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***Abstract* — In this paper reliability and bandwidth demands of existing, new and expected classes of applications running over Fiber To The Home (FTTH) networks to private users and small enterprises are analysed and discussed. Certain applications such as home security and telemedicine are likely to require high levels of reliability in the sense that the demands for network availability are high; even short times without connectivity are unacceptable. To satisfy these demands, physical redundancy in the networks is needed. It seems to be the case that - at least in the short term - most reliability-critical applications do not require much bandwidth. This implies that redundancy do not need to be by fiber, but can be ensured by e.g. coax, copper or wireless solutions. However, implementing these solutions need careful planning to ensure the physical redundancy. In the long term, it is more likely that physical redundancy by fiber will be requested, either due to reliability-critical bandwidth-critical applications or due to the general dependency on network connections. The paper is ended by a discussion and suggestions for further research. In particular, further research in combined wired/wireless networks and implementations of fiber redundancy is encouraged.**

***Keywords* — Network Planning, Quality of Service, Access Networks, Fiber To The Home, Convergence.**

1. Introduction

The convergence of communication technologies[1] has led to a large number of applications being capable of operating over a common communications infrastructure. This trend is supported by the implementation of fiber access networks, also known as Fiber To The Home (FTTH), which offer always-on functionality together with huge bandwidths. This can be seen in existing FTTH implementations, where telephony, radio, television, Video on Demand and broadband Internet is delivered through the same single fiber connection. Since broadband Internet is included, the same fiber is likely to be used for Internet based applications such as surveillance, control of Intelligent houses, health monitoring etc.[2][3]. While it is practical and cost-efficient to have one general-purpose network instead of a mixture of dedicated networks, it also affects reliability and dependability: when one single fiber is used for virtually all medias, the increasing dependability on this one connection must be considered. Furthermore, applications such as telemedicine and surveillance, where even a short time without connectivity may be very critical, may by themselves require a level of reliability, which can only be obtained by physical redundancy. Breach of a wired connection is expected to take from hours to days to restore.

Despite the development of reliability-critical applications and increasing general dependency, most FTTH implementations today do not offer any physical redundancy to the end user. Recent research has dealt with developing and describing robust network topologies[4], but since redundancy in the last mile in FTTH networks is assumed to be expensive and often impractical, only little attention has been paid to this. We recently showed that wireless back-up connections could be designed as an integrated part of a FTTH network[5]. However, the potential bandwidth of a wireless network is much smaller than that of a fiber network due to the limited and shared bandwidth.

The main objective of this paper is to initiate a discussion of reliability and redundancy demands in last-mile FTTH implementations. This is done in two steps.

First, reliability and to some extent bandwidth demands of existing applications as well as applications expected to become widely used within 10-15 years are analysed. Only applications for private households and small enterprises are taken into account since public institutions and larger enterprises are expected to be connected by individual solutions rather than by general-purpose access networks. In particular, ordinary access networks are not expected to carry applications such as tele operations, control traffic for nuclear power plants or traffic for a complete emergency central.

Second, a discussion is given on the possibilities of offering physical redundancy in the last mile, and areas for further research are identified.

The work presented complements existing research in application demands, which has mainly focused on bandwidth and Quality of Service. The reliability offered is highly dependent on the physical topologies, and in case of FTTH networks, these are expected to have a long lifetime. Since they are expensive to change once implemented, they should be designed either to meet future reliability demands, or at least in a manner such that they are easily extended to meet these. In order to be able to do so, knowledge of reliability demands is crucial both for research in reliable networks and for practical network planning.

2. Methods

The analysis of reliability and bandwidth demands is carried out in three steps. Identification of existing applications is done by studying published literature on Internet applications as well as the services offered by major Danish FTTH providers. Identifying applications which will become widely used during the next 10-15 years is harder, because new applications are being developed all the time, and many technical and non-technical factors influence their success and speed of propagation. However, important trends are pointed out.

