Decision Making Methods and Uncertainty Modeling for the Development of a Roadmap for Future Home Networks

Georgia Dede[1]

National and Kapodistrian University of Athens
Department of Informatics and Telecommuncations
gdede@di.uoa.gr

Abstract. In recent years there is a need for supporting broadband services in home and office networks. Towards this end, there has been great progress in technologies of high bandwidth, which resulted to an interest for the evolution of home networks and many standards have been developed for the interconnection of the devices. Given the increasing technological development, it would be interesting to investigate the technical solutions and the possibility to achieve high bit rate connectivity. Towards this end, this thesis aims to investigate the development of a roadmap as a key for ensuring the smooth development of future home networks, and also prescribe their course and determine the most appropriate technological solutions for the development of such systems. However, apart from technical difficulties, the network designer should take into consideration the different economic and social issues affecting the adoption of home network systems. In view of such difficulties, the need for a roadmap of home network systems arises in order to address all these issues.
This thesis investigates the major aspects affecting the development of future home networks and creates an effective roadmap for their development based on multicriteria decision making methods. Although most decision makers rely on decisions based partly on intuition, such an approach is not effective especially in a demanding business environment. It is therefore particularly important to investigate the effectiveness of these methods under different conditions, taking into account the influence of uncertainty that may undermine these processes.
This thesis aims both to contribute to a roadmap implementation in next-generation home networks, based on multi-criteria decision making and also study critical issues of uncertainty lurking in decision making processes and may affect the final result. The study and the development of the above lies on the Analytical Hierarchy Process (AHP), and especially in pairwise comparison method.

1 Dissertation Summary

Home Networking Systems (HNS) will play a crucial role in achieving end-to-end broadband service provision, enabling the penetration of the future internet. Traditionally, in-building networks, for instance in corporate or academic settings, have a tenfold higher capacity than their access points to the rest of the telecommunication infrastructure. Since Fiber-To-The-Home (FTTH) promises

[1] Dissertation Advisor: Thomas Sphicopoulos, Professor

symmetric access data rates of at least 100 Mbit/s per household [1], HNS should support gigabit per second data transmission, limiting the latency time below 10msec. Inside new buildings, optical fiber systems may provide the ultimate solution in terms of bandwidth and range. However, installing fiber cables inside older buildings is usually not preferred, since it is accompanied with increased cost and user discomfort.

1.1 Roadmap for Future Home Networks

Considering the vision of future HNS, there is a variety of technological solutions that could contribute to the development and further growth of next-generation HNS, to achieve high speed connectivity. Such solutions include Ethernet, Power Line Communications (PLC), Wifi, 60 GHz and the optical solutions wireless or wired.

In the context of home networking, extension is a fundamental functionality. As shown in Figure 1, network extension aims to extend the HNS coverage. Conceivably, every network device may extend the network acting as a “multi-hopper”. The extender device may act as a router by forwarding data for other network nodes and can also generate and receive packets of supporting ad-hoc network functionalities.

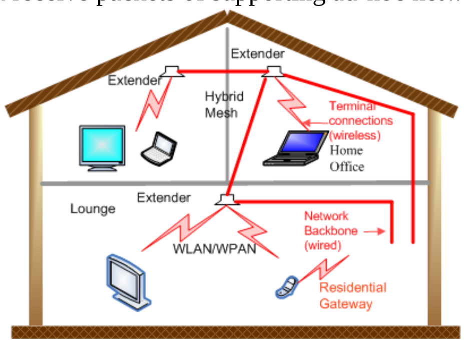

Figure 1. Illustration of hybridization of technologies inside the HN

There are various technology solutions that could be considered for network extension, each with their own particular characteristics. Radio systems, such as WiFi, are already commercially available and 802.11n promises up to 600Mb/s data rates using multiple-input multiple output (MIMO) techniques [2], but the actual network throughput should be lower. Systems operating at the unlicensed 60GHz band [3] and short range Ultra Wide Band (UWB) [4] systems can provide higher data rates. Wireless gigabit-per-second transmission is feasible at 60GHz, but such systems have not reached full technological maturity. State-of-the-art PLC [5] provide hundreds of megabit-per-second wireline connectivity using the already installed power cables of the house. Extending them in the gigabit regime is however a challenge because of the particularities of the power line channel. Optical Wireless Systems (OWS) [1] may also provide high data rates, possibly reaching 10Gb/s in the future, in either the infrared or visible spectrum region. However, there are still important technical limitations. In Line-of-Sight (LOS) OWS, blocking is a serious issue. In diffuse configurations (no need for LOS path), one obtains a poorer signal to noise ratio.

