Designing A Power-line Network for Information Appliance Communication

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Abstract—

Supporting the multimedia communication between information appliance (IA) devices is an important design issue for the intelligent homes of the future. The power-line network provides an attractive infrastructure because of its wide availability of power-line wiring and power sockets. In this paper, we have investigated the traffic patterns generated by possible IA devices. With reasonable assumptions, we have investigated three IA placement methods and their impact for supporting different traffic types. In conjunction with the placement methods, it appears that the number of branches is indeed an important design factor. We particularly propose an effective placement procedure called the *Minimize Trunk Traffic (MTT)* method to yield a significant performance improvement among all IA traffic types. By using the MTT placement method, the overall recommendation from this study suggests that a typical home network based on power-line communication should be designed with five or six branches.

Keywords—

Power Line Communication, Home Network Design, Multimedia Applications, Real-Time Traffic

I. Introduction

The concept of Information Appliances (IA) is rapidly becoming a reality. Many next-generation appliances come with embedded processors for communication. For instance, on April 7, 2001, IBM and Carrier announced that they will produce a new air conditioner with JAVA support that can send e-mails to manufacturers for errors or the user can send commands to the air conditioner to pre-adjust room temperature. We believe that it will not be too long until our homes will eventually have many kinds of IA devices communicating with themselves and the outside.

How to provide the right infrastructure for connecting these IA devices is open at this moment. Many competing networking technologies exist to support this mission. An extensive study of infrastructure options and technologies that can be used in home networks can be seen in [1]. However, a power line network already exists in every home, and power sockets are available in every room for accessing it. Therefore, a home power line network can be a very attractive infrastructure for supporting the IA multimedia communication. However, the quality of power lines is not ideal for signal transmission since the channel contains lots of noise, interference and fading. Fortunately, the recent advancement of signal modulation technologies [2], [3], [4], [5], [6], [7], [8] makes channel imperfection less severe and signal transmission through power lines feasible [9].

In North America and many other countries, the common power line topology in residential homes is tree-like, as depicted in Figure 1. Typically there are two trunk power lines, 110V and 220V. Each trunk power line then can be divided into branches. Since we expect the multimedia-enabled IA communication to run across different homes via the Internet, it is important to preserve the bandwidth available on the main trunk for Internet traffic.

Current research shows that the maximum raw data rate of power line communication is possibly around 15 Mbps [9]. However, the effective data rate is expected to be around 10 Mbps or less. We were interested in exploring various methods to investigate the impact of different performance results. In order to collect the performance of a power line network, we conducted a series of simulations.

The first method that we investigated did not im-

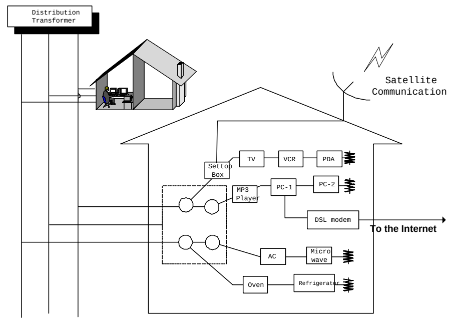

Fig. 1. Power Line Topology in a Home

pose any rule of where and how the IA devices should be placed. We call this placement "*Random Placement.*" The overall performance trends suggest that five branches should be considered to support IA communication, based on *Random Placement Method(RPM)*.

During the process of investigation, we suspected that a better performance perhaps can be achieved if the network system takes advantage of human habits by placing the IA devices in a clustering manner. Therefore, we designed the second method as a scheme termed "*Conventional Placement.*" However, the performance comparison between these performance results and the performance results of the *RPM* was less than one percent difference.

With the above two preliminary results, we found that the trunk traffic congestion dominated the network performance. The above two placements cannot perform well since the communication relationships of IA devices were not involved in placing IA devices. We then propose an algorithm "*Minimize Trunk Traffic (MTT) Placement*" that minimizes the total trunk traffic amount and lowered the congestion likelihood of the overall system. The simulation results showed that "*MTT Placement*" method can effectively reduce the typical congestion likelihood of an individual traffic below seven percent, and the typical jitter likelihood of a real-time traffic below 11 percent.