In the second part of the analysis, applications are classified according to how critical they are with regard to reliability and bandwidth, using rather narrow classification schemes. The applications are first divided into two groups, depending on how critical they are to short-term outages (from a few minutes to a few hours). The group of reliability-critical applications are those, which carry life/death responsibility as well as applications where even short-term outages are likely to lead to significant economic losses. In both cases, it is crucial that no single failure cause the connectivity to break. All other applications are categorized as being non-critical. The reliability-critical applications are also called high-reliability demanding (or simply high-reliability), and the non-critical applications called low-reliability demanding (or simply low-reliability). Since focus is mainly on the last-mile reliability, the importance of applications is seen from a single-user point of view: for example, a small set of private households may be able to live without applications such as WWW for a limited time, whereas disconnecting a whole city or a whole municipality may have other implications. Reducing the risks for such large network failures does not necessarily require redundancy in the last mile, and these problems are not discussed further. For certain groups of applications it is crucial that at least one application from each group has a high level of reliability, but less important which one. For example, it is crucial for a community that radio and television are not simultaneously unavailable because broadcast communication is important in case of catastrophes, emergencies, wars etc. Since the high-reliability high-bandwidth applications are the most important to consider when designing redundancy, high-reliability applications are treated most in-depth with regard to bandwidth. The applications are divided into two groups - high-bandwidth and low-bandwidth - depending on whether they use high-quality video or not[6]. This is due to the assumption that applications not using high-quality video are able to run over other access technologies than FTTH, including wireless, copper and coax. However, Many applications, which can run over slow Internet connections, run better over fast connections, and each of the access technologies offer different bandwidths depending on a number of parameters.

In the last part of the analysis, network reliability and needs for redundancy are discussed in a broader perspective. The classifications given above are loosened up, such that also less reliability-critical applications are discussed.

It is in place to motivate the method used; offering physical redundancy is one way to obtain a high availability, but choices of equipment, wiring, cables and ducts are also important. In the end, measures such as availability, mean time of failure and mean time of repair may be more appropriate to use - and more interesting for the end users - than redundancy or no redundancy. The reason for using the method described is that the degree of the redundancy is highly dependend on the physical topologies and structures of the network, whereas the other factors are more a matter of equipment. FTTH Networks are expected to have a long lifetime, at least 30 years, and they are designed to be upgradeable by changing end equipment only. Together with the fact that the major cost of FTTH networks are the duct costs, this means that the equipment is both cheaper and easier to upgrade than the physical topologies. Therefore, these topologies should to the largest possible extent be chosen to meet the demands of the future, including demands for redundancy. The applications classified as reliability-critical are applications, for which it is unacceptable that a single cable cut can disconnect the network, independent of the reliability of the equipment used.

3. Identifying applications

The digitalization of communication has created a base for media convergence, and more and more applications are being designed to communicate over IP. An example is telephony, which has traditionally been sent over circuit switched networks. The use of Voice over IP is increasing fast, and TV over IP is likely to be the next step. In order to identify the different groups of applications, this section is divided into Applications today, Current applications moving from LAN to WAN environments and New applications. The aim is not to give a complete list of applications, but to cover the most widely used applications today, as well as those expected to become widely used the next 10-15 years. The list may not cover all groups of applications, but we believe it is representative for the most widely used applications today.

3.1 Applications today

3.1.1 Classical Internet applications

Well known Internet applications today are WWW, Telnet, Email, FTP and other types of file-transfers, e.g. Peer-to-Peer. WWW-traffic can be split into a number of applications including entertainment, information retrieval, home banking, business use and shopping. Many of the applications are client-server applications, where the servers have traditionally been placed at places with dedicated connections. However, private servers are becoming increasingly popular.

3.1.2 Person-to-person communication

The Internet is to an increasing extent being used for real-time person-to-person communication such as instant messaging, Voice over IP, chat and video-chat/video-conferencing. These can be one-to-one, one-to-many or many-to-many.

3.1.3 Entertainment and broadcast

Internet-based broadcast services like radio and television, and also other non-interactive services such as Video on Demand are, becoming increasingly popular, and are also implemented in most FTTH solutions. Slightly more interactive services are for example digital television, where the viewers can vote or by other simple means provide feedback while watching television. Today, radio programs where the listeners can participate in the program by phone are popular. This also defines some level of interactiveness, which may be transferred to the television as well, since the bandwidth of FTTH networks allows the viewers to participate through video sessions. Other kinds of interactive entertainment include gaming over networks.

3.1.4 E-learning

E-learning is mainly based on technologies already listed, including WWW, file-transfers and real-time person-to-person communication. Therefore, it is not further discussed.

3.1.5 Home offices

More and more companies offer the employees the possibility to work fully or partly from home. This brings a number of technologies into play, including various person-to-person communication means and remote access to desk tops and data. A number of new technologies are expected to be used as well, as described in section 3.3.

3.2 Current applications moving to WAN

3.2.1 Telemedicine and health care

Much research today is made in the area of tele health and medicine. This area is not quite new, and many fields exist within it[7]. We shall differ between tele care/monitoring and other applications. Tele care/monitoring includes real-time monitoring of ill or elderly people, for example by sending information on heart rate, cardiograms or lung functions directly to a hospital for real-time analysis. Possibly, information can also be send the other way, and used e.g. for adjusting medication. Other applications such as information search, e-learning and real-time consultations are covered by previously discussed technologies.