The above discussion illustrates that future HNS will probably consist of hybrid systems and technology roadmapping is key in ensuring their smooth deployment. This thesis seeks to shed light in this problem, contributing to the technological roadmapping of HNS in general. At first, we evaluate various crucial technological and socio-economic issues that affect the deployment of future HNS taking into account popular broadband services such as HDTV and VoIP. Moreover, focusing on the extension functionality, we consider three possible alternative technologies for network extension namely IEEE 802.11n, 60GHz radio and PLC. To rank these alternatives, the AHP methodology is used [6] as a fundamental part of an effective technology roadmapping introduced in [7]. The main objective is to evaluate the prospects of the various home networking technologies both from a technical and a socio-economic point-of-view.

1.2 Optical House Vision

Given the large capacity of optical communications systems in long haul and metropolitan area networks, one could think of using optics at the home network as well [8]. Short range, fiber systems [9] may be used inside the home to ensure that no bottlenecks will occur in end-to-end HN services. However, one should also bear in mind that optical technologies are faced with a different set of requirements when deployed inside the customer premises. For example, in existing buildings, residents would be eager to avoid new cable installations which may come at an increased cost and discomfort.

OW systems [10] are already being widely applied in point-to-point outdoor connections in the access network [11]. Recent years have seen a growing interest in indoor applications as well, in both the infrared (IR) [12] and the visible portion [13] of the spectrum. The latter technology, also known as visible light communications (VLC), relies on white light emitting diodes (LEDs) which are used to provide illumination and communication simultaneously. The advantages of OW technology include the virtually unlimited available bandwidth, its inherent security (since the electromagnetic field at these frequencies cannot pass through walls) and limited interference with domestic appliances and conventional radio communication systems. In addition, provided that certain eye safety regulations are met, electromagnetic radiation at these wavelengths is safe, since mankind has been exposed to it for centuries, because of the Sun. Multi-Gb transceivers have already been developed and commercialized for fiber systems. However, since the issue of cost is of paramount importance near the customer premises, low-cost components should be used.

The above considerations illustrate that OW may constitute a good candidate for enabling the delivery of many broadband services such as HDTV and Web 2.0 applications including content sharing, on-line gaming, etc. Unlike conventional radio wireless systems however, OW is not a mature technology and there are several issues concerning their deployment that remain unclear. For example the choice of backbone HN supporting Gb/s. PLC can offer an interesting solution. Alternatively, if one wants to abandon the no-new-wire concept, optical fibers can be used for hotspot interconnection. Another issue to resolve is what the actual system to be used for wireless connections. Do we rely on IR or VLC or both?

The above issues are complicated by the fact that technology penetration depends on a blend of economic, social and performance-related criteria [14]. According to the above, in this thesis we also attempt to shed some light in this complex problem, using AHP. Five alternative deployment scenarios are identified and ranked based on the findings of several carefully designed pairwise comparisons. The importance of the various criteria involved in the deployment of the network are evaluated and discussed. The obtained results form a key part of the optical wireless roadmap.

1.3 Uncertainty Issues in Decision Making

A fundamental problem in decision making is to grade the importance of a set of alternatives and assign a weight to each of them. The importance of alternatives usually depends on several criteria which can be evaluated within the decision making framework in which pairwise comparisons (PWC) are an essential ingredient [15]. PWC enables the ranking of alternatives by allowing the experts to compare the various criteria or alternatives in pairs instead of assigning their priorities in a single step [16]. This reduces the influence of subjective point of views, associated with eliciting weights directly. The influence of uncertainty due to the imperfect and subjective expert judgments is of paramount importance when considering the credibility of the outcome of a decision making process. Several studies have attempted to shed some light on this issue in the context of PWC. [17]-[21].

The main purpose of our work is to provide a suitable characterization of the impact of uncertainty in PWC. A first step in order to characterize the impact of uncertainty in PWCs, is to identify a suitable measure for quantifying its effects. Assume for instance that N different alternatives are pairwise compared by M experts, each with possibly a different view on the ranking of the alternatives. PWC aims at providing an average ranking, encompassing all these diverse opinions of the experts. It is of course natural to expect that the credibility of the overall process will be increased as the size of the expert group increases. Therefore, one possible way of measuring the trustworthiness of the results is to define the probability of rank reversal (P_{RR}) as follows: Let $W_1,\ldots,W_N$ be the weights calculated by the PWC in the case of a very large group of experts ($M\to\infty$). In a practical situation where M is finite, uncertainty may undermine the PWC and the calculated weights w_k may turn out different than W_k. Uncertainty can be due to the difference of opinion among the experts or inconsistent pairwise comparisons. The probability of rank reversal is defined as: $P_{RR} = P\left\{\text{the ranking obtained by } w_i\ , 1 \le i \le N,\ \text{is different than that of } W_i\ \right\}$.

According to the aforementioned, we propose an uncertainty model to address two major issues concerning the probability of rank reversal in pairwise comparisons. The first issue highlights the relations between the probability of rank reversal and the group size of experts participating in surveys. The procedure is based in Monte Carlo simulations (MC).