In summary, we have found the proper topology of a power line layout and the proper appliance setups are important design issues to maximize the usage of power line bandwidth. The overall recommendation from our study suggests that a typical home network based on power-line communication should be designed with five or six branches so that the design tradeoff can be balanced among different IA traffic types.

The remainder of this paper is organized as follows: Section II discusses the application nature on a power line communication network and the human behavior for using IA appliances. The data traffic model, according to human behavior, is thus defined. Section III presents the performance results and analysis. Section IV concludes this paper.

II. PROBLEM NATURE AND PROPOSED SOLUTIONS

Unlike conventional thinking that treats power line trunks and branches as a whole channel, we believe a set of effective solutions can be found by taking advantages of the physical topology. It is obvious that if some IA devices may communicate within their own branches, then there is no need for broadcasting the traffic via the trunk lines.

In order to accomplish the above design, separating trunk traffic from branch traffic is a required capability for our power line-based networks. A filter design is therefore required at the edge of the trunk and branch power lines. This filter should be able to separate signal, recognize packets, and do proper actions according to the the information contained in the packet header. There are many methods that can help us building a filter. For example, space division method, time division method and frequency division.

We propose one of the filter designs which uses frequency division. This device is depicted in Figure 2. A low-pass filter prevents high frequency(i.e, data signal) passing through wire conjunction serves our deign goal. While the decision circuit decides whether to broadcast this packet to other branch or not.

With the filter design in place, we are in the right position to tackle the research question:

What is the optimal method to place different IAs over the given set of power sockets?

To answer this important question, we need to fully understand the IA data traffic characteristic over the power line network. We have surveyed

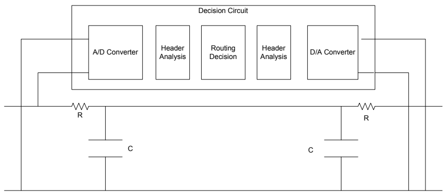

Fig. 2. A power line filter design

and list the following patterns in Table I.

TABLE I
PEOPLE HABIT IN PLACING APPLIANCES

Cluster	Appliances
1	TV, VCR and Set-top box
2	Microwave, Oven and Refrigerator
3	Digital Music Player, Digital Camera, PC1
4	PC2
5	Air Conditioner
6	PDA base
7	Front door camera

Table II shows the results of a survey from which we inferred usage and traffic patterns generated by typical IAs. The table also suggests some current and future PLC applications. For instance, when merchandise is advertised on a digital TV service, the product information (such as the barcode or webpage) can be downloaded to your computer through a power line. Afterwards, you can send your order information from the computer to the supplier or you can use the downloaded URL to browse the product web page and get more details. We also anticipate the ability to record music or videos through a power line. For example, when a song is broadcast on TV or a music channel, you can download the song directly to an MP3 player through the power line. Another application is the opportunity to record digital video directly into a PC or even a digital VCR.

The behavior of IA communication can be quite complex. By analyzing a typical household environment, we have summarized the typical traffic characteristics in Table III. These values are based on likely information size. For example, the instruction size that the refrigerator sends to the microwave in row 1 is estimated by the number of steps required to cook the food (1 byte), the cooking time for each step (4 bytes for each step), the

TABLE II
POWER LINE COMMUNICATION APPLICATION SURVEY IN A HOME

Row No.	Source Node	Destination Node	Frequency Per Day	Possible time period
1	Refrigerator	Microwave	8 times	7:00-9:00, 11:00-1:00, 17:00-19:00, 21:00-23:00
2	Microwave	AC	2 times	7:00-9:00, 11:00-1:00, 17:00-19:00, 21:00-23:00
3	TV	Refrigerator	3 times	11:00-1:00, 17:00-23:00
4	TV	VCR	3 times	11:00-1:00, 17:00-23:00
5	TV	Computer	3 times	11:00-1:00, 17:00-23:00
6	TV or Settop box	PDA or MP3 player	3 times	11:00-1:00, 17:00-23:00
7	Computer	PDA or MP3 player	1 time	11:00-1:00, 17:00-23:00
8	Computer	Computer	1 time	6:00-24:00
9	Settop box	Computer	1 time	11:00-1:00, 17:00-23:00
10	Computer	Internet	1 time	11:00-1:00, 17:00-23:00
11	VCR	Computer	1 time	6:00-24:00
12	Front door camera	Computer	3 times	6:00-24:00