3.2.2 Remote home control

Various applications in the field of remote control of homes are being developed, and the perspectives are many: it is possible to control such things as temperature and electric equipment from a remote location, for example by WWW[8]. This also allows for home security solutions, where the high bandwidth is used for sending audio and video. This can be used to record video/audio clips of alarm events, but also to get real-time video from the home to watch for example pets and kids.

3.3 New applications

It is impossible to predict what applications will become the most widely used during the next 10-15 years, but given the trends in communication and networking, the following factors are expected to be important in application development:

- Allways-on
- High bandwidth
- QoS

The main difference between FTTH and today's broadband solutions is the bandwidth, which allows for real-time video and similar. This will probably lead to further developments in the area of entertainment and video conferencing. While the possible developments in the field of entertainment are virtually unimaginable, the developments in video meetings and video conferencing also hold great potentials. For example, it will become easier to teach people in their private homes, and even the teacher can sit in his private home. Not only the teacher can be seen, but also presentations, videos and similar, and the communication can be both ways. Similarly, it will become easier to hold meetings over distance, and cooperation over distance will be facilitated.

Machine-to-machine communications is another important field, expected to develop as more intelligent machines are entering the private houses. Until now, transfer of high-quality video has been considered the major bandwidth consumer, but this may change in the future. Today, most companies and institutions make back-ups of data more or less manually. This is often done with small intervals, e.g. each night or each week. In near future, even non-critical private data such as photo albums and home videos are expected to be stored or backed-up in storage area networks. It is also expected that working from home will become still more common, all together adding to increasing needs for remote back-ups.

Similarly, it is a common vision that in near future, it will become possible to access private data, desk-top configurations, settings and applications from any computer connected to the Internet. Making this transparent to the user also requires huge bandwidths.

4. Analysis of bandwidth and reliability demands

4.1 Applications today

4.1.1 Classical Internet applications

For most of these applications, shorter outages are acceptable, and as such they are not considered reliability-critical. Certain WWW applications such as home banking may however be critical, because it is important to be able to pay bills and perform other important transactions on time. The increasing use of home banking may also decrease the number of bank branches, thus limiting the alternatives to home banking. Such problems are worsened if telephony uses the same last-mile technology as WWW. Access to WWW may be important in case of war, disasters or similar. However, it is assumed that information in these cases can as well be carried via TV, radio or some other broadcast media, and therefore it is not considered critical.

The bandwidth demands varies between applications, but in general the more bandwidth the better performance. This is in particular so for transfer of images and video, which are common in file transfers and also becoming increasingly integrated with WWW-surfing.

A special remark is given to server hosting; the bandwidth demands can vary greatly, but ordinary Internet connections are not assumed to be used for reliability-critical information, and they are therefore categorized as non-critical. If redundancy is offered they will more likely be used also for reliability-critical applications and data.

Thus, most applications are low-reliability low-bandwidth or low-reliability high-bandwidth. Some high-reliability low-bandwidth applications also exist.

4.1.2 Person-to-person communication

As for WWW access, it is assumed that most important information to the public can be delivered through broadcast medias, and therefore most of these applications are not considered reliability-critical.

In section 1, it was defined that only reliability demands for ordinary households and small enterprises were considered, but it is not so trivial to define what is an ordinary household. For example, fire fighters, policemen, soldiers and civil defence people are usually normal people, moving to and from normal houses. Therefore, it is desirable if the normal communication network offer a reliability satisfactory also for these purposes. Thus, voice communication is categorized as reliability-demanding.

With regard to bandwidth, the video applications require much bandwidth while the rest do not. Therefore, this group of applications contain both low-reliability high-bandwidth, low-reliability low-bandwidth and high-reliability low-bandwidth applications.

4.1.3 Entertainment and broadcast

Entertainment and broadcast contain many different applications. The broadcast applications are considered reliability-critical because they are important in case of catastrophes, disasters, wars, and in general for communication of messages in case of water pollutions, fires etc. It does not matter if radio or television is used: the most important is that there is at least one media available. Other applications in this field are not considered reliability-critical.

With regard to bandwidth, simple radio communication does not require much bandwidth, and even some low-quality television can be sent using only a limited bandwidth. This is especially so if broadcast protocols can be used, eliminating the shared-bandwidth problems of coax and wireless technologies. Some of the other not reliability-critical applications require high bandwidths.