Although this is a valid approach, it is often preferable to have a theoretical model for estimating the P_{RR}. A theoretical model is often much more straightforward to implement and requires much less computational time than Monte Carlo simulations. It can also form a solid basis for understanding and extending the PWC application framework. So as an extension to the aforementioned numerical model of estimating the P_{RR}, this thesis also discusses how the probability of rank reversal can be estimated theoretically. We show that instead of using MC, P_{RR} is estimated through the multivariate normal cumulative distribution function (MVNCDF).

2 Results and Discussion

2.1 Towards a Roadmap for future Home Networks

This thesis explains various critical technological and socio-economic issues in order to investigate their influence on the development of future home networks. In this section, the first steps towards a roadmap for the next generation home network have been undertaken. Based on pairwise comparison surveys conducted within the ICT-OMEGA project consortium [22], a number of technical, economic and social issues determining the penetration of future home networks have been evaluated and prioritized. It was shown that experts rate social acceptance of primary importance for successful product commercialization. Within this criterion, health issues have proven the main concern, possibly reflecting some public skepticism on biological effects of electromagnetic radiation. It seems that as time goes by, health issues will crucially affect the deployment strategies for home networks. Regarding performance issues, coverage was deemed as the most important performance measured followed by downstream bit rate. If fiber installation is not an option, the existing technologies (radio, PLC, OW or some hybrid alternative) may provide a broadband alternative each with its own merits and drawbacks however. Compatibility with existing solutions and home appliances was also highly weighted. From the economic point-of-view, the installation cost turned out to be the major factor. Wireless solutions and even PLC are compatible with the “no new wire” approach and could therefore a hybrid solution can lead to reduced installation costs. Various requirements for HDTV and VoIP, envisioned to be major service application scenarios for future home networks have been considered and weighted.

Furthermore, we analyze the creation processes for a roadmap, associated with home networking systems, and specifically to the functionality of the network extension. It was shown that future HNS will probably consist of hybrid systems and technology roadmapping is key in ensuring their smooth deployment. This section aims to contribute towards this end, by ranking three possible alternative technologies for network extension, namely IEEE 802.11n, Radio 60GHz and PLC. OW systems are not considered in this work, since the majority of the experts believed that this technology is still relatively quiet immature. For example, it remains unclear which OW configuration will prevail from a number of possible choices, including VLC and IR systems which can be LOS, diffuse or both. Such issues prevent reliable forecasting of several performance-related measures. Furthermore UWB was not considered in the HNS roadmap since they can provide high bandwidth short range links at small distances, but at distances longer than 10m the throughput is comparable to that of 802.11g.

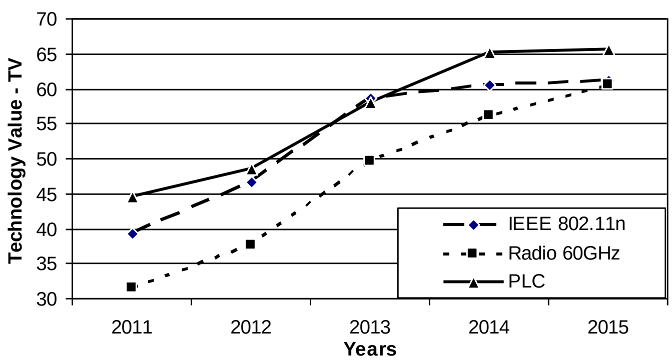

Figure 2. TV for the technology alternatives for network extension

The results, presented in Figure 2, focus on network extension but are also indicative for the rest of the home network components as well. AHP indicates that PLC takes some precedence over the wireless alternatives. 802.11 is ranked second best while 60GHz system are regarded as a longer term alternative, which could provide gigabit per second connectivity. In this thesis the merits of hybrid integration of these technologies, either in the PHY or a higher network layer are also discussed. Indeed, PLC would be the most ubiquitous connection in the home, while all the devices would include additional interface to support the benefits of intelligent switching to include a wireless extension. Hybrid radio/PLC systems, combining the merits of both technologies could also provide an alternative. Products combining both technologies at the PHY have already been commercialized. The issue of hybridization is more interesting when the PLC and the 60GHz systems are combined together: 60GHz can provide high bandwidth wireless connection within the room while PLC can be used to extend the connectivity across multiple rooms of the house. In order for PLC to provide the future home network backbone however, its capacity must be extended in the Gbps regime. A sensitivity analysis was also performed in order to estimate the uncertainties involved and it was deduced that they do not in general undermine the results of the ranking.

2.2 Envisioning Optical House Scenario

This thesis also focuses on the evaluation of the potential OW technologies in the development of home network, towards the vision of a future home or office network based entirely on optical systems.