power level for each step (2 bytes), and the packet header size. Added together, the entire instruction size is 160 bytes. Row 7 exemplifies storing digital music from a computer to an MP3 player. The 50 Mbyte traffic volume is calculated from the number of songs in an album, the length of a song (5 minutes), the encoded data rate (128kbps), and the packet header size. The frequency and the time period during which each event occurs are also shown. By using this data and typical household dynamics for concurrent events, we can generated a traffic flow for the power line network for a typical day.

These traffic types and volumes represent typical daily applications by using these IA devices. However, the most complex behavior appears **between** these devices, which will be explained later. Table I and Table III will be the basis of our investigation in this article.

The rest of this section will introduce the different placement strategies.

TABLE III
APPLICATION TRAFFIC AMOUNT IN A HOME

Row No.	**From Node**	**To node**	**Estimated data size**
1	Refrigerator	Microwave	160 bytes
2	Microwave	AC	72 bytes
3	TV	Refrigerator	750 bytes
4	TV	VCR	11KBytes
5	TV	Computer	360 bytes
6	TV or Settop box	PDA or MP3 player	15 Mega bytes
7	Computer	PDA or MP3 player	50 Mega bytes
8	Computer	Computer	60 MB to 180 MB
9	Settop box	Computer	320 MB to 640 MB
10	Computer	Internet	44 MB to 131 MB
11	VCR	Computer	320 MB to 640 MB
12	Front door camera	Computer	110 MB to 1100 MB

A. Random Placement Method

The first method that we investigated, the **RPM**, does not impose any rule of where and how the IA devices should be placed. Therefore, individual traffic coming from the IA devices potentially will collide in the branches and trunk lines. If the overall traffic exceeds the maximal 10 Mbps bandwidth, it is more likely that our power line-based network will suffer extra collisions and associated damage/delay in the application level.

When the combined traffic exceeds 10 Mbps, we define the status of the network as **saturated**. According to our analysis into the traffic patterns from the possible IA devices, we have termed **demanding traffi c** as the kind of traffic that usually consumes a large amount of bandwidth capacity. Certainly the effect of the combined traffic from all the devices will influence the network dynamic, but we have found that the demanding traffic is largely responsible for saturating the network bandwidth.

From a conservative point of view, we wanted to model the probability network traffic that would exceed the total network capacity. Many of these situations exist, but a typical example is when one demanding traffic crosses the branches while at least one other traffic is also crossing the branches.

Suppose there are b branches, and the total number of traffic streams is N. By assuming all devices are randomly distributed to all the branches, then the probability that the network will becomes saturated is as follows.

$$(1 - \frac{1}{b})[1 - (\frac{1}{b})^{N-1}]$$

The term of $(1 - \frac{1}{b})$ represents that probability that demanding traffic is communicating via the main trunk. The second term $[1 - (\frac{1}{b})^{N-1}]$ represents that at least one other traffic is also crossing the main trunk. Figure 3 demonstrates the performance tradeoffs between the parameters of b and N.

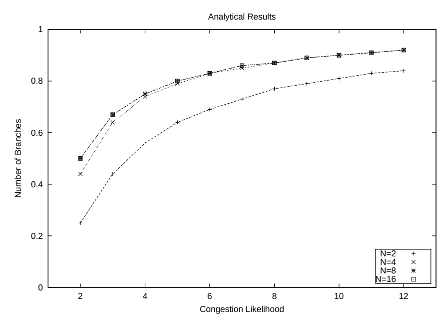

Fig. 3. Numerical results of the congestion likelihood on the trunk with design parameters of b and N

Figure 3 indicates that the number of the traffic streams is indeed over the limitation of network capacity. A small number of data streams therefore need to be regulated or scheduled. There is close matching between the numerical results and simulation results. We will discuss the details of the simulation later in this paper.