In conclusion, this group of applications contain low-reliability high-bandwidth, low-reliability low-bandwidth and high-reliability low-bandwidth applications.

4.1.4 Home offices

The more specific applications are described and analysed in other sections, and due to the definition of reliability-critical, they are not classified as such. However, the increasing focus on performance, quality and reliability of computers and networks in businesses[9] is expected to be reflected in the requirements to home offices, such that the demands will approach those of the business networks. This does, at least, increase the general reliability demands.

4.2 Current applications moving to WAN

4.2.1 Telemedicine and health care

The tele care and monitoring applications are high-reliability, whereas the other health applications are low-reliability.

The bandwidth demands are harder to determine, because the field is developing so fast. Currently, most of the high-reliability applications transmit only small amounts of data, and as long as the applications are machine-to-machine, they are expected to require only low bandwidths. This assumption is supported for a part of the patients, since they are ensured mobility by making it possible to communicate over the mobile phone network, thus not requiring a broadband connection. The demands may increase in the future if the applications are integrated with video monitoring. The bandwidth demands of the low-reliability applications are higher, because they involve high-quality video presentations and conferencing. However, some of the applications require less bandwidth.

Therefore, this group of applications contain low-reliability high-bandwidth, low-reliability low bandwidth and high-reliability low-bandwidth applications. In the future, high-bandwidth high-reliability application may be developed, but these will probably not become widely used unless the reliability demands can actually be satisfied.

4.2.2 Remote home control

The demands for reliability depend on a number of factors, including the application design. For example, applications for controlling windows, doors and electric equipment should be designed to handle network failures in a specified manner, and as such they are not reliability-critical. Home security and home surveillance/monitoring are however considered high-reliability demanding because it should not be possible to interrupt their functions by cutting a wire.

The bandwidth demands depend on whether video transmissions are integrated in the applications or not. Today, home surveillance is usually done using sensors, and if a sensor is activated, the alarm is started and a message passed to some control centre and/or a phone number. This does not require much bandwidth. If the alarm is integrated with one or more video cameras, the bandwidth demands are higher. Monitoring of children who are home alone will usually require a number of cameras, which should preferably but not necessarily be able to send data simultaneously. For all the cases listed, human action eliminating the consequences in case of network failures can be taken; monitoring children or pets only make sense if someone can take action if something goes wrong, and for alarm systems, actions can be taken similar to that of the alarm going off. On the other hand, it is also in both cases desirable to have a (possibly low-bandwidth) back-up in order to avoid a collection of houses being disconnected and emptied by thieves. Therefore, such low-bandwidth applications are characterized as high-reliability demanding. In addition, there are other low-reliability low-bandwidth and low-reliability high-bandwidth applications.

4.3 New applications

During the analysis, a number of low- and high-bandwidth demanding applications were identified, but none of these seem to be reliability-critical. However, it is likely that a wider deployment of FTTH networks will lead to more bandwidth-demanding applications being developed, including applications demanding reliability. This is particularly so if the reliability is offered, such that a base for such applications exist.

5. The broader perspective

Even for applications not categorized as reliability-critical, there is an increasing dependency on broadband networks. When working from home, critical situations may occur, if an email is to be sent by a certain deadline, or if a lecturer has to give a lecture at a certain time. It may also be necessary to access informations at the WWW, make a voice call or participate in an important video meeting at a given time. Many more cases could be mentioned. It follows that in order to fully benefit from the technological opportunities, the connections must be reliable.

For the FTTH providers, redundancy also play another important role: it allows for more efficient planning of maintenance and repairs. If physical redundancy is offered, a single error becomes less critical and may not require instant repair.

As stated in section 1 and shortly discussed in section 4.1.2, only reliability-criticalness for ordinary home end users and small enterprises were considered. However, it is likely to expect an increasing demand for redundancy, either for specific purposes or because of general dependability on networks. Such specific purposes also cover those not considered reliability-critical in this paper.

6. Conclusion

It turns out that the applications analysed fall in three main categories: High-bandwidth not reliability-crtical applications, low-bandwidth reliability-critical applications and low-bandwidth not reliability-critical applications.

The main application categories which are reliability-critical are the following.

- Telemedicine including health monitoring.
- Surveillance, home security, home control applications and other applications communicating machine-to-machine.
- Communication applications such as voice and radio.

Future development may lead to more integration of high-quality video in these applications, creating demands for both high bandwidth and high reliability.

In addition to these specific reliability-demands, the general dependability on network connections is also expected to increase: the trend of individuals, businesses and communities relying to an increasing extent on communication networks is expected to continue.