Towards this end, we consider five different scenarios. The first one scenario (A_1) relies on bidirectional IR line-of-sight connections and a PLC backbone. The second scenario (A_2) is similar to A_1 with the exception that VLC lamps are also providing with downstream connectivity, enhancing the coverage of the overall system. The VLC and IR subsystems can be combined at a higher network layer such as the MAC layer thereby constituting a hybrid system. Note also that in this scenario, VLC is used for downstream data only. The other two architectures A_3 and A_4 are similar to A_1 and A_2 respectively except that the plastic optical fiber (POF) is used at the backbone instead of PLC. Architectures A_1 and A_2 have the merit of remaining compatible with the no-new-wires approach. Both PLC and POF are expected to achieve Gb/s connections in the near future. All the aforementioned wireless alternatives are not yet commercially available solutions but have been successfully demonstrated in the lab. The fifth alternative (A_5) is to extend the POF connections right up to the user terminals. No wireless connections are provisioned in this scenario.

In this section, an evaluation of the potential of OW technologies for home/office network deployments was carried out. A number of important findings were obtained which must form part of any type of carefully designed roadmap for optical home networking technologies. The first finding concerned the identification and ranking of various factors and criteria determining the deployment of such systems. It was made clear, that since home networking systems will be placed at the customer premises, there are many social and economic factors that must be taken into account. Social aspects were shown to be of paramount importance and health issues can provide a serious incentive for installing IR and VLC hotspots which are inherently safe. The results obtained by the surveys were justified taking into account the nature of the optical wireless systems. Next, we identified and ranked the five architecture scenarios using the AHP framework. The results suggest that a combination of VLC and IR hotspots, along with a PLC backbone provides the most favorable option, but is closely followed by IR hotspots connected with a PLC backbone. In any case, the results clearly indicated the advantages of PLC backbone in terms of ease of installation in older buildings. The ranking results were also further elaborated using sensitivity analysis and MC simulation. It was found that under uncertainty the priorities of the alternatives are correlated and this correlation reduces the P_{RR}. The hybrid VLC/IR with PLC backbone solution is almost never surpassed by the IR PLC alternative, even if all parameters are randomly perturbed by ±10%.

This section provided a framework to identify factors that could speed up or impede the deployment of optical communication technologies in the home network. It is the our hope that it would constitute a first step for bridging the gap between the important research work carried out in the field, and the socio economic requirements that will guarantee the business prospects of their wide scale deployment.

2.3 Convergence Properties and Practical Estimation of P_{RR}

The present section chapter attempts to deal with both points, presented in 1.3. We first develop a model for incorporating uncertainty in PWC and consider a suitable measure for quantifying the uncertainty level. We then discuss how P_{RR} varies with the group size M depending on the uncertainty level and extract several interesting conclusions from this variation. It is shown that there is not much sense in using more than M=15 experts in the decision making process because the rate of decrease of P_{RR} is already small for M >15. We then address the issue of how P_{RR} can be estimated from just the values of the pairwise comparison matrices $\mathbf{P}^{(m)}$ obtained by the experts. Given this information, we discuss a numerical method for estimating P_{RR} based on Monte Carlo simulation. The results indicate that for a sufficiently large group of experts, one can obtain a reasonable approximation to the actual value of P_{RR}.

Concerning the first issue of how this probability is reduced by augmenting the number of experts participating in the surveys, the results dictate that there is not much to be gained by increasing the number of experts beyond 15, even if uncertainty level is large, as shown in the example presented in Figure 3. This seems to hold regardless the number of criteria, the level of uncertainty, the weight estimation method and other parameters changed in our model.

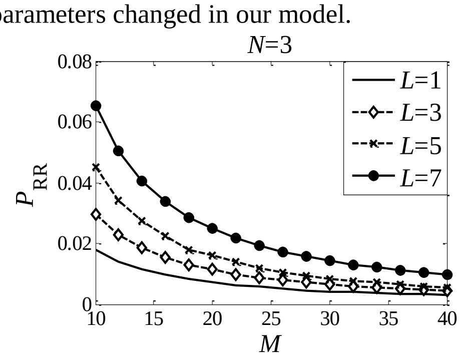

Figure 3. P_{RR} as a function of the number of experts for different levels of uncertainty L

Using perturbation theory we have argued that the convergence of the probability of rank reversal with the number of experts is not crucially dependent on the uncertainty statistics. We have also shown numerically that the choice of comparison scale and weight selection method does not significantly affect the convergence. Regarding the second issue of how the P_{RR} can be estimated in practice, from the elements of the PWC of a single expert group, two alternative methods have been discussed for extracting information on the statistical behavior of the uncertainty-induced perturbations. The first one is based on the average value, while the second one on the standard deviation of the actual data, It was shown that standard deviation provides reasonable good accuracy and can therefore be used in practical applications of the method for estimating the credibility of the outcome. Interestingly enough, this conclusion holds under other situations such as fuzzy pairwise judgments, alternative preference scales, weight estimation methods and accounting for a different uncertainty level for each expert in the group.