B. Conventional Placement Method

The RPM does not reflect how people actually place their IA devices. In reality, people place IA devices according to convenience rather than randomly. Based on the analysis of the human behavior in placing IA devices listed in Table I, the "*Conventional Placement Method*" was investigated.

We believe that this pattern of clusterings can be viewed as a special case of random placement. The above pattern from human habits should be classified as one of those cases. Nevertheless, we still put this placement method into our simulator for measuring the typical performance.

C. Minimize Trunk Traffic Placement Method

A detailed analysis of the traffic types and communication patterns should help us find an effective method to reduce the overall traffic on the trunk. From Table III, the typical traffic amount and frequency can be analyzed for their complex behavior between these devices. Attention must be paid in placing IA devices so the bandwidth of the system can be fully utilized and reduce the likelihood of overall congestion .

In Figure 4, the communication relationships of these appliances is depicted. The notation of this figure is described as follows: A circle represents an appliance and an arrow represents a communication traffic. A bi-directional arrow means two-way communication between two appliances. A string on an arrow line represents the duration and the frequency of communication. A heavy weighted arrow line represents a demanding traffic. A dashed line represents real-time traffic.

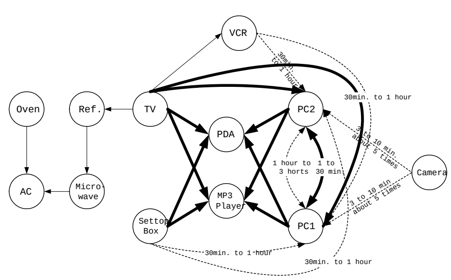

Fig. 4. Communication relationship between appliances

The idea of the **MTT Placement Method** is to confine the most heavy traffic in the local branch, that is, IA devices in the *"demanding set"* should be placed into the same branch first, then, if there are remaining sockets, devices in the *"real-time set"* and *"other set."* should be placed into that branch. This can be done by carefully decomposing the communication relationships graph into three different types of clusters.

TABLE III: Minimize Trunk Traffic Placement Algorithm

```
1  Assign_demanding(current_set)
2  {
3    do
4    {
5      if (there exists a branch with enough sockets) then
6           assign all appliances in current_set to this branch.
7      else
8      {
9      select an appliance with the least traffic amount
          from current_set.
10      move the selected appliance and associated traffic
          from current_set into temporary_set.
11      recalculate associated traffic amount to appliances.
12      }
13   } while (current_set is not assigned).
14   while (temporary_set is not empty)
15   {
16      randomly select a branch with at least one socket.
17      move an appliance from temporary_set to selected branch.
18   }
19
20 }
21
22 Assign(current_set)
23 {
24  if (one of the appliances in current_set
    has been assigned into a branch) then
25          selected that branch.
26  else
27      randomly select a branch.
28  if (selected branch can accommodate
      all appliances in current_set) then
29          assign all appliances into that branch.
30  else
31      minimize trunk traffic by either search for a new branch
        that can accommodate all appliances in current_set
        or assign partial appliances in current_set into selected branch.
32}
33
34 main()
35 {
36      calculate the traffic amount in each node.
37      put the demanding traffic into demanding_set_pool.
38      put real-time traffic into real-time_set_pool.
39      put other traffic into other_set_pool.
40      while (demanding_set_pool is not empty){
41          select a demanding_set.
42          Assign_demanding(demanding_set). }
43      while (real-time_set_pool is not empty){
44          select a real-time_set from real-time_set_pool.
45          Assign (real-time_set).}
46      while (other_set_pool is not empty) }
47          select an other_set from other_set_pool.
48          Assign (other_set). }
49 }
```

The algorithm works as follows: First, it calculates the traffic amount on each node in Line 36. The traffic amount is calculated by adding all in-going and out-going traffic amount on a node. Then traffic are assigned into different sets according to type and amount. Traffic with an amount larger than a predefined threshold value are assigned to demanding sets, real-time traffic are assigned into real-time sets, and other traffic are assigned into other sets. These works are done in Lines 37 to 39.

