_i}\right)\cdot t_{xi} + t_{0i}\cdot p_i \cdot \left[\frac{1-p_i^{r_i-1}}{1-p} - (r_i-1)\cdot p_i^{r_i-1}\right]$$

The minimum value for the Time Out that guarantees that only one message will be in the system at a time is equal to the delay of the longest trajectory in the system without returning to initial state and is given by,

$$T_{0\max} = h\cdot(t_{xd} + t_{od}\cdot(r_d-1) + t_{xu} + t_{ou}\cdot(r_u-1))$$

Values below this one may cause the presence of more than one message in the system and, thus, may produce collisions. Nevertheless if they occur with low probability, it may be good to reduce *To* to achieve lower average delays.

AMR scenario

Modeled scenario uses physical bus model and transparent repeaters to emulate a logical tree environment. A linear bus topology consists of a main run of cable with all nodes and devices (meters and concentrator) connected to the linear cable. This topology is not suitable to model AMR system. A tree topology combines characteristics of linear bus and star topologies. It consists of groups of star-configured nodes connected to a linear bus backbone cable.

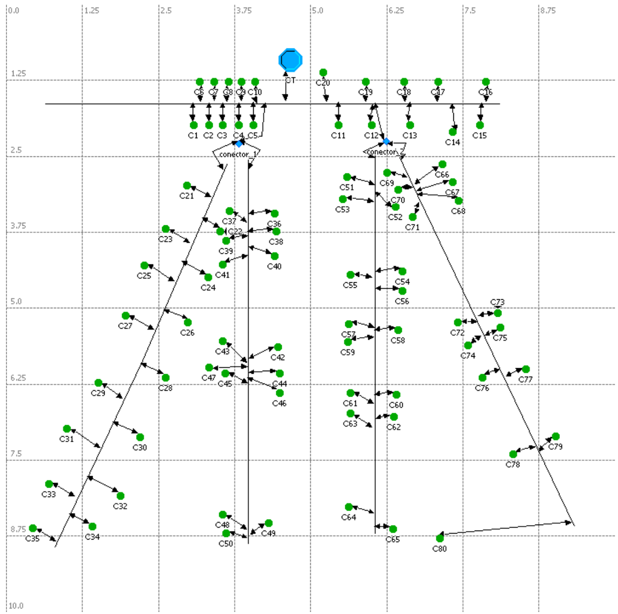

Figure 6: Tree topology

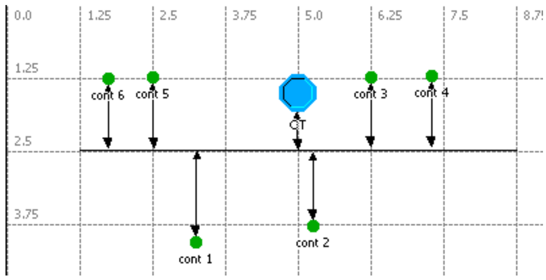

Figure 5: Bus topology

Some Results

The model developed here has been applied to a system which may be typical of a meter reading situation (one command downlink followed by a longer uplink answer containing the reading of the meter under test). The parameters have been adjusted to the following values: nominal speed of 4800bit/s, commands of 64 bits of length, returning data from the meters of 256 bits and acknowledgments of 32 bits.

Delay and throughput as a function of p, r, h, F and To have been obtained and some of them are represented in the following figures.

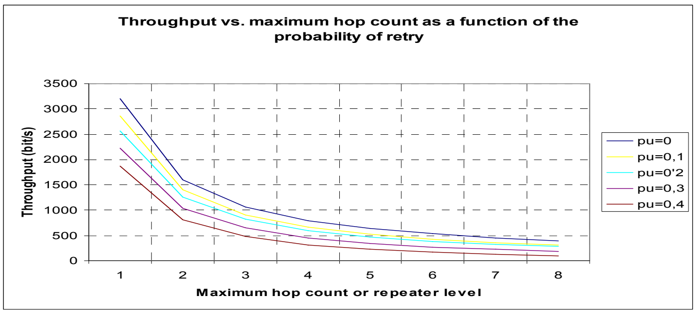

Figure 7: Throughput vs. maximum hop count as a function of the retry probability

Figure 7 shows that system throughput is almost inversely proportional to the hop-count level. This means that any policy for structuring the tree should take into account hop count as its most important parameter.

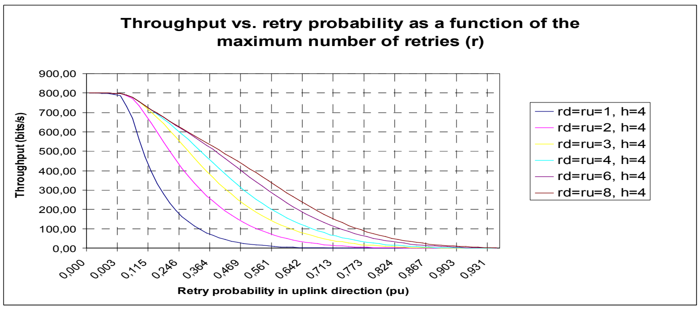

Figure 8: Throughput vs. retry probability as a function of the maximum number of retries.

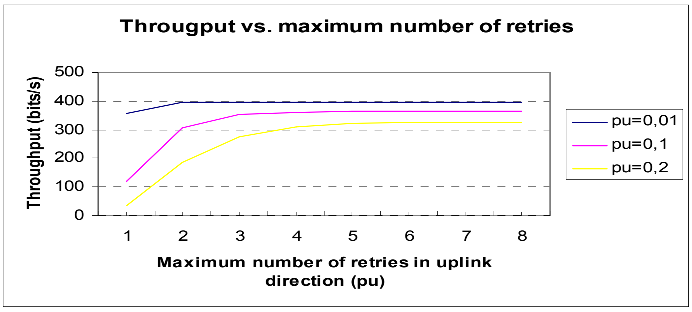

Figure 9: Throughput vs. maximum number of retries

Figures 8 and 9 show that the maximum number of retries should be at least 3 to operate efficiently in the range of retry probabilities typical for these systems (1-20%).

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