2.4 Theoretical Estimation of P_{RR}

In this thesis a theoretical model is also proposed, based on MVNCDF, in order to estimate the probability of rank reversal and investigate the impact of uncertainty in the final outcomes of pairwise comparisons. Towards this end, we have introduced uncertainty in the opinion of experts developing the corresponding model, taking into account s_w and s as the perturbation strengths of the perturbations of each expert from the ideal weights and PWC matrices, respectively. This approach is formulated for two alternative weight estimation methods: the eigenvalue (EV) and the geometric mean (GM) method. We show that the MVNCDF yields accurate results compared to MC simulations regardless of the number of criteria and the weight estimation method used.

We consider N alternatives and their ideal weights W_k are chosen so that $W_{k-1} \geq W_k$ for $2 \leq k \leq N$. In the event of no rank reversal, one would therefore have $w_{k-1} \geq w_k$. In the case of the EV, the average perturbations of the weights are determined as $\delta\omega_k = w_k - W_k$

and in the absence of any rank reversal we will have $W_1+\delta w_1 \geq W_2+\delta w_2 \geq \ldots \geq W_N+\delta w_N$. The probability of no rank reversal P_n is therefore $P_n=P(\delta w_1-\delta w_2>W_2-W_1,..., \delta w_{N-1}-\delta w_N>W_N-W_{N-1})$ while the probability of rank reversal is simply $P_{RR}=1-P_{n.}$ Since $y_k=\delta\omega_k-\delta\omega_{k-1}$ will follow a Gaussian-like distribution, P_{RR} can be approximated by the MVNCDF, once the covariance matrix and the mean values of y_k are determined. It is easy to see that $\langle y_k\rangle=\langle\delta\omega_k\rangle-\langle\delta\omega_{k-1}\rangle$ and the covariance matrix is

$$C_{\kappa\mu}=\left\langle y_\kappa y_\mu\right\rangle-\left\langle y_\kappa\right\rangle\left\langle y_\mu\right\rangle=c_{\kappa\mu}-c_{\kappa,\mu-1}-c_{\kappa-1,\mu}+c_{\kappa-1,\mu-1}-\left\langle y_\kappa\right\rangle\left\langle y_\mu\right\rangle \qquad (1)$$

where $c_{ij}=\langle\delta\omega_i\delta\omega_j\rangle$. After some mathematical manipulation, we can show that:

$$\left\langle \delta w_k\right\rangle=\sum_{r=2}^{N}x_{rk}\sum_{p,q}\frac{W_p}{W_q}(f_5-1)\frac{\upsilon_{pr}x_{q1}}{\boldsymbol{\upsilon}_k^{\mathrm{T}}\mathbf{x}_k\lambda_1} \quad (2) \qquad c_{ij}=\frac{1}{M\lambda_1^2}\sum_{k=2}^{N}x_{ki}\sum_{l=2}^{N}\frac{x_{lj}}{F_{kl}}E_{kl} \quad (3)$$

where E_{kl} is given by:

$$\begin{aligned}E_{kl}&=N^2\left(f_7-2f_5+1\right)\sum_{I_1}W_zW_p\Omega_{zp}{}^{(kl)}+\left(2-f_5\left(f_6+1\right)\right)\sum_{I_2}G_{zn}{}^{(kl)}+N^2\left(f_5-1\right)^2\sum_{I_3}W_zW_p\Omega_{zp}{}^{(kl)}\\&+N\left(1-f_5\right)\sum_{I_4}W_p\Omega_{zqp}{}^{(kl)}+N\left(f_4-2f_5+1\right)\sum_{I_5}^{N}W_z{}^2\Omega_{zz}{}^{(kl)}+N\left(f_1f_5^2-2f_5+1\right)\sum_{I_6}W_m{}^2\Omega_{zp}{}^{(kl)}\\&+N\left(1-f_5\right)\sum_{I_7}W_z\Omega_{znp}{}^{(kl)}\end{aligned} \qquad (4)$$