After classifying all traffic, we begin to assign IA devices,that is, Lines 40 to 48. We first deal with the heaviest traffic in the branches, that is, assign the demanding set to branches. A current set is chosen from the demanding set pool and then processed in the *Assign_demanding* procedure. The *Assign_demanding* procedure searches for a branch that can accommodate all IA devices of the current set. This process is continued until we find a branch that the system can accommodate in the current set. When all the demanding sets are assigned, the algorithm then handles the real-time traffic.

The following Figure 5 is the relationship graph resulted from our proposed MTT algorithm.

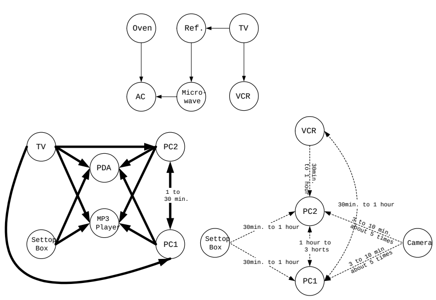

Fig. 5. Complete decomposition includes three components: a demanding set, a real-time set and an other set

From Figure 5, we can see that the trunk data traffic will be minimized if we move the *"demanding set,"* *"real-time set"* and *"other set"* to different branches. According to our simulation results, the average improvement can be in the significant range of 18 percent.

III. Performance Results and Analysis

In this section, we present our simulation results for the above various placement methods. Note that IA market is still in its infant stage; thus, many IA devices that we envision are not available yet. By assuming the capability of these IA devices, our simulation tools emulate the interactions between IA devices, branch segments, and the main trunk of the power line channels.

We assume 13 sockets are available for 13 appliances. With our envisioned scenarios, there are at most 13 IA devices. In order to reduce the possible variation of the single simulation run, we have performed each experiment with 36500 different runs and 36,500 sets of performance data. At this time, we do not assume that any Medium Access Control (MAC) protocols are implemented over these IA devices. Therefore our interest is to investigate the "likelihood" that 10 Mbps traffic has been reached by the IAs on the branches and the main trunk. The higher the likelihood is, the worse system performance we can expect between these IA communications. From these collected 36,500 sets of data, we then extract the following daily traffic likelihood in the granularity of 24 hours.

Three performance metrics are particularly interesting to us: (1) **Daily traffic congestion likelihood** reflects how likely the network bandwidth has been utilized to almost 100 percent. Likelihood in the power-line trunk and branches are collected, and results are averaged over the number of branches; and (2) **Real-time traffic jitter likelihood** estimates the possibility that a real-time IA device may suffer potential jitters. The above performance metrics will be jointly presented with our investigated placement strategies and proposed MTT algorithms.

A. *Performance Results Based on the Random Placement Method and the Conventional Placement Method*

The performance results shown in Figure 6 include only the mean congestion likelihood.

A.1 Congestion Likelihood within the Trunk

When the number of the branches is increased from two to three, the average likelihood of congestion is increased from 43.77 percent to 66.9 percent, that is, 52.8 percent performance degradation. This performance degradation is consistent with our mathematical analysis from the earlier section of the paper.