7. Discussion

The analysis showed that not all applications expected to become widely used within 10-15 years should be vulnerable to single points of failure in the last-mile technologies serving private end users and small enterprises. On the other hand, the most reliability-critical applications seem not to require much bandwidth, indicating that some low-bandwidth alternatives can be used for back-up to the individual private end users and small enterprises.

In an environment of converged communications, these alternatives can be provided using todays broadband solutions such as copper and coax, as far as they are available. However, physical redundancy is only ensured if these networks and the FTTH networks do not share ducts and nodes. Unless specially planned for, they mostly do so. Even if physical redundancy is ensured, it is unsure if there is base for maintaining a complete cabled network only for back-up purposes.

Wireless back-up solutions provide sufficient bandwidth for the most critical applications. This motivates further research to be conducted on design of integrated wired/wireless solutions, where the physical connections are fully independent, and where seamless protection and restoration schemes are

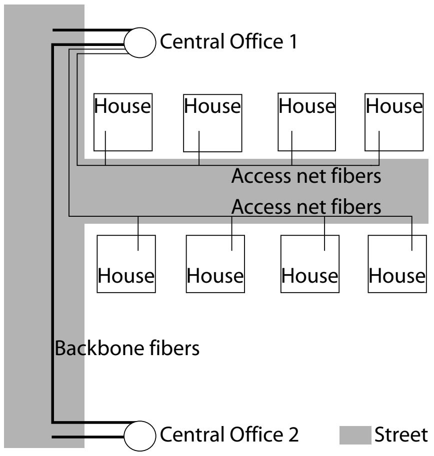

Figure 1. Typical FTTH-wiring on a residential street with houses on both sides of the street. The solution may be fiber rich (providing a single fiber for each house), or the fibers may be shared.

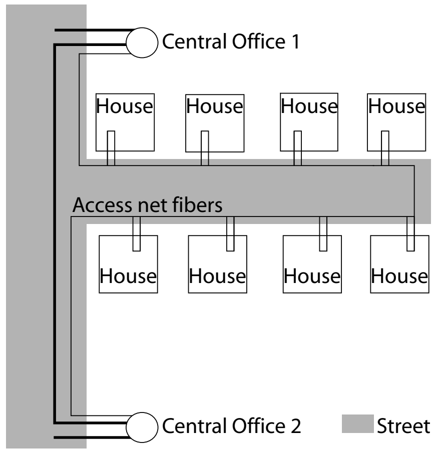

Figure 2. Proposed FTTH-wiring, ensuring physical redundancy. Compared to Figure 1, each house is now provided with a double wiring and connected to two Central offices.

supported. In order to obtain a sufficient bandwidth for back-up purposes, the base stations need to be placed not too far from each other, and will most likely be connected by the FTTH fiber infrastructure. It is therefore necessary to connect these base stations in a manner ensuring physical redundancy.

A final possiblity, and probably the most appropriate long-term strategy, is to implement the FTTH networks in a way ensuring complete physical redundancy. Until now, this has been considered impractical and expensive, but apparently this does not always hold. For example, consider a FTTH implementation on a residential street with houses on both sides of the street. Figure 1 shows the usual wiring, but if the wiring is done as shown in Figure 2 instead, wired redundancy is ensured. While the cost in terms of equipment and fiber may be a bit higher, the duct costs (which are the most significant) are only slightly higher. In order to take advantage of this redundancy, it is however necessary to develop configurations and preferably passive equipment supporting restoration/protection schemes.

It is certain that designing FTTH networks with redundancy is cheaper than designing non-redundant networks and adding the redundancy later on. We therefore believe that the FTTH implementations where possible should be designed either to offer redundancy or in a way, such that redundancy can be added afterwards by changing as little a part of the infrastructure as possible. Doing so also makes it possible to offer redundancy to those requesting it, even when people are moving, without needs for additional investments.

Despite the possibilities of offering wired redundancy, wireless solutions have some major benefits due to the different failure characteristics. In particular, it is more difficult to disconnect a household on purpose, because the wires cannot be cut, making it suitable for surveillance and monitoring. A wireless back-up is also - in a larger scale - less vulnerable to failures caused by e.g. wars or nature catastrophes, but due to the shared-bandwidth problem this would require a larger number of base stations to ensure sufficient capacity in such cases.

As a final remark, it should be mentioned that the most demanding applications are likely to be developed only if they are supported by the infrastructures. Unless sufficient redundancy - even in the last mile - is ensured, the networks will remain unreliable, and it will not be possible to fully benefit from the technological opportunities. Thus, the importance of a carefully planned infrastructure should not be underestimated.

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