Where M is the number of experts and $1\leq m\leq M$. $\Omega_{ij}{}^{(kl)}=\upsilon_{ik}\upsilon_{jl}$, $\Omega_{ij\nu}{}^{(kl)}=\upsilon_{ik}x_{j1}\upsilon_{\nu l}$, $G_{ij}{}^{(kl)}=\upsilon_{ik}x_{j1}\upsilon_{jl}x_{i1}$, while I_i is the set of quadruples (z,n,p,q) for which a) $n=q$ and all other elements are distinct if for $i=1$, b) $z=q$, $n=p$ and $z\neq n$ if $i=2$, c) all elements are distinct for $i=3$, d) $z=q$ and the rest elements distinct for $i=4$, e) $z=p$, $n=q$ and $z\neq n$ for $i=5$, f) $z=p$ and while all other elements are distinct for $i=6$ and finally g) $n=p$ and all the other are distinct for $i=7$. Also we have $F_{kl}=(\boldsymbol{\upsilon}_k\cdot\mathbf{x}_k{}^{\mathrm{T}})(\boldsymbol{\upsilon}_l\cdot\mathbf{x}_l{}^{\mathrm{T}})$, $f_1=1+s_w{}^2/12$, $f_2=1+s^2/12$, $f_3=(1-½\, s_w)^{-1}-(1+½\, s_w)^{-1}$, $f_4=s_w{}^{-1}f_3f_2f_1$, $f_7=s_w\log f_3$,

$$f_5=s_w{}^{-1}\log\left(\left(1+0.5s_w\right)\left(1-0.5s_w\right)^{-1}\right) \quad (5) \qquad f_6=s^{-1}\log\left(\left(1+0.5s\right)\left(1-0.5s\right)\right)^{-1} \quad (6)$$

Equations (1)-(6) can be used to determine the mean values and the covariance matrix of the weight perturbations that can be used to calculate the MVNCDF which as previously discussed provides an estimate for P_{RR}.

In a similar way we can estimate the P_{RR} through the MVNCDF in the case where the GM method is used for the estimation of the weights from the PWC matrices. Taking into account the uncertainty model, the average weights w_k can be expressed:

$$w_k=W_k\left(\prod_{m=1}^{M}\prod_{j=1}^{N}\frac{\delta_{kj}{}^{(m)}}{W_j}\right)^{\frac{1}{MN}} \quad (7) \qquad \delta_{kp}=\frac{1+\Delta w_k{}^{(m)}}{1+\Delta w_p{}^{(m)}}\left(1+\Delta w_{kp}{}^{(m)}\right) \quad (8)$$

We define the perturbations $\delta z_k^{(m)}$ of the logarithmic weights as $\delta z_k^{(m)}=\ln w_k^{(m)}-\ln W_k$ and also define their successive differences $v_k=\delta z_k-\delta z_{k-1}$ which follow a Gaussian distribution. The P_{RR} can be approximated from the MVNCDF once the covariance matrix and the mean values of v_k are determined. Taking into account that $\langle v_k\rangle=\langle\delta z_k\rangle-\langle\delta z_{k-1}\rangle$ the covariance matrix is:

$$R_{\kappa\lambda}=\left\langle v_\kappa v_\lambda\right\rangle-\left\langle v_\kappa\right\rangle\left\langle v_\lambda\right\rangle=r_{\kappa\lambda}-r_{\kappa,\mu-1}-r_{\kappa-1,\mu}+r_{\kappa-1,\mu-1} \qquad (9)$$

where $r_{ij}=\langle\delta z_i\delta z_j\rangle-\langle\delta z_i\rangle\langle\delta z_j\rangle$ is the correlation matrix. After some mathematical manipulations we can show that:

$$\left\langle \delta z_k \right\rangle = \frac{1}{NM} \sum_{m=1}^{M} \sum_{j=1}^{N} \left\{ \left\langle \ln(1+\Delta w_{kj}{}^{(m)}) \right\rangle - \ln W_j \right\} \tag{10}$$

$$r_{k\lambda} = \frac{1}{N^2 M^2} \left\{ \begin{array}{l} N^2 M Q_{k\lambda} + M \sum_{pq} Q_{kp\lambda q} \\ -NMf_7 + (NM-2)(N-1) f_9{}^2 \end{array} \right\} \tag{11}$$

where $Q_{k\lambda} = f_7$ or $Q_{k\lambda} = f_{10}$ for $k=\lambda$ and $k\neq\lambda$ respectively and $Q_{kp\lambda q} = f_8 - f_9{}^2$ for the cases where a) $k=\lambda=p=q$, b) $k=\lambda$, $p=q$, $p\neq k$, c) $k\neq\lambda$, $k=q$, $\lambda=p$, otherwise is zero and:

$$f_7 = s_w{}^{-1} \left[(0.5s_w+1)\left(\ln^2(0.5s_w+1)-4\right) - (1-0.5s_w)\left(\ln^2(1-0.5s_w)-4\right) \right] \tag{12}$$

$$f_8 = s^{-1} \left[(0.5s+1)\left(\ln^2(0.5s+1)-4\right) - (1-0.5s)\left(\ln^2(1-0.5s)-4\right) \right] \tag{13}$$

$$f_9 = s^{-1} \left[-s + (0.5s+1)\ln(0.5s+1) + (0.5s-1)\ln(1-0.5s) \right] \tag{14}$$

$$f_{10} = s_w{}^{-1} \left[-s_w + (0.5s_w+1)\ln(0.5s_w+1) + (0.5s_w-1)\ln(1-0.5s_w) \right] \tag{15}$$

Equations (7)-(15) determine the covariance matrix and hence the MVNCDF can be used to provide an estimate for the P_{RR} in the case of GM method as well.