Increasing the branch number from three to four leads to the likelihood of trunk congestion from 66.9 percent to 74.71 percent, that is, a further per-

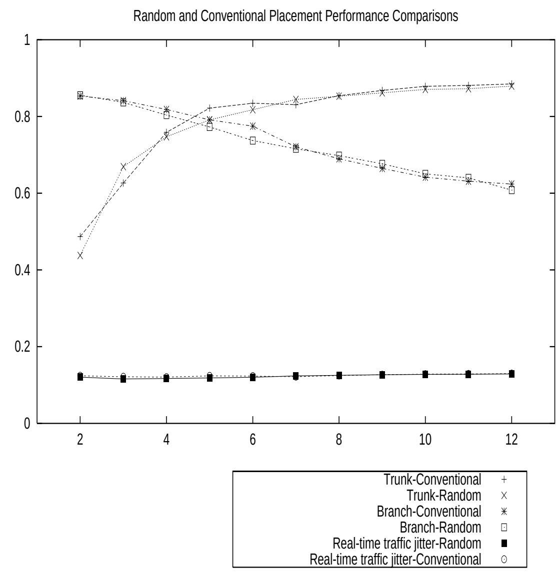

Fig. 6. Daily congestion likelihood with the Random Placement Method and Conventional Placement Method

formance degradation of 11.6 percent. The performance trend continues with the similar manner for the rest of cases from the five-branch to the 12-branch systems.

The performance results indicated the congestion likelihood in the trunk increased by increasing the number of branches. Since IA devices are scattered to more branches, more traffic issued by the source IA devices have the need to go through the trunk to reach the destination devices.

A.2 Congestion Likelihood within a Branch

When the number of branches is equal to two, the average congestion likelihood within each branch is 85.53 percent. When the network increases the branch number from two to three, the congestion likelihood decreased to 83.67 percent, that is, 2.1 percent performance improvement. The trend continues with a steady decreasing rate when the branch number keeps increasing. The congestion likelihood decreased to 80.36 percent, which is about four percent of performance improvement. When the branch number increased from four to five, the performance improvement is about 3.8 percent, and from five- to six-branches, the improvement becomes 4.6 percent. The improvement becomes 2.9 percent, 2.5 percent, 3.1 percent, 3.8 percent, 1.6 percent and 5 percent when the number of branches increased to seven-, eight-, nine-, 10-, 11- and 12-branches.

Statistically speaking, the congestion likelihood within a branch will decrease by about 3 percent when the number of branches is increased by one. That brings us the 60.79 percent likelihood for the case of a 12-branch system. After we trace the details of the simulation, it appears that the network likely have more than two IA devices placed within a branch because of random placement. Therefore, there is a high likelihood that congestion occurs within this branch, while the rest of the branches remained to be fine. Furthermore, since the statistics were collected within a time span of 24 hours, any event causing the congestion at any time will be counted.

A.3 Real-time Traffic Jitter Likelihood

The above discussion focused on daily traffic analysis, and the following description addresses the real-time traffic performance. The jitter likelihood is observed when the real-time traffic is involved in a network congestion. When the branch number is two, the average jitter likelihood is 12.07 percent. The likelihood goes down to 11.58 percent when the number of branches increases to three, then goes up slightly to 11.70 percent when there are four branches. It eventually goes up to 12.90 percent with 12 branches.

The simulation results suggest that separating the power line into three to five branches should produce the best result for real-time traffic. However, the trend shows that the branch number contributes little on the jitter likelihood. By using random placement, no significant benefit is generated for supporting real-time traffic.

A.4 Performance Results Based on the Conventional Placement Method

The differences between these *random placement* and *conventional placement* is limited. In the case of trunk congestion likelihood, when there are two branches, the congestion likelihood in *Conventional Placement* is 62.6 percent which is lower than it is in the *Random Placement* (66.9 percent). However, increasing the number of branches to three, the congestion likelihood increased to 75.9 percent which is higher than in the *Random Placement* (74.7 percent). The congestion likelihood in the *Conventional Placement* remains higher than the *Random Placement* when the total number of branches is larger than three. An exception is observed when there are seven branches, in this case, the *Conventional Placement* had less congestion likelihood, 83 percent, than the *Random Placement*, 84.4 percent.

A similar trend is seen in the case of branch congestion likelihood. When there are two branches the congestion likelihood in the *Conventional Placement* is 85.3 percent which is a little bit lower than it is in the *Random Placement* (85.5 percent). However, increasing the number of branches from two to three, four, five, six and seven, the congestion likelihood decreased to (84.1 percent, 81.8 percent, 79.1 percent, 77.5 percent and 72.1 percent) and are all higher than it is in the *Random Placement*. Then the congestion likelihood in the *Conventional Placement* becomes lower than the *Random Placement* again when the total number of branches is larger than seven and eventually it becomes higher when there are 12 branches (62.4 percent vs. 60.8 percent). The overall differences of real-time traffic jitter likelihood between the *Conventional Placement* and the *Random Placement* are less than one percent.

B. Performance Results Based on the Minimize-Trunk-Traffic Placement Method

Based on the observation of the previous two experiments, we try to minimize traffic amount in the trunk so that each individual communication traffic will experience the least congestion likelihood in the trunk, thus decreasing the overall congestion likelihood.

B.1 Congestion Likelihood within the Trunk

Figure 7 depicts performance gain over the congestion likelihood in the trunk when the *Minimize-Trunk-Traffic Placement Algorithm* is used. We also listed two other curves from the *Random Placement* and the *Conventional Placement* for comparison purpose.

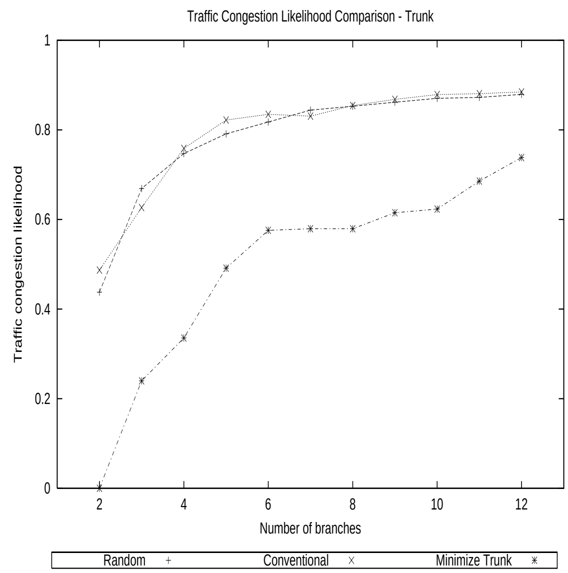

Fig. 7. Daily congestion likelihood in the trunk using proposed MTT Algorithm.

Our proposed MTT method performed significantly better than the other two placements. When there are two branches, the congestion likelihood in the *Minimize-Trunk-Traffic Placement Algorithm* is almost 0. However, the *"Random placement"* and the *"Conventional placement"* suffers 43.8 percent and 48.7 percent congestion likelihood, respectively. When we increased the number of branches to three, the congestion likelihood in *Minimize-Trunk-Traffic Placement Algorithm* increased to 24 percent while the other two placement methods are also increased to 66.9 percent (64.2 percent improvement) and 62.6 percent (61.7 percent improvement), respectively. The trend continues when we increased the number of branches all the way up to 12 where it is the worst case and we still get 16.6 percent improvement over the *"Conventional placement"* and 16.0 percent improvement over the *"Random placement."*

B.2 Congestion Likelihood within the Branch

As we have seen in the previous subsections, diverting the communication traffic from trunk to branch lessened the congestion in the power line trunk and increased the congestion degree within the branch. Figure 8 depicts the congestion likelihood when the *Minimize-Trunk-Traffic Placement Algorithm* is applied while comparing with the other two placement methods.