The above equations hold for linear or non-linear weights for both EV and GM methods.

Moreover, we describe how the proposed theoretical model for the estimation of P_{RR} can be used in practical situations, where the decision maker has no prior knowledge of the statistical parameters involved (i.e. W_k, s and s_w). Our method is based on the fact that these parameters can be inferred by the elements of the pairwise comparison matrices obtained by the experts. The estimates $\tilde{s}$ and $\tilde{s}_w$ for the perturbation strengths s and s_w are determined through the second central moments of the pairwise comparison elements. We can easily show that the sum of the moments of the upper diagonal elements is given by:

$$\sum_{i<j} \left\langle \left(P_{ij}^{(m)} \right)^2 \right\rangle = s_w{}^{-1} f_1 f_2 f_3 \sum_{i<j} \frac{W_i^2}{W_j{}^2} \tag{16}$$

The parameters f_k are defined previously. The moments in the left hand-side can be approximated using the mean values I_{ij} of the squares of the actual elements provided by the experts, $\left\langle \left(P_{ij}^{(m)} \right)^2 \right\rangle \cong \frac{1}{M} \sum_m \left(P_{ij}^{(m)} \right)^2 = I_{ij}$. To obtain the best possible estimates $\tilde{s}$, $\tilde{s}_w$ and $\tilde{W}_k$ for the statistical parameters s, s_w and W_k we could try least square fitting the approximation to the left hand side of (16) to its right hand side. This would lead to a constrained multi-variable minimization problem which may be hard to solve. We instead choose to minimize the following parameter,

$$Q(\tilde{s}, \tilde{s}_w) = \left[\frac{1}{M} \sum_m \sum_{i<j} \left(P_{ij}^{(m)} \right)^2 - \tilde{s}_w{}^{-1} \tilde{f}_1 \tilde{f}_2 \tilde{f}_3 \sum_{i<j} \frac{w_i{}^2}{w_j{}^2} \right]^2 \tag{17}$$

In (17), the parameters $\tilde{f}_k$ are calculated from the equations provided for f_k in Section 2.5 by replacing s with $\tilde{s}$ and s_w with $\tilde{s}_w$, i.e. $f_1 = 1 + \tilde{s}_w^2/12$, $f_2 = 1 + \tilde{s}^2/12$ and $f_3 = \left(1 - \frac{1}{2}\tilde{s}_w\right)^{-1} - \left(1 + \frac{1}{2}\tilde{s}_w\right)^{-1}$ and we have also assumed that the average weights w_i provide a fair approximation for the original weights W_k (i.e. $\tilde{W}_k \cong w_k$). This approximation simplifies the minimization and provides reasonably accurate results. The two-dimensional minimization of the function $Q(\tilde{s}, \tilde{s}_w)$ can be performed using standard minimization methods or exhaustive search and yields the estimates $\tilde{s}$ and $\tilde{s}_w$. The estimated value $\tilde{P}_{\mathrm{RR}}$ of the probability of rank reversal can be determined in the same way as previously, where we apply the estimates $\tilde{s}$ and $\tilde{s}_w$ instead of the original statistical parameters s and s_w and use w_k as the as an approximation for the original weights W_k.

In this section, we have discussed a theoretical method for calculating the probability of rank reversal which quantifies the uncertainty of the outcome of pair wise comparisons. The method is based on the MVNCDF of the successive average weight differences. We have also theoretically calculated the mean value and cross correlation matrices of these differences that are needed in order to correctly use the MVNCDF. This was carried out both for the eigenvalue and the geometric mean methods of estimating the weights. The value of the theoretical method is twofold: first, it simplifies the estimation procedure, since we no longer need to rely on tedious and time-consuming Monte Carlo simulations used in numerical estimations of the probability of rank reversal. Second, much like any theoretical model, it can constitute a good starting point for further developing and extending the PWC framework. Our approach relies on a reasonable statistical uncertainty model that takes into account both the difference of opinions among the experts and the inconsistency in the completion of the pairwise comparison matrices. We have compared the results obtained through the MVNCDF, with those obtained through numerical simulations and a good agreement is observed, as representatively presented in Figure 4.

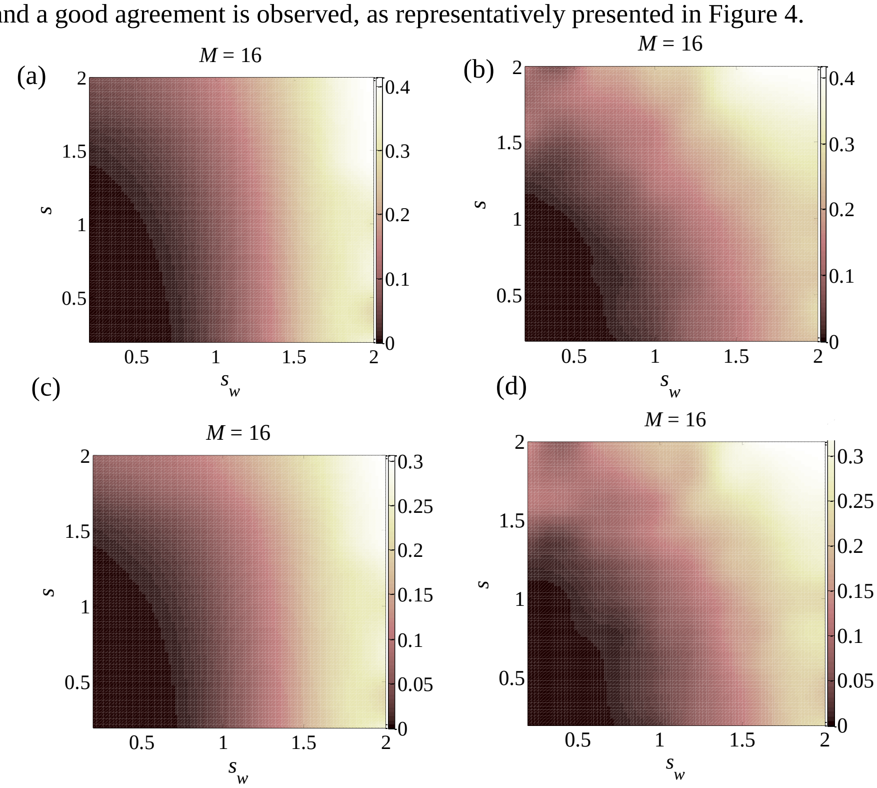

Figure 4. P_{RR} as a function of s and s_w for N=4 criteria and M=16 experts obtained by (a) the MVNCDF for EV, (b) MC simulations for EV, (c) the MVNCDF for GM, (d) MC simulations for GM

The results also show a slight advantage of the GM method over the eigenvalue method in terms of the probability of rank reversal. Finally, we discuss a procedure for estimating the probability of rank reversal in practice, where the statistical parameters are unknown. We show how that these parameters can be estimated just from the pairwise comparison matrices of the experts and that the error in the probability of rank reversal is reasonable. The methodology presented in this chapter can be used to extend the pairwise comparison framework in order to provide some information on the credibility of the final outcomes of the decision making process.

3 Conclusions

In this thesis, an effective roadmap for the next generation home network has been developed. Based on pairwise comparison surveys, a number of technical, economic and social issues determining the penetration of future home networks have been also evaluated. Using the AHP the ranking of the various technological alternatives comprising of IEEE802.11, 60GHz systems and PLC has been accomplished. The results focus on network extension but are also indicative for the rest of the home network components as well. AHP indicates that PLC takes some precedence over the wireless alternatives. 802.11 is ranked second best while 60GHz system are regarded as a longer term alternative, which could provide gigabit per second connectivity. The thesis also discussed the merits of hybrid integration of these technologies, either in the PHY or a higher network layer. A sensitivity analysis was also performed in order to estimate the uncertainties involved and it was deduced that they do not in general undermine the results of the ranking.

In this thesis an evaluation of the potential of OW technologies for home/office network deployments was carried out. A number of important findings were obtained which must form part of any type of carefully designed roadmap for optical home networking technologies. The results suggest that a combination of VLC and IR hotspots, along with a PLC backbone provides the most favorable option. In any case, the results clearly indicated the advantages of PLC backbone in terms of ease of installation in older buildings. The ranking results were also further elaborated using sensitivity analysis and Monte Carlo simulation.

Considering the uncertainty issues that may undermine the decision making processes, we have applied an uncertainty model to address two important issues concerning the probability of rank reversal in pairwise comparisons. The first issue concerned how this probability is reduced by augmenting the number of experts participating in the surveys. The results dictate that there is not much to be gained by increasing the number of experts beyond 15, even if uncertainty level is large. The second issue concerned the problem of how the probability of rank reversal can be estimated in practice, from the elements of the pairwise comparison matrices of a single expert group. Two alternative methods have been discussed for extracting information on the statistical behavior of the uncertainty-induced perturbations and one of them provides reasonable good accuracy.

Finally, we have discussed a theoretical method for calculating the probability of rank reversal which quantifies the uncertainty of the outcome of pairwise comparisons. The method is based on the MVNCDF. We have compared the results obtained through the MVNCDF, with those obtained through numerical simulations and a good agreement is observed. Finally, we discussed a procedure for estimating the probability of rank reversal in practice from actual user data, where the statistical parameters are unknown.

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