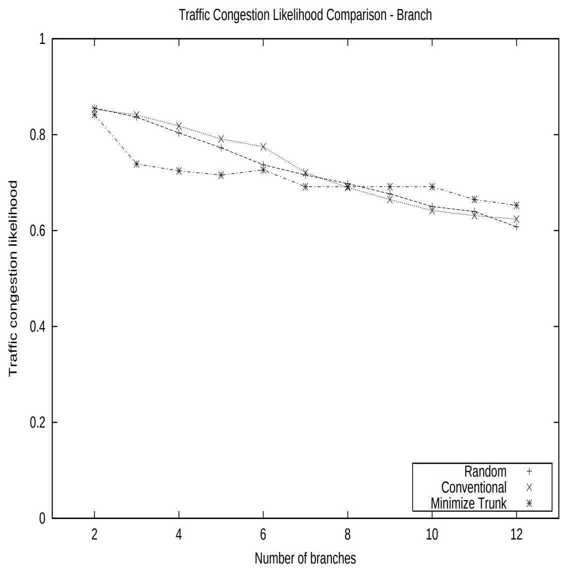

Fig. 8. Average daily congestion likelihood among the branches with the Proposed MTT Algorithm.

When comparing the *Minimize-Trunk-Traffic Placement Algorithm* results with the other two placement methods, we can see that the *Minimize-Trunk-Traffic Placement Algorithm* performs better to some degree than the other two placement methods when the number of branches is less than eight. For example, when the number of branches is two, there is 1.6 percent improvement over the *"Random placement"* and 1.3 percent improvement over the *"Conventional placement."* Increasing the number of branches from two to three, the improvements over the other two placements are 11.7 percent and 12.2 percent, respectively. The trend continues but with less improvements in each increment of the number of branches. Though the congestion likelihood among the branches in the *Minimize-Trunk-Traffic Placement Algorithm* is higher than the other two placements when the number of branches was more than seven, the differences are limited.

B.3 Real-time Traffic Jitter Likelihood

Figure 9 depicts the real-time jitter likelihood with the *"MTT Placement,"* while comparing with the *"Random Placement"* and the *"Conventional Placement."*

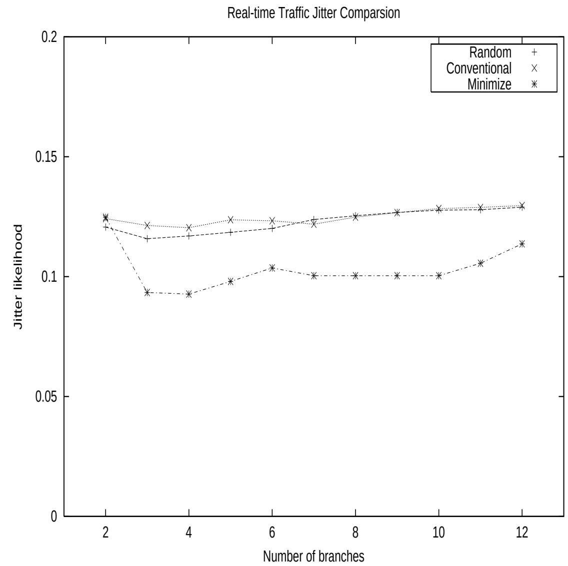

Fig. 9. Real-time traffi c jitter likelihood using our proposed MTT Algorithm.

If we exclude the extreme case, that is, the number of branches being two and 12, our performance results showed a consistent jitter likelihood, and the jitter likelihood is within the range from 9.3 percent to 10.6 percent. The improvement over the *"Random Placement"* and the *"Conventional Placement"* were within the range of 13.7 percent and 23 percent.

IV. Conclusion

Since we believe that the home power line network eventually has to connect to the Internet, the power line trunk bandwidth should be preserved. We first explored *Random Placement* with no rules in placing IA devices, then a *"Conventional Placement"* was investigated using human behavior in placing IA devices. We observed that increasing the number of branches in the power line network increased the congestion likelihood within the power line trunk. However, increasing the number of branches in the power line network decreased the congestion likelihood of a power line branch.

We have confirmed that the bottleneck of the power line network was the power-line trunk. Based on the above observation, we developed an *"MTT Placement"* algorithm that would decrease the power line trunk traffic as much as possible. Our proposed algorithm effectively reduced the congestion likelihood compared to the *"Random Placement"* and the "*Conventional Placement.*". If we exclude the extreme cases, when the number of branches was 2 or 12, the overall improvement over the other two placements ranged from 21.8 percent to 29.7 percent.

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